

Nebulae and Star Clusters Series

Seyfert Galaxies

by KANEKO Noboru



Chijin Shokan



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Preface

The discovery of activity in galactic nuclei is one of the greatest achievements of modern astronomy, and Seyfert galaxies — the subject of our research — are known as the objects that display the most typical nuclear activity of all.

The astronomical term “Seyfert galaxy” has become fairly widely known in recent years, but the material presented about them is clearly fragmentary. It is fortunate if even a few pages of an astronomy book are allotted to the subject. Yet the problems that Seyfert galaxies pose are not simple enough to be explained in a few pages. Seyfert galaxies are an independent field of research in their own right, and at the same time they are deeply connected with radio galaxies and quasars, and further with the formation and evolution of galaxies. Considering this importance of Seyfert galaxies, I do not think I am the only one who feels that the fact that not a single book has been published dealing with them leaves our astronomical knowledge unbalanced. In this sense, the addition of Seyfert galaxies to this series — quite apart from whether the author is the right person to write this volume — can be called a meaningful undertaking for the popularization of galactic astronomy. If this book can fill a blank field, nothing would give me greater pleasure.

I offer my heartfelt thanks to Mr. Ichikawa Masanori [市川正徳] of Chijin Shokan, who took care of the publication of this book; to Professor Ōno Yōrō [大野陽朗] and Professor Sakashita Shirō [坂下志郎], who continued to encourage me over these three years; to everyone in the Astrophysics Laboratory at Hokkaido University; and — though it is a personal matter — to my wife as well.

March 1982

KANEKO Noboru [兼古 昇]

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Chapter I. The Discovery of Activity in Galactic Nuclei

1. The Nucleus of the Andromeda Galaxy

When the Andromeda Galaxy M 31 is observed with a large telescope, a bright, almost stellar point can be seen at its center. This is the nucleus of M 31, known as the quasi-stellar nucleus. Figure 1.1 is a high-resolution photograph of the nucleus of M 31 taken with the 91 cm stratospheric telescope. Its visual magnitude is $V = 12.6$ and its diameter is 10 pc. The nucleus of M 31 is not perfectly spherical; it is somewhat flattened in the direction 63 degrees from north toward east (position angle = P.A. 63°).

The nucleus of M 31 rotates at the high velocity of 104 km/s at maximum, with its minor axis as the rotation axis (Figure 1.2). For the nucleus to exist stably against this rotational motion, the centrifugal force produced by the rotation must be balanced by the nucleus's own gravity, and the mass of the nucleus is calculated to be 160 million times the solar mass ($1.6 \times 10^8 M_\odot$). This corresponds to about one-thousandth of the total mass of M 31. In the solar neighborhood the mean stellar density is $0.6 M_\odot$ per cubic parsec, so the mass within a sphere 10 pc in diameter would be only $30 M_\odot$. Even globular clusters, the densest of star clusters, are about 10 pc in size, yet their mass is $\sim 10^5 M_\odot$. The nucleus of M 31 is thus denser than any star cluster. Table 1.1 summarizes the properties of the nucleus of M 31.

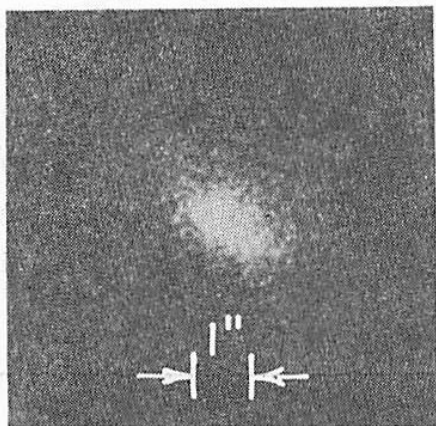


図 1.1 M 31 の準恒星状核. 成層
 圏望遠鏡(stratoscope)は口
 径 91 cm, $f/100$ の光学系を
 持ち, 気球によって高度 25
 km の上空に運ばれる. この
 写真は 103 aG フィルムと
 GG-13 フィルターの組合せ
 ($\lambda\lambda 3,600\sim 6,000\text{\AA}$) で, 24
 分露光された. $1''=3\text{ pc}$ (E.
 S. ライトマン, R. E. ダニ
 エルソン, M. シュワルツシ
 ルド 1974).

Figure 1.1 The quasi-stellar nucleus of M 31. The stratoscope has a 91 cm aperture and an $f/100$ optical system, and is carried by balloon to an altitude of 25 km. This photograph was taken with a combination of 103 aG film and a GG-13 filter ($\lambda\lambda 3,600\sim 6,000\text{ \AA}$), with an exposure of 24 minutes. $1''=3\text{ pc}$ (E. S. Light, R. E. Danielson, M. Schwarzschild 1974).

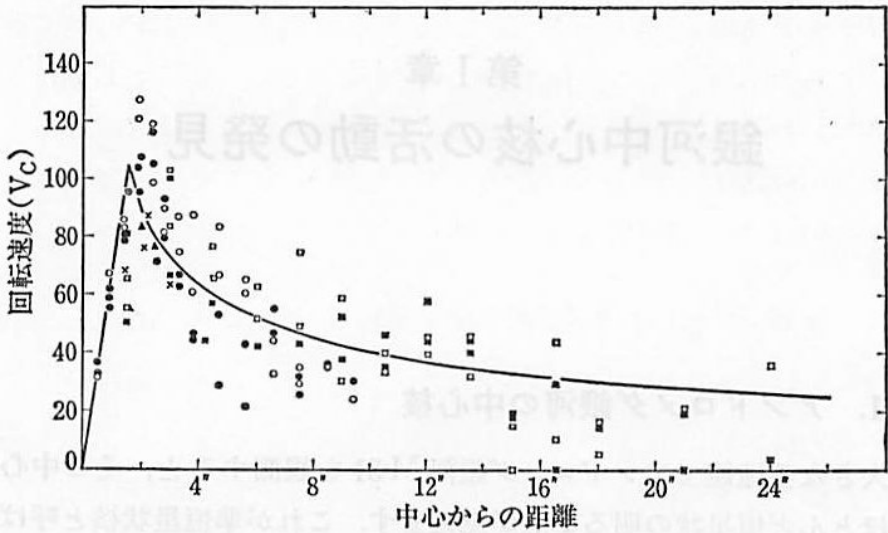


図 1.2 M 31 準恒星状核の回転曲線. 丸印はリック天文台 3 m 望遠鏡のクーデ分光器にラルマン電子カメラを取付けて得た資料. 角印は主焦点分光器による. $\times$ 印は 1959 年の結果. 黒く埋めた印は北東側, 空白印は南西側を示す. (M. F. ウォーカ 1974).

Figure 1.2 Rotation curve of the quasi-stellar nucleus of M 31. Circles denote data obtained with a Lallemand electronic camera attached to the coude spectrograph of the Lick Observatory 3 m telescope. Squares are from the prime-focus spectrograph. Crosses are the 1959 results. Filled symbols indicate the northeast side, open symbols the southwest side. (M. F. Walker 1974).

Vertical axis: rotation velocity (V_c) Horizontal axis: distance from center (4", 8", 12", 16", 20", 24")

Table 1.1 The quasi-stellar nucleus of M31

Quantity	Value
Diameter	10 pc
Mass	$1.6 \times 10^8 M_{\odot}$
Mean density	$3 \times 10^5 M_{\odot}/\text{pc}^3$
Apparent magnitude (V)	12.6
Luminosity	$5.5 \times 10^6 L_{\odot}$
Mass-to-light ratio (M/L)	$30 M_{\odot}/L_{\odot}$
Maximum rotation velocity	104 km/s
Rotation period	$3.1 \times 10^5 \text{yr}$
Velocity dispersion (σ)*	120 km/s

* D. C. Morton and T. X. Thuan (1973)

2. Nuclei with Emission-Line Spectra

The nucleus of the Andromeda Galaxy has a very quiescent character. Spectroscopic observations show only stellar absorption-line spectra within this nucleus, so it is thought to be an enormous aggregate of stars.

There are, however — though not many — galaxies with strong emission-line spectra indicating the presence of ionized gas within the nucleus. These were discovered gradually through early spectroscopic observations of galaxies. In 1908, E. A. Fath discovered that NGC 1068 has an emission-line spectrum. V. M. Slipher is famous as the astronomer who discovered the redshift in galaxy spectra that indicates the expansion of the universe, but in 1917 he noticed that the emission lines of NGC 1068 were not monochromatic. In 1918, W. W. Campbell and J. H. Moore discovered that the emission lines of NGC 1068 were as much as 30 Å broad, and that the emission lines of NGC 4151 were similarly broad. In 1926, E. P. Hubble reported that the emission-line spectrum of NGC 4051, like those of NGC

1068 and NGC 4151, resembles that of a planetary nebula. By the first half of the 1930s, NGC 1275, NGC 3516, and NGC 7469 had also become known as galaxies with emission-line spectra.

These galactic nuclei with emission-line spectra, however, scarcely became objects of study for the astronomers of the time. On page 46 of E. P. Hubble's celebrated 1936 book *The Realm of the Nebulae*, the properties of galactic nuclei are described as follows:

In general the nuclei are almost stellar and are too small to be studied by photographic methods. In late-type spiral nebulae (M 33) the nucleus stands out from the faint surrounding regions and resembles a globular cluster. In rare cases the nucleus appears stellar against any direct test. In general such nuclei are relatively bright and show an emission-line spectrum resembling that of a planetary nebula (with N_2^* brighter than H_β). Therefore, in spite of their appearance, they cannot be considered single stars in the ordinary sense.

Yet on page 51 he goes no further than to state:

The relatively rare stellar nuclei with emission-line spectra resembling planetary nebulae have already been mentioned. The significance of these spectra is unknown, but considering how rare they are, they may be ignored at the preliminary stage of investigation.

3. Seyfert's Observations

In 1943, Carl K. Seyfert (Figure 1.3) published a paper entitled "Nuclear Emission in Spiral Nebulae." He regarded galaxies in which many highly excited emission lines are localized in the nucleus as special, though few in number, and listed the 12 then known as galaxies belonging to this anomalous class. He further selected six of them — NGC 1068, NGC 1275, NGC 3516, NGC 4051, NGC 4151, NGC 7469 — and carried out detailed observations of (1) the magnitude of the nucleus, (2) the color temperature of the continuous spectrum, (3) the profiles of the emission lines,

and (4) the emission-line relative intensities. The 1.5 m and 2.5 m telescopes of Mount Wilson Observatory were used for the observations. As a result, he brought to light the following remarkable facts.

* The forbidden line of doubly ionized oxygen, [O III] $\lambda 4959$.

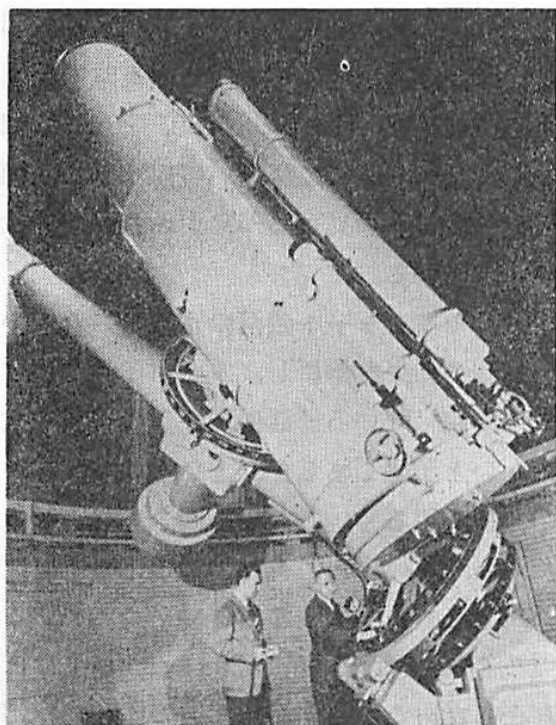


図 1.3 カール K. セイファート (左) と J. J. ナッソー (右). 写真の望遠鏡はワーナー & スワージー天文台の 24/36 インチ・シュミット・カメラ. (スカイ & テレスコプ, 1965 年 7 月号 8p)

Figure 1.3 Carl K. Seyfert (left) and J. J. Nassau (right). The telescope in the photograph is the 24/36-inch Schmidt camera of the Warner & Swasey Observatory. (*Sky & Telescope*, July 1965 issue, p. 8)

- a. The nucleus is so small as to be almost indistinguishable from a star, and yet is extremely bright. The fraction of the light of the whole galaxy

contributed by the nucleus is 6% in NGC 1068, the lowest, and reaches as much as 48% in NGC 4151, the highest.

- b. The emission lines have widths of several tens of ångströms. In NGC 1068 the hydrogen Balmer lines and the forbidden lines have almost identical profiles, with widths corresponding to Doppler velocities of as much as 2500–3600 km/s. In NGC 4151 the forbidden lines are all relatively narrow, 1000–1800 km/s, but the Balmer lines have widths of 7500 km/s. The same is true for NGC 3516, NGC 4051, and NGC 7469.
- c. The emission-line spectra show an extremely wide range of ionization states, from the forbidden lines emitted by neutral nitrogen and oxygen — [N I] $\lambda 5199$, [O I] $\lambda\lambda 6300, 6364$ — to those of doubly ionized oxygen and neon — [O III] $\lambda\lambda 4959, 5007$, [Ne III] $\lambda 3869$ — and on to [Fe VII] $\lambda 6086$ of six-times-ionized iron. The relative intensities differ somewhat from galaxy to galaxy, but on the whole they resemble those of the planetary nebula NGC 7027.

These three properties are what constitute the present-day definition of a Seyfert galaxy. Analyzing his observational results, Seyfert anticipated that the widths of the Balmer lines emitted by hydrogen atoms must be related to the scale of the “activity phenomenon” occurring within the nucleus. This was because the broader the Balmer lines of a galaxy, the brighter its nucleus, and the higher the fraction of the total galactic light contributed by the nucleus. He further confirmed that no broadened emission-line spectra were present in NGC 5471, a gaseous nebula in a spiral arm of M 101; in NGC 604, in a spiral arm of M 33; or in 30 Doradus, the giant gaseous nebula in the Large Magellanic Cloud. From this he inferred that the nuclei emitting the emission-line spectra he had observed must be fundamentally different from ordinary gaseous nebulae. He closed his paper with the words: “Further discussion will be published as a contribution being prepared jointly with

Dr. R. L. Minkowski.” However, so far as the present author is aware, this joint paper was never published.

4. Radio Galaxies and Galactic Nuclei

The importance of the galactic nuclei that Seyfert observed came to be recognized anew in the latter half of the 1950s. This was owed to the progress of radio astronomy, which began with K. Jansky’s discovery in 1931 of radio waves coming from the direction of the center of the Milky Way and with G. Reber’s pioneering observations.

In 1949, J. G. Bolton, G. J. Stanley, and O. B. Slee succeeded in identifying the radio source Centaurus A in Centaurus and the radio source Virgo A in Virgo with the elliptical galaxies NGC 5128 and M 87 respectively. A particularly noteworthy example is the optical identification of the radio source Cygnus A in Cygnus. When F. G. Smith succeeded in 1951 in determining the precise position of Cygnus A, W. Baade and R. Minkowski discovered there in 1954 a faint 17th-magnitude object that looked as though two galaxies were colliding (Figure 1.4). Furthermore, in 1956, R. Minkowski carried out spectroscopic observations of NGC 1275, the radio source Perseus A in Perseus, and announced the discovery of emission-line components thought to come from galaxies colliding at the high velocity of 3000 km/s.

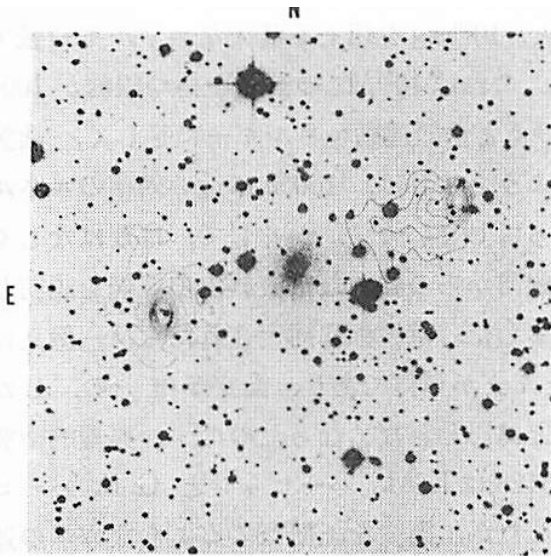


図 1.4 はくちょう座の電波源 Cygnus A. 波長6cmで観測された対状電波源が写真に重ねられている。(A. T. モフエット 1975).

Figure 1.4 The radio source Cygnus A in Cygnus. The double radio source observed at a wavelength of 6 cm is superimposed on the photograph. (A. T. Moffet 1975).

Why, then, should two colliding galaxies emit powerful radio waves? The explanation initially favored was plasma oscillation of high-temperature gas within the galaxies. It soon became clear, however, that any attempt to explain the observations in this way required the plasma density to be too high, contradicting the observational facts. The correct answer was supplied by I. S. Shklovsky. In 1953 he predicted that synchrotron radiation — emitted when high-energy electrons are accelerated by a magnetic field — was the radiation mechanism responsible for the radio and visible light of the Crab Nebula, which was produced by a supernova explosion, and that as evidence of this, strong polarization should be observed. This prediction was immediately confirmed by observation. That the outflowing object — the “jet” — which appears to be ejected from the nucleus of M 87 (Figure 4.19) also emits synchrotron light was splendidly demonstrated by W.

Baade's polarization observations carried out in 1956, and synchrotron radiation became beyond doubt.

When G. R. Burbidge applied this synchrotron radiation theory to radio sources such as Cygnus A and calculated a lower limit to the total energy carried by the high-energy particles, it turned out to be an enormous quantity exceeding 10^{60} erg. This is equal to the kinetic energy of a galaxy of mass $10^{11} M_{\odot}$ moving at a velocity of 1000 km/s, so that interpreting radio galaxies by the collision hypothesis would require an energy-conversion mechanism of nearly 100% efficiency. Thus it became evident that the collision hypothesis, brilliantly though it had been proposed, could not explain the mechanism of the powerful radio emission from galaxies. Most of the galaxies identified with radio sources — M 87 of Virgo A, for example — are single objects, and collision no longer seemed to be the sole, still less the necessary, explanation of radio galaxies. NGC 5128, regarded as a typical colliding galaxy, was observed by E. M. Burbidge and G. R. Burbidge, but no gas motions attesting to a collision were found at all.

Once the collision hypothesis was rejected, the origin of radio galaxies came to be sought in explosive phenomena in the nucleus. As early as 1958, V. A. Ambartsumyan had published the view that a large amount of matter must be being ejected from galactic nuclei. In 1960 I. S. Shklovsky, and subsequently in 1961 G. R. Burbidge, put forward the supernova hypothesis, according to which supernova explosions occur at an abnormally high frequency inside the nucleus because of the high density there, producing the high-energy particles required for the radio emission. F. Hoyle and W. A. Fowler, on the other hand, proposed in 1963 the supermassive-star hypothesis: that a single star of enormous mass — as much as $10^8 M_{\odot}$ — a supermassive star, forms inside the nucleus of a galaxy, and that the process of the hypersupernova explosion arising from its rapid evolution is the origin of Seyfert galaxies and radio galaxies.

What made this explosion theory of galactic nuclei decisive was surely the observations of C. R. Lynds and A. R. Sandage. In 1963 they carried out spectroscopic observations of M 82 (Figure 4.1), an irregular galaxy that is a radio source and also looks abnormal optically, and announced the interpretation that the irregular structure extending perpendicular to the galactic plane is a jet ejected from the nucleus at a velocity of 1000 km/s. In the same year G. R. Burbidge, E. M. Burbidge and A. R. Sandage compiled the monumental review “Evidence for the Occurrence of Violent Event in the Nuclei of Galaxies,” in which they discussed the activity of Seyfert galaxies and radio galaxies as explosions of the nucleus.

5. The Discovery of Quasars

The importance of Seyfert galaxies was further reinforced by the discovery of quasars (quasar, in Japanese 準星; Quasi-Stellar Object = QSO), which have emission-line spectra optically very similar to theirs.

The year 1963 became a memorable year of discovery. Using lunar occultation of the radio source 3C 273, C. Hazard, M. B. Mackey and A. J. Shimmins established that it was a double radio source with a separation of 20". M. Schmidt then discovered, at the position of 3C 273 determined to an accuracy within 1", a 13th-magnitude blue stellar object accompanied by a jet (Figure 1.5). The blue object and the jet were separated by exactly 20". On a low-dispersion spectrogram taken with the 5 m telescope of the Hale Observatories, broad emission lines at wavelengths $\lambda = 5632, 3239, 5798$ and $4750 \text{ \AA}$ were clearly recorded. Schmidt showed that if these emission lines are interpreted as being redshifted by $z = \Delta\lambda/\lambda = 0.158$, they agree beautifully with H_{β} $\lambda 4861$, Mg II $\lambda 2798$, [O III] $\lambda 5007$ and H_{γ} $\lambda 4102$ respectively. If this redshift of $z = 0.158$ is interpreted by Hubble's law, the distance turns out to be as far as 950 Mpc, the absolute

magnitude exceeds -26 , and the object becomes 100 times brighter than an ordinary galaxy. 3C 48, first identified by A. R. Sandage in 1961, was also shown by the observations of J. L. Greenstein and T. A. Matthews to be a -25 magnitude object lying at a distance of 2,200 Mpc ($z = 0.368$).

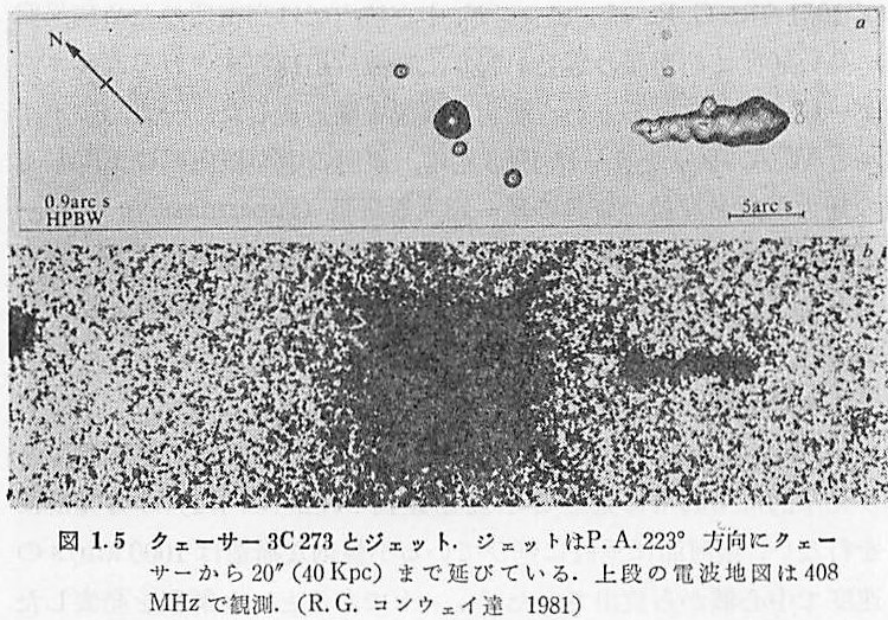


Figure 1.5 The quasar 3C 273 and its jet. The jet extends from the quasar out to 20" (40 kpc) in the direction P. A. 223°. The radio map in the upper panel was observed at 408 MHz. (R. G. Conway et al. 1981) (Symbols in the figure: a — arrow marking N, 0.9 arc s HPBW, a 5 arc s scale bar / b — optical photograph)

Along with this extreme luminosity, another thing that astonished astronomers was light variation. H. J. Smith and D. Hoffleit measured photographic plates taken at Harvard Observatory between 1893 and 1953 and found that 3C 273 varies with a period of about 10 years, and that a flare up exceeding one magnitude occurred around 1930. Photoelectric photometry by T. A. Matthews and A. R. Sandage also showed 3C 48 varying by about 0.4 magnitude in one year. For light variation to

occur on a time scale of one year, the size of a quasar must be less than one light year (~ 0.3 pc). The reason is that if it were larger than this, the variation would be smoothed out while light propagated across the interior of the quasar. In this way there emerges a picture of a quasar in which light 100 times brighter than a galaxy is emitted from a region less than one ten-thousandth the size of a galaxy.

Besides their large redshifts, the emission-line spectra of quasars have the characteristic of being extremely broad. This similarity to Seyfert galaxies was clearly pointed out in the review by the Burbidges published in 1963.

Building on the discovery of quasars and on the suggestion by F. Hoyle and W. A. Fowler that the release of gravitational energy by the gravitational collapse of a supermassive star is the energy source of radio galaxies, a symposium on the theme of quasars and gravitational collapse was held in Dallas, Texas, also in 1963, on October 16–18.

In 1964 a model of quasars was proposed by J. L. Greenstein and M. Schmidt. They argued skillfully that quasars are not highly evolved objects like neutron stars within the Milky Way, nor massive objects (local objects) located in the outskirts of the Milky Way, but are extremely distant galaxies; and from spectroscopic observations they concluded that in 3C 273 ionized gas of number density $N_e \sim 3 \times 10^6/\text{cm}^3$ is confined within a region of radius $R \sim 1$ pc, and in 3C 48 ionized gas of $N_e \sim 3 \times 10^4/\text{cm}^3$ is confined within $R \sim 10$ pc. The quasar model they proposed is one in which an energy source of about $10^9 M_\odot$ emitting ultraviolet light ($R \lesssim 0.1$ pc) is surrounded by a gas cloud, similar to a planetary nebula, at $R \approx 1$ – 10 pc that radiates the emission-line spectrum.

Thereafter the identification of quasars advanced rapidly, until about 150 had been catalogued by around 1967 and ten times that number by 1980. For the early optical identifications, a method was used in which two slightly displaced images

were made on a single photographic plate with different filters, centered on the position of the radio source, so as to pick out objects that are especially bright in the ultraviolet. In the course of these observations A. R. Sandage noticed the existence of strange objects that, like quasars, have an ultraviolet excess but do not coincide with radio sources, and he regarded them as objects that get in the way of (interlopers in) optical identification. When they were observed, however, BSO 1 — a 17th-magnitude blue object (Blue Stellar Object = BSO) — showed $z = 0.241$, and the 15th-magnitude Ton 256 in the Tonantzintla catalogue showed $z = 0.1307$, redshifts as large as those of quasars. Interpreted by Hubble's law, their absolute magnitudes become $M_B \approx -23$, which agrees with the luminosity of the brightest galaxies. Moreover, their emission-line spectra have exactly the same characteristics as the Seyfert galaxy NGC 4151, with narrow forbidden lines and very broad Balmer lines. In 1965 Sandage boldly inferred that these constitute a new class of object, quasi-stellar galaxies (Quasi-Stellar Galaxy = QSG), which are weak in radio but optically similar to quasars, and that most of the blue stars fainter than 16th magnitude seen at high galactic latitude are QSGs, so that they must be far more numerous than the radio quasars.

At present QSGs are called quasars without any particular distinction, but in connection with Seyfert galaxies it is surely important to keep the distinction in mind. The reason is that most Seyfert galaxies, like QSGs, are very weak in radio.

6. The Study of Seyfert Galaxies

The study of Seyfert galaxies began with the question of how to interpret the emission-line widths. In 1959 L. Woltjer gave criteria defining Seyfert galaxies, and reasoned that since the fraction of galaxies satisfying these criteria is a few percent of Sa and Sb galaxies, if all spiral galaxies possess an “emission-line nucleus” as an evolutionary stage, then its lifetime must be a few percent of the age

of the universe (~ 15 billion years). If the emission-line widths of some 1000 km/s are regarded as expansion motion, the gas would all escape from the nucleus in $\sim 10^5$ years, which conflicts badly with the age of Seyfert galaxies he had derived ($\sim 10^8$ years). He therefore proposed a stationary rotation model, in which the widths of the emission lines are produced by the Doppler effect accompanying rotational motion of the nucleus.

E. M. Burbidge, G. R. Burbidge and K. H. Prendergast, also in 1959, observed the velocity field of NGC 1068 and determined its mass. This paper was probably the first to use the term “Seyfert galaxy.” The mass they derived within a radius of 2 kpc was $2.7 \times 10^{10} M_{\odot}$ ($H_0 = 75 \text{ km/sec Mpc}$), and the mass of the nucleus is less than one tenth of this value. Since this was far too small compared with the 10^{10} – $10^{11} M_{\odot}$ required by Woltjer’s rotation model, they strongly rejected the rotation model and maintained that the emission lines are broadened by the Doppler effect due to outflow of gas from the nucleus. They also questioned and rejected the possibility of the electron-scattering model proposed by G. Field in 1958, asking how it could explain the difference between the profiles of the Balmer lines and the forbidden lines seen in NGC 4151. In 1963 the Burbidges also attempted observations of NGC 7469 and showed that, as with NGC 1068, it does not have the large mass that the rotation model would require.

The physical state of the ionized gas radiating the emission-line spectrum of NGC 1068 was studied in 1965 by E. A. Dibay and U. I. Pronik, and by D. E. Osterbrock and R. A. R. Parker. The results obtained — an electron number density $N_e \sim 10^4/\text{cm}^3$ and an electron temperature $T_e \sim 10^4 \text{ K}$ — were similar to those of ordinary gaseous nebulae and planetary nebulae.

In 1965 E. M. Burbidge and G. R. Burbidge observed in detail the velocity field of NGC 1275, the radio source Perseus A. They concluded that the 3,000 km/s emission-line component discovered by R. Minkowski does not belong to colliding

galaxies but is a jet produced by an explosion in the nucleus, and the Burbidges considered that this completely refuted the collision hypothesis. In Chapter III, however, we shall see this collision theory revived once again.

In 1965 I. S. Shklovsky drew attention to the similarity between Seyfert galaxy nuclei and quasars, and argued that there is no qualitative difference between the two: quasars are radio galaxies in their active phase, and Seyfert galaxies are normal galaxies whose nuclei have entered an active phase. Observationally too, properties similar to those of quasars began to be discovered one after another. In 1966 W. A. Dent and F. T. Haddock found that the 8,000 MHz radio intensity of NGC 1275 had increased monotonically by 68% over four and a half years, and argued that this was strong evidence for the similarity between Seyfert galaxies and quasars. In 1967 the strong infrared emission of NGC 1068 was discovered by A. G. Pacholczyk and W. Z. Wisniewski, and the light variation of NGC 4151 by W. S. Fitch, A. G. Pacholczyk and R. J. Weymann. The latter discovery in particular established the similarity between Seyfert galaxy nuclei and quasars as an undeniable fact. At the same time this deprived of its basis the claim of those researchers who had doubted that quasar redshifts could be interpreted by Hubble's law, on the grounds that quasars would be too bright for galaxies and that the size inferred from the time scale of the light variation would be far too small for a galaxy.

Encouraged by the discovery of the light variation, A. G. Pacholczyk and R. J. Weymann argued that entirely new kinds of observational material on Seyfert galaxies (infrared light and millimeter-wave radio emission, for example) and a great deal of unpublished material must be accumulating, and called for people to bring it together and examine the problem of galactic nuclei not from the quasar side but from the Seyfert galaxy side. For three days, 14–16 February 1968, spanning the new moon, they held at the Steward Observatory of the University of

Arizona a conference entitled “Seyfert Galaxies and Related Objects.” Here the morphological characteristics of Seyfert galaxies, their continuum spectra and the variation and polarization thereof, infrared and radio observations and theory, the newly discovered Seyfert galaxies (3C 120 = II Zw 14, III Zw 2, Mkn 9, Mkn 10, VV 144, VV 150), theoretical interpretation of the physical state of the nucleus, and the connection with quasars were all discussed comprehensively.

Thus Seyfert galaxies came to be given their proper place. It was established that Seyfert galaxies are not merely something supplementary to the study of quasars, but constitute an independent field of research in their own right. This had required 25 years since Seyfert published his paper, including a 15-year blank period.

If we divide the study of Seyfert galaxies into a first and a second period on either side of the 1968 conference on Seyfert galaxies, the second period may be characterized as follows.

- (1) The discovery of new Seyfert galaxies. There are now more than 200, and southern Seyfert galaxies have also come to be known.
- (2) The extension of the wavelength range. Seyfert galaxies have come to be observed over all wavelength ranges — radio, infrared, visible and ultraviolet, and X-rays. In wavelength ranges where atmospheric absorption is strong, balloons, rockets, aircraft and artificial satellites are used for the observations.
- (3) A dramatic improvement in observational accuracy through the development of new instruments. This applies over the whole wavelength range from radio to X-rays. Besides making it possible to observe fainter Seyfert galaxies, the resolving power in radio and X-rays has improved dramatically.
- (4) The accumulation of observational material over long periods. This has made it possible to analyze the time variability of radio, infrared, visible and X-ray

emission.

Another great achievement of the second period was the introduction, by E. Ye. Khachikian and D. W. Weedman (1971; 1974) and by D. Weedman (1973), of a method of classifying Seyfert galaxies into type 1 and type 2 in analyzing their observational material, and the demonstration that this captures one essential aspect of Seyfert galaxies. Type 1 means those in which, as in NGC 4151, the Balmer lines are many times broader than the forbidden lines; type 2 means those in which, as in NGC 1068, there is no difference between the widths of the two and both are comparatively narrow.

Now let us stop this historical survey here and, from the next chapter, enter into the study of Seyfert galaxies themselves.

Chapter II. Catalogs of Seyfert Galaxies

1. Definition of Seyfert Galaxies

In general a Seyfert galaxy is defined as one that satisfies the three properties pointed out by Seyfert. To repeat the criteria:

- (1) it has a bright, small nucleus;
- (2) the spectrum of the nucleus contains high-excitation emission lines;
- (3) the widths of the emission lines are abnormally broad.

In 1963, when E. M. Burbidge, G. R. Burbidge and K. H. Prendergast fixed the above three properties as the definition of a Seyfert galaxy, NGC 2783, NGC 3077, NGC 4258 and NGC 6814 among the 12 objects listed by Seyfert were excluded from the Seyfert galaxies as not satisfying them. In 1971, however, M.-H. Ulrich confirmed that the emission-line spectrum of NGC 6814 is Seyfert-like, so that 9 objects in Seyfert's list are Seyfert galaxies. These are often called the classical Seyfert galaxies. The three that were excluded ceased to be Seyfert galaxies, but they have peculiar aspects of their own. NGC 2783 is a representative example of a hot spot galaxy, having in its central region several giant ionized-hydrogen regions. The irregular galaxy NGC 3077 forms a small group together with M 81 and M 82, and the Sb-type spiral galaxy NGC 4258 is also a peculiar galaxy with radio arms.

The 9 classical Seyfert galaxies are summarized in Table 2.1. Apart from the elliptical galaxy NGC 1275, the other 8 are all spiral galaxies. Moreover, NGC 1275 is a powerful radio galaxy. For this reason there is a view that Seyfert galaxies should be restricted to spiral galaxies that are not radio sources, but in this book we shall interpret the term as broadly as possible without being bound by

morphology, and regard everything whose emission-line spectrum is Seyfert-like as a Seyfert galaxy.

Table 2.1 The classical Seyfert galaxies

NGC	Morphological type	Apparent magnitude	Notes
1068	Sb	9.9	M 77, 3C 71; central object of the NGC 1068 group.
1275	E	13.0	3C 84, Perseus A; central object of the Perseus cluster.
3227	Sb	11.7	Double galaxy with NGC 3226; member of the NGC 3190 group.
3516	Sa	12.2	
4051	Sb	11.0	Member of Canes Venatici Cloud II.
4151	Sb	11.2	Member of Ursa Major Cloud I (z).
5548	Sa	13.3	
6814	Sb	12.1	NGC 6814 group.
7469	Sa	13.0	Double galaxy with IC 5283.

Let us return to the definition of a Seyfert galaxy and examine it a little more closely. Even though we say the nucleus is small, once the distance exceeds 100–200 Mpc, one second of arc — the smallest angle that can be observed — comes to correspond to as much as 500–1000 pc, so criterion (1) becomes ambiguous. It is better regarded as a supplementary criterion signifying that the emission-line spectrum we are concerned with does not come from the disk region of a spiral galaxy or from gaseous nebulae within an irregular galaxy. The high-excitation emission lines of (2) mean lines such as [O III] $\lambda\lambda 4959, 5007$ of doubly ionized oxygen, [Ne III] $\lambda 3869$ and [Ne V] $\lambda 3426$ of doubly and quadruply ionized neon,

and [Fe VII] $\lambda 6086$ of six-times-ionized iron; that is to say, they are not only the forbidden lines of neutral or singly ionized species, [O I] $\lambda 6300$, [O II] $\lambda 3727$, [N II] $\lambda 6583$, [S II] $\lambda \lambda 6717, 6731$. Note, however, that among type 1 Seyfert galaxies there are some in which the forbidden lines are relatively very weak and which show only a spectrum consisting of Balmer lines and helium broadened to more than 10,000 km/s together with singly ionized iron; so for type 1 Seyfert galaxies, criterion (2) is not necessarily an indispensable condition.

Thus in the end (3) remains as the essential criterion for a Seyfert galaxy. Then how broad must the lines be for a galaxy to be classified as a Seyfert? To discuss this we must first define the emission-line width. Figure 2.1 is a schematic diagram of an emission-line profile. Two widths are used according to the purpose: the full width at half maximum (FWHM), where the intensity falls to half of its peak value, and the full width at zero intensity (FWOI), where the intensity becomes zero. Figure 2.2 shows spectrograms of [O III] $\lambda \lambda 4959, 5007$ in the Seyfert galaxy Mkn 3 and of H_{α} and [N II] $\lambda 6584$ in the non-Seyfert galaxy NGC 4569.

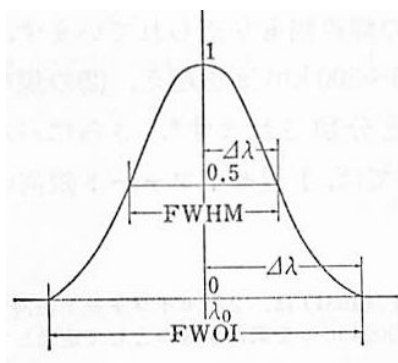


図 2.1 輝線幅の定義. 強度が 2 分の 1 に落ちる幅を全半値幅 (FWHM), 強度がゼロに落ちる幅を全ゼロ強度幅 (FWOI) と呼び, 一般にこれらはドップラー速度

$$w = \frac{2\Delta\lambda}{\lambda_0} \cdot c \quad (\text{km/s})$$

で表わされる. ここで λ_0 は輝線の中心波長, $\Delta\lambda$ は中心から測った半値幅, $c = 3 \times 10^5$ km/s は光速である.

Figure 2.1 Definition of the emission-line width. The width at which the intensity falls to one half is called the full width at half maximum (FWHM), and the width at which the intensity falls to zero is called the full width at zero intensity (FWOI); in general these are expressed as Doppler velocities

$$w = (2\Delta\lambda/\lambda_0) \cdot c \quad (\text{km/s})$$

Here λ_0 is the central wavelength of the emission line, $\Delta\lambda$ is the half width measured from the center, and $c = 3 \times 10^5 \text{ km/s}$ is the speed of light. (Symbols in the figure: ordinate marks 1 and 0.5, central wavelength λ_0 , half width $\Delta\lambda$ measured from the center, FWHM, FWOI)

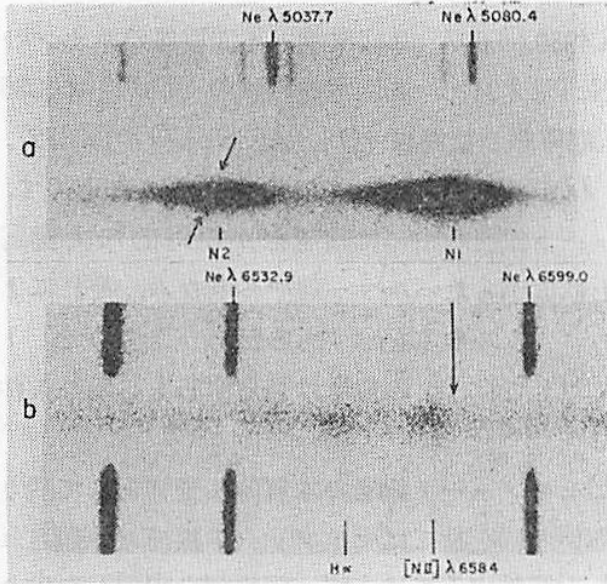


図 2.2 Mkn 3 と NGC 4569 のスペクトル。
セイファート銀河
Mkn 3では輝線が幅
広いことに注意。
(D. W. ウィードマン 1970)。

Figure 2.2 Spectra of Mkn 3 and NGC 4569. Note that the emission lines are broad in the Seyfert galaxy Mkn 3. (D. W. Weedman 1970). (Symbols in the figure: a — comparison lines Ne $\lambda 5037.7$, Ne $\lambda 5080.4$, emission lines N2, N1 / b — comparison lines Ne $\lambda 6532.9$, Ne $\lambda 6599.0$, emission lines H_{α} , [N II] $\lambda 6584$)

Table 2.2 Comparison of emission-line widths (D. W. Weedman 1970)

Galaxy	Line width (FWHM) km/s	Seyfert type
NGC 449	780	2
Mkn 3	900	2
IC 450	925	1/2
Mkn 34	530	2
NGC 4569	370	
NGC 4385	130	

Table 2.2 gives emission-line widths (FWHM). For comparison, the line widths of other Seyfert galaxies and of non-Seyfert galaxies are also given. As can be seen from this, if the FWHM exceeds 400–500 km/s and criterion (2) is satisfied, the galaxy is classified as a type 2 Seyfert galaxy*. If in addition the Balmer lines have an FWOI of several thousand km/s, it is placed in the group of type 1 Seyfert galaxies.

* J. M. Shuder and D. E. Osterbrock (1981) define a type 2 Seyfert galaxy as one satisfying $I([\text{O III}]\lambda 5007)/I(H_{\beta}) \geq 3$ and $\text{FWHM} \geq 300$ km/s.

2. The Search for Seyfert Galaxies and Markarian Galaxies

Searching for Seyfert galaxies is unglamorous work, but it is extremely important. The study of the origin and evolution of Seyfert galaxies requires knowledge of many samples at different evolutionary stages, and in probing their statistical properties and morphological characteristics a complete sample including galaxies as distant as possible is required. It is no exaggeration to say that research since 1970 has been sustained by the patient efforts of B. E. Markarian in this direction.

Markarian attached objective prisms with apex angles of $1^\circ.5$ and 3° to the 1 m Schmidt telescope of the Byurakan Observatory in Armenia and has continued a search for the group of galaxies called Markarian galaxies, which have strong continuum emission in the ultraviolet region; the first list, containing 70 galaxies, was published in 1967. The fourteenth list, published in 1979, goes up to the 1399th object, Mkn 1399**. Galaxies brighter than 13th magnitude are excluded from his list on the grounds that they have already been catalogued. When the objective prism with an apex angle of $1^\circ.5$ is used, the detection limit is 17th magnitude. Using a method similar to Markarian's, M. G. Smith is carrying out a search for peculiar galaxies in the southern sky (Figure 2.3).

** Also written Mrk 1399 or Mk 1399.

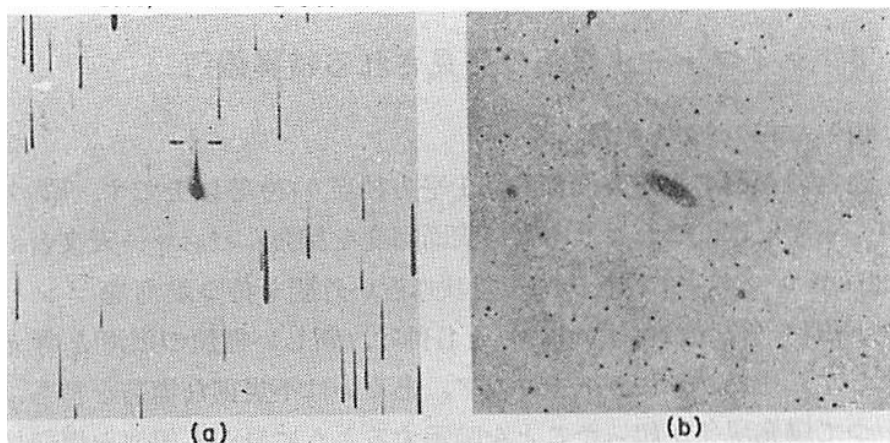


図 2.3 Tololo 0109-383(b) と対物プリズム・スペクトル写真(a).
(M. G. スミス 1975).

Figure 2.3 Tololo 0109-383 (b) and its objective-prism spectrogram (a). (M. G. Smith 1975).

When Markarian published his first list, he described the motivation for the observations as follows. “In general a correspondence is seen between the color and the spectral type of the central region of a galaxy, but some galaxies with blue central regions do not satisfy this correspondence. These are thought to be due to an anomaly in the stellar composition, or to anomalous radiation from the nucleus; but whatever the reason, galaxies with comparatively blue central regions and early-type spectra deserve special attention.”

The search lists being maintained chiefly by Markarian and Smith contain various kinds of galaxies. First of all, they can be divided into galaxies with a bright nucleus and galaxies in which, as in irregular galaxies, the emission-line spectrum is emitted from the galaxy as a whole. The former can be further divided into those in which the emission lines are broad as in Seyfert galaxies, and emission-line-nucleus galaxies in which they are not. Those that have a Seyfert-like spectrum but are almost stellar are classified as quasars. In Markarian’s lists about 10% are Seyfert galaxies.

3. Peculiar Galaxies in Which Seyfert Galaxies Are Found

(1) Compact galaxies

The mean surface brightness of an ordinary galaxy is 20th magnitude or fainter per square second of arc. F. Zwicky named galaxies that have a higher surface brightness than this and a nearly stellar appearance on the 120 cm Schmidt plates of Palomar Observatory “compact galaxies,” and regarded them as a new class of galaxy. He also called galaxies with jets or flares, or with irregular structure, which appear to hint that an explosive event occurred in the past, “post-eruptive galaxies,”

and distributed catalogues of them in seven installments. For example, III Zw 55 means the compact galaxy listed 55th in the third catalogue distributed. The catalogue “Catalogue of Selected Compact Galaxies and of Post-Eruptive Galaxies,” published in 1971, lists 3700 galaxies. Through the spectroscopic observations of W. L. W. Sargent and others, more than ten Seyfert galaxies have been found in this catalogue (Figure 2.4).

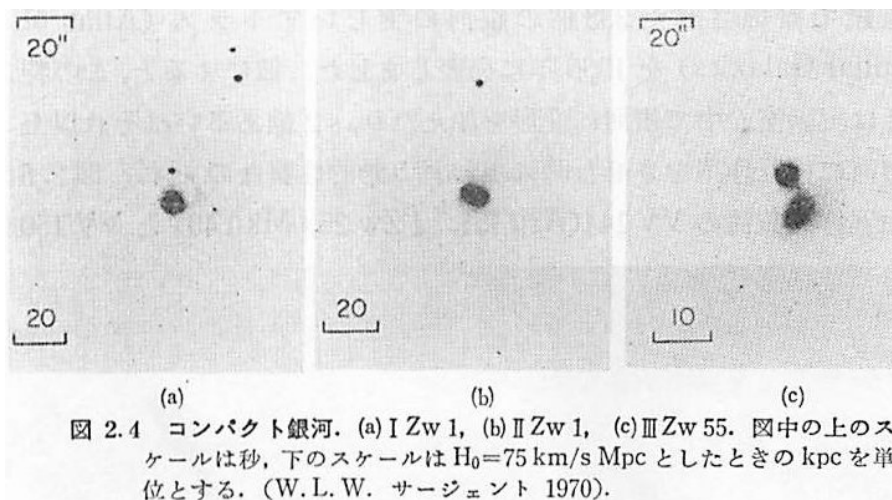


Figure 2.4 Compact galaxies. (a) I Zw 1, (b) II Zw 1, (c) III Zw 55. The upper scale in each panel is in seconds of arc, and the lower scale is in kpc for $H_0 = 75 \text{ km/s Mpc}$. (W. L. W. Sargent 1970).

Like Zwicky, M. A. Arakelian has listed 591 galaxies with high surface brightness. Among them, Akn 79, Akn 120 = Mkn 1095, Akn 202 = Mkn 705, Akn 564 and others are Seyfert galaxies.

(2) Interacting galaxies and Arp's peculiar galaxies

The Soviet astronomer B. A. Vorontsov-Velyaminov used the Sky Survey Atlas taken with the 120 cm Schmidt telescope of Palomar Observatory to compile a

catalogue of galaxies in which two or more galaxies are interacting with one another (interacting galaxies), and published it in 1960. It registers 355 interacting galaxies. The double galaxy formed by the classical Seyfert galaxy NGC 3227 and NGC 3226 is listed in this catalogue as VV 209 = Arp 94, and NGC 7469 with IC 5283 as VV 254 = Arp 298.

H. Arp selected peculiar galaxies that cannot be explained on the basis of Hubble's morphological classification of galaxies, drawing on the lists of Zwicky and Vorontsov-Velyaminov and others as well as on his own discoveries, and in 1966 published a beautiful atlas of 338 galaxies photographed with the 5 m telescope (Atlas of Peculiar Galaxies). According to him, this peculiarity is a dynamical property that appears when a galaxy is deformed in the laboratory, or when two or more galaxies are made to interact. Figure 2.5 shows photographs of the interacting galaxies VV 144 (Arp 151, I Zw 25, Mkn 40) and VV 150 (Arp 322, Mkn 176).

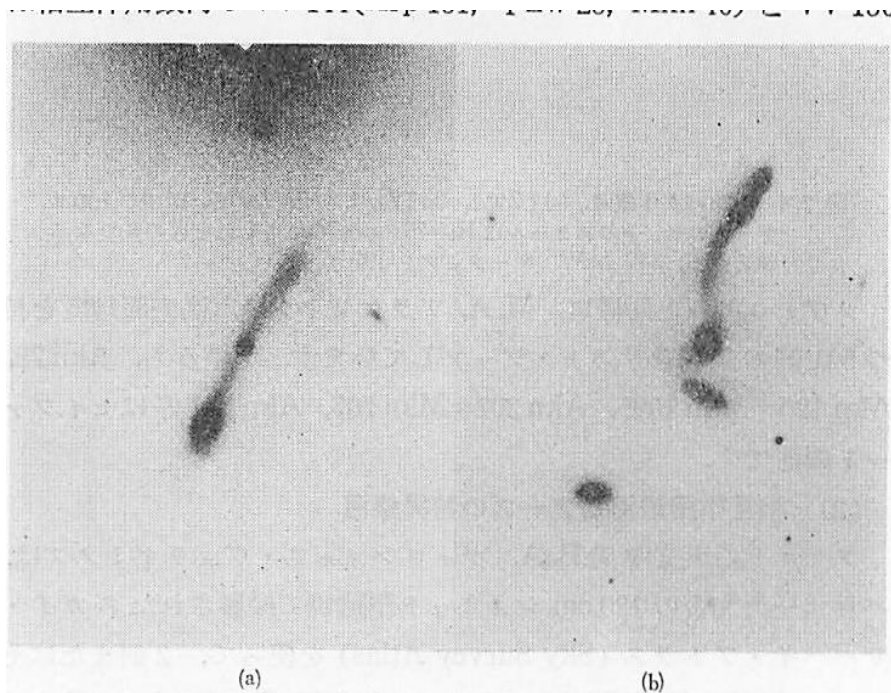


Figure 2.5 Interacting galaxies. (a) VV 144. (b) VV 150. (H. Arp 1966).

(3) N galaxies and D galaxies

In 1964 T. A. Matthews, W. W. Morgan and M. Schmidt modified Morgan's classification scheme and attempted a morphological classification of radio galaxies. N galaxies and D galaxies came into general use as a result of this paper, and are explained as follows.

- (i) N galaxy — a galaxy having a bright stellar “Nucleus” that contains most of the light of the system.
- (ii) D galaxy — a galaxy having an elliptical nucleus surrounded by an extended envelope.

Morgan's classification scheme, published in 1958, was for ordinary spiral galaxies, and according to it an N galaxy is described as "a system in which a small brilliant bright nucleus is superposed on a considerably fainter background." Accordingly, N galaxies are of the same kind as compact galaxies. In fact the Seyfert galaxy 3C 120 is at once an N galaxy and the compact galaxy II Zw 14 (Figure 3.47).

For D galaxies the explanation is "a system that has no definite spiral or elliptical structure but shows rotational symmetry. This category includes such well-known 'Dustless' galaxies as NGC 4111 and NGC 4762." A D galaxy that is elliptical-like is also denoted DE, and an elliptical galaxy that is D-like is denoted ED. At the center of a cluster of galaxies there is often located a D galaxy several times or more larger than an ordinary galaxy, and such D galaxies are specially called cD galaxies, following the spectroscopic notation in which "c" denotes a supergiant (Figure 2.6).

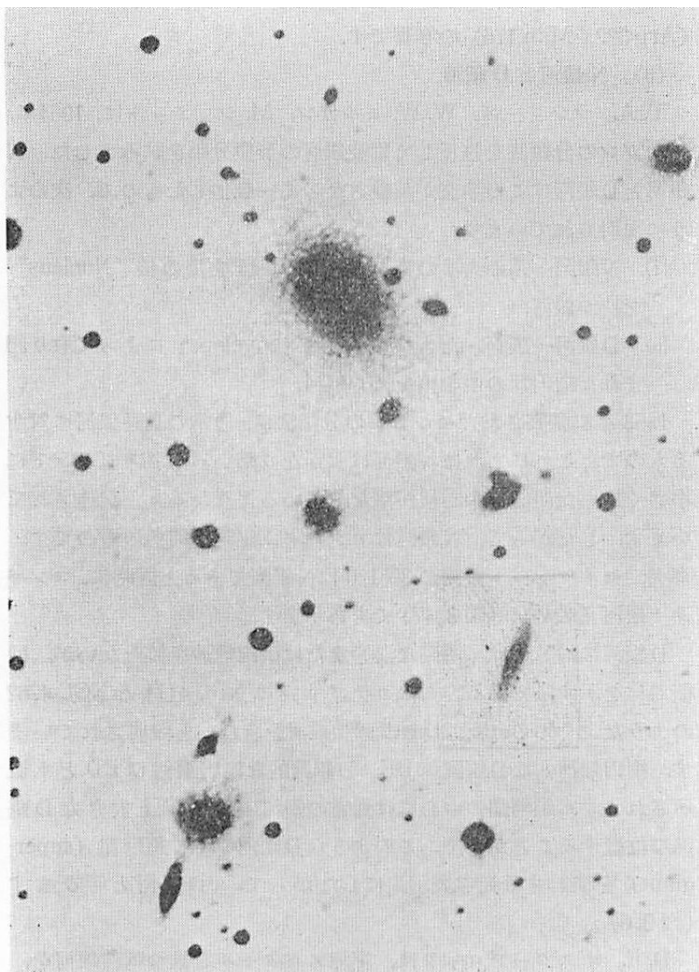


図 2.6 cD 銀河 NGC 6166. この銀河は 3C 338 と呼ばれ、銀河団 Abell 2199 の中心天体である。比較のために、同一のスケールで M31 が挿入されている。(W. W. モルガンと J. R. レッシュ 1965).

Figure 2.6 The cD galaxy NGC 6166. This galaxy is also called 3C 338 and is the central object of the cluster of galaxies Abell 2199. For comparison, M31 has been inserted at the same scale. (W. W. Morgan and J. R. Lesh 1965).

D. E. Osterbrock classified radio galaxies that emit an emission-line spectrum into

(i) broad-line radio galaxies (Broad Line Radio Galaxy = BL radio galaxies), and

(ii) narrow-line radio galaxies (Narrow Line Radio Galaxy = NL radio galaxies), and set them in correspondence with type 1 and type 2 Seyfert galaxies. Curiously, a strong tendency is seen for BL radio galaxies to belong to the N galaxies and NL radio galaxies to the D galaxies (Table 2.3). In general, at present only BL radio galaxies are regarded as Seyfert galaxies.

Table 2.3 NL radio galaxies and BL radio galaxies

NL/BL	Galaxy	Morphological type
NL radio galaxy	3C 405	cD 3
	3C 433	D 4
	3C 33	DE 4
	3C 327	DE 3-4
	3C 98	ED 3
	3C 192	EO
BL radio galaxy	3C 390.3	N
	3C 227	N
	3C 445	N
	3C 120	N
	3C 382	D 3
	NGC 1275	ED 2

(4) X-ray galaxies

Many Seyfert galaxies have also been discovered in the course of optically identifying X-ray sources. Since a number of stars and galaxies fall within the error box representing the accuracy of the positional determination of an X-ray source, the method used to identify the source is to take an objective-prism photograph with a Schmidt telescope and search out blue objects and emission-line galaxies. The X-ray source 2A 1914-589 was identified with ESO 141-G 55 and H 1834-653 with ESO 103-G 35, and both of these are Seyfert galaxies. Recently, too, J. M.

Shuder (1980) confirmed that the emission-line X-ray galaxies NGC 2110, NGC 2992, NGC 5033 and NGC 5506 have H_α emission lines with FWOI = 2,300–5,700 km/s. Most X-ray galaxies are thought to be Seyfert galaxies.

4. Catalogs of Seyfert Galaxies

A catalogue of Seyfert galaxies is compiled at the end of the book as Table A.1. The first line of the table gives the representative name of the Seyfert galaxy, and the second line lists other names. The third line gives the right ascension (α) and declination (δ) of the object for the equinox of 1950. Seyfert types 1 and 2 are given in the fourth line. The fifth line is the redshift cz (km/s). The distance d can be obtained from Hubble's law

$$d = cz/H_0 = v_0/50\text{Mpc}$$

Here $c = 3 \times 10^{10}$ cm/s is the speed of light and $H_0 = 50\text{km/s Mpc}$ is the Hubble constant*.

The sixth and seventh lines are the apparent size θ'' and the apparent magnitude m , but these are only rough guides. To obtain the actual length l and the absolute magnitude M , the following formulae can be used.

$$l = 4.848d \cdot \theta\text{pc},$$

$$m - M - 25 = 5\log d.$$

* $H_0 = 75$ and $H_0 = 100\text{km/s Mpc}$ are also frequently used as the Hubble constant. In this book, unless otherwise stated, $H_0 = 50\text{km/s Mpc}$ is adopted.

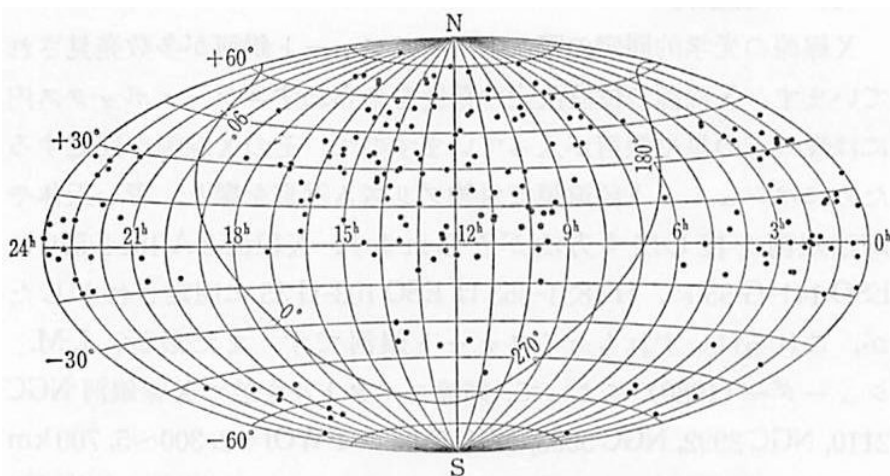


図 2.7 セイファート銀河の分布. 赤経, 赤緯を座標軸として天球上にプロット. 図中の曲線は銀河面.

Figure 2.7 Distribution of Seyfert galaxies. Plotted on the celestial sphere with right ascension and declination as coordinate axes. The curve in the figure is the galactic plane. (Symbols in the figure: declinations $+60^\circ$, $+30^\circ$, -30° , -60° / right ascensions 0^h , 3^h , 6^h , 9^h , 12^h , 15^h , 18^h , 21^h , 24^h / galactic longitude marks 0° , 90° , 180° , 270° / N, S)

Figure 2.7 is a plot on the celestial sphere of the Seyfert galaxies of Table A.1. Clearly the search for Seyfert galaxies is incomplete. In particular, almost no searching has been done in the southern sky. If an all-sky search down to 17–18th magnitude were carried out, the total number of Seyfert galaxies would probably reach about 1,000.

J. Huchra and W. L. W. Sargent (1973) and V. Yu. Terebizh (1980) have investigated the luminosity function $\Phi(M_p)$ of Seyfert galaxies. The luminosity function gives the number density of Seyfert galaxies per cubic Mpc per magnitude. Figure 2.8 shows the result obtained by Huchra and Sargent from an analysis of 242 objects in Markarian's lists I–IV. The black points are the space number density of galaxies brighter than $m_p = 11.75$, with the member galaxies of the Local Group and the Virgo cluster excluded. The open circles are Markarian

galaxies and the crosses are the Seyfert galaxies among the Markarian galaxies. On this basis they concluded that about 5% of all galaxies ($M_p \leq -22$; $H_0 = 75$) are Markarian galaxies, and that 10% of these are Seyfert galaxies. Accordingly 0.5% of all galaxies are Seyfert galaxies. In Terebizh's analysis, based on 121 Seyfert galaxies, the result obtained is that 0.4% of all galaxies in the range $-19 \geq M_p \geq -23$ ($H_0 = 75$) are Seyfert galaxies, with a space number density of $6.3 \times 10^{-5}/\text{Mpc}^3$. If the Hubble constant is taken to be $H_0 = 50 \text{ km/s Mpc}$, this number density becomes $1.9 \times 10^{-5}/\text{Mpc}^3$.

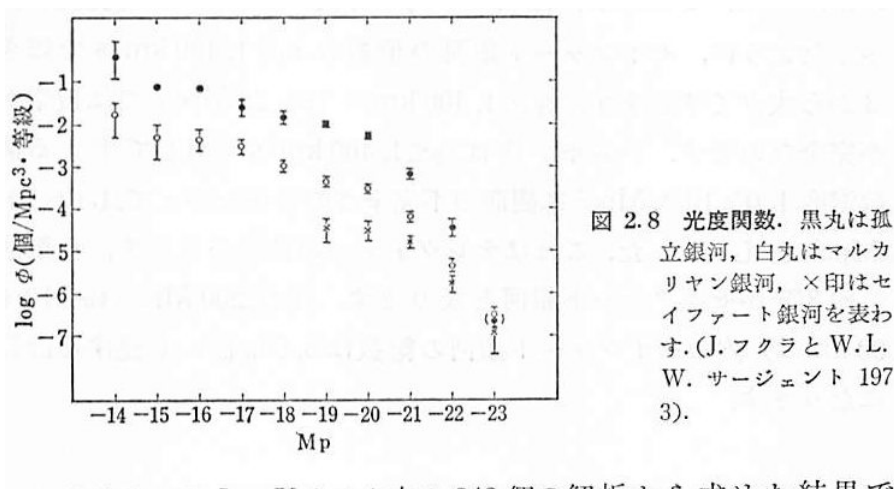


Figure 2.8 The luminosity function. Filled circles denote isolated galaxies, open circles Markarian galaxies, and crosses Seyfert galaxies. (J. Huchra and W. L. W. Sargent 1973). (Ordinate: $\log \Phi (\text{number}/\text{Mpc}^3 \cdot \text{magnitude})$, from -1 to -7 / abscissa: M_p , from -14 to -23)

If Seyfert galaxies were distributed uniformly, the number of Seyfert galaxies $N(\leq d)$ within a distance d should be proportional to the volume of space $4\pi d^3/3$. Using equation (2.1), this can equivalently be stated as: the number $N(\leq v_0)$ of Seyfert galaxies with recession velocities less than v_0 is proportional to v_0^3 . However, as S. M. Simkin, H. J. Su and M. P. Schwartz (1980) showed, the number

of Seyfert galaxies departs greatly from a slope of 3 for $v_0 \geq 1,400\text{km/s}$. For $v_0 \geq 1,400\text{km/s}$ ($d \geq 28 \text{ Mpc}$) the search is incomplete. Simkin and her collaborators applied a correction for observational incompleteness to the number density $1.0 \times 10^{-4}/\text{Mpc}^3$ obtained for $v_0 \leq 1,400\text{km/s}$, and arrived at $1.6 \times 10^{-4}\text{Mpc}^3$. This is 8 times Terebizh's result, and makes about 3% of all galaxies Seyfert galaxies. It works out that the total number of Seyfert galaxies within a radius of 200 Mpc ($v_0 \leq 10,000\text{km/s}$) reaches as many as 5,000.

Chapter III. Morphology I. Seyfert Galaxies

1. NGC 1068

NGC 1068 is M 77, the only Seyfert galaxy listed in the Messier catalogue; in the radio-galaxy catalogues it is called 3C 71. Its distance is 22 Mpc. This corresponds to about 700 times the diameter of the Milky Way galaxy.

In Hubble's classification scheme, NGC 1068 is an Sb-type spiral galaxy. Following de Vaucouleurs' classification it is (R)SA(rs)b. Here (R) indicates that it has a ring structure on the outside, and (rs) that it has a structure intermediate between a ring (r) and a spiral (s) on the inside. SA means a normal spiral galaxy; a barred spiral galaxy is written SB. Morgan, moreover, classifies it as gS3–gD3. The g corresponds to the stellar spectral type G, and S-D indicates that it is either a spiral galaxy or a D galaxy. The numeral 3 is a parameter expressing the apparent flattening, having the same meaning as the numerals in the Hubble classification E 0, E 1, E 2, ... for elliptical galaxies; but in Morgan's classification scheme 0 is not used, and the numbering begins at 1: 1, 2,

As (R)SA(rs)b indicates, NGC 1068 has, in addition to spiral arms in the ordinary sense, arms both inside and outside, so that in appearance it has a triple-arm structure. We shall therefore examine each of these regions separately.

(1) The outermost region

Let us begin with the outermost region (Figure 3.1). Rather than a disk, this region has a ring structure 40×35 kpc in size, connected tangentially to the main disk region (the dark central part of Figure 3.1) by two thin arms. P. W. Hodge (1968) called NGC 1068 a ring galaxy.

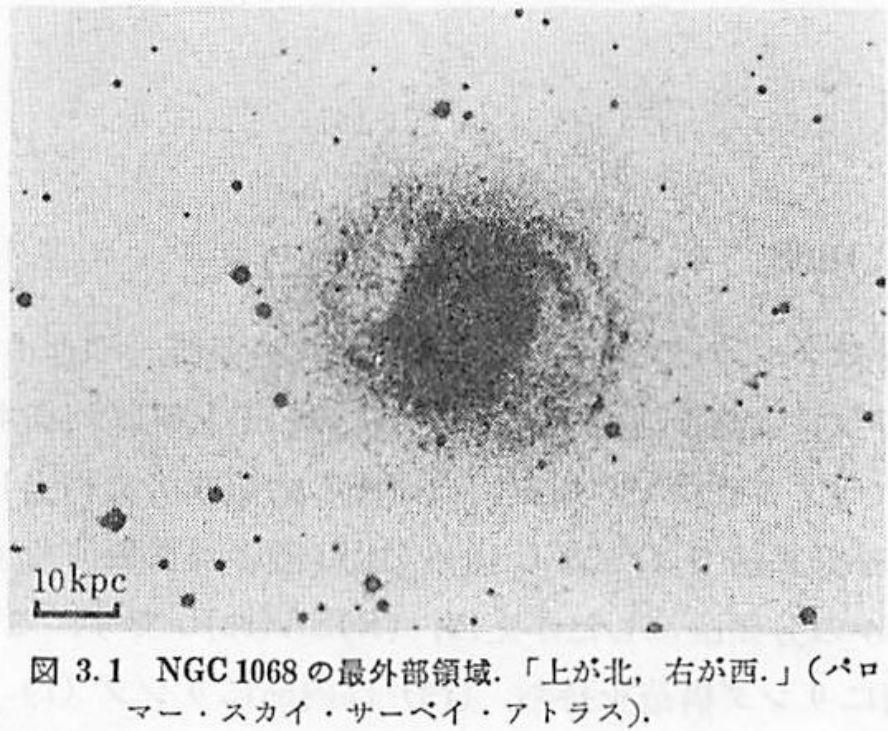


Figure 3.1 The outermost region of NGC 1068. “North is up, west is to the right.” (Palomar Sky Survey Atlas). Scale bar in the figure: 10 kpc.

Is the outermost region made of stars, or of gas? To answer this question, spectroscopic observations of the outermost region are needed. However, since its surface brightness is no more than a few tenths of that of the moonless night sky, this is almost impossible to carry out. According to the photometric observations of M. G. Smith, D. W. Weedman and H. Spinrad (1972), the color index of the outermost region 10 kpc from the center is $B-V = 0.8-0.9$, in agreement with the average value for Sb types. We may therefore infer that the outermost region of NGC 1068 is made up mainly of ordinary stars; but many problems remain unstudied — why is there a ring structure, and why do the arms touch tangentially along the major-axis direction of the main disk region as in a barred galaxy?

Recently, T. Heckman, B. Balick and W. T. Sullivan (1978) observed NGC 1068 in the 21 cm radio emission line emitted by neutral hydrogen gas. Figure 3.2 shows the results they obtained.

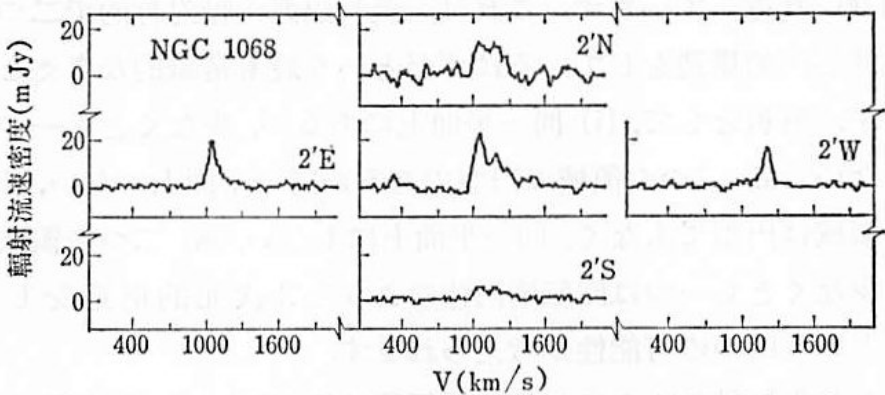


図 3.2 NGC 1068 の中性水素 21 cm 輝線輪郭. 輻射流速密度の 1 ミリ・ジャンスキー (mJy) は $10^{-29} \text{W/m}^2 \text{Hz}$. (T. ヘックマン, B. バリック, W. T. サリバン 1978).

Figure 3.2 21 cm neutral hydrogen line profiles of NGC 1068. One millijansky (mJy) of radiation flux density is $10^{-29} \text{W/m}^2 \text{Hz}$. (T. Heckman, B. Balick, W. T. Sullivan 1978). Vertical axis: radiation flux density (m Jy), ticks 0, 20. Horizontal axis: V(km/s), ticks 400, 1000, 1600. Panel labels: NGC 1068 (center), 2'N, 2'E, 2'W, 2'S.

Besides the profile centered on the nucleus, 21 cm line profiles are shown at four points 2' (12 kpc) away to the east, west, south and north. The beam of the 305 m Arecibo radio telescope used for the observations has a size of $3' \times 5'$. The line velocities at the points 2' away to the north and south agree with that at the center, but at the point 2' to the east the velocity is displaced from the central velocity by -100 km/s , and at the point 2' to the west by $+100 \text{ km/s}$. This means that the neutral hydrogen gas within the outermost region is in rotational motion with the north-south direction as the rotation axis, the eastern side approaching us and the western side receding.

Figure 3.2 also shows that the neutral hydrogen gas within NGC 1068 is distributed relatively uniformly and has no tendency to concentrate in the optically bright main disk region. Were there such a tendency, the radio intensity at the center would have to be far stronger than elsewhere. The total mass of neutral hydrogen gas in NGC 1068 obtained by Heckman and his colleagues is $M_{\text{HI}} = 3.5 \times 10^9 M_{\odot}$.

(2) The main disk region

The main disk region has a size of $15 \times 10 \text{ kpc}$. Since the diameter of the Milky Way galaxy is about 30 kpc, the main disk region of NGC 1068 belongs to the comparatively small class.

As you will already have noticed, the major axes of the outermost region and of the main disk region differ by about 90° . This contradicts the most common-sense idea that a spiral galaxy should be axisymmetric and that the two regions should have a concentric structure. Four possible interpretations may be considered: (i) they lie in the same plane, but at least one of them is not circular; (ii) the two regions are circular but do not lie in the same plane; (iii) the two regions are neither circular nor in the same plane; (iv) at least one of the two regions has a three-dimensional structure such as a spheroid of revolution.

However, as we saw earlier, the outermost region rotates at a velocity of about 100 km/s, and the two regions each possess spiral arms, so possibility (iv) may be ignored. Also, since the two arms of the outermost region appear to be tangentially connected to the main disk region, possibilities (ii) and (iii) also seem unlikely. Probably the main disk region is elliptical or bar-shaped, with the outermost arms extending from its two ends.

Figure 3.3 shows negative prints in blue (B) and infrared (I) taken with the 188 cm telescope of the Okayama Astrophysical Observatory. Infrared photographs of

NGC 1068 have almost never been published, and are very rare. In these photographs one can see the spiral arms within the main disk region and the bright arms of the inner region, which we shall examine in the next section. The former, the main arms, are clearest in the B photograph, and many knots (knot = ionized hydrogen regions) are scattered along the arms. H. Arp (1966) regarded these amorphous spiral arms as peculiar and added NGC 1068 to his atlas of peculiar galaxies. These knots may be interpreted as evidence that the main disk region of NGC 1068 contains more ionized gas than an ordinary Sb-type galaxy. In the I photograph the main arms become very smooth, but the thin, smooth arm on the eastern side can be seen to extend from one end of an arm in the inner region. This too seems not unrelated to an outflow of gas from the inner region.

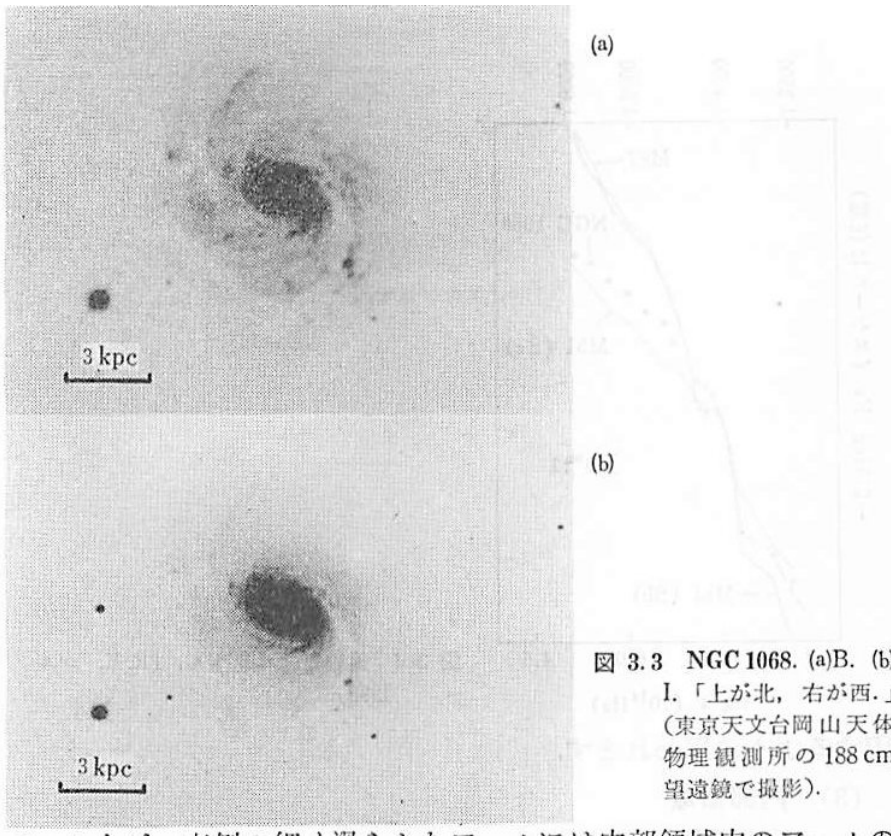


Figure 3.3 NGC 1068. (a)B. (b)I. “North is up, west is to the right.” (Photographed with the 188 cm telescope of the Okayama Astrophysical Observatory, Tokyo Astronomical Observatory). Scale bar in each photograph: 3 kpc.

NGC 1068 is classified as Sb type from the morphology of the arms in the main disk region, but the color index of this region is very blue, $B-V \approx 0.7$, which is characteristic of Sc types. Figure 3.4 is the continuum spectrum of a region $6'$ (35 kpc) in diameter observed by R. E. Schild (1972) with a small telescope of 10 cm aperture. It is clearly different from that of the elliptical galaxy M 87 or the Sb-type spiral galaxy M 81, and closely resembles that of the Sc-type M 51. Having these two incompatible characters at once is the morphological peculiarity of the main

disk region. This appears to arise from the fact that NGC 1068 contains more ionized gas than an ordinary Sb-type galaxy.

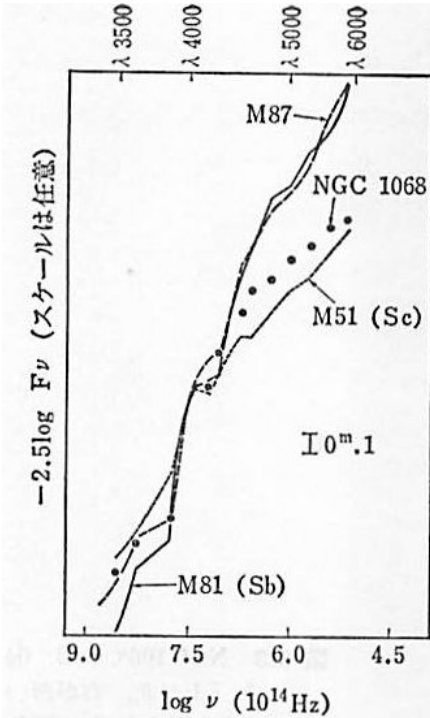


図 3.4 連続光スペクトル. (R. E. Schild 1972).

因するように思われます。

(2) 内部領域

Figure 3.4 Continuum spectra. (R. E. Schild 1972). Vertical axis: $-2.5 \log F_\nu$ (scale arbitrary). Horizontal axis: $\log \nu$ (10^{14} Hz), ticks 9.0, 7.5, 6.0, 4.5. Upper axis: $\lambda 3500$, $\lambda 4000$, $\lambda 5000$, $\lambda 6000$. Curves labeled: M87, NGC 1068, M51 (Sc), M81 (Sb). A scale bar of $I 0^{m.1}$ is shown in the figure.

(3) The inner region

The structure of the inner region changes markedly with the color in which it is observed. Figure 3.5 shows U, B and I photographs taken with different exposure

times. In analyzing these, one must bear in mind that ultraviolet photographs record mainly the emission-line spectrum and continuum emitted by gas, whereas infrared photographs record chiefly the light of the stars that make up the galaxy. In other words, the U photograph may be taken to represent roughly the distribution of ionized gas, and the I photograph the distribution of stars.

The structures in U and I are in contrast. In the former, one sees that a ring-shaped arm about 3 kpc in diameter, containing several giant ionized hydrogen regions, has formed at the boundary between the main disk region and the inner region, and that the nucleus is surrounded by a gas cloud extending toward the northeast. There is almost no light from the stars that constitute the framework of the galaxy. In the infrared, by contrast, one sees a bright core in the central region and a bar resembling that of a barred galaxy, while the ring-like arm containing ionized gas is not visible at all. The surface brightness changes abruptly and discontinuously at the boundary between the inner region and the main disk region of NGC 1068, and the cause of this lies in the fact that the inner region contains an extremely large amount of ionized gas.

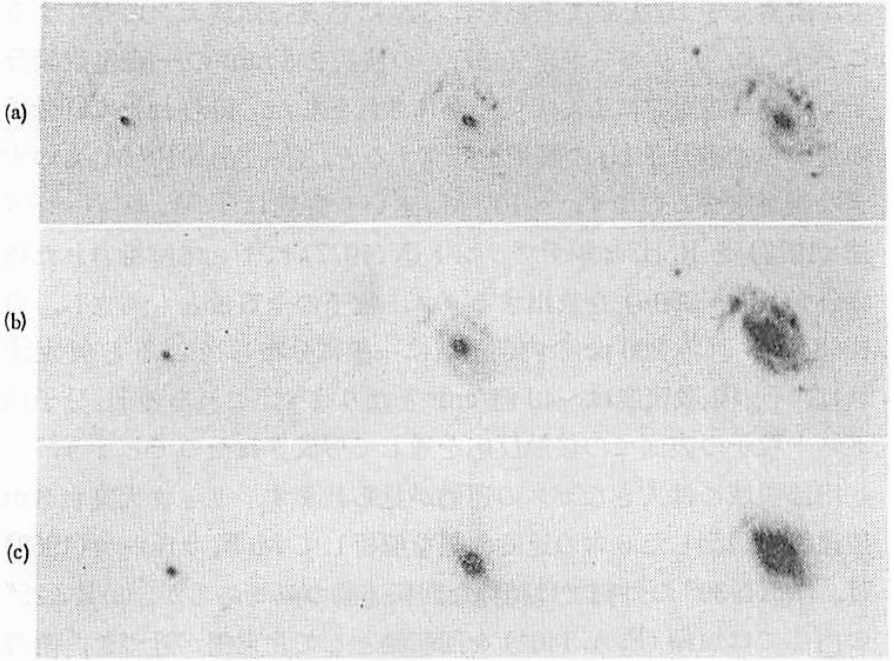


図 3.5 NGC 1068 の内部領域. (a) U (2 分, 6 分, 15 分), (b) B (10 秒, 40 秒, 2 分), (c) I (1 分, 3 分, 10 分). 上が西, 右が北. (東京天文台岡山天体物理観測所の 188cm 望遠鏡で撮影).

Figure 3.5 The inner region of NGC 1068. (a) U (2 min, 6 min, 15 min), (b) B (10 s, 40 s, 2 min), (c) I (1 min, 3 min, 10 min). West is up, north is to the right. (Photographed with the 188 cm telescope of the Okayama Astrophysical Observatory, Tokyo Astronomical Observatory).

The total luminosity of the ionized hydrogen regions contained in the arm within the inner region is $L \approx 5 \times 10^{41} \text{ erg/s}$; if we take them to be the same as ordinary giant ionized hydrogen regions, the total mass of gas contained in them is estimated at $M_{\text{gas}} \sim 3 \times 10^8 M_{\odot}$. This corresponds to one-tenth of the total neutral hydrogen gas mass of NGC 1068. However, the 2.6 mm radio observations of the carbon monoxide molecule CO by L. J. Rickard and collaborators (1977) revealed that within the inner region of NGC 1068 there exists hydrogen gas far exceeding this

amount, not as atomic hydrogen H but as molecular hydrogen H_2 . When the mass of molecular hydrogen H_2 is computed from the amount of CO molecules obtained, a value as large as $(5-36) \times 10^9 M_\odot$ is derived. A mass of $\sim 10^{10} M_\odot$ is also compatible with the total mass of dust grains emitting the far-infrared (30–300 μ) analyzed by T. W. Jones and collaborators (1977) and R. H. Hildebrand and collaborators (1977); and if we assume it to be uniformly distributed over an inner region 3 kpc in diameter and 200 pc thick, the number density becomes $\sim 40 \text{ cm}^{-3}$. These H_2 molecules were presumably formed through contact reactions on the surfaces of dust grains.

Large gas motions are seen in the inner region. Analyzing six velocity curves observed with the 3 m telescope of Lick Observatory, M. F. Walker (1968) concluded that (i) outside $R \gtrsim 30''$ there is only pure rotational motion, but (ii) inside $R \lesssim 25''$ there is, in addition to a rotational motion about the minor axis (P. A. 140°) in which the northeastern side approaches and the southwestern side recedes, an expansion motion of about 150 km/s. The 1×10^7 years required to cross the inner region at this expansion velocity gives one time scale for the activity of NGC 1068.

From the velocity curves Walker calculated the mass within a diameter of $80''$ to be $(3.2-6.6) \times 10^9 M_\odot$ ($H_0 = 100$). If we take the Hubble constant to be $H_0 = 50 \text{ km/s Mpc}$, it is $(6.4-13.2) \times 10^9 M_\odot$. This is of the same order as the mass of molecular hydrogen obtained above. Since the $\sim 1 \times 10^{10} M_\odot$ obtained by Walker is the mass of stars and gas combined, if these mass determinations can be trusted, molecular hydrogen accounts for at least half of the total mass.

(4) The nuclear region and the [O III] gas cloud

The nuclear region is a gas cloud about 1 kpc in diameter surrounding the nucleus, and corresponds to the fourth component of the multiple structure. As is clearly

apparent in the ultraviolet photograph of Figure 3.5, this region extends toward the northeast (P. A. 30° – 40°) and has long been called the “flare.” M. F. Walker (1968) showed that the emission lines are not merely broad but possess a definite structure, and he resolved four giant gas clouds (Figure 3.6) in the nuclear region. Each gas cloud has an internal motion of about 500 km/s and is moving with a velocity of 300–600 km/s. Since these velocities far exceed the escape velocity from the nucleus, Walker’s gas clouds — or the flare — must be regarded as having been ejected from the nucleus as a result of the galactic nuclear activity.

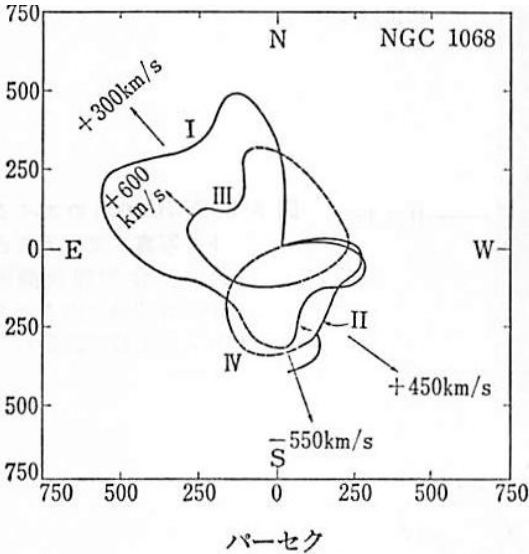


図 3.6 中心核領域に分解され
ガス雲. (M. F. ウォーカー
1968).

Figure 3.6 Gas clouds resolved in the nuclear region. (M. F. Walker 1968). Both axes in parsecs, ticks 750, 500, 250, 0, 250, 500, 750. Orientation marks N, S, E, W. The four gas clouds I, II, III, IV are labeled with velocities +300km/s, +600 km/s, +450km/s, -550km/s.

The present authors rotated the position of the spectrograph slit in 15° steps through the nucleus with the 188 cm telescope of the Okayama Astrophysical Observatory and obtained a large number of spectrograms. To our surprise, the forbidden line [O III] $\lambda 5007$ at wavelength 5007 Å, emitted by doubly ionized

oxygen, appears strongly only in the direction of the flare (Figure 3.7). No such asymmetry is seen in H_α $\lambda 6563$, H_β $\lambda 4861$, or $[\text{N II}]$ $\lambda\lambda 6548, 6583$. Interestingly, strong polarization is also observed in this direction (A. Elvius 1978). Figure 3.8 shows the $[\text{O III}]$ gas cloud drawn by tracing the extent of $[\text{O III}]$ $\lambda 5007$; on several of the spectrograms, $[\text{O III}]$ $\lambda 5007$ reaching 6–7 kpc from the nucleus is recorded. Its essential nature is unknown at present, but it appears to be closely related to the flare and to Walker's gas clouds. The flare and Walker's gas clouds may perhaps be part of the $[\text{O III}]$ gas cloud. In any case, since no sign of winding by galactic rotation is seen in the shape of the $[\text{O III}]$ gas cloud, the age of the $[\text{O III}]$ gas cloud must be comparable to, or less than, the rotation period ($\sim 10^8$ years).

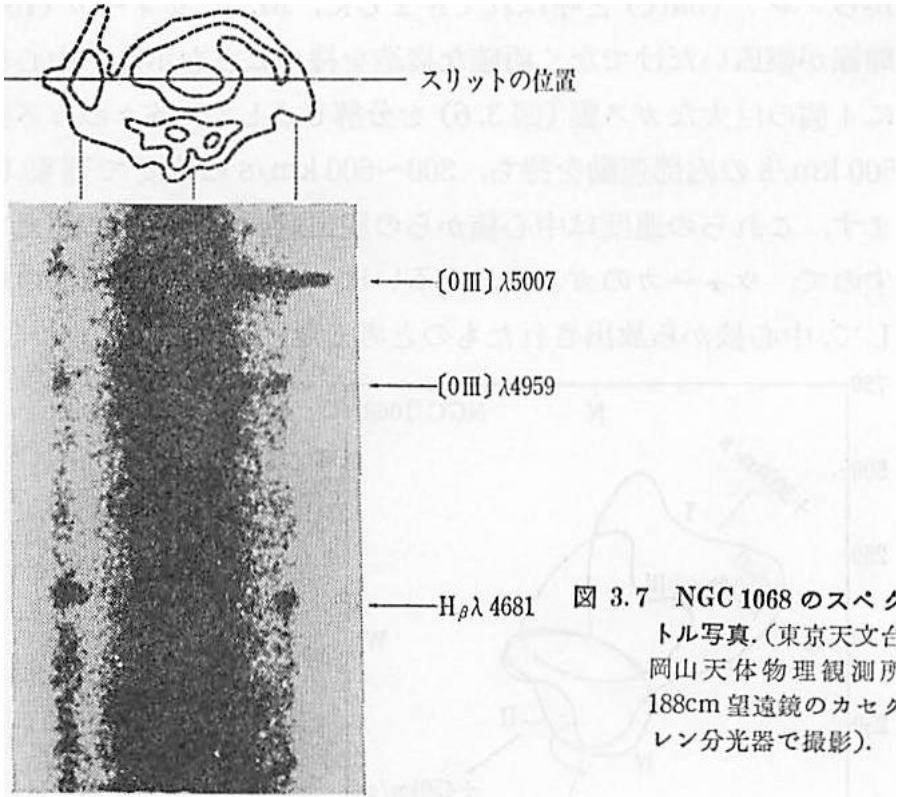


Figure 3.7 Spectrogram of NGC 1068. (Photographed with the Cassegrain spectrograph of the 188 cm telescope of the Okayama Astrophysical Observatory, Tokyo Astronomical Observatory). Above, an outline drawing of the galaxy with a line marking “the position of the slit.” Emission lines labeled in the spectrum: [O III] $\lambda 5007$, [O III] $\lambda 4959$, H_{β} $\lambda 4861$.

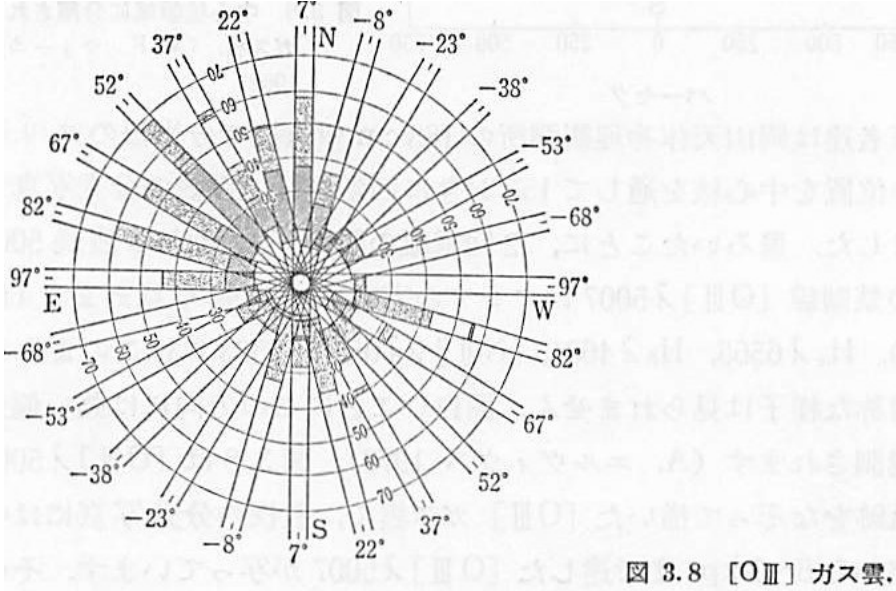


Figure 3.8 The [O III] gas cloud. A polar diagram showing the extent of [O III] along slits at various position angles through the nucleus. Position angles labeled: 7°, 22°, 37°, 52°, 67°, 82°, 97°, -8°, -23°, -38°, -53°, -68°. Orientation marks N, S, E, W. Concentric circles labeled: 30, 40, 50, 60, 70 (arcsec).

As may be seen from the fact that NGC 1068 is called 3C 71, this galaxy is a powerful radio source for a spiral galaxy. Figure 3.9 is a comparison between the optical structure and the intensity distribution measured along the east–west direction of NGC 1068 at a wavelength of 6 cm by A. G. de Bruyn and A. G. Willis (1974); the radio source agrees well with the ~ 1 kpc nuclear region. This is also a general radio characteristic of Seyfert galaxies. Figure 3.10 is the 4,885 GHz (6.1 cm) radio map obtained by A. S. Wilson and A. G. Willis (1980). In addition to the

central radio source No. 2, the northern radio source No. 1 and the southwestern No. 3, both 750 pc from the center, are resolved. Wilson and Willis are inclined to identify these with the double radio sources of radio galaxies. According to the radio observations of K. I. Kellermann and collaborators (1970) and P. C. Crane (1979), the size of the point-like radio source within the nucleus is 1–30 pc.

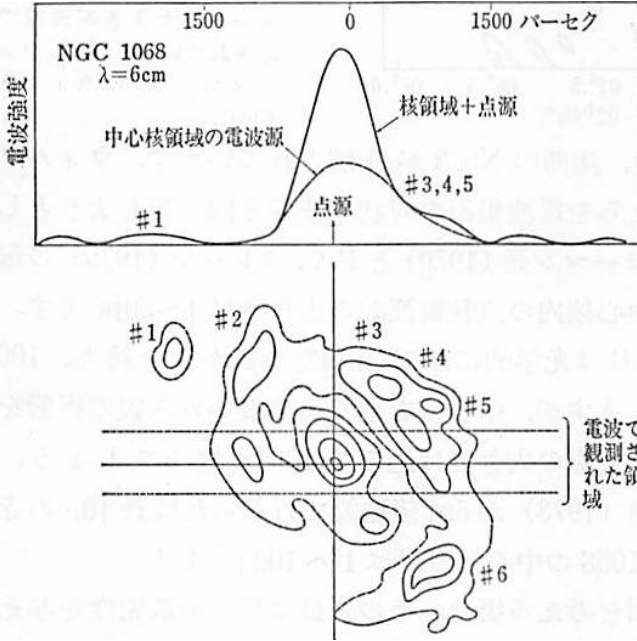


図 3.9 NGC 1068 の電波構造.

Figure 3.9 The radio structure of NGC 1068. Upper panel: NGC 1068, $\lambda = 6\text{cm}$. Vertical axis: radio intensity. Horizontal axis: 1500, 0, 1500 parsecs. Curves labeled “radio source of the nuclear region,” “nuclear region + point source,” “point source,” together with #1 and #3,4,5. Lower panel: a contour map showing radio sources #1–#6, with a band on the right indicating “the region observed in radio.”

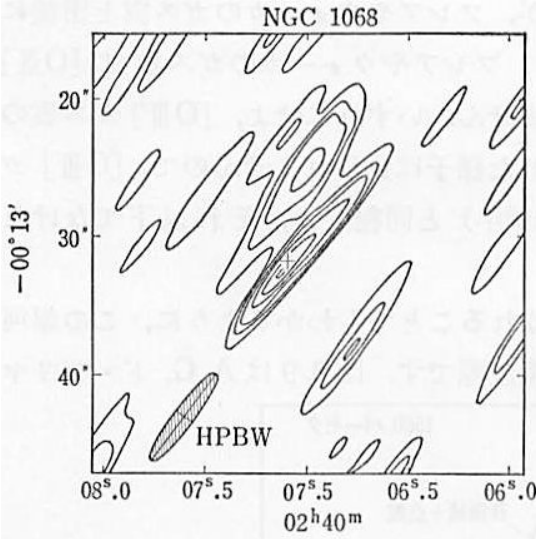


図 3.10 NGC 1068 の電波地図
ビームの大きさが斜線
示されている。(A. S. ウ
ルソンと A. G. ウィリ
1980).

Figure 3.10 Radio map of NGC 1068. The beam size is indicated by hatching. (A. S. Wilson and A. G. Willis 1980). Vertical axis: declination $-00^{\circ}13'$, ticks $20''$, $30''$, $40''$. Horizontal axis: right ascension $02^{\text{h}}40^{\text{m}}$, ticks $08^{\text{s}}.0$, $07^{\text{s}}.5$, $07^{\text{s}}.0$, $06^{\text{s}}.5$, $06^{\text{s}}.0$. HPBW is marked in the figure.

Optically the nucleus of NGC 1068 has an extent of about $1''.5$, which is thought to be 100–200 pc; but since it is affected by the dense gas clouds surrounding the nucleus, the actual size is probably less than 100 pc. In the 10μ infrared observations made with the 5 m telescope by E. E. Becklin and collaborators (1973), the diameter of the nucleus of NGC 1068 is $1'' \sim 100$ pc.

When considering the cause of nuclear activity, the mass is important knowledge because it gives the number density of stars. D. O. Richstone and D. C. Morton (1975) obtained the stellar velocity dispersion from a high-dispersion spectrum of the nucleus and derived $(0.6\text{--}2.4) \times 10^9 M_{\odot}$ for the mass within a radius of 140 pc. In the case of M 31 the mass is $6 \times 10^8 M_{\odot}$ within a radius of 200 pc and $2.7 \times 10^9 M_{\odot}$ within 400 pc, so NGC 1068 cannot be said to be particularly abnormal as a spiral galaxy.

2. NGC 4151

The representative Seyfert galaxy NGC 4151 is classified as Sa/Sab, (R')SAB (rs) ab/b, gkS 4 pN. Here (R') means a pseudo-ring and p means peculiar. Its distance, 20 Mpc, is almost the same as that of NGC 1068. Like NGC 1068, NGC 4151 outwardly has a fourfold structure — outermost region, bar region, inner region and nuclear region — but on closer examination it proves to have properties very different from those of NGC 1068.

(1) The outermost region and the bar region

Figure 3.11 is a beautiful photograph taken with the 5 m telescope by H. Arp (1977), showing the outermost region (40×30 kpc) and the bar region (15×10 kpc) of NGC 4151. The surface brightness of the outermost region of NGC 4151 is far lower than that of NGC 1068, and in this photograph two plates have been printed in superposition in order to bring out the faint outermost structure.

Along the two thin, faint arms within the outermost region, a number of patches thought to be ionized hydrogen regions can be seen. This gas arm can also be seen clearly in the detailed 21 cm radio observations made by A. Bosma, R. D. Ekers and J. Lequeux (1977) (Figure 3.12).

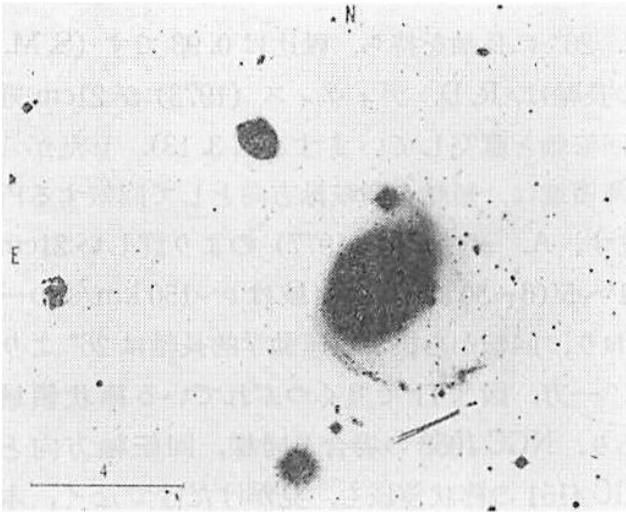


図 3.11 NGC4151の最外部領域. 5m($f/3.67$) 望遠鏡で撮影された 90分露光の 2 枚の IIIaJ 乾板が重ね書きされている. (H. アープ 1977).

Figure 3.11 The outermost region of NGC 4151. Two IIIaJ plates of 90-minute exposure taken with the 5m ($f/3.67$) telescope have been printed in superposition. (H. Arp 1977). Orientation marks N, E and a scale bar (value illegible) appear in the figure.

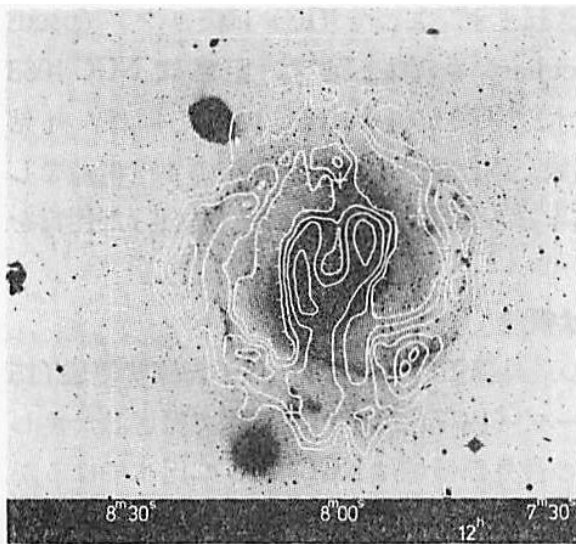


図 3.12 中性水素ガスの分布. 21cm電波地図が NGC 4151 の写真に重ねられている. (A. オスマ, R. D. エッカーズ, J. ルクー 1977).

Figure 3.12 Distribution of neutral hydrogen gas. A 21cm radio map is superimposed on a photograph of NGC 4151. (A. Bosma, R. D. Ekers, J. Lequeux 1977). Right-ascension ticks along the bottom: $8^{\text{h}}30^{\text{s}}$, $8^{\text{h}}00^{\text{s}}$, $7^{\text{h}}30^{\text{s}}$ (12^{h}).

The total mass of neutral hydrogen is $M_{\text{HI}} = 4 \times 10^9 M_{\odot}$. The outermost region of NGC 4151 is rich in gas, but for some reason it is thought to be in an underdeveloped state as a stellar system.

The outermost region has its major axis at P. A. 26° , with an axial ratio of 0.93 (S. M. Simkin 1975). This major axis is perpendicular to the rotation axis determined from the 21cm radio observations of R. D. Davies (1973) (Figure 3.13). The outermost region of NGC 4151 may therefore be regarded as a disk rotating with the minor axis as the direction of the rotation axis. In the more detailed 21cm observations of A. Bosma and collaborators (1977), the region of radius $R = 1'-5'$ (6–30 kpc) rotates with a constant velocity of $v \sim 150$ km/s, and the kinematic major axis determined from the rotation is 19° , somewhat smaller than 26° . On the other hand, the major axis of the bar region, which is burned out black in Figure 3.11, lies at 116.5° , and as in the case of NGC 1068 it coincides with the direction of the rotation axis. The bar region of NGC 4151 too is presumably a genuine bar, and not merely one in appearance. From the apparent shape alone one cannot determine the inclination of the galaxy.

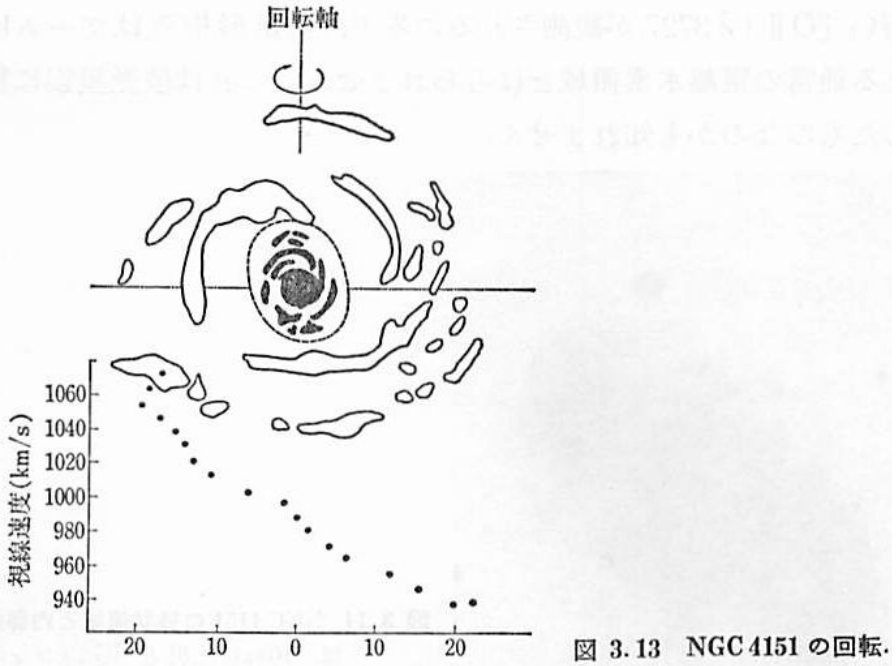


図 3.13 NGC 4151 の回転.

Figure 3.13 The rotation of NGC 4151. Upper panel: schematic drawing of the galaxy with its rotation axis. Lower panel: vertical axis, radial velocity (km/s), ticks 940, 960, 980, 1000, 1020, 1040, 1060; horizontal axis, r (kpc), ticks 20, 10, 0, 10, 20.

In general, the photographs published as NGC 4151 show the bar region (Figure 3.14). Within it one can see a spherical inner region about 5 kpc in diameter and what appear to be spiral arms. From this structure NGC 4151 is classified as Sa or Sab type; but to interpret the bar region as a rotating disk containing ordinary spiral arms entails serious difficulties.

Then what exactly is this amorphous region containing many knots, patches and filaments seen within the bar region? R. D. Davies (1973) held that an explosion far more violent than the activity now taking place in the nucleus of this galaxy must have occurred in the past, and that the amorphous structure of the bar region was produced by an explosion along the polar direction. S. M. Simkin (1975)

attempted spectroscopic observations of the bar region. In the spectra at P. A. 123° and 127° , only weak $[\text{O II}] \lambda 3727$ is observed from the northwestern and southeastern ends of the bar region, and the amorphous structure cannot be regarded as ordinary ionized hydrogen regions lying within arms. It may perhaps be something resembling a diffuse nebula.

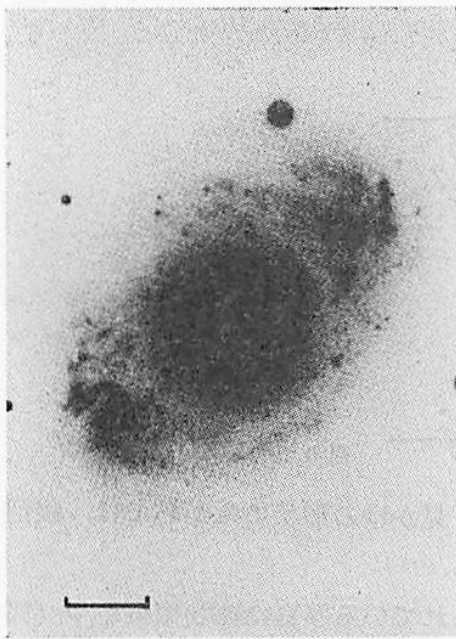


図 3.14 NGC 4151 の棒状領域と内部領域. 103aO 乾板と GG 13 フィルターの組み合わせで, 30 分露光, 5 m 望遠鏡. 図中のスケールは 2 kpc. (G. R. バービッジ, E. M. バービッジ, A. R. サンデッジ 1963).

Figure 3.14 The bar region and inner region of NGC 4151. A combination of a 103aO plate and a GG 13 filter, 30-minute exposure, 5 m telescope. The scale in the figure is 2 kpc. (G. R. Burbidge, E. M. Burbidge, A. R. Sandage 1963).

(2) The inner region and the nuclear region

The inner region (Figure 3.14) is nearly spherical, and were it not for the amorphous structure within the bar region it would look like a small elliptical

galaxy. If we define an N galaxy as a system possessing a bright compact core and a faint envelope, then NGC 4151 is precisely the typical case.

The present author (1980) used photographic plates in three colors — blue (B), visual (V) and infrared (I) — taken with the Okayama 188 cm telescope to measure the luminosity distribution of the inner region. Figure 3.15 shows the surface brightness $\mu(R)$ in magnitudes per square arcsecond, plotted with the one-fourth power of the radius R as abscissa. From this we find that the surface brightness distribution of the inner region follows the one-fourth-power law proposed by G. de Vaucouleurs: $\mu(R) - \mu(O) \propto R^{1/4}$. Inside $R \lesssim 5''$ it departs from this law, but this is due to the contribution of nuclear light spread by atmospheric seeing. In B and V it departs from the one-fourth-power law outside $R \gtrsim 25''$, but as is easily seen from Figure 3.14 this is the contribution of the amorphous region. In I it follows de Vaucouleurs' law out to $R = 40''$ (4 kpc), the limit of the measurement. Since this law holds for elliptical galaxies and for the central bulges of spiral galaxies, the inner region of NGC 4151 is presumably a stellar system of central-bulge type. At the same time it is also clear that the amorphous structure within the bar region is not a stellar system. The luminosity of the system obeying the one-fourth-power law is estimated at $L_v = 7 \times 10^9 L_\odot$. If we assume a mass-to-light ratio of $M/L_v = 10 M_\odot/L_{v_\odot}$ for the galaxy, the total mass of the inner region is calculated to be $M = 7 \times 10^{10} M_\odot$.

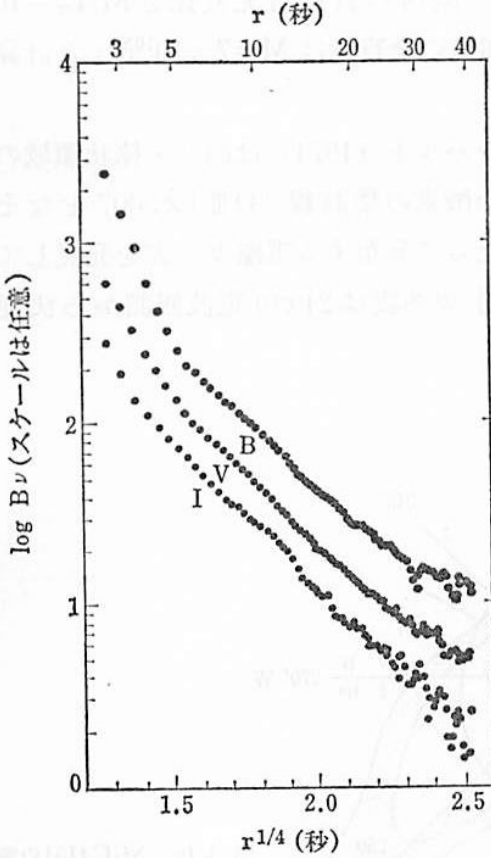


図 3.15 NGC 4151 の表面輝度分布. B_v と $\mu(r)$ との間には, $\mu(r) = -2.5 \log B_v + \text{定数}$ の関係がある. (兼古昇 1980).

Figure 3.15 The surface brightness distribution of NGC 4151. Between B_v and $\mu(r)$ there is the relation $\mu(r) = -2.5 \log B_v + \text{constant}$. (Kaneko, N. 1980). Vertical axis: $\log B_v$ (scale arbitrary), ticks 0, 1, 2, 3, 4. Horizontal axis: $r^{1/4}$ (arcsec), ticks 1.5, 2.0, 2.5. Upper axis: r (arcsec), ticks 3, 5, 10, 20, 30, 40. Three sequences labeled B, V, I.

K. J. Fricke and M. Reinhardt (1974) carried out spectroscopic observations of the inner and bar regions and, by tracing the forbidden line of doubly ionized oxygen [O III] $\lambda 5007$, discovered an ionized gas cloud distributed over both regions (Figure 3.16). This [O III] gas cloud is markedly flattened toward the direction of the rotation plane of NGC 4151 determined from 21 cm radio observations. The

radial velocity at $R = 20''$ (2 kpc) also shows a rotational motion in which the northeastern side recedes and the southwestern side approaches, so this gas cloud may be regarded as lying in the rotation plane of the galactic disk.

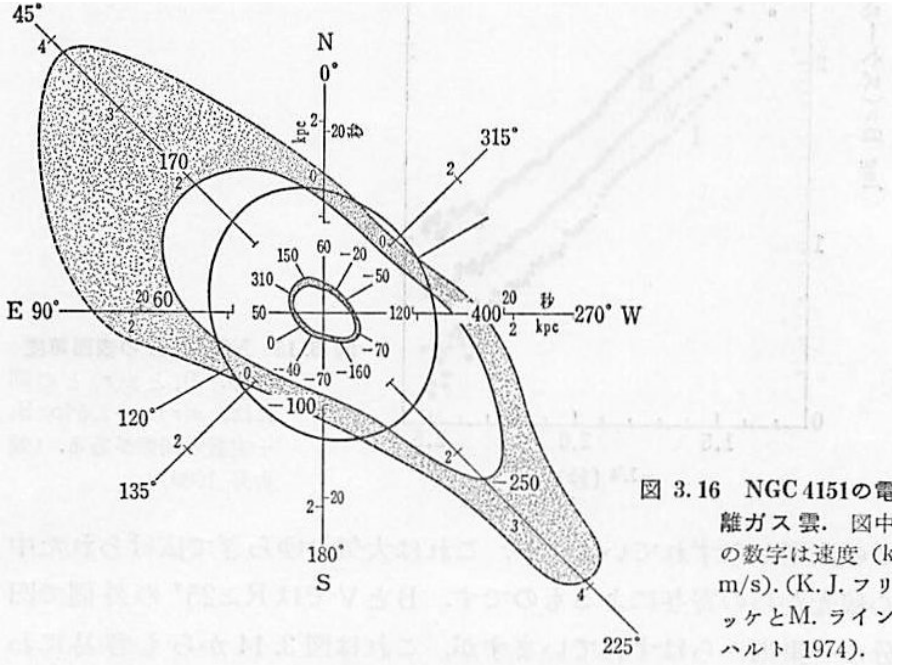


Figure 3.16 The ionized gas cloud of NGC 4151. The numbers in the figure are velocities (km/s). (K. J. Fricke and M. Reinhardt 1974). Position angles labeled: 0° (N), 45° , 90° (E), 120° , 135° , 170° , 180° (S), 225° , 270° (W), 315° . Scale: 20 arcsec / 2 kpc, with radial marks at 2, 3, 4 (kpc). Velocity values in the figure: 150, 310, 50, 0, 60, -20, -50, -70, -40, -160, 120, -100, -250, 400, etc.

In the nuclear region there exist four ionized gas clouds 200–300 pc in diameter, related to the [O III] gas cloud (Figure 3.17). As in the case of NGC 1068, these were resolved by analysis of the emission-line profile of [O III] $\lambda 5007$. M. H. Ulrich (1973), who succeeded in this observation, interpreted them — since the gas

clouds have velocities of ~ 200 km/s — as having been produced by an explosion in the nucleus, and estimated the time scale at 1×10^6 years.

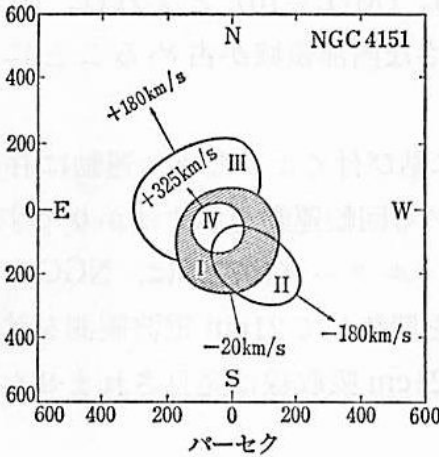


図 3.17 中心核領域内の電離ガス雲.
(M.H. ウルリッヒ 1973).

Figure 3.17 The ionized gas clouds within the nuclear region. (M. H. Ulrich 1973). Both axes in parsecs, ticks 600, 400, 200, 0, 200, 400, 600. Orientation marks N, S, E, W. The four gas clouds I, II, III, IV are labeled with velocities +180km/s, +325km/s, -20km/s, -180km/s.

Against this explosion hypothesis, K. S. Anderson (1974) argues that it would be more appropriate to interpret the motion as rotation. His reason is that the nuclear region is slightly flattened along P. A. 35° , coinciding with the direction of the rotation plane of the outermost region. K. J. Fricke and M. Reinhardt (1974) also re-measured Ulrich's spectrograms and confirmed that the velocity field is indeed rotational, so the position that regards it as an explosion is difficult to maintain. Thus the interpretation that the gas cloud extending out to $R \sim 4$ kpc discovered by Fricke and Reinhardt is distributed continuously as far as the nuclear region, and is in rotational motion sharing a common rotation axis with the neutral hydrogen gas in the outermost region, appears to be the correct one.

If the velocity field of NGC 4151 is due to rotational motion, the mass can be calculated. K. S. Anderson (1974) estimated, for the nucleus and for the whole, $M(R \leq 2'') \simeq 3 \times 10^9 M_{\odot}$ and $M(R \leq 2') \simeq 1.4 \times 10^{11} M_{\odot}$. If the mass of the inner region is taken to be $7 \times 10^{10} M_{\odot}$ ($M/L = 10$), then the comparatively small inner region accounts for about half of the total mass of NGC 4151.

In the end, no gas motion connected with an explosive phenomenon exists in NGC 4151. Both the neutral hydrogen gas and the ionized gas show nothing but rotational motion. A. Bosma, R. D. Ekers and J. Lequeux (1977) attempted 21cm radio observations in the expectation of non-rotational gas motion in the nuclear region of NGC 4151, but no 21cm absorption line indicating such motion was found.

The only active region of NGC 4151 is the nucleus. M. Schwarzschild (1973) sent a 91 cm stratospheric telescope to an altitude of 24 km and succeeded in photographing the nucleus of NGC 4151. The size of the nucleus obtained was an upper limit of $0.''08$ (8pc) or less, which compared with the theoretically expected 0.1–0.01 pc is still only a large value. Radio emission comes from a region of 200–300 pc corresponding to Ulrich's gas clouds, but in NGC 4151 it is not strong enough to be of concern.

(3) NGC 4151 and the peculiar galaxies around it

If one arranges B. A. Vorontsov-Velyaminov's interacting galaxies and H. Arp's peculiar galaxies "skillfully," one can make a moving picture suggesting a process in which attendant companion galaxies split off from, or are ejected by, a parent main galaxy. When large redshifts were discovered in quasars, J. Terrell (1964) put forward the local hypothesis, interpreting them as nearby objects (local objects) ejected from the Milky Way galaxy at relativistic velocities. F. Hoyle and G. R. Burbidge (1966) also suggested the possibility that quasars had been ejected, not by

the Milky Way galaxy, but by nuclear explosions in radio galaxies. The vast body of observational material accumulated since then, however, has done nothing but strengthen the resemblance between Seyfert galactic nuclei and quasars.

In spite of this situation, H. Arp of the Hale Observatories has gone on searching for observational evidence suggesting that quasars and companion galaxies have been ejected from a parent main galaxy. On his view, a redshift is the sum of a component representing Hubble's expansion of the universe and an "unknown" component, and the distance of an object ought to be determined from indicators other than the redshift. H. Arp (1977) found around NGC 4151 six galaxies and two quasars, together with a group of five small galaxies arranged in a chain, and has tried to establish that they were ejected from NGC 4151. Figure 3.18 is his sketch. Comparing it with Figure 3.11 makes the correspondence easy to see. Arp draws attention to the fact that NGC 4156 lies at the tip of an arm of NGC 4151, and regards this as one piece of evidence that the two galaxies form not merely an apparent but a real group. Likewise the galaxy G 1 also lies at the tip of an arm. Since the galaxy G 2 lies within the strange bar-like filament of NGC 4156 (Figure 3.19), Arp interprets this too as having been produced by a further explosion in NGC 4156.

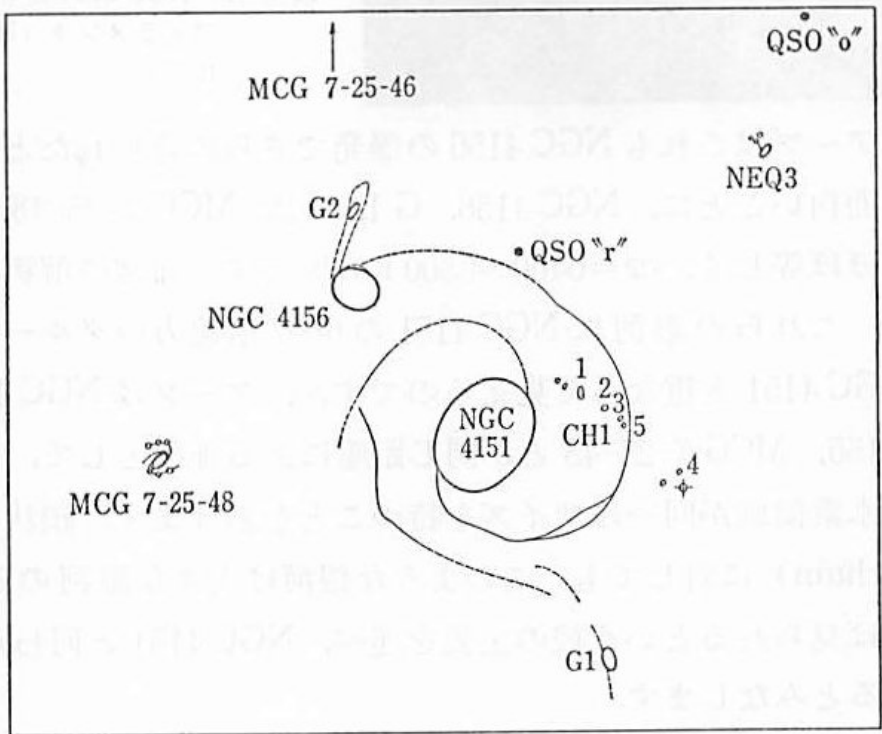


図 3.18 NGC 4151 の周辺の銀河とクエーサー. (H. アープ 1977).

Figure 3.18 Galaxies and quasars around NGC 4151. (H. Arp 1977). Labels in the sketch: MCG 7-25-46 (top, with arrow), QSO “o” (upper right), NEQ3, G2, QSO “r”, NGC 4156, NGC 4151, CH1 (with the numbers 0, 1, 2, 3, 4, 5 nearby), MCG 7-25-48 (left), G1 (lower right).

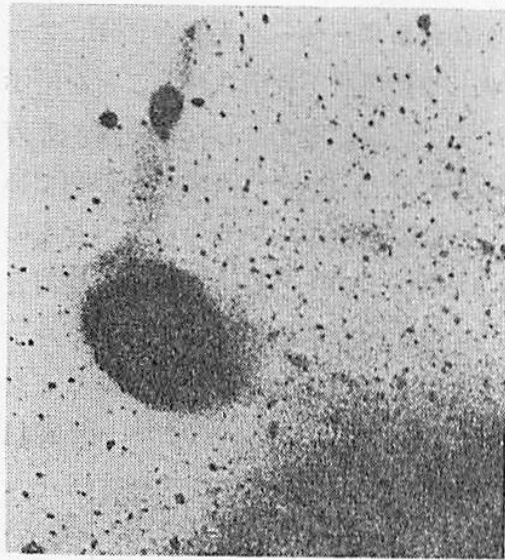


図 3.19 NGC 4156 と G2 を結ぶ
フィラメント. (H. アープ
1977).

Figure 3.19 The filament connecting NGC 4156 and G2. (H. Arp 1977).

Interestingly, the redshifts of NGC 4156, G 1, G 2 and MCG 7-25-48 are nearly equal, $cz = 6400\text{--}6800$ km/s. On the ordinary interpretation these galaxies form a group 6–7 times farther away than NGC 4151 and happen by chance to be superposed on it; but Arp cites, as evidence that NGC 4151, NGC 4156 and MCG 7-25-48 lie at the same distance, the fact that their H II regions have the same size. As for the chain galaxies (CH = chain), he states his contention that such galaxies are often seen near large galaxies, and regards them as having some relation to NGC 4151.

Arp’s claim is far too bold for ordinary astronomers to accept, but as a purely morphological argument based on observational material it contains things that

cannot be denied. For example, the apparent size of H II regions is in fact used as a distance indicator. In the case of NGC 4151, however, one may object that what Arp took to be an H II region (Figure 3.14) cannot be regarded as an ordinary H II region and cannot be equated with those of NGC 4156.

Let us avoid going any deeper into Arp's hypothesis and confine ourselves to showing one other example. Figure 3.20 shows NGC 4319 ($v_R = 1,700\text{km/s}$) and Mkn 205 ($v_R = 11,000\text{km/s}$), famous as a spiral-galaxy/quasar pair, in which a bridge connecting the two can be seen. It is doubted, however, whether this is a real bridge. A. G. Willis (1979) has pointed out that Mkn 205 has radio properties more like those of a Seyfert galaxy than of a quasar.

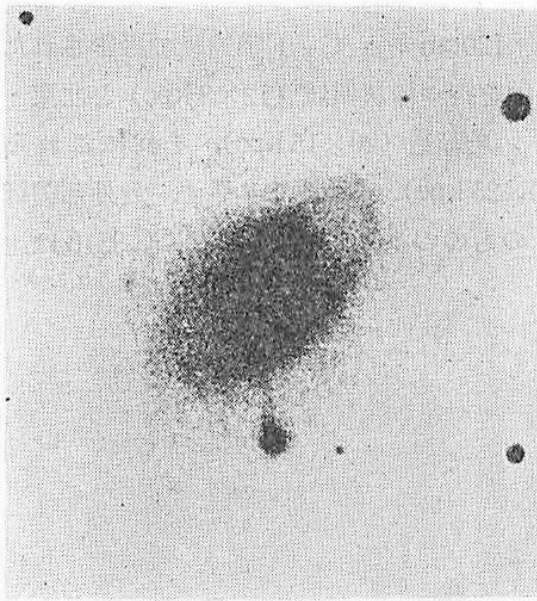


図 3.20 NGC 4319 と Mkn 20
5. 撮影には H_α の干渉
フィルターとイメージ
増幅管が使用され、露
光時間は30分、5m 望遠
鏡. (H. アープ 1971a).

Figure 3.20 NGC 4319 and Mkn 205. An H_α interference filter and an image tube were used for the photograph; exposure time 30 minutes, 5 m telescope. (H. Arp 1971a).

3. NGC 3516 and NGC 3783

NGC 1068 is an SA-type and NGC 4151 an SAB-type spiral galaxy. Here we examine the structure of two SB-type Seyfert galaxies.

(1) NGC 3516

NGC 3516 is somewhat distant, lying at 52 Mpc. In the Hubble classification it is Sa/SBO, and in the Morgan classification $kB^?R$ 4. Here $B^?$ means “barred galaxy?”, and R means that the system has no definite spiral or elliptical structure but is rotationally symmetric. In de Vaucouleurs’ classification it is (R)SB(s)O.

Figure 3.21 shows NGC 3516 photographed with the 120 cm Schmidt telescope of Palomar Observatory. One can distinguish a bar region with its major axis running north–south (12×8 kpc), a ring structure flattened in the northeast–southwest direction (20×15 kpc), and a faint outermost region enclosing them (30×25 kpc). The outermost region is only half the size of those of NGC 1068 and NGC 4151, so NGC 3516 is comparatively compact.

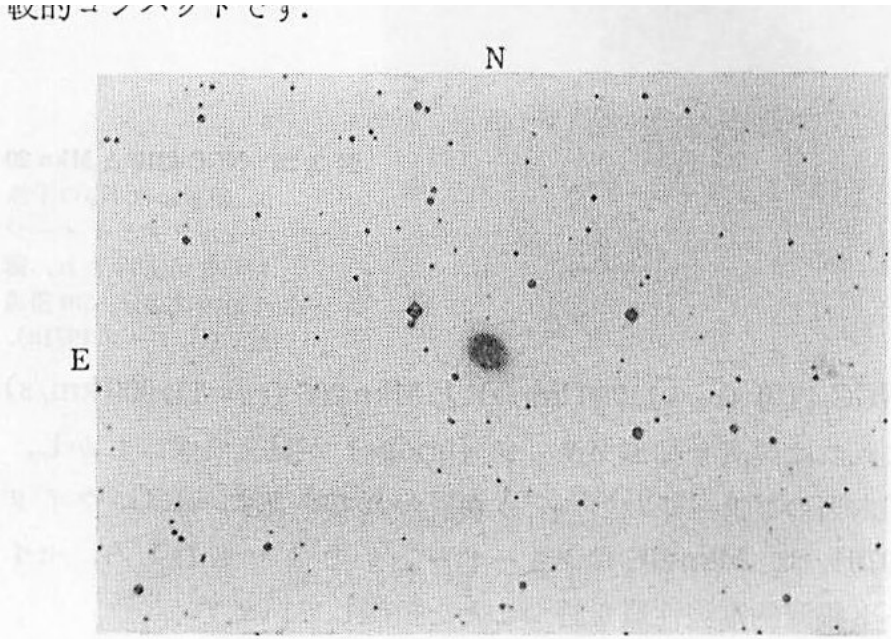


Figure 3.21 NGC 3516. (Palomar Sky Survey Atlas). N is marked at the top of the photograph and E at the left edge.

Figure 3.22 shows photographs of the nuclear region in ultraviolet light, infrared light and the H_{α} emission line, taken by T. F. Adams (1977) with an image tube attached at the Cassegrain focus of the 2.1 m telescope of McDonald Observatory. In the H_{α} photograph the nuclear region extends along the major axis of the outermost region — that is, in a direction nearly perpendicular to the bar region — and reaches a length of more than 3 kpc. This structure is partly hidden by the diffraction image of the bright nucleus, but it is visible in the ultraviolet photograph as well, and part of it on the southwest side continues into a curved filament. In the infrared photograph no such structure is seen; it consists of a small round nucleus and a bar region extending north–south.

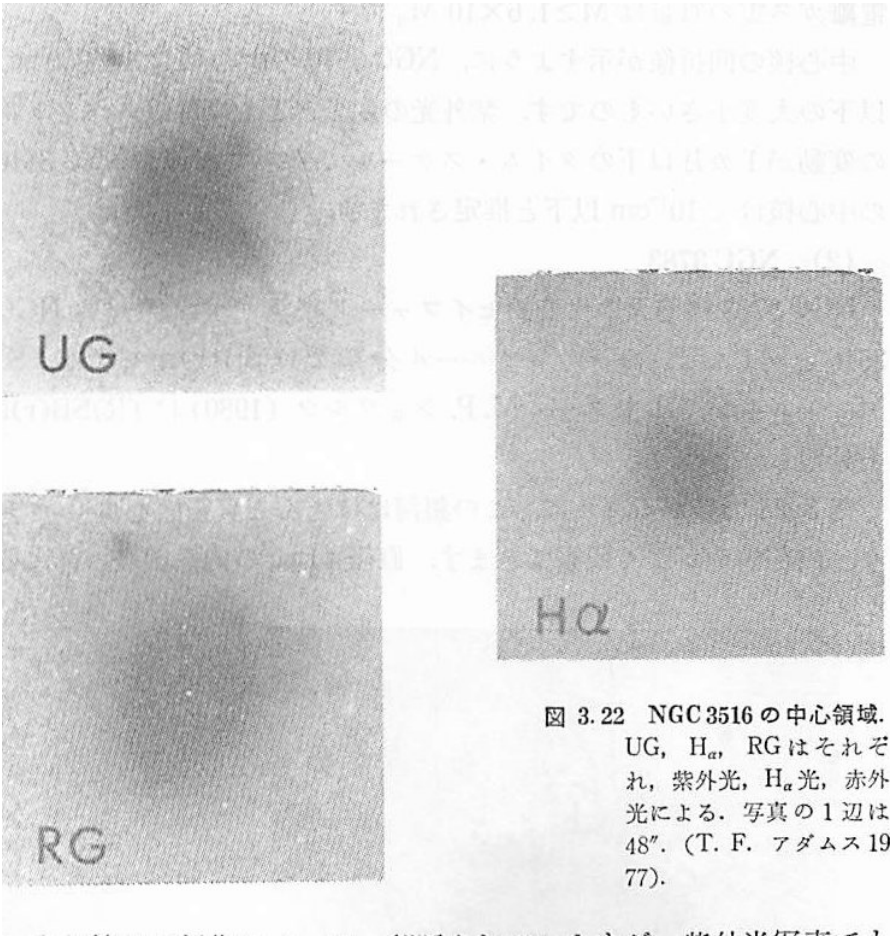


図 3.22 NGC 3516 の中心領域.

UG, H_{α} , RG はそれぞれ、紫外光, H_{α} 光, 赤外光による。写真の 1 辺は $48''$ 。(T. F. アダムス 1977)。

Figure 3.22 The central region of NGC 3516. UG, H_{α} and RG are taken in ultraviolet light, H_{α} light and infrared light respectively. One side of each photograph is $48''$. (T. F. Adams 1977).

NGC 3516 too has ionized gas clouds in a central region of a few kpc. According to the spectroscopic observations of M.-H. Ulrich and D. Péquignot (1980), the ionized gas clouds are concentrated within a radius of 2 kpc, but extend out to 7 kpc in the north-northeast–south-southwest direction, and the velocity field is

irregular and cannot be thought of as rotation. The mass of the ionized gas clouds is $M \geq 1.6 \times 10^7 M_{\odot}$.

As the diffraction image of the nucleus shows, the nucleus of NGC 3516 is very small, less than $1''$ (250 pc). Variations of the emission-line spectrum accompanying the ultraviolet light variation occur on a time scale of less than one month, so the nucleus of NGC 3516 is estimated to be $\leq 10^{17}$ cm or smaller.

(2) NGC 3783

NGC 3783 is a representative Seyfert galaxy of the southern sky. Its distance is the same as that of NGC 3516. In de Vaucouleurs' classification it is SB(r)a, but S. M. Simkin, H. J. Su and M. P. Schwarz (1980) classified it as (R)SB(r)a.

As Figure 3.23 shows, this galaxy is seen almost exactly face-on, so its internal structure can be observed well. Outside the inner region of 4 kpc diameter there is a ring of 8 kpc diameter, and the two are connected by a thin bar running northwest–southeast. As in NGC 1068, the surface brightness changes discontinuously inside and outside the ring, and irregular structures thought to be H II regions are seen along the ring. Arms extend outward from the points where the bar meets the ring, occupying a region about 15 kpc in diameter. The outermost region is larger still, as much as 40×50 kpc (Figure 3.24).

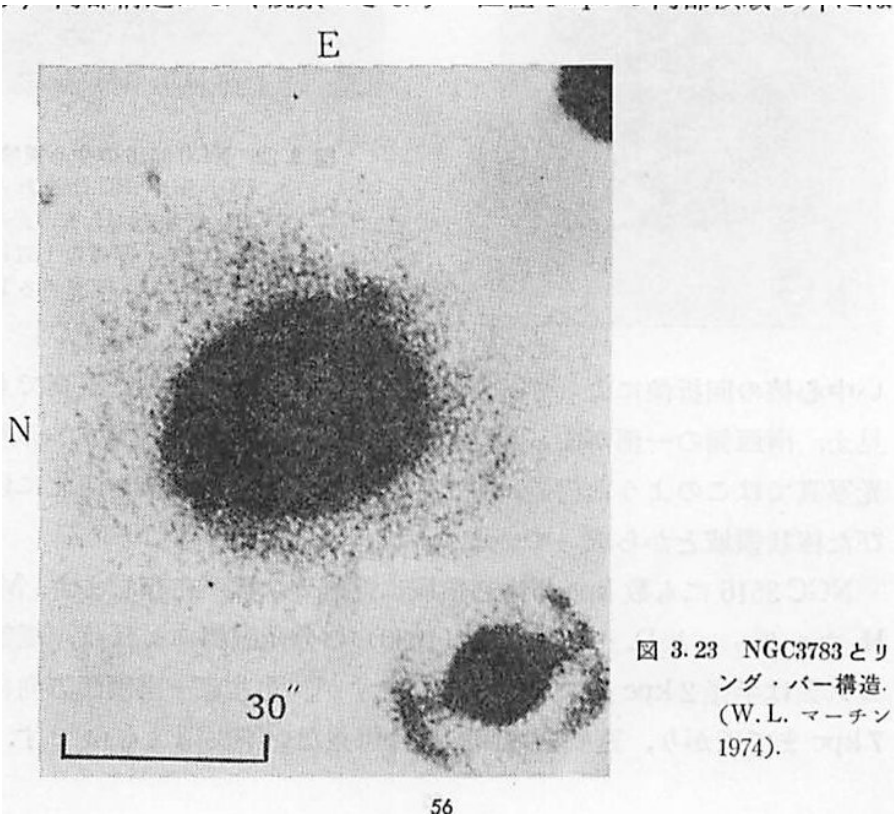


Figure 3.23 NGC 3783 and its ring-bar structure. (W. L. Martin 1974). E is marked at the top of the photograph and N at the left edge; a 30'' scale bar at lower left.

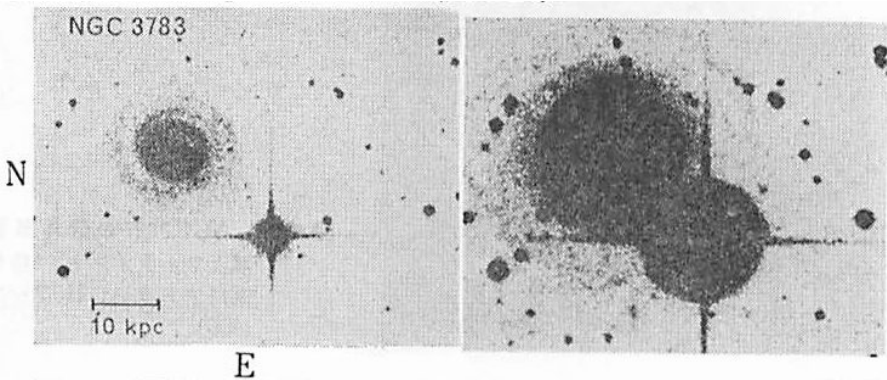


図 3.24 NGC 3783 の外部アームと最外部領域. (S. M. シムキン, H. J. スー, M. P. シュワルツ 1980).

Figure 3.24 The outer arms and outermost region of NGC 3783. (S. M. Simkin, H. J. Su, M. P. Schwarz 1980). The label “NGC 3783” appears in the left-hand photograph; N at the left edge, E at the bottom, scale bar 10 kpc.

4. NGC 3227 and NGC 7469

These two Seyfert galaxies are double galaxies, and are also interacting galaxies in Vorontsov-Velyaminov's sense.

(1) NGC 3227

NGC 3227 forms a double galaxy with NGC 3226 and is also called VV 209 and Arp 94. NGC 3227 is classified as Sb, g? S 4 p and SAB(s)ap in the respective systems. The companion galaxy NGC 3226 is an E 2 or E 3 elliptical galaxy, and an arm of NGC 3227 appears to link up with this companion. Taking the distance of NGC 3227 as 22 Mpc, the apparent separation of the two galaxies is 13 kpc. A

filament extending further to the north is also visible, and the ring-like outermost region enclosing both galaxies has an extent of roughly 45×35 kpc (Figure 3.25).

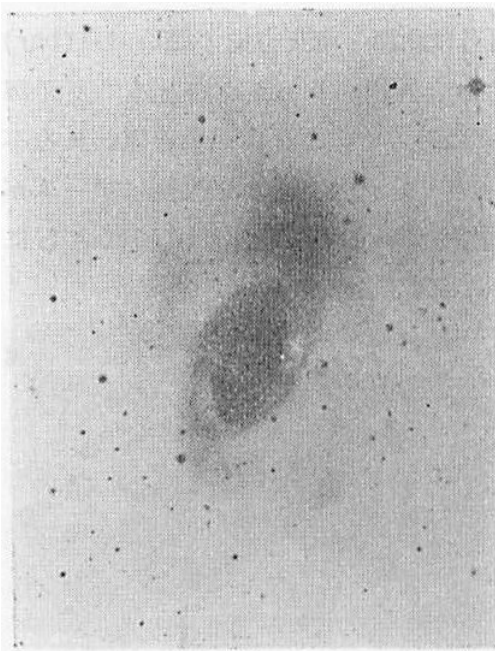


図 3.25 NGC 3227 の最外部領域とフィラメント. (特異銀河アトラス, H. アープ 1966).

3. 25).

Figure 3.25 The outermost region and filament of NGC 3227. (Atlas of Peculiar Galaxies, H. Arp 1966).

The part of Figure 3.25 that is burned out black is an amorphous disk region containing H II regions (Figure 3.26). No definite spiral arms are recognized in this region, and it also resembles a bar region. Moreover, although the quasi-stellar nucleus stands out conspicuously, no clear central bulge is recognized. This is a property common to the faintest group of Seyfert galaxies (NGC 1566, NGC 3227, NGC 4051), which sets the lower limit to the absolute luminosity of Seyfert galaxies.

According to the observations of V. C. Rubin and W. K. Ford (1968), the radial velocities of NGC 3227 and NGC 3226 are $v_R = 1,175$ and $1,350$ km/s respectively, a difference of $\Delta v_R = 175$ km/s. This velocity difference is reasonable for a double galaxy, but the velocity difference along the arm in the direction of NGC 3226 is abnormally large, reaching as much as ~ 800 km/s at maximum. The center of the neutral hydrogen 21 cm emission-line profile observed with the 305 m radio telescope also deviates greatly from the radial velocities of the two galaxies, and traces of a strong gravitational interaction are seen (G. R. Knapp, F. J. Kerr, B. A. Williams 1978). It is quite conceivable that NGC 3227/3226 are galaxies in the course of an encounter (A. Toomre and J. Toomre 1972).

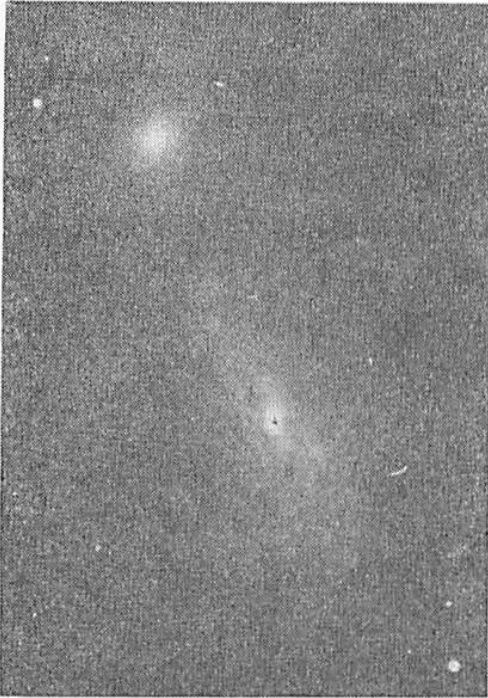


図 3.26 NGC 3227. (東京天文台岡山天体物理観測所の 188 cm 望遠鏡で撮影).

Figure 3.26 NGC 3227. (Photographed with the 188 cm telescope of the Okayama Astrophysical Observatory, Tokyo Astronomical Observatory).

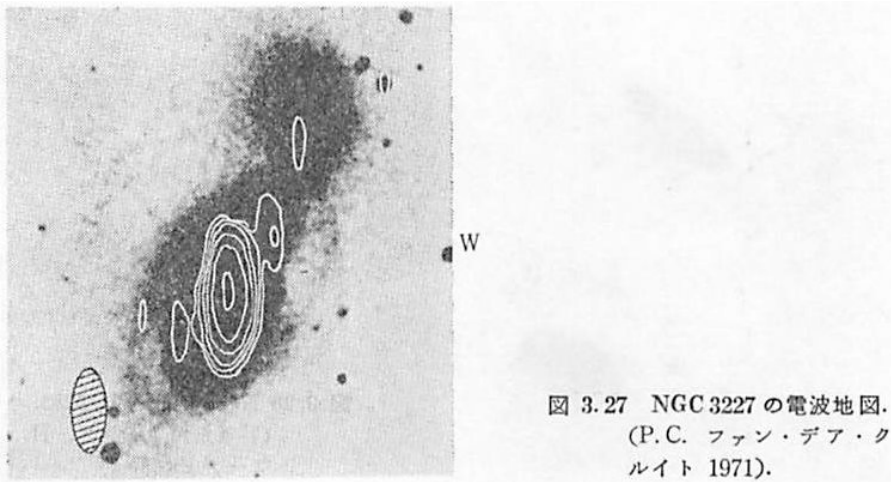


Figure 3.27 Radio map of NGC 3227. (P. C. van der Kruit 1971). Radio contours are superimposed on the optical photograph. W is marked at the right edge; the hatched beam is at lower left.

Figure 3.27 shows NGC 3227 as seen at 1415 MHz. There is only a radio source centered on the nucleus, and no radio emission comes from the companion galaxy NGC 3226. The radio luminosity of NGC 3227 between 10^7 and 10^{11} Hz is $L_R = 8.7 \times 10^{38}$ erg/sec. This is no more than a weak radio source. In X-rays, however, it is powerful, with $L_X(2 - 10 \text{ KeV}) = 1.3 \times 10^{42}$ erg/s. That it should be so bright in X-rays seems not to be unrelated to the fact that NGC 3227 is an interacting galaxy.

(2) NGC 7469

NGC 7469 is classified as Sa, g? S 3 :pN and (R')SAB(rs)a. The companion galaxy IC 5283 is an irregular galaxy, and the apparent separation of the two galaxies is 35

kpc. We have already mentioned that this double galaxy is called VV 254 and Arp 298.

Figure 3.28 shows NGC 7469 from the Atlas of Peculiar Galaxies. At least three regions can be distinguished in it. One is the outermost region, 40×30 kpc, which has a single arm or ring shape. The second is the main disk region, whose size is 11×17 kpc. Unlike NGC 1068 and NGC 4151, the major axes of the outermost region and the main disk region point in the same direction. In the photograph of Figure 3.29 the structure of the main disk region and of a third, inner region (~ 5 kpc) can be seen. The inner region is flattened in the direction P.A. 45° , and C. Barbieri, S. di Serego Alighieri and M. Zambon (1977) have found in it three condensations numbered 1, 2 and 3. Number 4 is the point where the ring-like arm makes contact. The nucleus of NGC 7469 too is no doubt surrounded by an enormous gas cloud. The emission-line spectrum is also observed over a region $3''.7$ in diameter. Figure 3.30 is a map of NGC 7469 observed at 4885 MHz by J. J. Condon (1981). The radio source consists of a halo $4''$ (2 kpc) in diameter and an unresolved core less than $0''.3$ in diameter, and the ratio of their radio intensities is 7 to 2.

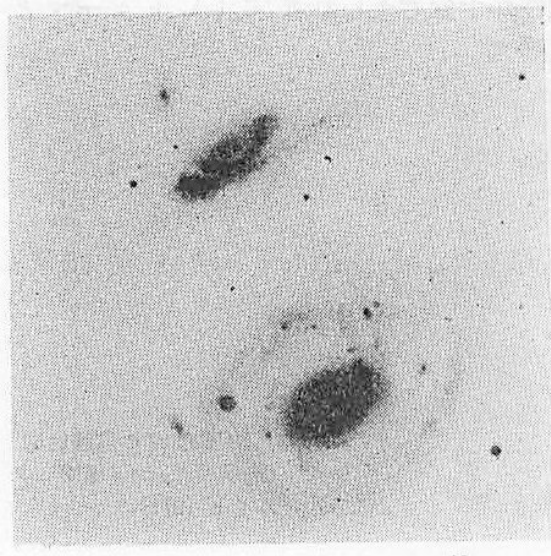


図 3.28 NGC 7469 と IC 5283.
(特異銀河アトラス, H.
アープ 1966).

Figure 3.28 NGC 7469 and IC 5283. (Atlas of Peculiar Galaxies, H. Arp 1966).

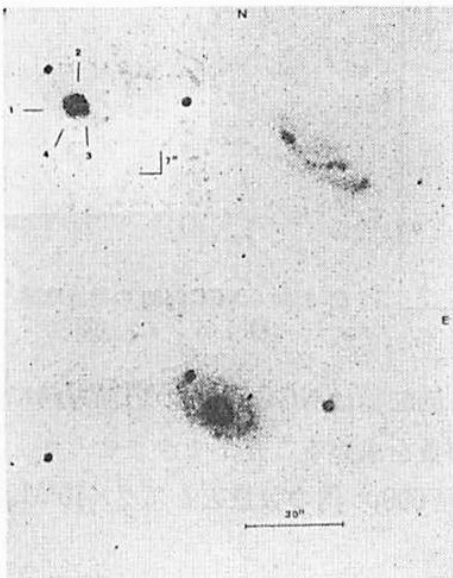


図 3.29 NGC 7469 の内部と中心核領
域. 左上は中心核領域. (C. バ
ルビエリ, S. ディ・アリギエ

Figure 3.29 The interior and nuclear region of NGC 7469. Upper left is the nuclear region. (C. Barbieri, S. di Serego Alighieri, M. Zambon 1977). N at the top of the photograph, E at the right edge, scale bar 30", the label "NGC 7469" at lower left. The inset at upper left carries a 1" scale and the condensation numbers 1, 2, 3.

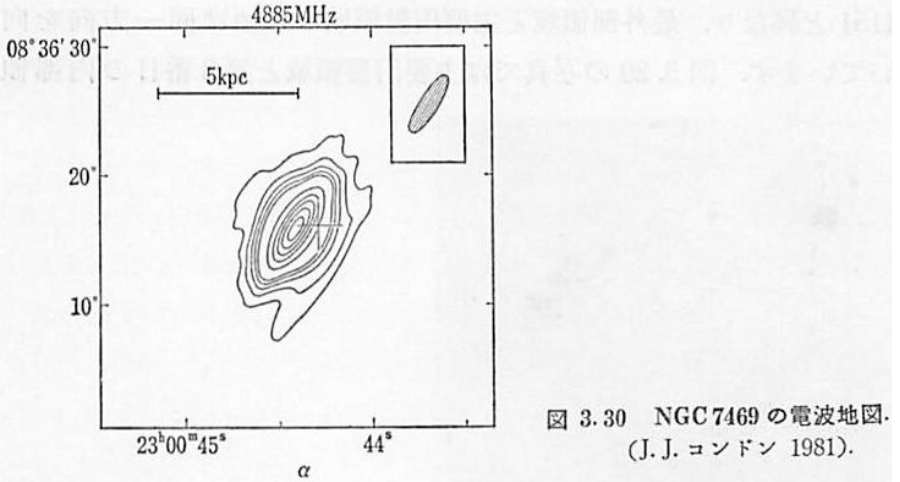


Figure 3.30 Radio map of NGC 7469. (J. J. Condon 1981). 4885 MHz at the top, scale bar 5 kpc, ordinate δ ($08^{\circ}36'30''$, $20''$, $10''$), abscissa α ($23^{\text{h}}00^{\text{m}}45^{\text{s}}$, 44^{s}), beam ellipse in the box at upper right.

The velocity curve of NGC 7469 is asymmetric on the northern side because of the gravitational interaction with the companion galaxy IC 5283. The rotation axis lies along the minor axis of NGC 7469. Because of the asymmetry the total mass cannot be obtained, but K. S. Anderson (1973) obtained $2 \times 10^9 M_{\odot}$ for the mass within a radius of 600 pc.

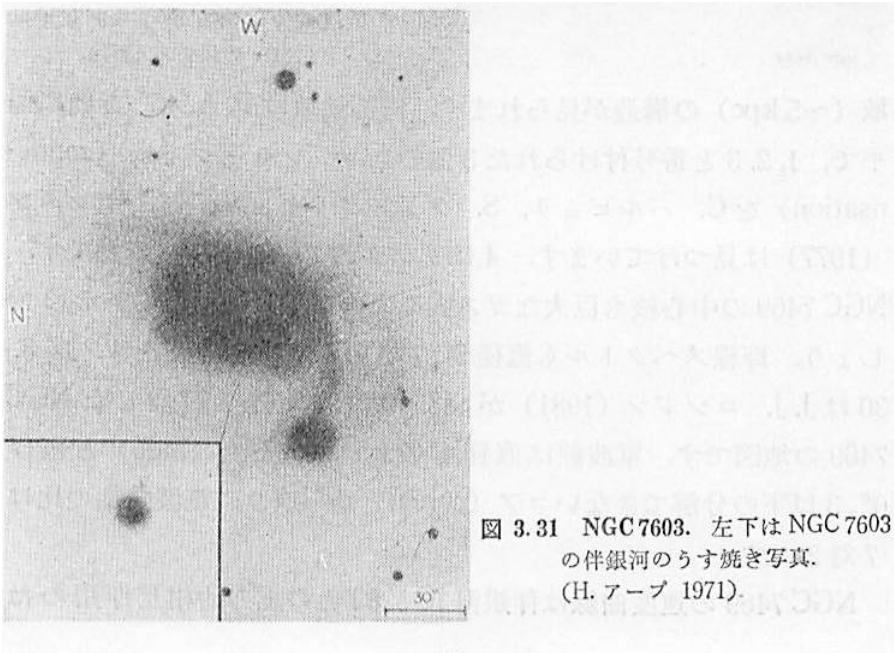


図 3.31 NGC 7603. 左下は NGC 7603
の伴銀河のうす焼き写真。
(H. アープ 1971).

Figure 3.31 NGC 7603. Lower left is a lightly printed photograph of the companion galaxy of NGC 7603. (H. Arp 1971). W at the top of the photograph, N at the left edge, 30" scale bar at lower right.

The companion galaxy IC 5283 has a very odd morphology and even looks like an interacting galaxy made up of three components. Filaments can also be seen in the Atlas of Peculiar Galaxies. The radial velocity of IC 5283 is 4,710 km/s, in good agreement with the 5,075 km/s of NGC 7469.

In the Seyfert galaxy NGC 7603 (Arp 92, Mkn 530), however, which at first sight looks like a double galaxy, the radial velocity of the companion is 16,900 km/s, about twice the 8,800 km/s of the main galaxy. On the ordinary interpretation they are galaxies at distances of 180 and 340 Mpc respectively that happen to be superposed and so appear as a double galaxy — but the bridge connecting the two

galaxies is too fine a thing to allow one to deny that they form a double galaxy (Figure 3.31).

5. NGC 1275

NGC 1275 is an elliptical galaxy at the center of the Perseus cluster of galaxies, also known as the radio source 3C 84 or Perseus A. It is also a powerful X-ray source. Ever since the collision hypothesis of W. Baade and R. Minkowski (1954) it has been a much-discussed object.

(1) The Perseus cluster

The Perseus cluster is registered as number 426 in the cluster catalogue of G. O. Abell (1958), and so is called Abell 426. L. P. Bautz and W. W. Morgan (1970) classified clusters into three types on the basis of how large the central galaxy of the cluster is. Those containing a very large cD galaxy are classed as type I (Abell 2199; Figure 2.6), those with no definite central galaxy as type III (the Virgo cluster), and the intermediate ones as type II (the Coma cluster). The Perseus cluster is of type II-III, intermediate between II and III, so NGC 1275 is not so enormous as a central object of a cluster.

Many galaxies are lined up in a straight line running west from NGC 1275 (Figures 3.34; 3.35; 3.38). Taking the distance of the Perseus cluster as 108 Mpc, the apparent distance from NGC 1275 to IC 310 is 1,100 kpc. In the cluster classification of H. J. Rood and G. N. Sastry (1971), modelled on Hubble's tuning-fork classification, the Perseus cluster is taken as the typical L type (Figure 3.32). There is furthermore the astonishing fact that Abell 347, Abell 262 and other clusters are strung out in a chain in the same direction as NGC 1275–IC 310

(Figure 3.33). This is called the Perseus supercluster, and it has the enormous extent of $45^\circ \times 1.5^\circ$ (80×3 Mpc)*.

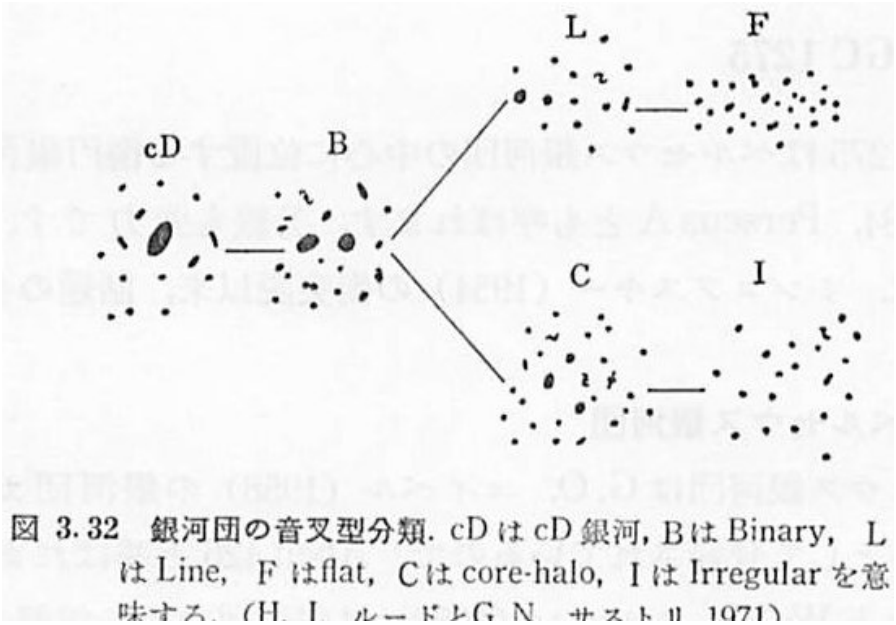


Figure 3.32 Tuning-fork classification of clusters of galaxies. cD means cD galaxy, B Binary, L Line, F flat, C core-halo and I Irregular. (H. J. Rood and G. N. Sastry 1971).

S. E. Strom and K. M. Strom (1978) have found that the Perseus cluster contains many flattened galaxies. Moreover, when the distribution of the major axes of the galaxies is examined, a peak is found in the east–west direction, the same as the direction of the chain of clusters. If this tendency has a physical meaning, we must interpret it as showing that the formation of clusters and the birth of individual galaxies were deeply related. As we saw above, it also agrees with the direction of flattening of the supercluster, and these facts seem to be important keys for unravelling the history of the universe.

* The Perseus supercluster contains eleven Seyfert galaxies: NGC 1275(2p), Mkn 1(2), Mkn 348(2), Mkn 352(1), Mkn 993(2), Mkn 1040(1), Mkn 1058(2), Mkn 1066(2), Mkn 1073(2), Mkn 1157(2), Akn 79(1). Here the figure in parentheses is the Seyfert type. (Graduation research of Sasaki, M. [佐々木実], Yamamoto, M. [山本将史] and Ichikawa, T. [市川哲雄] 1981).

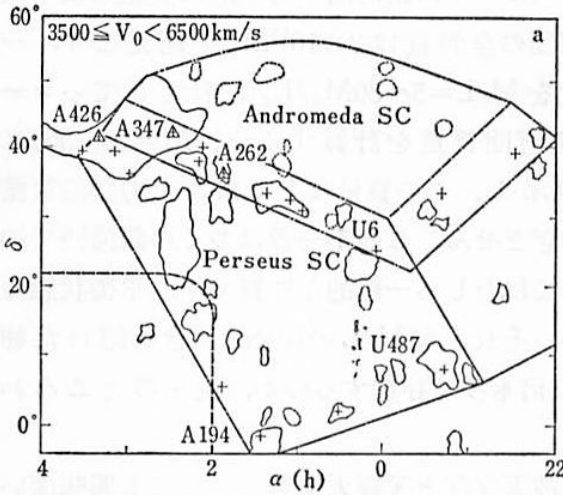


図 3.33 ペルセウス超銀河団. (J. エイナスト, M. ジョヴェール, E. サール 1980).

Figure 3.33 The Perseus supercluster. (J. Einasto, M. Jõeveer, E. Saar 1980). Markings in the figure: $3500 \leq V_0 < 6500$ km/s, “a” at upper right. Ordinate δ (60° , 40° , 20° , 0°), abscissa α (h) (4, 2, 0, 22). Labels: A426, A347, A262, U6, U487, A194, Andromeda SC, Perseus SC.

N. A. Bahcall (1974) investigated the structure of the Perseus cluster by counting galaxies brighter than 17.5 mag. The total number of galaxies counted within a diameter of 4 Mpc was 251, and the center of the cluster was at $\alpha(1950) = 3^h16^m.1$, $\delta(1950) = 41^\circ18'.5$. This position falls just midway between NGC 1275 and NGC 1272, its western neighbor. The shape of the cluster is elongated east–west, with an axial ratio of roughly 1 to 2. The surface number density of galaxies is well

represented by an isothermal model with a core radius of $8'$ (240 kpc), and the luminosity of the whole cluster is calculated to be $L = 1.2 \times 10^{13} L_{\odot}$. The luminosity of the core region is $L_c = 6 \times 10^{11} L_{\odot}$, four times that of NGC 1275.

The velocity dispersion of the galaxies in the Perseus cluster is famous for being very large. Approximating it by a normal distribution, its standard deviation is $\sigma_{v_0} = 1,420 \pm 140 \text{ km/s}$. To support so large a velocity dispersion by the cluster's own gravity — that is, if the Perseus cluster is in a dynamically stable equilibrium state — the total mass of the cluster must exceed $2 \times 10^{15} M_{\odot}$. On the other hand, if we assume a mass-to-light ratio for the galaxies of $M/L = 5\text{--}30 M_{\odot}/L_{\odot}$ and compute the cluster mass from the total luminosity obtained by Bahcall, we get $M = (6\text{--}36) \times 10^{13} M_{\odot}$. This mass, however, is only 3–18% of the dynamical mass obtained above. This discrepancy is known for many clusters and is in fact a rather general property of clusters. Whether the assumption of an equilibrium state is wrong, or whether hidden mass with an extremely large M/L exists in ten times greater quantity, is at present not known.

The Perseus cluster is an object of interest for radio astronomy and X-ray astronomy as well. Figure 3.34 is the radio map of the Perseus cluster drawn at 610 MHz by G. R. Gisler and G. K. Miley (1979). Many radio sources are resolved in it. Among these, No. 18 (IC 310), No. 33 (NGC 1265) and No. 28 (CR 15) show a tadpole-like structure with a long trailing tail. Radio sources of this kind are called tailed galaxies, and are found in especially large numbers in the Perseus cluster. They are produced when high-energy particles ejected from a galaxy are confined into the shape of a tail by the high-temperature plasma within the cluster. Even the interior of a cluster is not empty. Figure 3.34 also makes clear that NGC 1275 is surrounded by a large radio halo, $5'$ (150 kpc) in diameter, consisting of two components a and b. Component a coincides with NGC 1275, but component b lies midway between NGC 1275 and NGC 1272, coinciding with the cluster center

determined by Bahcall. A connection with the high-temperature plasma within the cluster may be supposed.

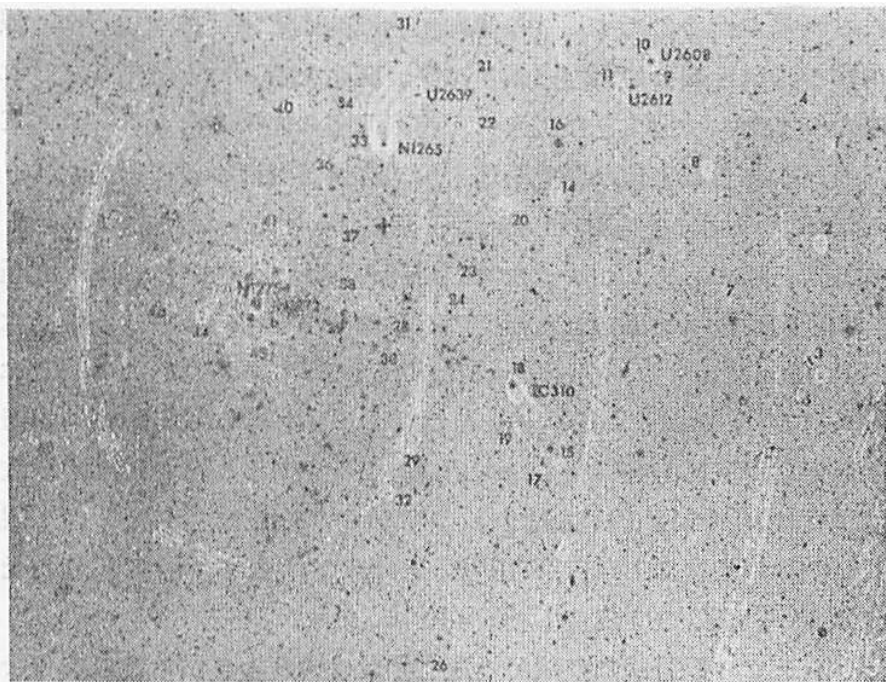


図 3.34 ペルセウス銀河団の電波地図. N は NGC, U は UGC を意味し, NGC 1275 の a と b は a, b 成分を表わす. 解像力は $54'' \times 82''$. (G. R. ギスラーと G. K. マイリー 1979).

Figure 3.34 Radio map of the Perseus cluster. N means NGC and U means UGC, and a and b for NGC 1275 denote the a and b components. The resolution is $54'' \times 82''$. (G. R. Gisler and G. K. Miley 1979). The figure carries radio-source numbers 4, 10, 11, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 26, 27, 28, 29, 31, 32, 33, 34, 36, 40 and others, together with the labels N1265, N1275a-b, U2608, U2612, U2639 and IC 310

In 1968 M. Ryle and M. D. Windram reported that, besides the $5'$ halo component 3C 84 A, there existed a cluster component 3C 84 B of 1–2 Mpc enclosing NGC 1265, 830 kpc from NGC 1275, and IC 310, 1,100 kpc away. This was believed for

a long time, but the radio observations of G. R. Gisler and G. K. Miley (1979) and of M. Birkinshaw (1980) showed it to be a ghost produced by incomplete analysis.

X-ray observations tell us still more clearly of the existence of gas within the cluster. Figures 3.35 and 3.36 are X-ray maps of the Perseus cluster and of the region around NGC 1275 observed from the Einstein X-ray satellite. In Figure 3.36, from A. C. Fabian et al. (1981), Lynds' filament, which we shall examine later, is inserted on the same scale. According to the analysis of G. Branduardi-Raymont et al. (1981), the luminosity of the point-like X-ray source in NGC 1275 is $L_X(0.5-3.0 \text{ KeV}) = 1 \times 10^{44} \text{ erg/s}$, and over the region of radius $9'$ (270 kpc) excluding the point-like X-ray source it is $L_X = 4 \times 10^{44} \text{ erg/s}$. Observations with the HEAO I satellite by M. P. Ulmer et al. (1980) have confirmed a cluster halo component extending out to as much as 5° ($\sim 9 \text{ Mpc}$) in diameter.

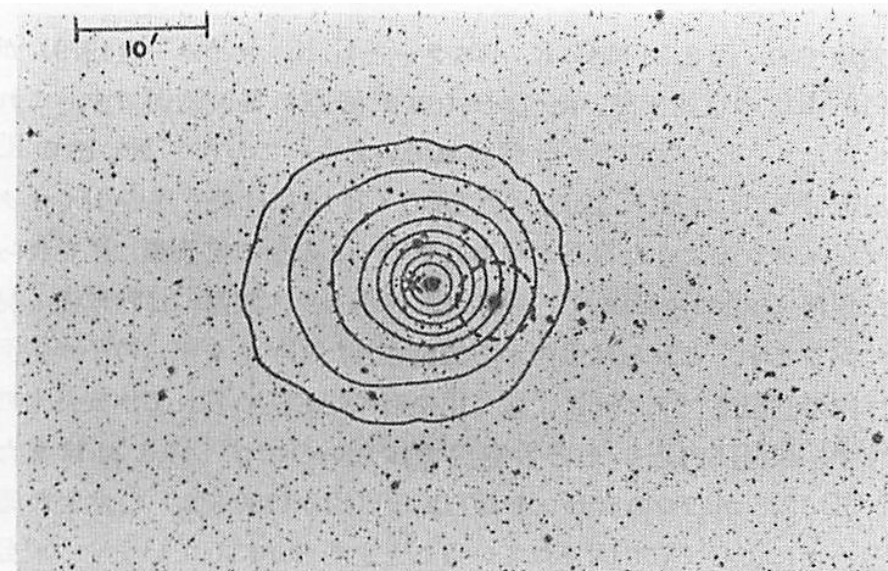


図 3.35 アインシュタイン X 線衛星から観測されたペルセウス銀河団
(G. ブランドゥアルディ・レイモンド達 1981)

Figure 3.35 The Perseus cluster observed from the Einstein X-ray satellite (G. Branduardi-Raymont et al. 1981) Scale bar $10'$ at upper left. X-ray contours are superimposed on the optical photograph.

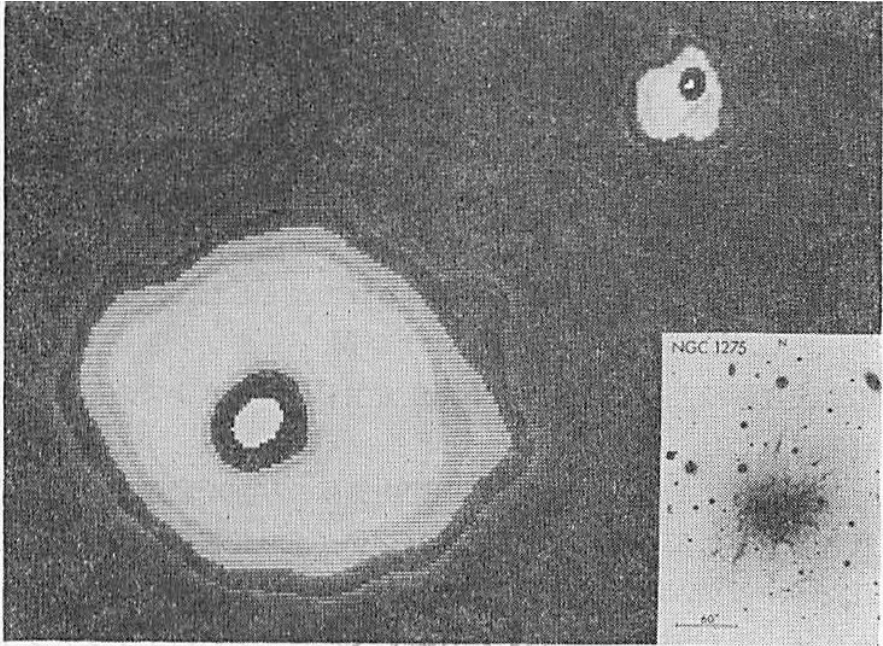


図 3.36 アインシュタイン X 線衛星から観測された NGC 1275 (A. C. ファビアン 達 1981).

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Figure 3.36 NGC 1275 observed from the Einstein X-ray satellite (A. C. Fabian et al. 1981). The inset at lower right carries “NGC 1275”, the orientation mark N, and a $60''$ scale bar.

Since the iron spectral line at 6.7 keV is observed, the cluster X-rays are thought to be thermal radiation from a high-temperature plasma at about 100 million degrees (10^8 K) (R. J. Mitchell et al. 1976). Calculating on the assumption of an isothermal gas-sphere model, in the case of the Perseus cluster the total mass is $4 \times 10^{14} M_{\odot}$ and the number density of the gas at the center is 4.5×10^{-3} particles/cm³ (Table

3.1). This total mass, compared with the cluster mass $M = (6-36) \times 10^{13} M_{\odot}$ obtained by assuming an M/L ratio,

Table 3.1 Properties of the intracluster gas (H. Gursky and D. A. Schwartz 1977)

Cluster	X-ray source	Core radius*	Number density at the center* ($particles/cm^3$)	Core mass Total mass ($M_{\odot}$)	Effective temperature (KeV)	Iron emission line (fraction relative to the cosmic abundance ratio)
Perseus cluster (Abell 426)	3U0316 + 41	15'±2'	$4.5 \pm 2 \times 10^{-3}$	$7 \pm 3 \times 10^{13}$ $4 \pm 2 \times 10^{14}$	7.0±0.4	0.45±0.08
Virgo cluster (M87)	3U1228 + 12	25'±4'	$5_{-3}^{+6} \times 10^{-3}$	$1.5_{-1}^{+2} \times 10^{12}$ $9_{-6}^{+11} \times 10^{12}$	2.8±0.2	0.40±0.21
Coma cluster (Abell 1656)	3U1257 + 28	16'±3'	$3 \pm 2 \times 10^{-3}$	$7 \pm 4 \times 10^{13}$ $5 \pm 3 \times 10^{14}$	9.3±1.3	0.38±0.23

* $n(r) = n_0(1+r^2/a^2)^{-3/2}$ is assumed, where $n(r)$ is the number density of the gas at radius r , n_0 the number density at the center, and a the core radius.

and with the dynamically computed mass $M = 2 \times 10^{15} M_{\odot}$. One sees how enormous a mass this is. Since the iron abundance ratio of clusters of galaxies is known to be no different from the cosmic abundance ratio, the hot intracluster gas cannot be material left over from the early universe; we must regard it as originating mainly in gas ejected from the galaxies within the cluster.

(2) The morphology of NGC 1275

Let us return to the study of NGC 1275. This galaxy is elliptical-like, but, as with the central objects of other clusters of galaxies, it possesses an enormous halo. This is readily seen by comparing the surface-brightness distribution of NGC 1275 with that of the elliptical galaxy NGC 1278, which lies 3' (90 kpc) to the north-northwest (Figure 3.37). In NGC 1275 the cut-off in radius seen in ordinary elliptical galaxies is not reached even down to the measurement limit of 28–29 mag per square second of arc. Consequently, although NGC 1275 is generally classified as the peculiar elliptical galaxy E 2p, it is more appropriate to classify it as a D galaxy. T. A. Matthews, W. W. Morgan and M. Schmidt (1964) classify NGC 1275 as ED 2.

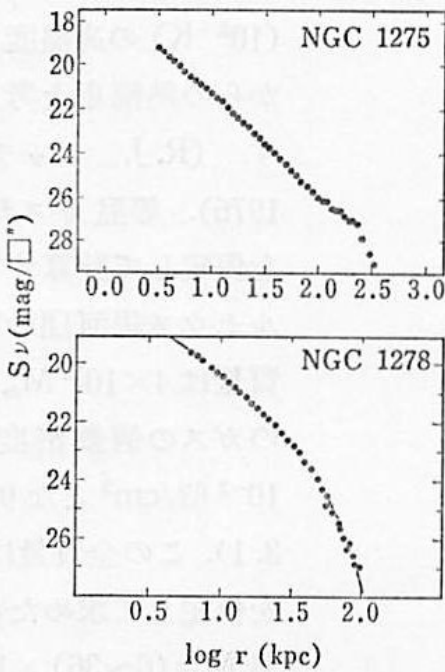


図 3.37 NGC1275 と NGC1278
の表面輝度分布 (A. エム
ラー 1976).

Figure 3.37 Surface-brightness distributions of NGC 1275 and NGC 1278 (A. Oemler 1976). — Vertical axis: S_V (mag/□") (upper panel 18, 20, 22, 24, 26, 28; lower panel 20, 22, 24, 26); horizontal axis: $\log r$ (kpc) (upper panel 0.0–3.0, lower panel 0.5–2.0). The upper panel is labelled NGC 1275, the lower panel NGC 1278.

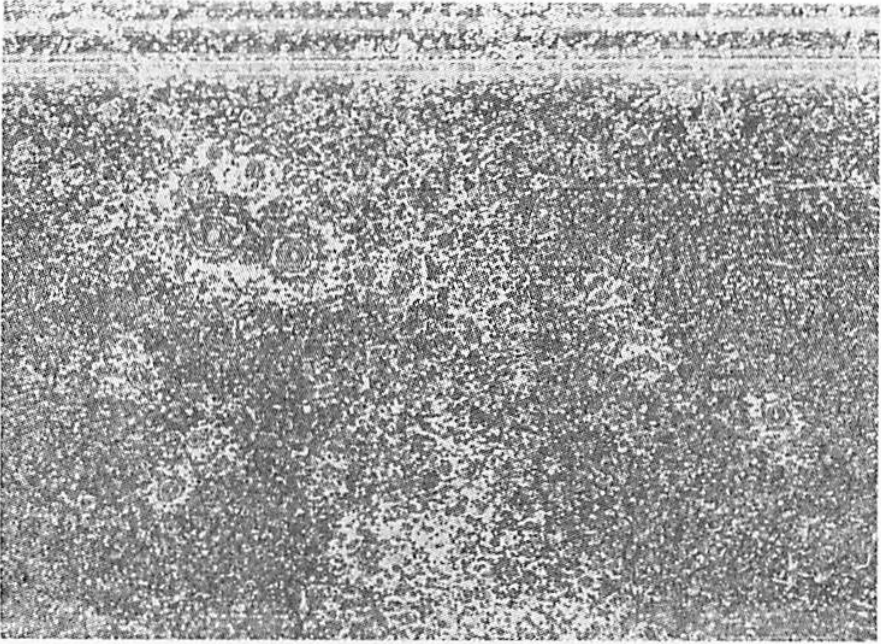


図 3.38 ペルセウス銀河団の微測濃度計トレース。(J. コルメ
ンディと J. N. バコール 1974).

Figure 3.38 Microdensitometer trace of the Perseus cluster of galaxies. (J. Kormendy and J. N. Bahcall 1974).

H. Arp and F. Bertola (1971), and J. Kormendy and J. N. Bahcall (1974), have discovered an enormous halo of diameter ≥ 400 kpc enveloping both NGC 1275 and NGC 1272, which lies ~ 150 kpc to the west (Figure 3.38). We saw earlier that the center of the Perseus cluster lies midway between NGC 1275 and NGC 1272; taking this into account, it is not impossible to regard the central object of the

cluster as the double galaxy NGC 1275/NGC 1272. Note, however, that whereas the radial velocity of NGC 1275 is 5,360 km/s, that of NGC 1272 is 4,340 km/s.

(3) The high-velocity filaments

First, let us compare photographs of NGC 1275 taken in different wavelength regions.

The upper photograph of Figure 3.39 was taken in blue light, the lower one in red light, and the middle one in ultraviolet light with a short exposure. In the blue-light and ultraviolet photographs an irregular structure containing numerous knots is recorded, extending from the north to the northwest side. This is what is called the high-velocity filaments, which W. Baade and R. Minkowski regarded as a galaxy in collision with NGC 1275.

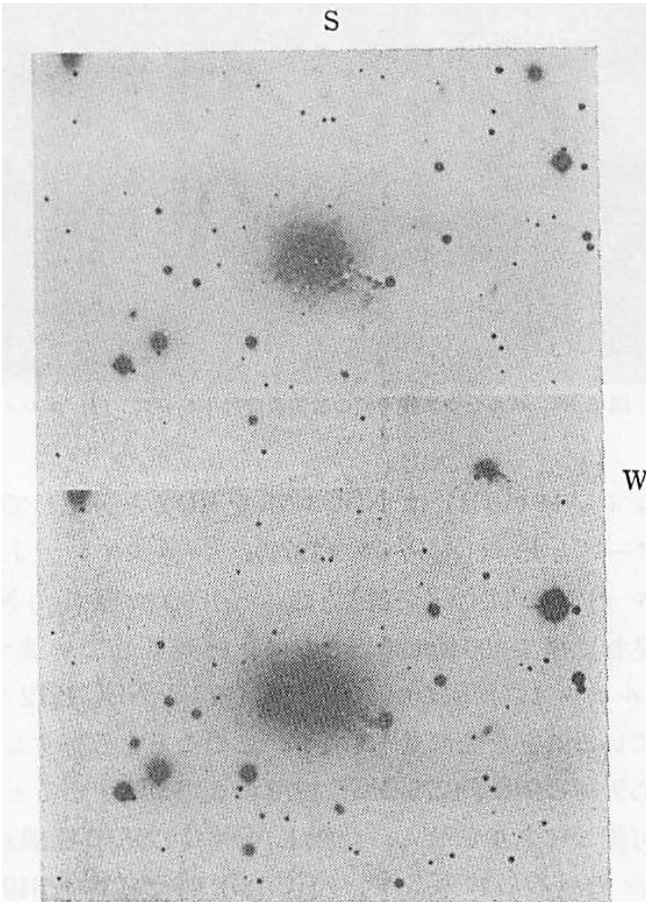


図 3.39 NGC 1275. 上は青い光 ($\lambda\lambda 3500-4800 \text{ \AA}$), 下は赤い光 ($\lambda\lambda 6000-6800 \text{ \AA}$), 中央は紫外光 ($\lambda\lambda 3300-3900 \text{ \AA}$) で撮影. 上が南, 右が西. (G. R. バービッジ, E. M. バービッジ, A. R. サンデッジ 1963).

Figure 3.39 NGC 1275. The top was taken in blue light ($\lambda\lambda 3500-4800 \text{ \AA}$), the bottom in red light ($\lambda\lambda 6000-6800 \text{ \AA}$), and the middle in ultraviolet light ($\lambda\lambda 3300-3900 \text{ \AA}$). South is up and west is to the right. (G. R. Burbidge, E. M. Burbidge, A. R. Sandage 1963). — The orientation marks S (top edge) and W (right edge) appear on the photograph.

In 1965, E. M. Burbidge and G. R. Burbidge carried out spectroscopic observations of NGC 1275 and showed that the filaments moving at a velocity of 3,000 km/s relative to NGC 1275 are confined to a narrow cone-shaped region in the northwest direction. The Burbidges interpreted this velocity field as a 3,000 km/s jet ejected by an explosion in the nucleus, and declared that they had completely refuted the collision hypothesis of W. Baade and R. Minkowski. This observation had the effect of further strengthening the trend of the scientific community at the time, which sought to explain all peculiar galactic phenomena by nuclear explosions.

However, this explosion hypothesis, which had seemed to be established as an unquestionable fact, came to be doubted once again through the 21 cm absorption-line observations of D. de Young, M. Roberts and W. Saslaw (1973) and of R. D. Ekers et al. (1976). The reason is that the 21 cm absorption line had a radial velocity of 8,100 km/s — shifted by 3,000 km/s with respect to NGC 1275, just like the high-velocity filaments (Figure 3.40). This means that the radio emission of NGC 1275 is being absorbed by a neutral hydrogen gas cloud that lies in front of NGC 1275 and is approaching it at a velocity of 3,000 km/s. On the explosion hypothesis, a jet having a recession velocity of 3,000 km/s relative to NGC 1275 would have to be directed away from us rather than toward us, and a decisive contradiction arises.

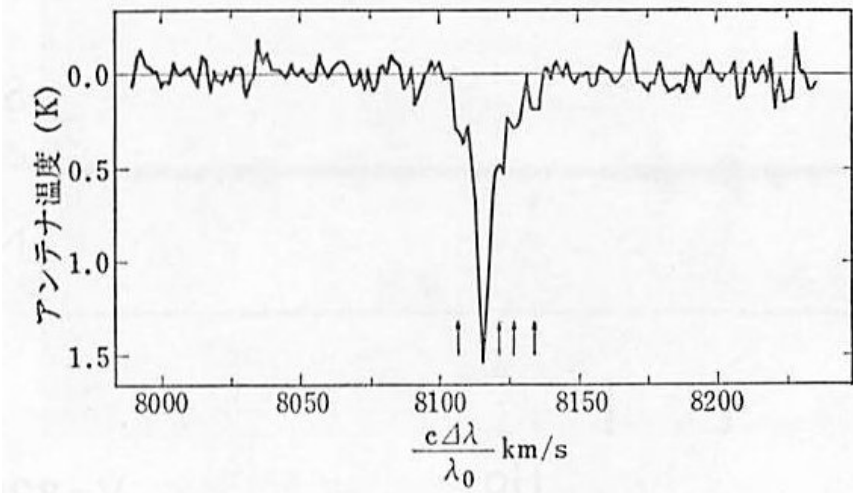


図 3.40 NGC 1275 の 21 cm 吸収線. (D. ド・ヤング, M. ロバーツ, W. サスロー 1973).

Figure 3.40 The 21 cm absorption line of NGC 1275. (D. de Young, M. Roberts, W. Saslaw 1973). — Vertical axis: antenna temperature (K) (0.0, 0.5, 1.0, 1.5); horizontal axis: $c\Delta\lambda/\lambda_0$ km/s (8000, 8050, 8100, 8150, 8200). Four arrows are marked near the bottom of the absorption feature.

V. C. Rubin et al. (1977) carried out detailed spectroscopic observations of the high-velocity filament region. The result was clearly unfavorable to the explosion hypothesis. Figure 3.41 is a spectrogram taken with the spectrograph slit set in the southeast–northwest direction through the nucleus. The dark line at the center is the continuous spectrum of the nucleus, and the lower horizontal line is the continuous spectrum of a star at the tip of the high-velocity filaments to the northwest. On the spectrum of the nucleus, strong emission lines of H_α and $[\text{N II}] \lambda 6583$ are visible, showing that the ionized gas cloud surrounding the nucleus occupies a region ~ 5 kpc in diameter. Emission lines are also visible below the continuous spectrum of the nucleus. These are H_α from the high-velocity filaments, which have a radial

velocity of 8,200 km/s, i.e. a recession velocity of 3,000 km/s relative to NGC 1275.

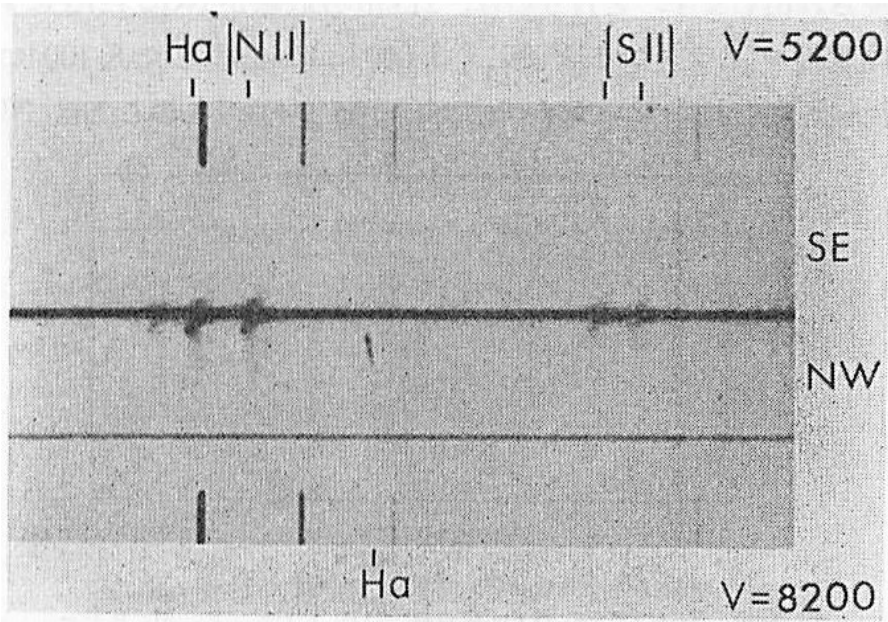


Figure 3.41 Spectrogram of NGC 1275. (V. C. Rubin et al. 1977). — Symbols in the figure: upper part $H\alpha$, $[N II]$, $[S II]$, $V = 5200$; at the right SE and NW; lower part $H\alpha$, $V = 8200$.

Rubin and her colleagues argue that if the high-velocity filaments had been ejected from the nucleus, this $H\alpha$ emission line ought to extend continuously from the nucleus. They further noted that on the northwest side, compared with the southeast direction, the continuous spectrum of the stars within NGC 1275 is weakened, and explained this as the result of the starlight being dimmed because the high-velocity filaments lie in front. The velocity field of the high-velocity filaments also varies continuously from 8,100 km/s on the east side to 8,400 km/s on the west side, suggesting a galactic rotation of about 150 km/s (Figure 3.42).

The size of the high-velocity filaments, 25×10 kpc, is not unreasonable for a single galaxy. The observations of S. M. Kent and W. L. W. Sargent (1979) also confirmed that the emission-line intensity ratios of the high-velocity filaments closely resemble those of ionized hydrogen regions in Sc-type galaxies, so the interpretation that the high-velocity filaments are an edge-on Sc-type spiral galaxy falling toward — or in collision with — NGC 1275 at a velocity of 3,000 km/s has several strong supporting arguments. The velocity dispersion of the Perseus cluster is very large, and a velocity of 3,000 km/s is not so large as to cast doubt on membership in the cluster. E. M. Burbidge, H. E. Smith and G. R. Burbidge (1978) still maintain that the explosion hypothesis is the most natural interpretation, on the grounds that Rubin and her colleagues were unable to observe the stellar absorption lines at $V = 8,200$ km/s that would prove the high-velocity filaments to be a galaxy; but recent observations are decisively unfavorable to this view.

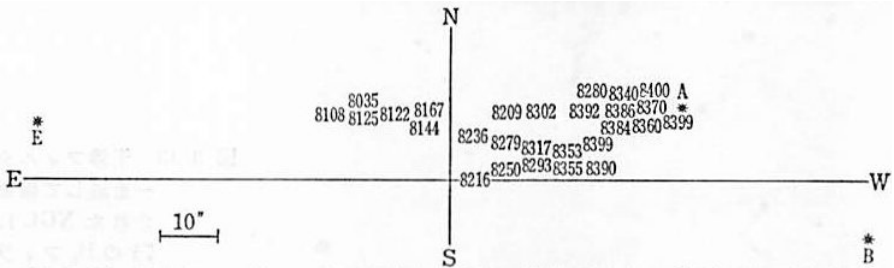


図 3.42 高速度フィラメントの速度場。図中の数字は各点の速度 (km/s) を表わす。(V.C. ルービン達 1977).

Figure 3.42 The velocity field of the high-velocity filaments. The numbers in the figure give the velocity (km/s) at each point. (V. C. Rubin et al. 1977). — N at the top of the figure, S at the bottom, E at the left, W at the right; scale bar 10" at the lower left. Symbols in the figure: *E at the left, *B at the lower right, A with * at the upper right. — Values in the figure (east = left side): 8035 / 8108, 8125, 8122, 8167 / 8144 — Values in the figure (west = right side): 8280, 8340, 8400 A / 8209, 8302, 8392, 8386, 8370 * / 8384, 8360, 8399 / 8236, 8279, 8317, 8353, 8399 / 8216, 8250, 8293, 8355, 8390

(4) The low-velocity filaments

Since the low-velocity filaments are seen in red light, one expects the red hydrogen emission line H_α $\lambda 6563$ to be the light of the filaments. NGC 1275 has a radial velocity of 5,200 km/s, so if these filaments have the same recession velocity as NGC 1275, the Doppler effect shifts the wavelength of H_α about 110 Å toward the red. Therefore, an H_α interference filter passing only a bandwidth of about 50 Å cannot record the filaments unless it is corrected for the radial velocity.

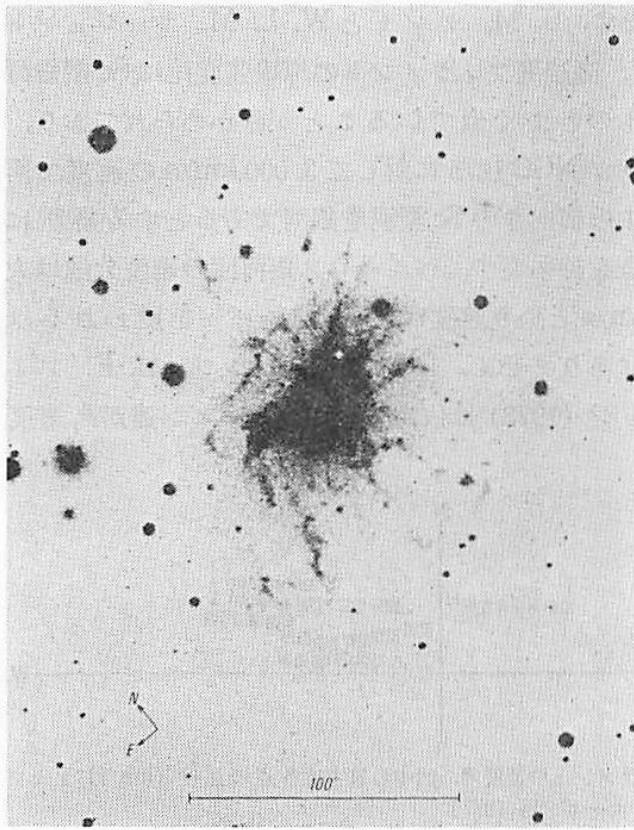


図 3.43 干渉フィルタ
ーを通して撮影
された NGC 12
75 の H_{α} フィラ
メント. (R. リ
ンズ 1970).

Figure 3.43 The H_{α} filaments of NGC 1275 photographed through an interference filter. (R. Lynds 1970). — N and E orientation marks at the lower left; scale bar 100".

R. Lynds (1970) therefore prepared six kinds of H_{α} interference filters whose central wavelengths were shifted in steps of 2,000 km/s from 2,000 km/s (6,607 Å) to 12,000 km/s (6,826 Å), attached an image intensifier tube at the Cassegrain focus of the 2.1 m telescope of Kitt Peak National Observatory, and attempted to photograph NGC 1275. The magnificent filamentary structure of Figure 3.43 was photographed through the filter at 6,694 Å (6,000 km/s). It does not appear with the 6,650 Å (4,000 km/s) filter. Figure 3.44 is NGC 1275 photographed at 6738 Å

(8,000 km/s). As expected, the low-velocity filaments do not appear, but the high-velocity filaments are clearly recorded.

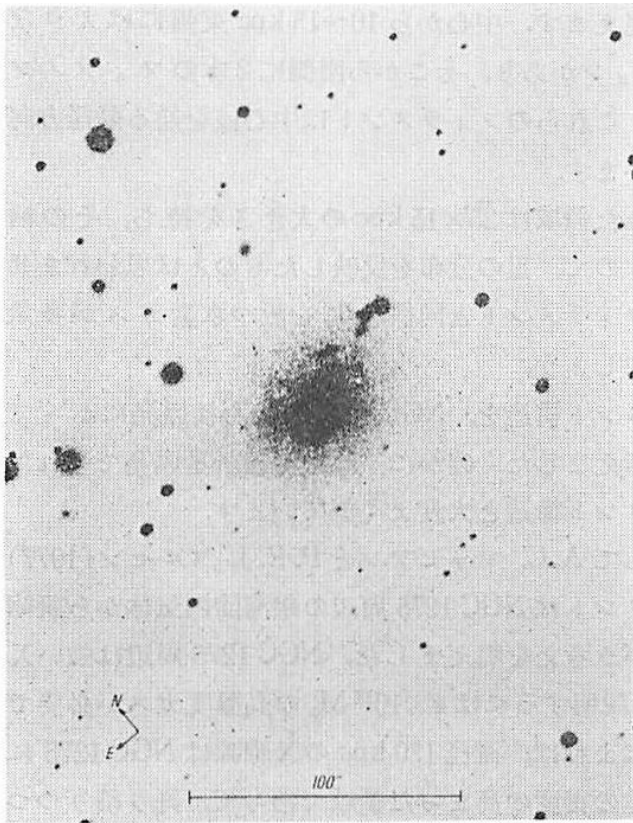


図 3.44 干渉フィルターを通して撮影された NGC1275 の高速度フィラメント (R. リンズ 1970).

Figure 3.44 The high-velocity filaments of NGC 1275 photographed through an interference filter (R. Lynds 1970). — N and E orientation marks at the lower left; scale bar 100".

The H_{α} filaments discovered by Lynds are enormous. The filaments on the north side reach out to 140" (70 kpc), and there are even traces reaching 180" (90 kpc). Looking closely at the photograph, one notices that the filaments are not necessarily radial with the nucleus as their origin. The filaments in the northern half

show a strong tendency to extend parallel to the north direction, and about 15 kpc from the center there are even filaments extending parallel to the high-velocity filaments, that is, in the east–west direction. Some 10–15 kpc east of the center there is a large H_α condensation, from which two filaments extend to the south. These filaments deviate greatly from the radial direction through the nucleus.

The dark, saturated central region has a size of 25×15 kpc, and since its outline is highly irregular it is not thought to reflect the distribution of stars. In this region too, as in the filaments, a large amount of hydrogen gas emitting H_α is presumably present.

Lynds considered the filamentary structure to have been formed by a nuclear explosion in NGC 1275. Indeed, it closely resembles the filamentary structure of the Crab Nebula, produced by a supernova explosion.

Against this explosion hypothesis, A. C. Fabian and P. E. J. Nulsen (1977) advanced the idea that the low-velocity filaments condensed out of the intracluster gas around NGC 1275. The region around NGC 1275 is a strong X-ray source, and to explain it $4 \times 10^{14} M_\odot$ of high-temperature gas was required. On their interpretation, the X-ray source 120 kpc in diameter is a region of enhanced density in the gas that has been accreting onto NGC 1275, and thermal instability arises in the flow of accreting gas, producing the filaments. This process was further examined by W. G. Mathews and J. N. Bregman (1978) and by L. L. Cowie, A. C. Fabian and P. E. J. Nulsen (1980), who showed that the properties of the intracluster gas revealed by the X-ray observations and the filament formation within the accreting gas flow are compatible even quantitatively.

Thus it became clear that the low-velocity filaments too were not produced by an explosion in the nucleus. The accretion hypothesis requires neither the ejection of a large amount of matter nor the release of an enormous amount of energy demanded

by the explosion hypothesis. As pointed out earlier, the fact that the low-velocity filaments are not radial in the sense of passing through the nucleus also seems to support the accretion hypothesis rather than the explosion hypothesis.

(5) The nucleus and the radio source

At the distance of NGC 1275 an angle of $1''$ corresponds to 500 pc, and moreover the nucleus is surrounded by an ionized gas cloud ~ 5 kpc across, so the structure of the nucleus and of the nuclear region cannot be studied directly by optical means.

In the radio, however, if one uses the technique of very long baseline interferometry (VLBI = Very Long Baseline Interferometer), constructed for example by combining radio telescopes on the American and European continents, the structure of a radio source can be observed with the extremely high resolution of a thousandth of a second of arc (~ 0.5 pc). Figure 3.45 is a picture of the radio source within the nucleus of NGC 1275. It was produced by I. I. K. Pauliny-Toth and twelve others — thirteen people in all — from VLBI observations using the 100 m radio telescope of the Max Planck Institute in West Germany together with three radio telescopes in the United States (the 43 m of the National Radio Astronomy Observatory, the 40 m of the Owens Valley Radio Observatory, and the 26 m of the Harvard Radio Astronomy Observatory). The central radio source is smaller than 0.1 pc,

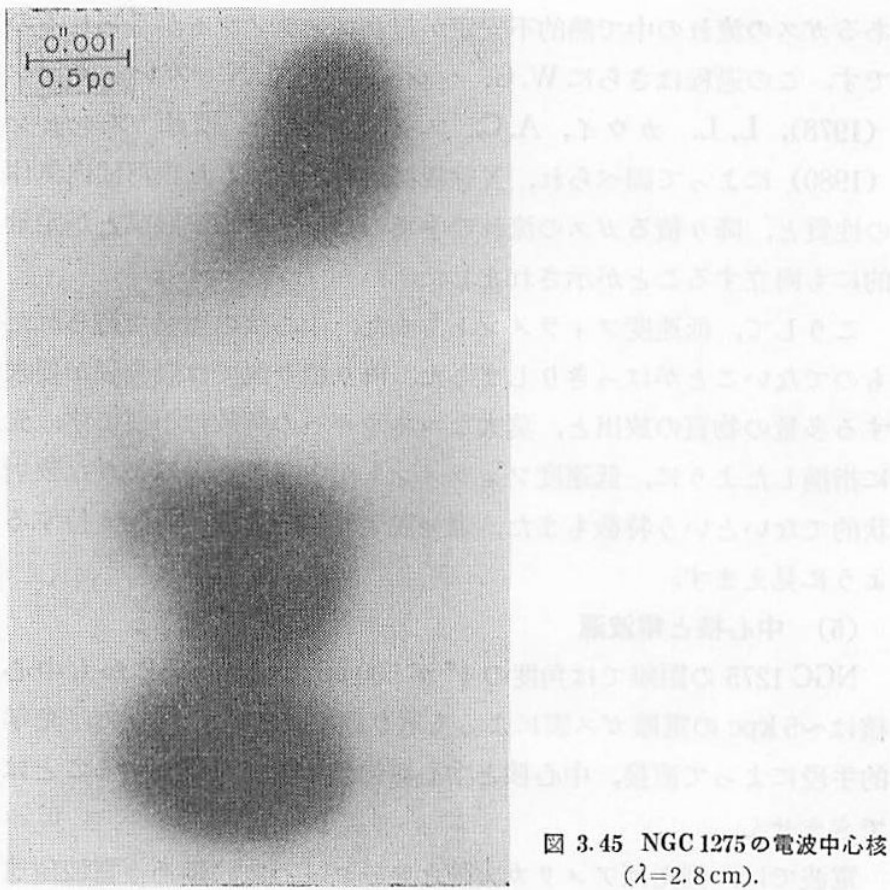


Figure 3.45 The radio nucleus of NGC 1275 ($\lambda = 2.8\text{cm}$). — Scale bars at the upper left: $0''.001 / 0.5\text{ pc}$.

and the two outer radio sources to the north and south are separated by 3 pc. The radio source changes its structure on a time scale of a year (E. Preuss et al. 1979). The expansion velocity is 0.06 pc/yr.

The variable radio source is called component A, and together with components B and C it forms the triple structure of the radio source of NGC 1275 (Figure 3.46). Component C is the contribution from the radio source of NGC 1275, $30''$ (15 kpc)

in diameter, and from the halo, $5'$ (150 kpc) in diameter. If component B (Figure 3.34) is disregarded, the radio source of component C, like component A, has its major axis in the north–south direction. Component B too, when observed at 609 MHz, is a double radio source separated by $0''.05$ (25 pc) north–south. All the radio sources of NGC 1275 extend in the same north–south direction, from ≤ 1 pc out to more than ~ 100 kpc. Moreover, this direction is also the direction of Lynds's $H\alpha$ filament system, and we must suppose that these phenomena have some common cause.

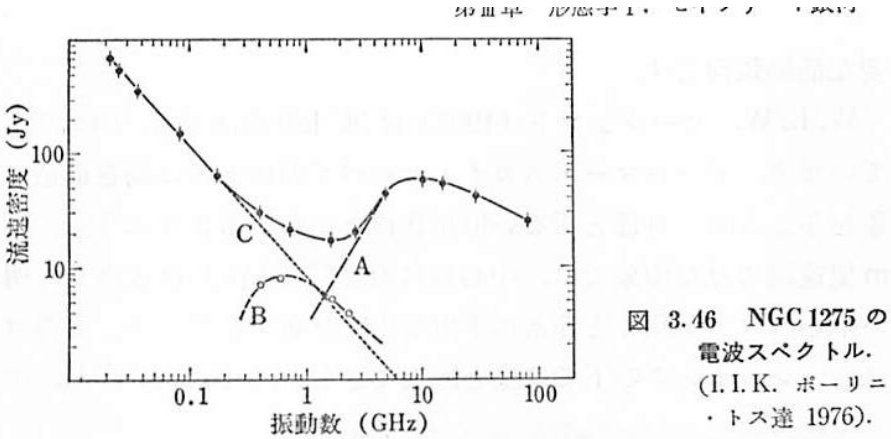


Figure 3.46 The radio spectrum of NGC 1275. (I. I. K. Pauliny-Toth et al. 1976). — Vertical axis: flux density (Jy) (10, 100); horizontal axis: frequency (GHz) (0.1, 1, 10, 100). The curves are labelled A, B and C.

6. 3C 120 and 3C 390.3

The Seyfert galaxies 3C 120 and 3C 390.3 are N galaxies and powerful radio sources. Their radio properties differ, however: whereas 3C 120 is a compact radio source, 3C 390.3 is a double radio source resembling Cygnus A (Figure 1.4) and Centaurus A (Figure 4.32).

(1) 3C 120

The radio source 3C 120 = PKS 0430+05 was identified in 1966 by M. Clark, J. Bolton and A. Shimmins with the compact galaxy II Zw 14 = II Zw 0430+05, and its Seyfert-galaxy character was discovered by E. M. Burbidge (1967). In 1968, moreover, M. V. Penston noticed that 3C 120 was registered in a catalogue of variable stars as BW Tauri = HV 10387. 3C 120 is also a powerful emitter in the infrared and in X-rays, and energetically it occupies a position intermediate between the classical Seyfert galaxies NGC 1068 and NGC 4151 and the quasars — an extremely important active galaxy.

W. L. W. Sargent (1967) describes 3C 120 as follows: “On the Palomar Sky Survey plates it appears to consist of a faint outer region giving the impression of spiral structure and a bright stellar nucleus. As seen with the 5 m telescope, the nucleus is about 5" (5 kpc) in diameter and, apart from the bright central core, has a very flat luminosity distribution. This core cannot be distinguished from a star under good seeing.” Figure 3.47 is a photograph of 3C 120 ($\lambda\lambda 3,900\text{--}5,400\text{ \AA}$) taken by H. Arp (1975) at the prime focus (f/2.7) of the 4 m telescope of Kitt Peak National Observatory. The overall size is $60 \times 100\text{ kpc}$, and the bow-shaped structure resembling the spiral arms noted by Sargent is clearly visible. The major axis is at P.A. 117° .

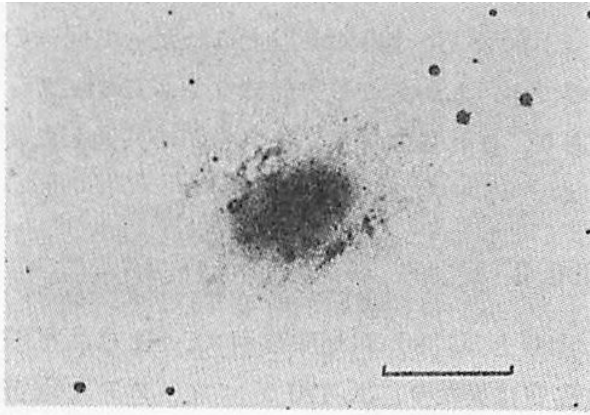


図 3.47 3C 120. 図中のスケールは 50 kpc. (H. アープ 1975).

Figure 3.47 3C 120. The scale in the figure is 50 kpc. (H. Arp 1975).

A. Sandage (1973) and M. F. Walker, C. D. Pike and J. D. McGee (1974) regarded the N galaxy 3C 120 as a giant elliptical galaxy whose nucleus is a mini-quasar. As is evident from Figure 3.47, however, it is impossible to recognize the characteristics of an elliptical galaxy in 3C 120. H. Arp (1975) regards 3C 120 as a kind of spiral galaxy as well, although it does not show a spiral pattern continuous down to the nucleus. “3C 120 is probably a spiral galaxy in which an abnormally strong explosive ejection has occurred. This explosive ejection presumably destroyed the continuous spiral structure, particularly the inner structure. In fact, in NGC 1068 and NGC 4151 too, continuous spiral structure exists only in the outer parts.” — so Arp argues.

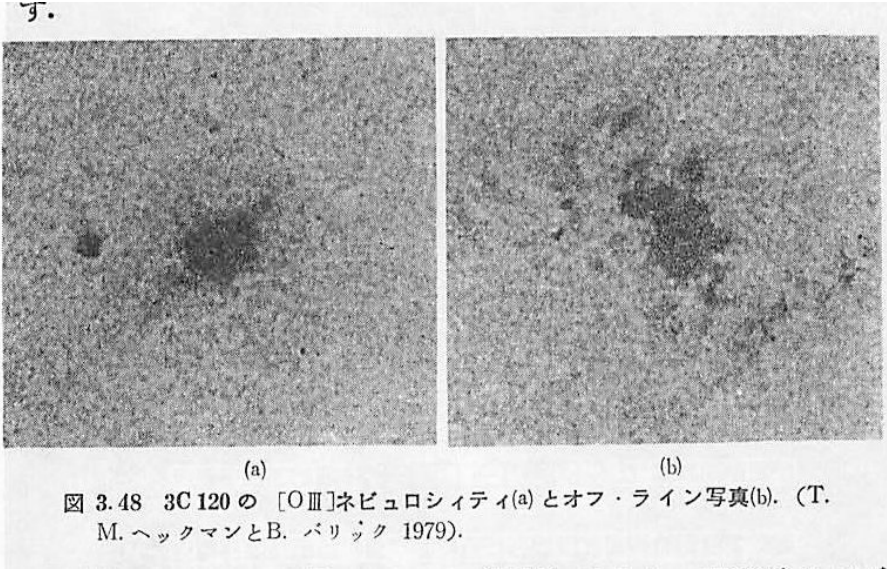


図 3.48 3C 120 の [O III] ねぶよしティ (a) とオフ・ライン写真 (b). (T. M. ヘックマンと B. バリック 1979).

Figure 3.48 The [O III] nebula of 3C 120 (a) and the off-line photograph (b). (T. M. Heckman and B. Balick 1979).

T. M. Heckman and B. Balick (1979) attached a video camera to the 2.1 m telescope and attempted photographic observations of 3C 120. Figure 3.48(a) is a photograph in [O III] $\lambda 5007$ alone, obtained by subtracting an off-line photograph (Figure 3.48(b)) — taken with the central wavelength shifted by $100 \text{ \AA}$ so as to avoid the light of [O III] $\lambda 5007$ — from a photograph taken through an interference filter whose central wavelength was matched to the emission line [O III] $\lambda 5007$. A gas cloud of $10''\text{--}15''$ ($10\text{--}15 \text{ kpc}$) surrounding the nucleus, and a nebulous structure (nebula) extending as far as $60''$ (60 kpc), are clearly recorded. Curiously, the major axis of this nebula lies in the direction of the minor axis of 3C 120 (P.A. 40°). The amorphous structure of Figure 3.47 is due to this nebula. According to the recent detailed observations of J. A. Baldwin et al. (1980), the velocity field of the nebula is disturbed but looks like rotational motion (Figure

Figure 3.49 The velocity field of [O III] $\lambda 5007$ in 3C 120. The numbers in the figure are velocities at each point in units of 10 km/s. The arrows indicate the direction of the rotation axis (Rotation), the major-axis direction of the radio source (Radio), and the minor axis of the isophote map (Isophotes). (J. A. Baldwin et al. 1980). — Vertical axis: ΔY (+20, +10, +6, +4, +2, 0, -2, -4, -6, -10, -16); horizontal axis: ΔX (-24, -20, -16, -12, -8, -4, 0, +4, +8, +12, +16, +20, +24). — Values in the figure (each row from left to right; blank cells omitted): — $\Delta Y = +20$: -10, -5, +2, +5, +7, +2, +8, +10, +23 — $\Delta Y = +10$: ★, -2, ?, 0, +7, -7 — $\Delta Y = +6$: -5, -8, -5, +12, +17, +12 — $\Delta Y = +4$: -7, -13, -10, -5, +10, +13, +7 — $\Delta Y = +2$: -17, -12, -2, +3, +13, +15 — $\Delta Y = 0$: -17, -7, -2, 0, +8, +7 — $\Delta Y = -2$: -7, -10, -3, +12, -12 — $\Delta Y = -4$: -12, -12, -8, -2, +8 — $\Delta Y = -6$: -18, +7, -15, -8, +17 — $\Delta Y = -10$: -46, -30, ?, -8, -8, +3, +8, 0 — $\Delta Y = -16$: -40, -38, -23, -8, ?, -10, -12, -13, -17

The off-line photograph of Figure 3.48(b) represents the distribution of the stars that form the skeleton of 3C 120. According to the observations of G. Wlérick, B. Westerlund and R. Garnier (1979), the surface-brightness distribution can be described by de Vaucouleurs's one-fourth-power law out to 25 kpc from the center, so 3C 120 may also be regarded as a galaxy of type S0 or SB0. The stellar system constituting 3C 120 consists of a central spheroidal inner region following the one-fourth-power law and a disk region 100 kpc in diameter, and within 60 kpc there exist highly excited gas clouds emitting [O III] $\lambda 5007$; this structure of 3C 120 recalls the characteristics of NGC 4151 as an N galaxy. Rather than a spiral galaxy or an elliptical galaxy, 3C 120 is more properly called an N galaxy.

Several possibilities have been discussed for the origin of the nebulosity of 3C 120. One is the idea that interstellar gas within the galaxy is being ionized by ultraviolet light from the nucleus. A second possibility is that it was ejected by an explosion in the nucleus; if this is correct, the velocity field of Figure 3.49 represents outward motion rather than rotation. A third idea is the interpretation that the galaxy is swallowing an enormous gas cloud that lay outside it. Unfortunately, however, we do not know which of these is correct, or whether there are yet other possibilities.

Because 3C 120 is at a distance of 200 Mpc, still farther than NGC 1275, we cannot observe optically the structure of the nuclear region within 1 kpc. It is certain, however, that an extremely small nucleus exists which emits powerful electromagnetic radiation from the radio to X-rays. Figure 3.50 is the radio nucleus of 3C 120 as mapped by A. C. S. Readhead et al. (1979) from VLBI observations. The radio source of 3C 120 is apparently expanding superluminally. The expansion velocity of the outburst that occurred in 1972 was $v/c = 4.1$, and in the 1974 outburst it reached as much as $v/c = 8.5$ (Figure 3.51). Here $c = 3 \times 10^{10}$ cm/s is the velocity of light. Corresponding variations in radio intensity have also been observed (Figure 3.52). 3C 120 is a good example showing that relativistic outbursts occur repeatedly within a nucleus smaller than 0.1–1 pc.

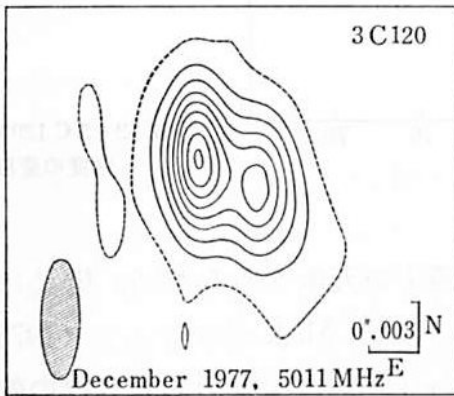


図 3 50 3C 120 の電波中心核 (50, 11 MHz). (A. C. S. リードヘッド達 1979).

Figure 3.50 The radio nucleus of 3C 120 (5,011 MHz). (A. C. S. Readhead et al. 1979). — Symbols in the figure: 3C 120; December 1977, 5011 MHz; scale bar $0''.003$; N and E orientation marks.

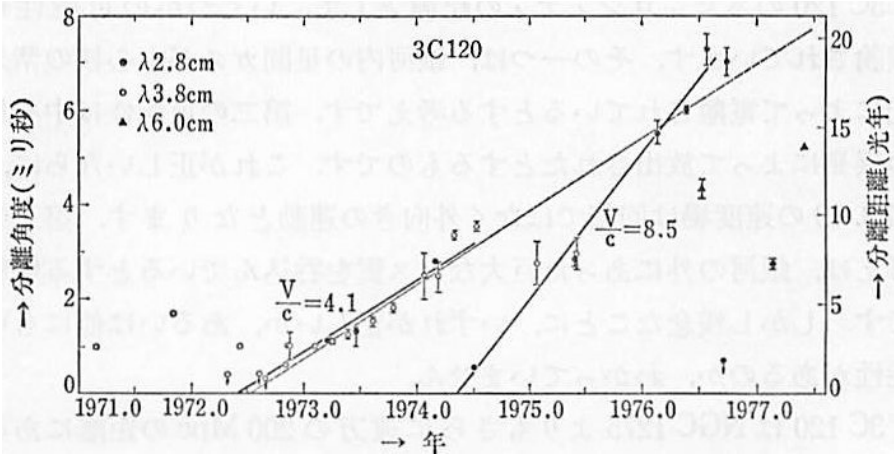


Figure 3.51 The superluminal outbursts of 3C 120. (G. A. Seielstad et al. 1979). — Left vertical axis: → separation angle (milliarcseconds) (0, 2, 4, 6, 8); right vertical axis: → separation distance (light years) (0, 5, 10, 15, 20); horizontal axis: → year (1971.0, 1972.0, 1973.0, 1974.0, 1975.0, 1976.0, 1977.0). Legend: ● $\lambda 2.8\text{cm}$, ○ $\lambda 3.8\text{cm}$, ▲ $\lambda 6.0\text{cm}$. The figure is labelled $V/c = 4.1$, $V/c = 8.5$, 3C 120.

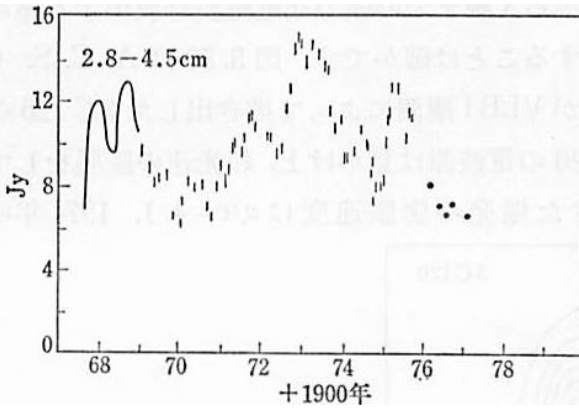


図 3.52 3C 120 の電波強度の変動。

Figure 3.52 The variation of the radio intensity of 3C 120. — Vertical axis: Jy (0, 4, 8, 12, 16); horizontal axis: +1900 (year) (68, 70, 72, 74, 76, 78). The figure is labelled 2.8–4.5 cm.

(2) 3C 390.3

Since 3C 390.3 is a distant object at 340 Mpc, almost nothing is known about its structure. In the photograph of Figure 3.53, made by superposing three plates taken by M. V. Penston and M. J. Penston (1973) with the 120 cm Schmidt telescope of Palomar Observatory, the diameter is about $20''$ –30 kpc. Galaxy A is a foreground object, but galaxy B shows the same redshift as 3C 390.3 and forms a group at an apparent separation of 160 kpc.

3C 390.3 is a double radio source resembling Cygnus A = 3C 405, and the apparent separation of the two radio sources is 300 kpc. At the center of 3C 390.3 there is a third radio source, and the recent VLBI observations of E. Preuss et al. (1980) have revealed that this radio source consists of a compact core component less than 0.6 pc in diameter together with a jet-like component (Figure 3.54). The jet coincides in direction with the double radio source.

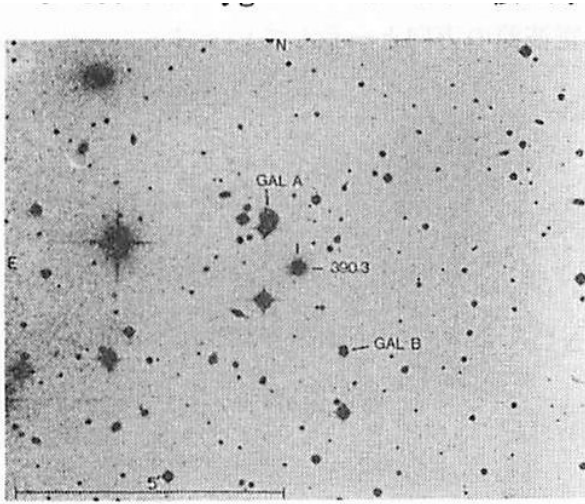


図 3.53 3C 390.3 (M. V.
ペンストンと M. J.
ペンストン 1973).

Figure 3.53 3C 390.3 (M. V. Penston and M. J. Penston 1973). — Symbols in the figure: N (top), E (left), GAL A, 390.3, GAL B; scale bar 5'.

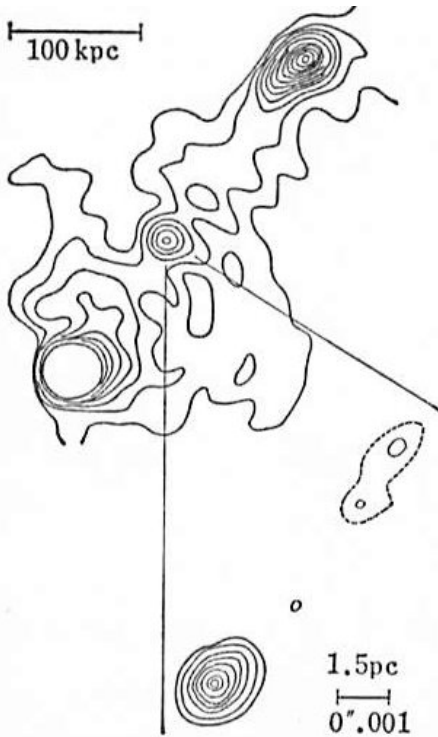


図 3.54 3C 390.3 の電波構造.
(E. プロイス達 1980).

Figure 3.54 The radio structure of 3C 390.3. (E. Preuss et al. 1980). — Scales in the figure: 100 kpc, and 1.5 pc / 0''.001.

Chapter IV. Morphology II. Peculiar Galaxies

1. M 82

What made M 82 (NGC 3034, 3C 231) famous is the filamentary structure spreading out along the polar direction. Figure 4.1 shows M 82 photographed through an $H\alpha$ interference filter; in order to increase the latitude of the printing paper, the technique of “automatic dodging” — superposing a positive made from the original plate — was used. Without this, the faint filamentary structure could not be brought out.

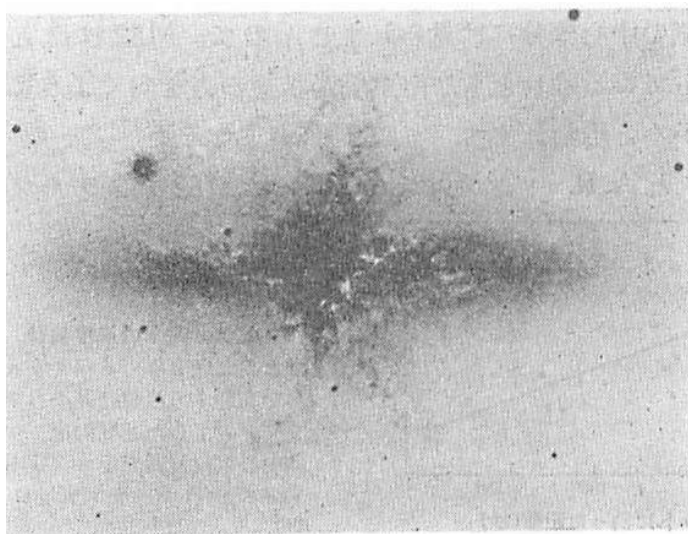


図 4.1 $H\alpha$ 干渉
フィルター
を通して撮
影されたM
82. 上が南
東フィラメ
ント, 下が
北西フィラ
メント. (C.
R. リンズ
と A. R.
サンデッジ
1963)

Figure 4.1 M 82 photographed through an $H\alpha$ interference filter. The southeast filaments are at the top, the northwest filaments at the bottom. (C. R. Lynds and A. R. Sandage 1963)

The filaments extend perpendicular to the galactic plane on both sides for about 2 kpc. A difference can be recognized between the southeast and the northwest

filamentary structures. On the southeast side they extend fairly well along the polar direction, but the northwest filaments form a fan shape split into two or three strands. If the exposure time is increased, the northwest filaments can be recorded out to 5 kpc (J. M. Deharveng and A. Pellet 1970). Absorption structure due to dust is visible in the $H\alpha$ photograph (Figure 4.1), but it is much clearer in the infrared photograph (Figure 4.2). This absorption is not seen in the central part of the southeast side, so although M 82 is almost edge-on, it appears to be slightly tilted so that the southeast side faces us.

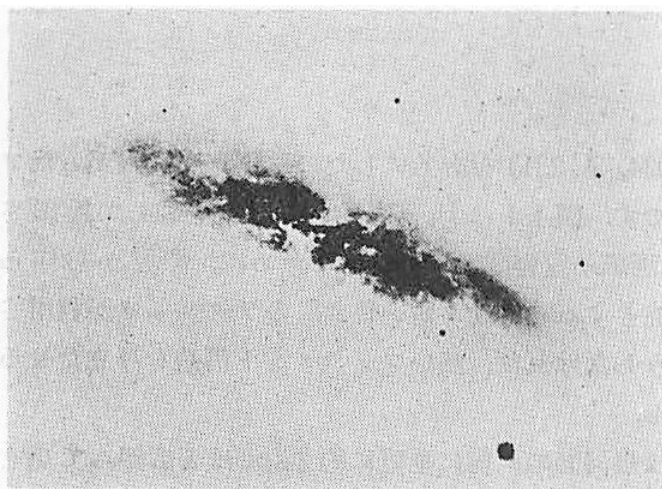


図 4.2 M82の赤
外写真. 上
が北, 右が
西. (A. B.
ソリンジャ
ー 1969).

Figure 4.2 Infrared photograph of M 82. North is up, west is to the right. (A. B. Solinger 1969).

C. R. Lynds and A. R. Sandage (1963) advocated an explosion hypothesis for the M 82 filaments. Figure 4.3 is the velocity curve along the filaments that they derived. It shows a gradient of 95 km/s per kpc. From its shape they estimated the inclination angle of the galactic plane of M 82 to be 8° , and applying the corresponding correction they obtained a velocity gradient seven times larger, 664 km/s per 1 kpc, concluding that “the filaments appear to be expanding out from the

center of the galaxy.” On this interpretation, the expansion velocity at the tips of the filaments exceeds 1,000 km/s. In this way the filaments of M 82, together with the 3,000 km/s jet of NGC 1275, came to be regarded as the most direct evidence for a nuclear explosion.

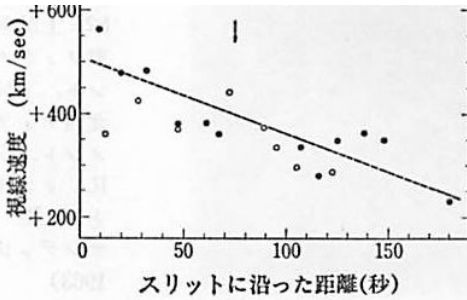


図 4.3 フィラメントの速度曲線。白丸と黒丸は2本のスペクトル写真を表わす。波線は最小自乗法でフィットした速度勾配。矢印は中心核の位置を示す (G. R. リンズと A. R. サンデッジ 1963)。

Figure 4.3 Velocity curve of the filaments. The open and filled circles represent two spectrograms. The dashed line is the velocity gradient fitted by least squares. The arrow indicates the position of the nucleus (C. R. Lynds and A. R. Sandage 1963). — Vertical axis: radial velocity (km/sec), +200 to +600. Horizontal axis: distance along the slit (arcsec), 0 to 150.

N. Visvanathan and A. Sandage (1972), in an attempt to establish that the filaments of M 82 are excited by synchrotron radiation just as in the Crab Nebula, undertook polarization observations of $H\alpha$. Their reasoning was that if their interpretation were correct, the $H\alpha$ emission line could not possibly be polarized. But the result, which they had not anticipated, revealed that $H\alpha$ too was polarized in exactly the same way as the continuum (Figure 4.4). This shook the Lynds–Sandage explosion hypothesis badly. The resemblance to the Crab Nebula turned out to be merely apparent.

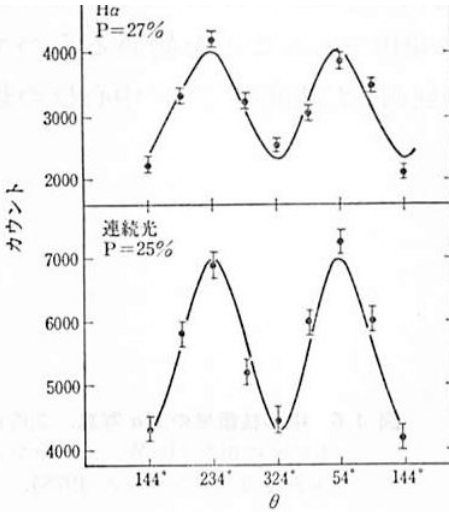


図 4.4 $H\alpha$ の偏光. $H\alpha$ も連続光も同一の倍正弦波解 (double-sine-wave solution) で近似できる (N. ヴィスヴァナサンと A. サンデッジ 1972).

Figure 4.4 Polarization of $H\alpha$. Both $H\alpha$ and the continuum can be approximated by the same double-sine-wave solution (N. Visvanathan and A. Sandage 1972). — Upper panel: $H\alpha$, $P = 27\%$ (counts 2000–4000). Lower panel: continuum, $P = 25\%$ (counts 4000–7000). Horizontal axis: $\theta = 144^\circ, 234^\circ, 324^\circ, 54^\circ, 144^\circ$. Vertical axis: counts.

Figure 4.5 is a polarization map of the halo region of M 82. The strength and angle of the polarization at each point are displayed as vectors. The plane of polarization is perpendicular to the radius vector through the nucleus and is roughly concentric, which clearly tells us that scattering by dust grains is the cause of the polarization. In the velocity field observed by H. M. Heckathorn (1972) as well, no gas motions attesting to an explosion in the nucleus were seen, and the result was that the explosion hypothesis was almost completely rejected.

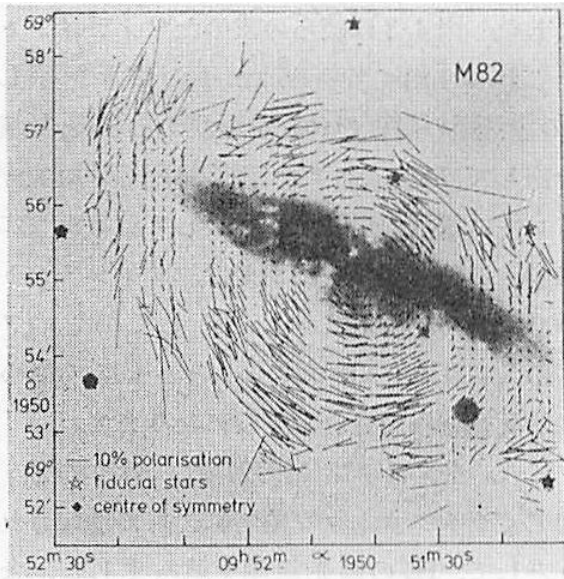


図 4.5 M82 の偏光地図。

偏光度と偏光角がベクトルで表示されている
—10% 偏光 (polarisation)

★星(fiducial stars)

◆中心(centre of Symmetry)

(R.G. ビンガム達 1976)。

Figure 4.5 Polarization map of M 82. The degree and angle of polarization are displayed as vectors — 10% polarisation ★ fiducial stars ◆ center of symmetry (R. G. Bingham et al. 1976). — Coordinates in the figure: $\delta(1950)$ $69^{\circ}52' - 69^{\circ}58'$, $\alpha(1950)$ $09^{\text{h}}51^{\text{m}}30^{\text{s}} - 09^{\text{h}}52^{\text{m}}30^{\text{s}}$. Labelled M82.

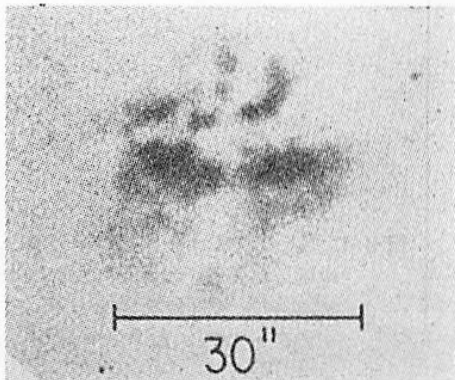


図 4.6 中心核領域の $\text{H}\alpha$ 写真。30'' は 450pc に相当 (R. W. オ・コンネルと J. J. マンガーノ 1978)。

Figure 4.6 $H\alpha$ photograph of the nuclear region. $30''$ corresponds to 450 pc (R. W. O'Connell and J. J. Mangano 1978).

Next the nuclear region becomes the issue. Since M 82 has a very complicated structure, let us first confirm the position of the nuclear region. Figure 4.6 is an $H\alpha$ photograph of the nuclear region taken by R. W. O'Connell and J. J. Mangano (1978). Figure 4.7 is a photograph taken by A. R. Sandage in blue light; comparing the two shows the correspondence.

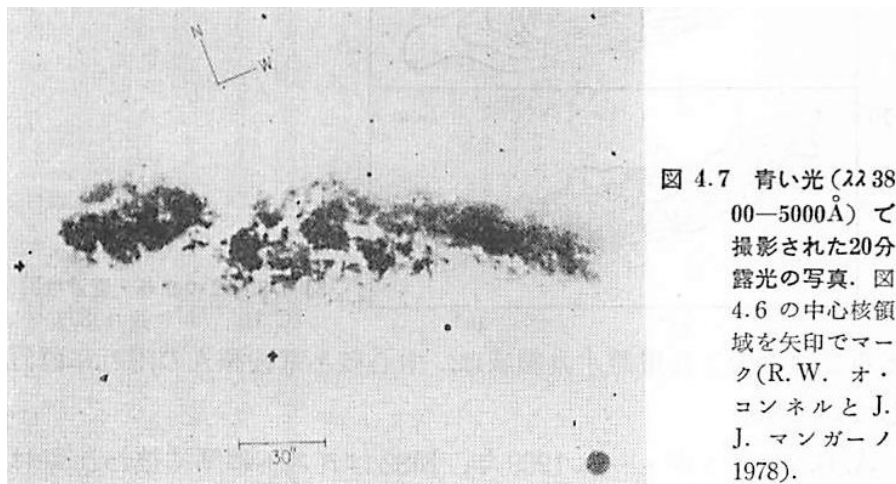


Figure 4.7 A 20-minute exposure taken in blue light ($\lambda\lambda 3800 - 5000\text{\AA}$). The nuclear region of Figure 4.6 is marked with an arrow (R. W. O'Connell and J. J. Mangano 1978). — The figure carries the orientation marks N and W and a $30''$ scale bar.

When an object is heavily veiled by dust, observations in the infrared and radio, which suffer little extinction, display their full power. Figure 4.8 is a map of the central region of M 82 drawn in infrared light at wavelengths of 2.2μ and 10μ and in the radio at 6 cm. The 2.2μ map represents the distribution of the stars that form the framework of M 82, and the peak corresponds to the nucleus. This also agrees with the position of the nucleus determined kinematically by E. M. Burbidge, G. R. Burbidge and V. C. Rubin (1964). In the 6 cm radio, on the other hand, the

strongest radio source lies about $10''$ (150 pc) from the nucleus, and this is A of the three radio sources A, B, C identified by P. J. Hargrave (1974). The 10μ map shows a character intermediate between those at 2.2μ and 6 cm. The two large ionized hydrogen regions visible in the $H\alpha$ photograph of Figure 4.6 are located near the nucleus and near radio source A.

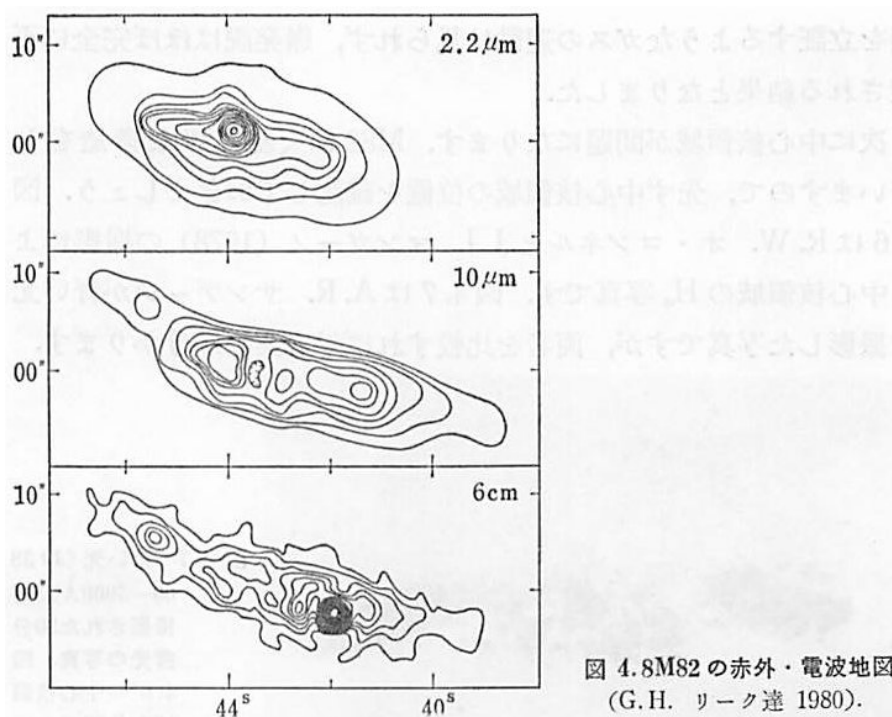


図 4.8 M82 の赤外・電波地図
(G. H. リーク達 1980).

Figure 4.8 Infrared and radio maps of M 82 (G. H. Rieke et al. 1980). — Three panels: 2.2μ , 10μ , 6cm. Vertical axis $00''$ – $10''$, horizontal axis $40''$ – $44''$.

In 1969 A. B. Solinger once argued that although M 82 is heavily veiled by dust, it possesses a Seyfert-galaxy-like nucleus, but no such indication has been found. The activity of M 82 lies rather in an explosive burst of star formation that occurred quite recently (10^7 – 10^8 years ago) within the nuclear region ($\lesssim 500$ pc). Twelve

giant star clusters thought to have been formed in this way have been resolved by the infrared photographic observations of S. van den Bergh (1971), and ten point-like radio sources that appear to be supernova remnants have been resolved by the 8,085 MHz (3.7 cm) radio observations of P. P. Kronberg and P. N. Wilkinson (1975) (Figure 4.9). However, B. Geldzahler et al. (1977) argue that the strongest radio source, A, has a radio luminosity $L(10^7 - 10^{10} \text{ Hz}) = 4.8 \times 10^{37} \text{ erg/s}$, several hundred times that of a supernova remnant, and that its diameter is also extremely small, $0.''0015$ (0.02 pc), so that it cannot be regarded as a supernova remnant. This radio source may rather be something similar to the compact radio sources found in galactic nuclei.

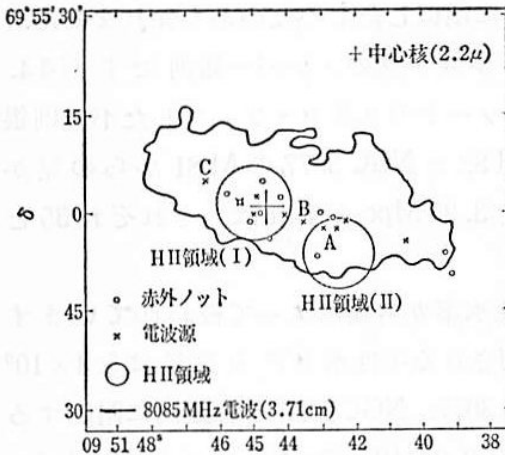


図 4.9 M82 の中心核領域の構造。二つの電離水素 (H II) 領域は図 4.6 の $H\alpha$ 写真に中心核と電波源 A は図 4.8 に認められる。

Figure 4.9 Structure of the nuclear region of M 82. The two ionized hydrogen (H II) regions can be recognized in the $H\alpha$ photograph of Figure 4.6, and the nucleus and radio source A in Figure 4.8. — Key in the figure: $\circ$ infrared knot / $\times$ radio source / $\bigcirc$ H II region / — 8085 MHz radio (3.71 cm). H II region (I), H II region (II), radio sources A, B, C. Vertical axis $\delta = 69^\circ 55' 30'', 15, 0, 45, 30$. Horizontal axis $\alpha = 09\ 51\ 48'', 46, 45, 44, 42, 40, 38$.



図 4.10 M81 グループ. M 81 を中心に上に M 82, 左に NGC 3077, 右下に NGC 2976 が 見える.

Figure 4.10 The M 81 group. With M 81 at the center, M 82 can be seen above, NGC 3077 to the left, and NGC 2976 at the lower right.

M 82 is a member galaxy of the M 81 (NGC 3031) group (Figure 4.10). Near M 81 one can also see NGC 3077, an irregular galaxy listed by Seyfert. Taking the distance of the group as 3.25 Mpc, the apparent distances of M 82 and NGC 3077 from M 81 are 35 and 45 kpc, respectively.

The M 81 group is veiled by a huge cloud of neutral hydrogen gas (Figure 4.11). The total mass of neutral hydrogen observed within the group is $5.4 \times 10^9 M_{\odot}$, and the masses of neutral hydrogen associated with each of the galaxies M 81, M 82, NGC 3077 and NGC 2976 are 2.2×10^9 , 7×10^8 , 1.0×10^9 and $1.6 \times 10^8 M_{\odot}$.

respectively. Thus about one quarter of the total mass is distributed in intergalactic space.

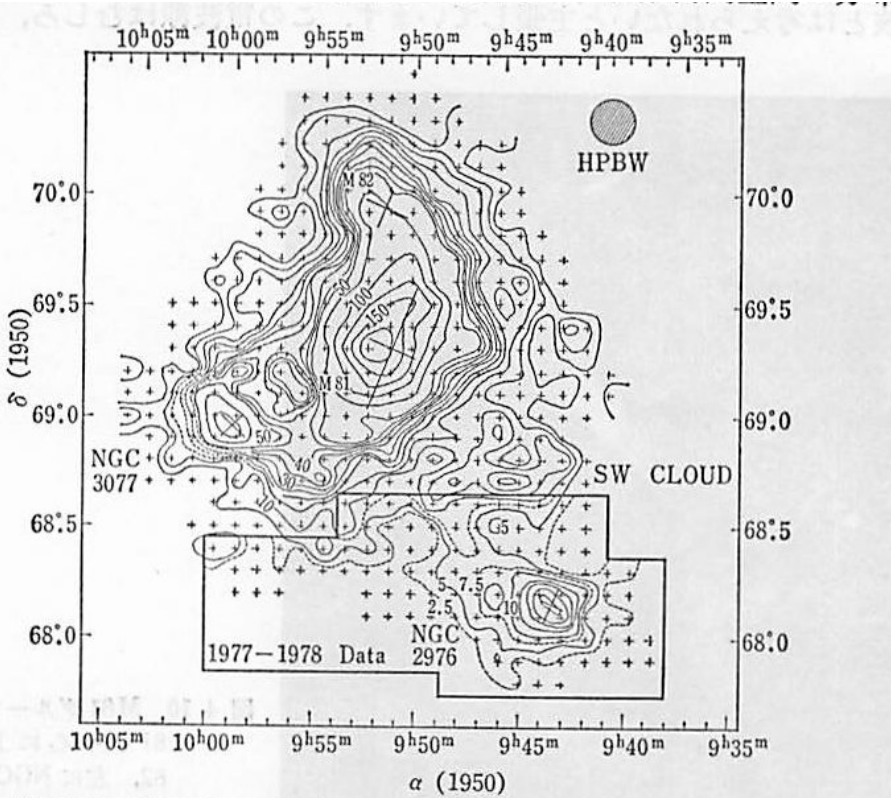


図 4.11 M81 グループの中性水素. コラム密度地図 (P. N. アップルトン, R. D. ディヴィス, R. J. ステフェンソン 1981).

Figure 4.11 Neutral hydrogen in the M 81 group. Column-density map (P. N. Appleton, R. D. Davies, R. J. Stephenson 1981). — Vertical axis $\delta(1950)$ $68^{\circ}.0$ – $70^{\circ}.0$, horizontal axis $\alpha(1950)$ $9^{\text{h}}35^{\text{m}}$ – $10^{\text{h}}05^{\text{m}}$. Labels in the figure: M 82, M 81, NGC 3077, NGC 2976, G5, SW CLOUD, HPBW, 1977–1978 Data. Contour values 50, 100, 150, 2.5, 5, 7.5, 10.

A. Elvius (1972) and A. Solinger, P. Morrison and T. Markart (1977), in order to explain the filaments and the activity of the nuclear region of M 82, supposed that

M 82 had plunged into a huge dense cloud of neutral hydrogen gas distributed within the M 81 group. The radio observations, however, seem rather to suggest that the neutral-hydrogen bridge is the result of tidal forces produced by an encounter between M 81 and M 82. One may suppose that neutral hydrogen gas stripped from M 81 in the encounter with M 82 fell onto M 82, forming the filaments, and that large-scale star formation took place in the nuclear region. If this interpretation is correct, M 82 must originally have been a gas-poor Irr0 or S0 type galaxy. Against this, R. W. O'Connell and J. J. Mangano (1978) point out the possibility that gas stripped from M 82 is falling back again, and argue that it is better to regard M 82 as having originally been a gas-rich Sc/Irr type galaxy.

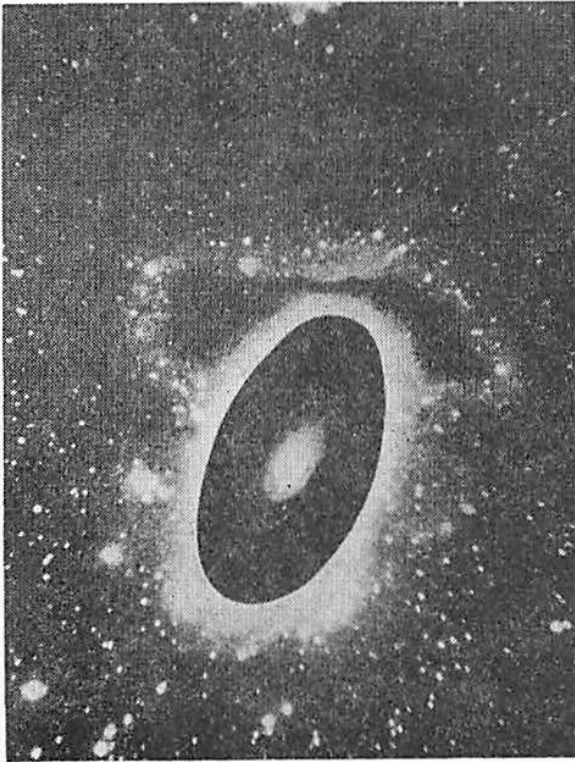


図 4.12 M 81 のリング構造. 上部にわずかに M 82 が見える.

Figure 4.12 Ring structure of M 81. A little of M 82 is visible at the top.

Figure 4.12 is a print made by superposing three Schmidt plates taken in blue light (4,700–5,400Å) by H. Arp (1965) at the sunspot minimum of 1964. Even in M 81, an Sb type galaxy that looks utterly ordinary and normal, there exists a ring structure that can only be described as strange, in the direction of M 82. Its surface brightness, however, is only 0.5% of the brightness of the night sky. Is it an interaction between M 81 and M 82, or a relic of activity in M 81? For us, M 82 still remains a mystery.

2. M 87

(1) The Virgo cluster and M 87

M 87 (NGC 4486) belongs to the Virgo cluster of galaxies. The size of this cluster is about 12° , or 4.2 Mpc, and 16 of the 34 galaxies registered in the Messier catalogue are members of the Virgo cluster. F. Zwicky estimates that it contains at least 1,000 galaxies. Figure 4.13 is a photograph of the central region of the Virgo cluster. The brightest galaxy in this cluster is M 49 (NGC 4472), but it lies 5° to the south of M 87 and so cannot be seen in this photograph. M 87 is the next brightest galaxy after M 49. As is clear from the photograph, this cluster has no dominant galaxy and its central concentration is not strong either.

Compared with the other cluster members, M 87 has morphologically peculiar aspects and its nuclear region is also very active, so it can be regarded as the central object of the Virgo cluster. Radio and X-ray observations show this even more clearly.

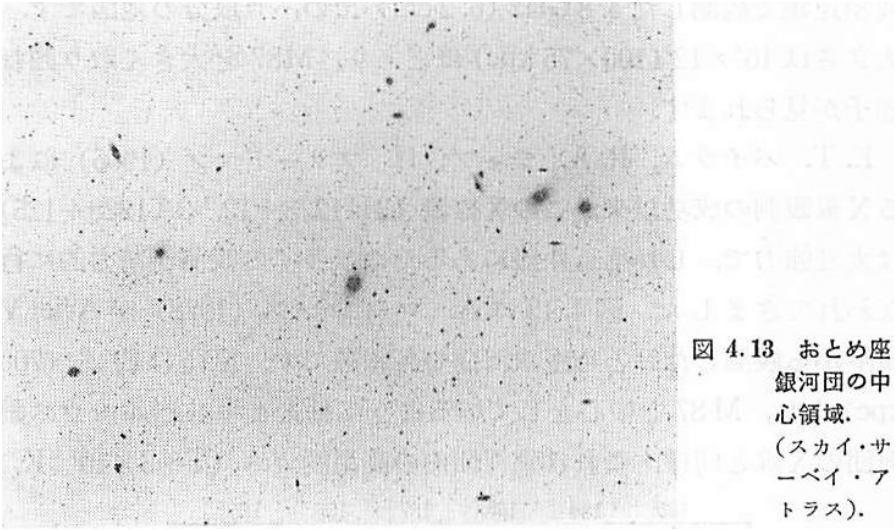


図 4.13 おとめ座
銀河団の中
心領域。
(スカイ・サ
ーベイ・ア
トラス)。

Figure 4.13 Central region of the Virgo cluster of galaxies. (Sky Survey Atlas).

The radio source of M 87 (3C 274, Virgo A) has a double structure consisting of a halo and a core, and at wavelengths longer than 1 GHz the halo becomes the main component. The total luminosity of the halo is $L(10^7 - 10^{10}\text{Hz}) = 3 \times 10^{41}\text{erg/s}$. Figure 4.14 is a map of the halo component at 4.8 GHz (6.2 cm) observed with the 100 m radio telescope by H. Andernach et al. (1979). Its size is about $16' \times 12'$ (100×75 kpc), and it can be seen to surround M 87 extensively.

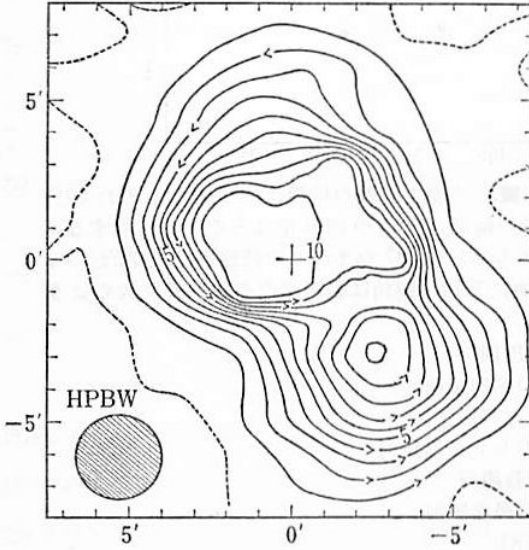


図 4.14 M87 の電波ハロ. +は銀河の中心核の位置 (H. アンダーナッハ達 1979).

Figure 4.14 The radio halo of M 87. The + marks the position of the nucleus of the galaxy (H. Andernach et al. 1979). — Both axes run from $-5'$ to $5'$. HPBW is indicated in the figure; contour values 5, 10.

Ever since the successful X-ray observations by E. T. Byram, R. A. Chubb and H. Friedman (1966), this X-ray source (3U 1228+12, 2A 1228+125) has been very intensively observed, being both very strong and nearby. Figure 4.15 shows the X-ray source of the Virgo cluster observed by A. Lawrence (1978) from the Ariel V satellite. It is about 2° (700 kpc) in diameter and appears to be centered on M 87. As with the X-rays from the Perseus cluster, this is due to thermal radiation from high-temperature gas within the cluster ($T \sim 3 \times 10^7$ K, $M \sim 1 \times 10^{13} M_\odot$).

Figure 4.15 X-rays from the Virgo cluster. The inner and outer ellipses are the contours of the X-ray source at which the intensity falls to 50% and 20% respectively; the quadrilateral inside is the error box for its center. The dashed circle around M 87 is the optical halo, and C_{CL} is the center of the cluster. The circles, triangles and squares are galaxies within the cluster, distinguished as follows: - ■ elliptical galaxy with $m_V \leq 11$ - □ elliptical galaxy with $m_V = 11 - 12$ - ● lenticular galaxy with $m_V \leq 11$ - ○ lenticular galaxy with $m_V = 11 - 12$ - ▲ spiral galaxy with $m_V \leq 11$ - △ spiral galaxy with $m_V = 11 - 12$

(A. Lawrence 1978). — Horizontal axis RA° , 1950.0 = 190–185. Vertical axis $DEC^\circ = 11-14$. Labels in the figure: M86, M84, M87, C_{CL} .

An X-ray map of M 87 observed from the Einstein satellite is shown in Figure 4.16. The resolution is $1'.5 \times 1'.5$. According to the analysis of D. Fabricant, M. Lecar and P. Gorenstein (1980), the mass of the high-temperature gas ($T = 2.9 \times 10^7$ °K) within a radius of $50'$ (230 kpc: $d = 15.7$ Mpc) is $1.0 \times 10^{12} M_\odot$ and its luminosity is $L(0.2-3 \text{ keV}) = 1.6 \times 10^{43} \text{ erg/s}$. Moreover, in order to support this high-temperature gas stably, a mass of $(1.7-4.0) \times 10^{13} M_\odot$ is required for the halo of M 87.

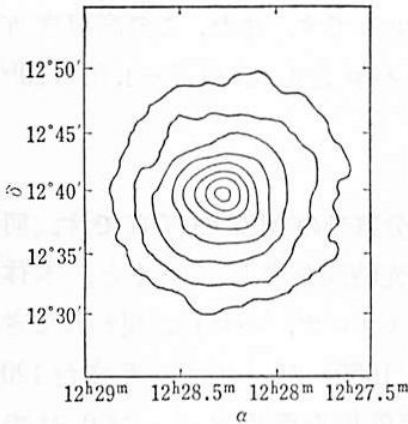


図 4.16 M87 の X 線地図(0.7–3.0KeV).
(D. ファブリカント, M. ルカール,
P. ゴーレンシュタイン 1980).

Figure 4.16 X-ray map of M 87 (0.7-3.0 KeV). (D. Fabricant, M. Lecar, P. Gorenstein 1980). — Vertical axis $\delta = 12^\circ 30' - 12^\circ 50'$, horizontal axis $\alpha = 12^h 27^m.5 - 12^h 29^m$.

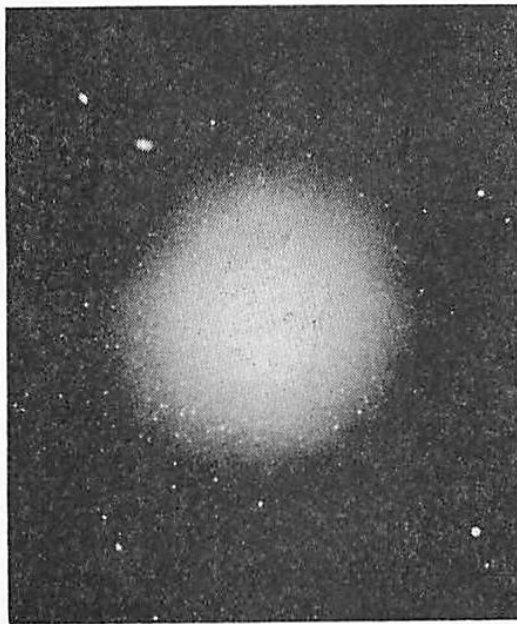


図 4.17 M87 (ハッブル・アトラス, A. サンデッジ 1961).

Figure 4.17 M 87 (Hubble Atlas, A. Sandage 1961).

(2) The corona region and the globular cluster system

Figure 4.17 is a 30-minute exposure photograph of M 87 taken in blue light. The diameter of the bright main body is about 10 kpc. As the exposure time is increased, an outermost region (corona, halo) spreading widely outside the main body appears. In the isodensity map (Figure 4.18) obtained by H. Arp and F. Bertola (1969), who traced with a density step of 0.01 a photographic plate taken with the 120 cm Schmidt telescope at Palomar Observatory, the corona region extends to a diameter of at least 1° (350 kpc). Whereas the main body of M 87 is an almost perfect sphere (EO/1), the corona region becomes more elliptical the further out one goes, being flattened to an axial ratio of $b/a \sim 0.5$ in the direction P. A. $140\text{--}150^\circ$. According to the photoelectric photometry of G. de Vaucouleurs and J.

L. Nieto (1978), the corona region appears from a radius of 25 kpc, and its luminosity is about 10% of the total luminosity ($B = 9.57$).

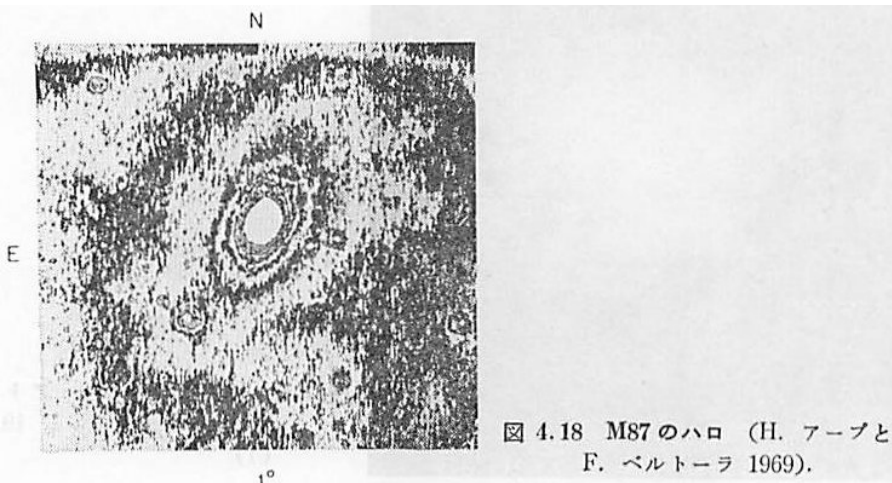


Figure 4.18 The halo of M 87 (H. Arp and F. Bertola 1969). — The figure carries the orientation marks N and E and a 1° scale bar.

A great many globular clusters swarm around M 87. Almost all of the objects scattered around M 87 in Figure 4.17 are globular clusters. According to the estimate of W. E. Harris and M. G. Smith (1976), the total number of globular clusters is 8,000. Since the Milky Way Galaxy and the Andromeda galaxy M 31 have 100–200, this number is astonishing. Within the Virgo cluster there are several elliptical galaxies as bright as M 87, but, quite mysteriously, only M 87 possesses such an enormous globular cluster system. One can only suppose that some special event which produced such a globular cluster system occurred in M 87 alone.

The corona region and the enormous globular cluster system of M 87 are presumably deeply connected with the fact that this galaxy is the central object of the Virgo cluster — in other words, that it is the “nucleus” of the cluster. M 87 is

classified as a peculiar elliptical galaxy, EO/1p, but it is thought to have the character of a D/ED galaxy.

(3) The jet

If a short-exposure photograph of M 87 is taken, a jet that appears to have been ejected from the nucleus is recorded (Figure 4.19). This jet was first discovered in 1918 by H. D. Curtis. It is about 2 kpc long, and several knots can be seen within it. In photographs whose spatial resolution has been improved by image processing, the nucleus and eight knots of magnitude 16–21 are beautifully resolved (Figure 4.20). Exactly the same jet can be seen in the radio as well (Figure 4.21).

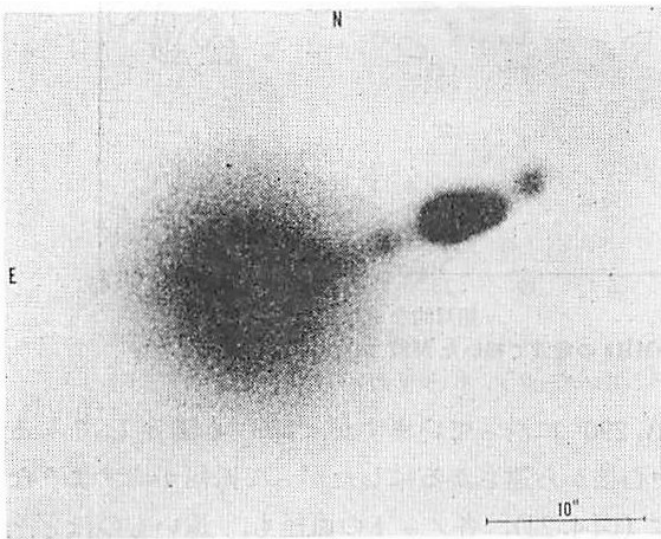


図 4.19 M87のジェット (H. アーブと J. ロール 1976).

Figure 4.19 The jet of M 87 (H. Arp and J. Lorre 1976). — The figure carries the orientation marks N and E and a 10" scale bar.

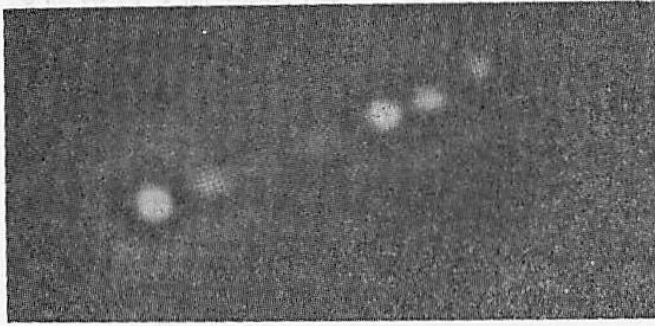


図 4.20 M87ジェットの画像処理された写真.
(H. アープと J. ロール 1976).

Figure 4.20 Image-processed photograph of the M 87 jet. (H. Arp and J. Lorre 1976).

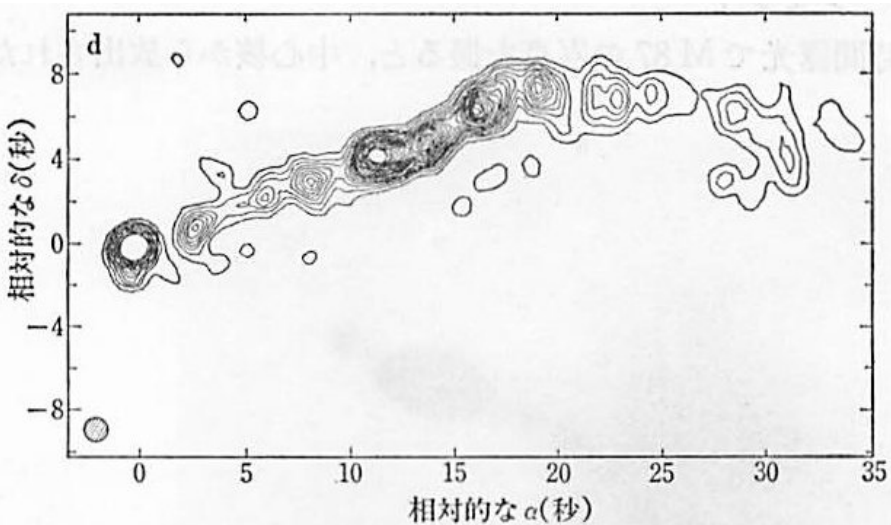


図 4.21 408MHz の電波で描いた M87 ジェット (J. D. ディヴィス, B. アンダーソン, I. モリソン 1980).

Figure 4.21 The M 87 jet mapped in the radio at 408 MHz (J. D. Davies, B. Anderson, I. Morrison 1980). — Vertical axis: relative δ (arcsec), -8 to 8. Horizontal axis: relative α (arcsec), 0 to 35.

The jet lies along P. A. 290° , but detailed measurement shows that the knots exhibit an undulation whose amplitude increases with increasing distance from the nucleus (Figure 4.22). The diameters of the knots also increase in proportion to their distance, the more distant ones being larger (Figure 4.23). G. de Vaucouleurs and J. L. Nieto (1979) interpreted this relation between distance and diameter as being due to gas spheres of plasma ejected from the nucleus continuing to expand at a constant velocity with time. Unfortunately, however, since the outflow velocity of the jet is unknown, the expansion velocity of the knots themselves is also unknown.

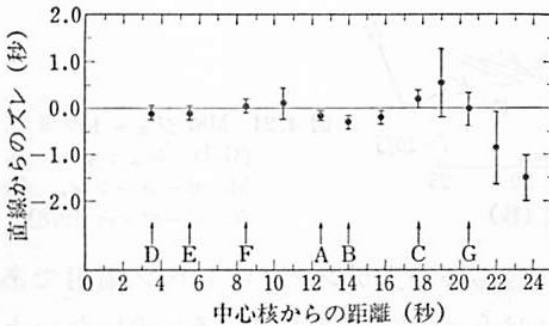


図 4.22 ジェットのうねり。
(F. N. オーエン, P. E. ハーディー, R. C. ビッグネル 1980)

Figure 4.22 Undulation of the jet. (F. N. Owen, P. E. Hardie, R. C. Bignell 1980) — Vertical axis: deviation from a straight line (arcsec), -2.0 to 2.0 . Horizontal axis: distance from the nucleus (arcsec), 0 to 24 . The positions of knots D, E, F, A, B, C, G are indicated by arrows.

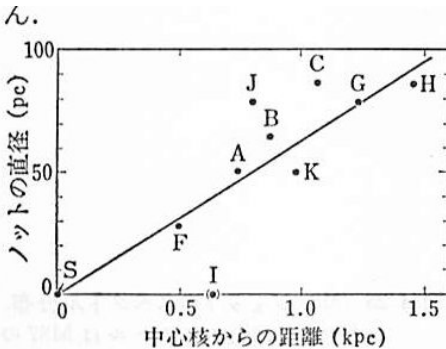


図 4.23 ノットの距離と直径 (G. ド・ヴォクルールと J. L. ニエト 1979).

Figure 4.23 Distance and diameter of the knots (G. de Vaucouleurs and J. L. Nieto 1979). — Vertical axis: diameter of the knot (pc), 0 to 100. Horizontal axis: distance from the nucleus (kpc), 0 to 1.5. Knots S, F, I, A, B, J, K, C, G, H.

The light of the jet is due to synchrotron radiation. This is guaranteed by both the polarization and the spectrum. In 1955 I. S. Shklovsky predicted that if the M 87 jet shone by synchrotron radiation, polarization should be observed, and this was immediately confirmed by W. Baade (1956) and W. A. Hiltner (1959). Figure 4.24 is a polarization map obtained by the photoelectric photometry of G. D. Schmidt, B. M. Peterson and E. A. Beaver (1978). At the strongest points it reaches about 20%.

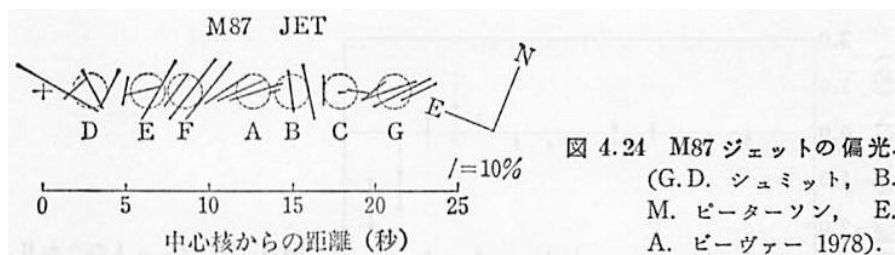


図 4.24 M87 ジェットの偏光.
(G. D. シュミット, B. M. ピーターソン, E. A. ビーヴァー 1978).

Figure 4.24 Polarization of the M 87 jet. (G. D. Schmidt, B. M. Peterson, E. A. Beaver 1978). — Labels in the figure: M87 JET, knots D, E, F, A, B, C, G, orientation marks N, E, scale $I = 10\%$. Horizontal axis: distance from the nucleus (arcsec), 0 to 25.

If the light of the jet is synchrotron radiation, its spectrum is expected to have the form $f_\nu \propto \nu^{-\alpha}$, but in the early observations the scatter was too large and the spectral slope α could not be determined. The spectrum determined by the author together with Masaki Nishimura and Kiyotaka Toyama (1973) from six photographs taken with the Okayama 188 cm telescope is shown in Figure 4.25. The slope is $\alpha = 1.7$. This also agrees well with the photoelectric photometry of T. D. Kinman, G. L. Grasdalen and G. H. Rieke (1974).

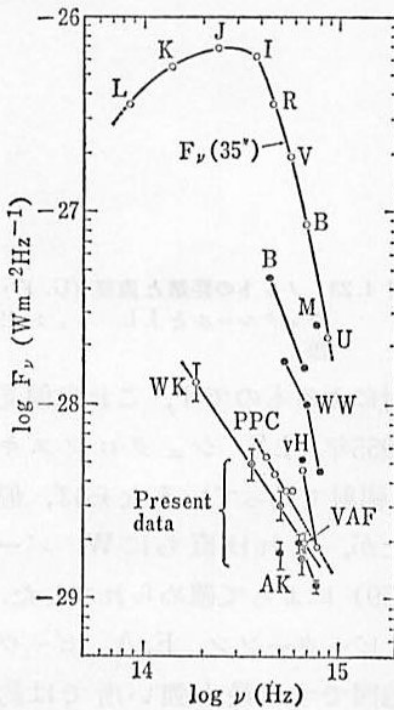


図 4.25 M87 ジェットのスペクトル分布.

上の多色測光スペクトルはM87の銀河光に対するもの。◎印が筆者と西村雅樹、外山清高の測定したB, V, Iで、他の測定値 (vH: van Houten 1961; B: Bless 1962; M: Moroz 1962; PPC: Proniket al. 1967; VAF: de Vaucouleurs et al. 1968; WK: Wisniewski and Kleinmann 1968; WW: Westerlund and Wall 1969; AK: Ables and Kron 1973) も示してある。(兼古昇, 西村雅樹, 外山清高 1973)。

Figure 4.25 Spectral distribution of the M 87 jet. The multicolor photometric spectrum at the top refers to the galactic light of M 87. The ● symbols are the B, V, I measured by the author with Masaki Nishimura and Kiyotaka Toyama; other measurements (vH: van Houten 1961; B: Bless 1962; M: Moroz 1962; PPC: Pronik et al. 1967; VAF: de Vaucouleurs et al. 1968; WK: Wisniewski and Kleinmann 1968; WW: Westerlund and Wall 1969; AK: Ables and Kron 1973) are also shown. (Kaneko, N., Nishimura, M., Toyama, K. 1973). — Vertical axis: $\log F_\nu$ ($Wm^{-2}Hz^{-1}$), -29 to -26. Horizontal axis: $\log \nu$ (Hz), 14 to 15. Labels in the figure: $F_\nu(35'')$, L, K, J, I, R, V, B, M, U, WK, PPC, vH, WW, VAF, AK, Present data.

According to observations from the IUE satellite (International Ultraviolet Explorer) by G. C. Perola and M. Tarenghi (1980), the synchrotron spectrum with $\alpha = 1.7$ extends into the ultraviolet as far as $\lambda = 1300\text{\AA}$. Since $\alpha \approx 0.5$ in the radio region, a break in the spectrum is expected somewhere in the infrared.

The knots within the jet vary in brightness. J. W. Sulentic, H. Arp and J. Lorre (1979) compared the photographs used by W. Baade (1956) for his polarization observations with photographs taken 22 years later in 1978, and found that they had brightened by about 30%. They regard this light variation as one piece of evidence that the knots are quasar-like compact objects ejected from the nucleus.

The usual interpretation, however, is that the jet is a flow of plasma ejected from the nucleus and that the knots are due to the pinch effect of magnetohydrodynamics, or else are shock waves arising from non-uniformity of the velocity within the jet. Even so, the essential nature of the jet is still hardly understood at all. Why can the nucleus eject plasma, or compact objects, in the form of a jet? What kind of acceleration mechanism operates within the jet to produce the relativistic electrons that emit synchrotron radiation? Such unsolved problems are piled high.

(4) The nuclear region and the filamentary gas clouds

H. Arp (1967) discovered a counter jet 3–4 kpc from the nucleus in the direction opposite to the jet, and M. F. Walker (1968) discovered a fan-shaped jet (orthogonal fan jet) on the north side, perpendicular to the jet, and they considered that these, like the jet, had been produced by an explosion in the nucleus. These features, however, are quite different in nature from the jet: they emit the $[O II]\lambda 3727$ and $H\alpha$ emission lines and do not emit synchrotron continuum radiation.

H. C. Ford and H. Butcher (1979) showed that filamentary gas clouds exist in the nuclear region of M 87 and that the counter jet and the fan-shaped jet are parts of them. Attaching an interference filter and a video camera to the 4 m telescope of Kitt Peak National Observatory, and carefully subtracting the starlight forming the background, they succeeded in obtaining a photograph of the $H\alpha$ filaments alone (Figure 4.26). Figure 4.27 is their sketch. Filament No. 1 corresponds to Arp's

counter jet, and Nos. 3, 4, 5 to Walker's fan-shaped jet. The filamentary region has an extent of 8×3 kpc, elongated in the same P. A. 110° — 290° direction as the jet. Each individual filament, too, if anything, appears to be aligned in this direction. Superimposed on Figure 4.26 is the radio map observed at 5 GHz (6 cm) by B. D. Turland (1975), and the radio structure shows good correspondence with the filament region.

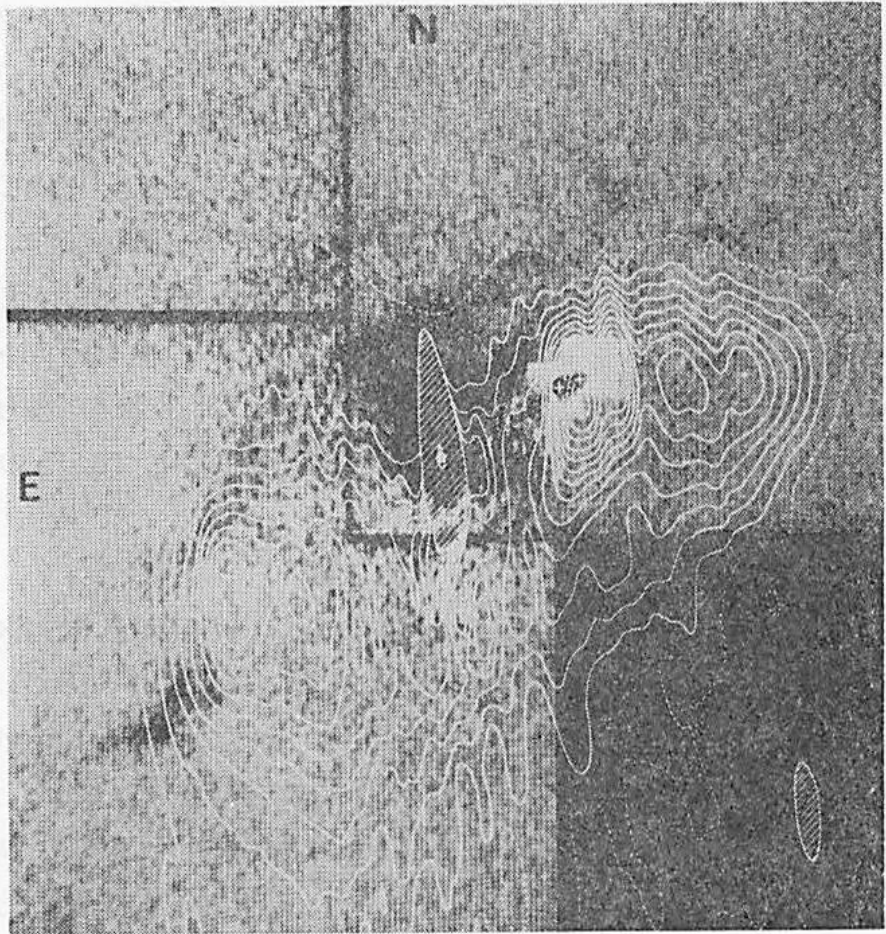


Figure 4.26 The $H\alpha$ filaments of M 87. (H. C. Ford and H. Butcher 1979). — The figure carries the orientation marks N and E.

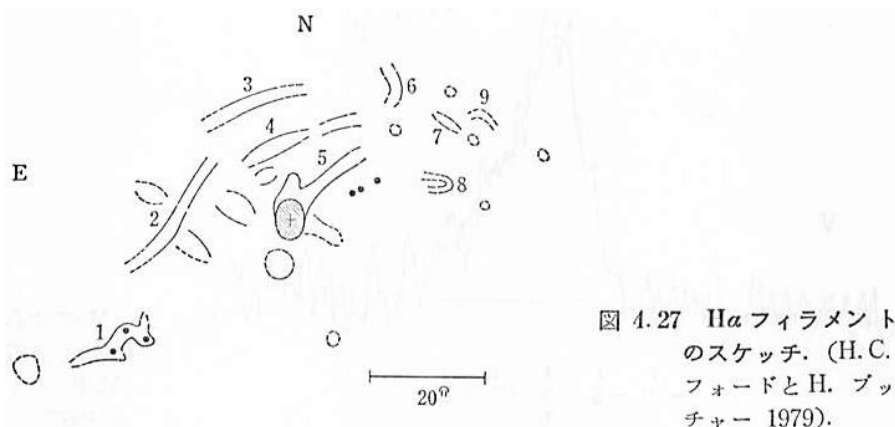


Figure 4.27 Sketch of the $H\alpha$ filaments. (H. C. Ford and H. Butcher 1979). Orientation: N (top), E (left). The filaments are numbered 1–9; the scale bar is 20".

Ford and Butcher carried out spectroscopic observations and investigated the physical properties of the filaments. Their results give an electron density and temperature of $N_e \approx 1600/\text{cm}^3$ and $T_e \leq 11,300^\circ\text{K}$, and a total filament mass of $M \sim 10^4 M_\odot$. Furthermore, the radial velocities of the filaments lie within 100 km/s of M87, and no large velocities such as would indicate ejection by an explosion in the nucleus are found.

If one takes account of the fact that M 87 sits at the center of a high-temperature intracluster gas, the following picture emerges as a natural interpretation. That is, high-temperature gas drawn in by the strong gravity of M 87 is raining down toward the nucleus, but a thermal instability sets in and the material condenses to form the filaments. Although the scale is different, the filamentary gas clouds of M 87 are exactly the same thing as the $H\alpha$ filaments of NGC 1275.

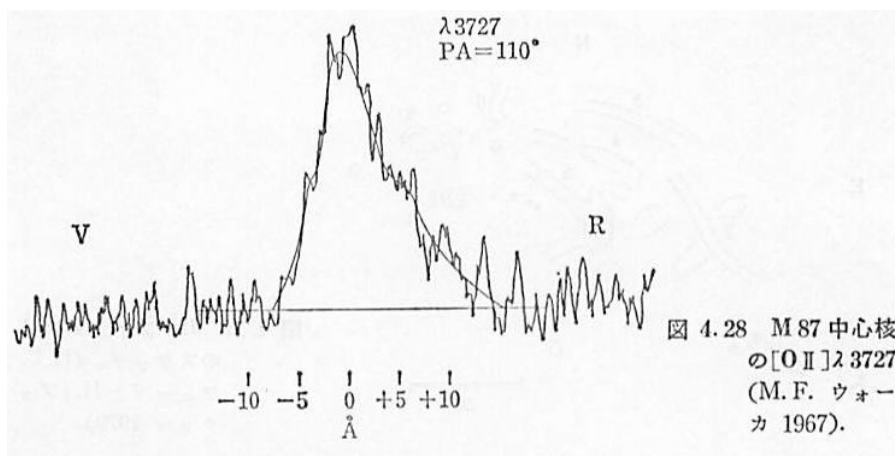


Figure 4.28 [O II] $\lambda 3727$ of the nucleus of M 87. (M. F. Walker 1967). At the top of the figure: $\lambda 3727$, $PA=110^\circ$. V is marked at the left and R at the right. The horizontal scale is $-10, -5, 0, +5, +10 \text{ \AA}$.

(5) The nucleus and a black hole

Although not strong, an emission-line spectrum is observed in the nucleus of M 87. The line profiles are asymmetric and broad, resembling those of type 2 Seyfert galaxies (Figure 4.28). The component redshifted by 650 km/s that is responsible for the asymmetry was also confirmed in the $H\alpha + [N \text{ II}]$ line profiles by H. C. Ford and H. Butcher (1979), so it is thought that at least two gas clouds of different velocity exist within the nucleus. Many observers have also confirmed that the emission lines are blueshifted by 140–210 km/s relative to the absorption lines. According to Ford and Butcher, the spectral intensity ratios of the nucleus resemble those of the filament system, and the same ionization and excitation mechanism is thought to be operating in both. Violent motions of gas clouds and the shock waves they produce are probably the appropriate explanation for these. The mass of ionized gas within the nucleus is of order $\sim 1,000 M_\odot$.

The nucleus is also a point-like radio source. In the 10.7 GHz (2.8 cm) observations of K. I. Kellermann et al. (1977), the size of that radio source is ~ 0.04 pc. So far, however, no changes in intensity or structure have been observed. Active nuclei are usually powerful infrared radiation sources, but curiously, the nucleus of M 87 does not emit strong infrared light.

In the May 1, 1978 issue of the *Astrophysical Journal*, two papers were published claiming that there must exist within the nucleus of M 87 a non-luminous object — a black hole — with a mass of $(3-5) \times 10^9 M_\odot$, and this became a sensational topic. The group of P. J. Young and five others attached a two-dimensional semiconductor-element detector to the 5 m and 1.5 m telescopes and observed the surface-brightness distribution of M 87 (Figure 4.29). Whereas there is a sharp cusp at the center of M 87, no such cusp is seen in NGC 4636, which is of the same E0 type and is a member of the Virgo cluster. If one tries to reproduce the surface-brightness distribution by model calculations, it is necessary to assume the existence at the center of a black hole with a mass of $3 \times 10^9 M_\odot$ (Figure 4.30).

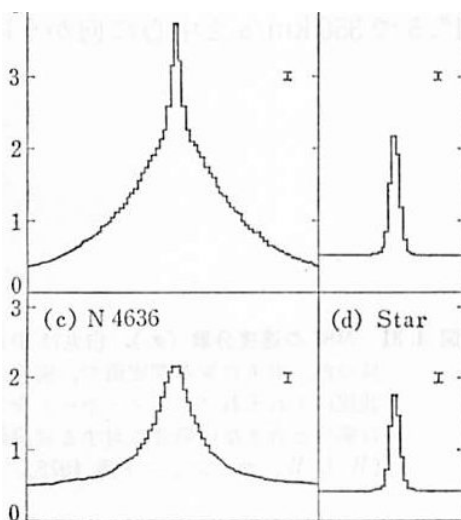


図 4.29 M87 中心核領域の表面輝度分布. 各ピクセルは $0.''5$ で, 測光は V 等級. (P. J. ヤング達 1978).

Figure 4.29 Surface-brightness distribution of the nuclear region of M87. Each pixel is $0.''5$, and the photometry is in V magnitudes. (P. J. Young et al. 1978). Four panels: (a) M87, (b) Star, (c) N 4636, (d) Star. Vertical scale 0–4 for (a) and (b), 0–3 for (c) and (d).

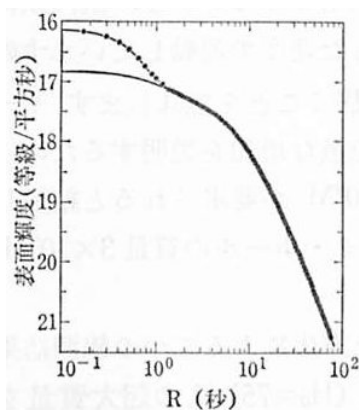


図 4.30 表面輝度分布のモデル計算. $r \leq 1.''5$ 内で観測と一致させるためには $\sim 3 \times 10^9 M_{\odot}$ のブラック・ホールを必要とする. (P. J. ヤング達 1978).

Figure 4.30 Model calculation of the surface-brightness distribution. To match the observations within $r \leq 1.''5$, a black hole of $\sim 3 \times 10^9 M_{\odot}$ is required. (P. J. Young et al. 1978). Vertical axis: surface brightness (magnitude/square arcsec) 16–21; horizontal axis: R (arcsec) 10^{-1} – 10^2 .

Meanwhile, a group of six led by W. L. W. Sargent carried out spectroscopic observations of M87 with the 4 m telescope of Kitt Peak National Observatory. The Image Photon Counting System developed at the University of London was used for the observations. Figure 4.31 shows the velocity dispersion they derived. It is 220 km/s at radius $R=72''$, 278 km/s at $9''.6$, and 350 km/s at $1''.5$ — that is, the velocity dispersion of the absorption lines increases sharply toward the center. Since the stars within an elliptical galaxy move at velocities in balance with the gravity produced by the stellar system, a large velocity dispersion means that they lie within a strong gravitational field. Sargent and his colleagues concluded that to explain the sharp increase in the velocity dispersion they had derived, a mass of $M = 5 \times 10^9 M_{\odot}$ within a radius of $1''.5$ is required. This value agrees well with the black-hole mass of $3 \times 10^9 M_{\odot}$ obtained by Young and his colleagues.

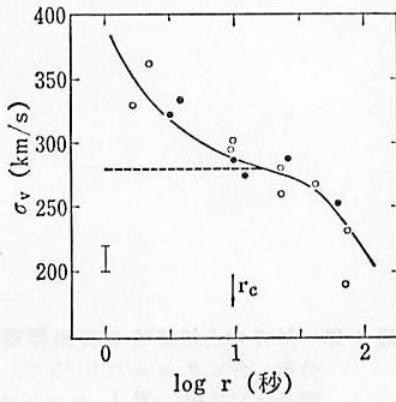


図 4.31 M87 の速度分散 (σ_v). 白丸は中心核の西, 黒丸は東の測定値で, 実線と波線はそれぞれブラック・ホールを含む場合と含まない場合に対する理論値 (W. L. W. サージェント達 1978).

Figure 4.31 Velocity dispersion (σ_v) of M87. Open circles are measurements west of the nucleus, filled circles east; the solid and dashed curves are the theoretical values for the cases with and without a black hole, respectively (W. L. W. Sargent et al. 1978). Vertical axis: σ_v (km/s) 200–400; horizontal axis: $\log r$ (arcsec) 0–2. A vertical line in the figure marks the position of r_c .

Thus the two observational results obtained by different methods and announced at the same time raised the possibility that a black hole of supermassive scale, $(3—5) \times 10^9 M_\odot$ ($H_0 = 75$), really exists within the nucleus of M 87. Recently, however, problems have been pointed out with these observations and their interpretation. A. Dressler (1980) observed under the excellent conditions of $0''.75$ seeing and showed that the velocity dispersion of the absorption lines is not as large as Sargent and his colleagues had indicated, being 350 km/s at $R \leq 0''.35$. M. J. Duncan and J. C. Wheeler (1980) have also shown that if an anisotropic velocity distribution is allowed, the cusp of M87 can be explained even without a black hole. The region under discussion in connection with the black hole is an extremely small region of $\leq 1''$. To decide whether a black hole exists, we shall probably have to wait for observations with the Space Telescope, which will have a resolving power of $0''.1$ or better.

3. NGC 5128 and NGC 1316

These are peculiar galaxies with a black band (dark lane) across the center, and they are also double radio sources. Their strange appearance evidently made some astronomers reluctant to regard them as galaxies: as late as 1949 D. S. Evans went so far as to state, “Since the surface-brightness distribution is spherically symmetric apart from the dark lane, and the spectrum is also that of a gaseous nebula, NGC 5128 is probably a planetary nebula. It would be worthwhile to examine IC 5267 and NGC 1316, which resemble it.”

(1) NGC 5128

NGC 5128 (PKS 1322-42, Centaurus A) is the nearest double radio source ($d=5$ Mpc). The overall size of the radio source is about 800 kpc, and besides the double radio source at $\delta = -42^\circ 30'$ and $-44^\circ 20'$, separated by 200 kpc, one can also recognize a pair of radio sources at $\delta = -39^\circ 30'$ and $-46^\circ 00'$ (Figure 4.32). Further inside, there exists a third double radio source separated by 9 kpc (Figure 4.33). This can also be seen in X-rays (E. J. Schreier et al. 1979).

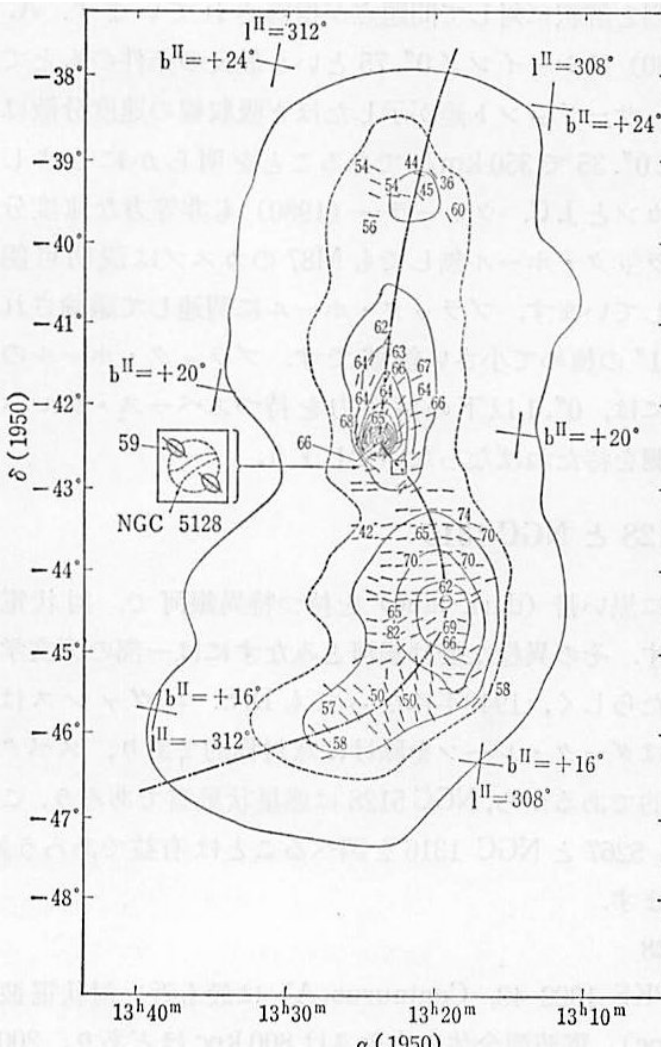


図 4.32 NGC5128
の電波構造
図中のベク
トルは磁場
の方向を示
し、数字は
ファラデー
回転の量
(Farady
rotation
measure)
を表わす。
(B. F. C.
クーパー,
R. M. プラ
イス, D.
J. コール
1965)

Figure 4.32 Radio structure of NGC5128. The vectors in the figure show the direction of the magnetic field, and the numbers represent the amount of Faraday rotation (Faraday rotation measure). (B. F. C. Cooper, R. M. Price, D. J. Cole 1965). Vertical axis: $\delta(1950) - 38^\circ$ to -48° ; horizontal axis: $\alpha(1950) 13^h10^m$ to 13^h40^m . Galactic-coordinate grid lines $l^{\text{II}}=308^\circ, 312^\circ$ and $b^{\text{II}}=+16^\circ, +20^\circ, +24^\circ$ are drawn. At upper left is an inset enlargement of the body of NGC 5128 (rotation measure 59). The rotation measures attached to the contours include 36, 42, 44, 45, 50, 51, 54, 56, 57, 58, 59, 60, 62, 63, 64, 65, 66, 67, 68, 70, 74, 82.

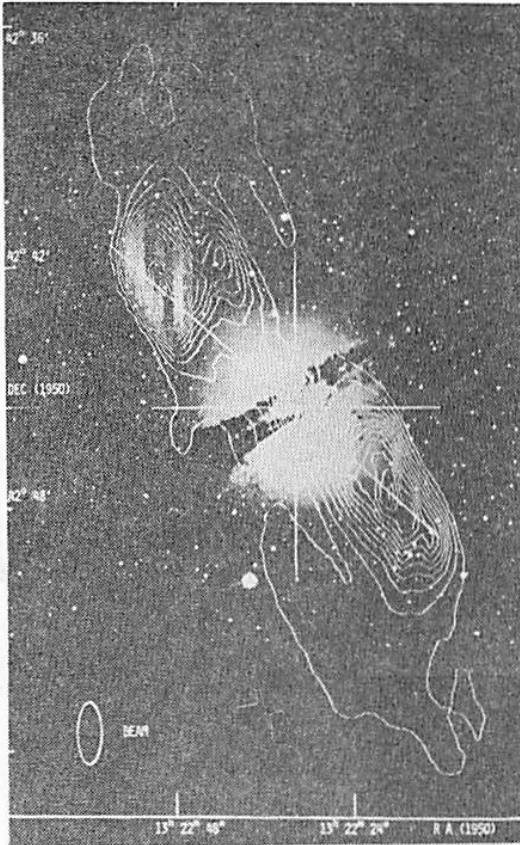


図 4.33 内部の対状電波源 (1.4GHz). (R. D. エカース 1974).

Figure 4.33 The inner double radio source (1.4 GHz). (R. D. Ekers 1974). Vertical axis: DEC (1950) $-42^{\circ}36'$, $-42^{\circ}42'$, $-42^{\circ}48'$; horizontal axis: R.A. (1950) $13^{\text{h}}22^{\text{m}}48^{\text{s}}$, $13^{\text{h}}22^{\text{m}}24^{\text{s}}$. The ellipse at lower left indicates the beam (BEAM).

NGC 5128, together with NGC 4945, NGC 5102, NGC 5236, NGC 5253 and NGC 5068, forms the NGC 5128 group. The distribution is chain-like, with a length of about ~ 2 Mpc. Interestingly, this appears to coincide with the direction of the double radio source. NGC 5253 has at times been suggested to be a Seyfert galaxy, but this is now denied. Nevertheless, although a type 1 supernova appears in a single galaxy only about once in 1000 years, two have been discovered in NGC 5253 — in 1895 and in 1972.

If one ignores the dark lane, NGC 5128 looks like a giant elliptical galaxy (Figure 4.34). In the Morgan classification it is DE3. The surface-brightness distribution is well represented by de Vaucouleurs' quarter-power law, and the apparent magnitude is $V=6.20$. Applying a correction for reddening gives $V_0 = 5.87$. This corresponds to an absolute magnitude of $M_v = -22.7$, so NGC 5128 is regarded as one of the brightest galaxies.



図 4.34 NGC 5128. (ハッブル・
アトラス, A. サンデッジ
1961).

Figure 4.34 NGC 5128. (Hubble Atlas, A. Sandage 1961).

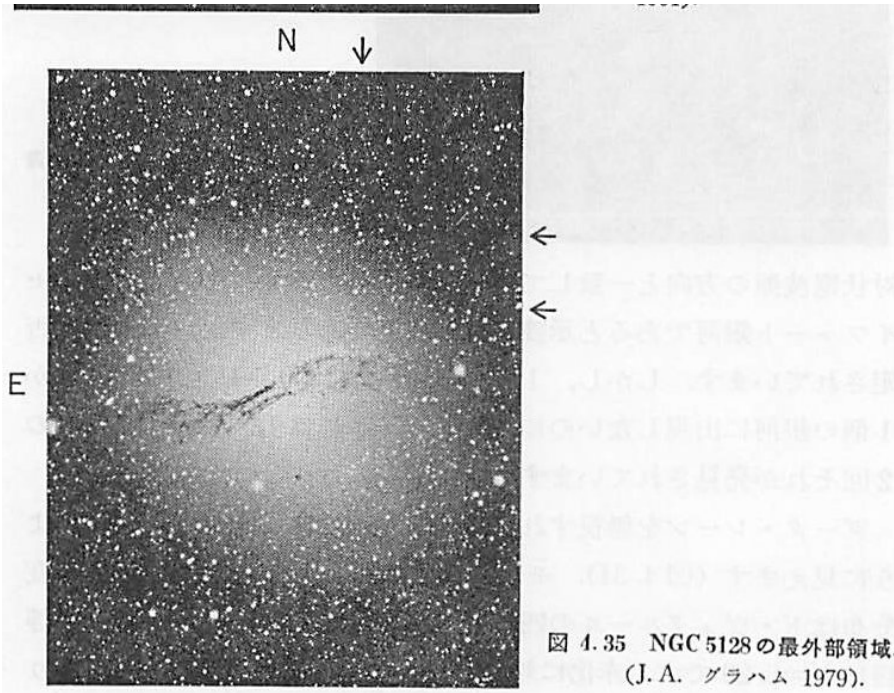


Figure 4.35 The outermost region of NGC 5128. (J. A. Graham 1979). N is marked at the top and E at the left. Two arrows on the right edge indicate the extent of the outermost region.

Figure 4.34 shows a region roughly 10 kpc in diameter. If the exposure time is increased, still more extended outer parts appear. Figure 4.35 is a photograph of the outermost region of NGC 5128 taken by J. A. Graham (1979) with the 4 m telescope at Cerro Tololo. Here the print has been made with reduced contrast in order to bring out the faint outermost parts. The image extends to 28 kpc along the major axis and 20 kpc along the minor axis, so NGC 5128 has a spindle shape elongated in the polar direction (the direction of the radio source). Whether this

shape is due to the stellar system, however, is unclear, since one possibility is a contribution from synchrotron radiation from the inner double radio source.

The dark lane, which made Sir J. Herschel call it “a most wonderful object,” lies perpendicular to the direction of the double radio source. When the collision hypothesis was advanced to explain radio galaxies, this dark lane was taken to be a spiral galaxy colliding with NGC 5128. Figure 4.36 shows the dark lane photographed through an $H\alpha$ interference filter. Eighteen compact ionized-hydrogen (H II) regions are marked on it, but S. van den Bergh (1976), using computer image processing, resolved 75 H II regions within the dark lane. Associations of blue stars are also observed still farther out. The two H II regions on which R. J. Dufour et al. (1979) made spectroscopic observations resemble in their properties the gaseous nebulae in the Milky Way galaxy, and their chemical composition also agrees with that of the Sun. In this way the many H II regions and stellar associations scattered within the dark lane all testify that active star formation is taking place within the dark lane even at the present time.

The rotation of the dark lane has been known for quite some time, from the observations of E. M. Burbidge and G. R. Burbidge (1959). The H II regions of Figure 4.36 likewise form a rotating ring of radius 4 kpc (Figure 4.37). The rotation period is $\sim 10^8$ /year. From this, J. A. Graham (1979) calculates the mass of NGC 5128 within a radius of 11 kpc to be $3 \times 10^{11} M_{\odot}$.

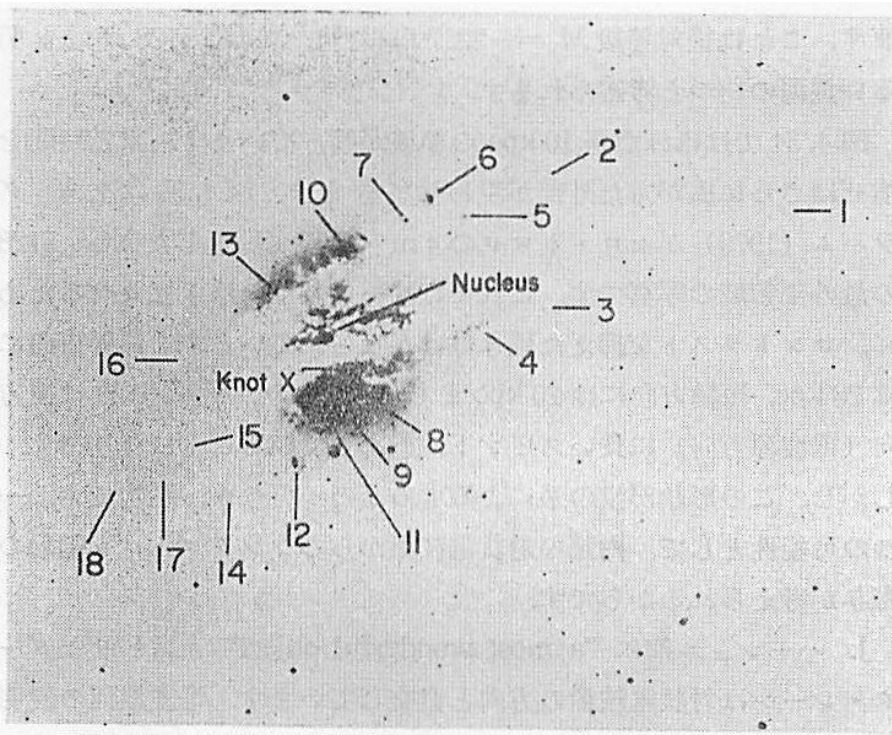


Figure 4.36 *H α* interference-filter photograph of NGC 5128. (J. A. Graham 1979). In the figure the H II regions are numbered 1–18, and the Nucleus and Knot X are indicated.

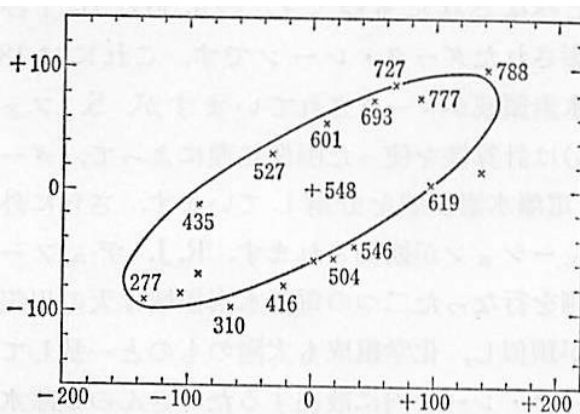


図 4.37 電離水素領域の速度場。数字は各領域の km/s を単位とする速度 (J. A. グラハム 1979)。

Figure 4.37 Velocity field of the H II regions. The numbers are the velocities of each region in units of km/s (J. A. Graham 1979). Both axes run $-200, -100, 0, +100, +200$ (relative position). The velocity values in the figure are 277, 310, 416, 435, 504, 527, 546, +548, 601, 619, 693, 727, 777, 788. The whole is enclosed by an inclined ellipse (the rotating ring).

How was the dark lane of NGC 5128 formed? It cannot be thought to have been made from gas released during the evolution of stars within NGC 5128, because it has been observationally established that the stars within NGC 5128 are not rotating. Even if it had been ejected by an explosion in the nucleus, the large rotational motion of the dark lane could not be explained. In the end, gas carrying angular momentum has to be supplied from outside. Two possible ways of doing this have been considered. One is the proposal of R. B. Larson (1972) that NGC 5128 plunged into a giant gas cloud; the other is the proposal of A. Toomre (1977) that a small galaxy was swallowed. J. A. Graham (1979) and R. J. Dufour et al. (1979) support the latter, interpreting the large S-shaped warp of the dark lane on the outside as marking the original path along which that galaxy fell in. The X-ray source of 6 kpc diameter observed at the center of NGC 5128 is thought to be thermal radiation from $6 \times 10^8 M_{\odot}$ of high-temperature gas, and this too was presumably produced by the collision with the galaxy.

A jet reaching $\sim 28'$ (42 kpc) from the nucleus in the direction of the radio source on the northeast side of NGC 5128 was recently discovered. Figure 4.38 shows the outer jet discovered by V. M. Blanco et al. (1975). The inner jet was discovered by R. J. Dufour and S. van den Bergh (1978), and the still more inward X-ray jet by the Einstein satellite observations of E. J. Schreier et al. (1979), revealing the astonishing new fact that the jet of NGC 5128 is continuous from the nucleus out to ~ 42 kpc (Figure 4.39). Probably the high-temperature gas ejected from the nucleus cooled at $R \sim 3$ kpc and became the jet visible in optical light.

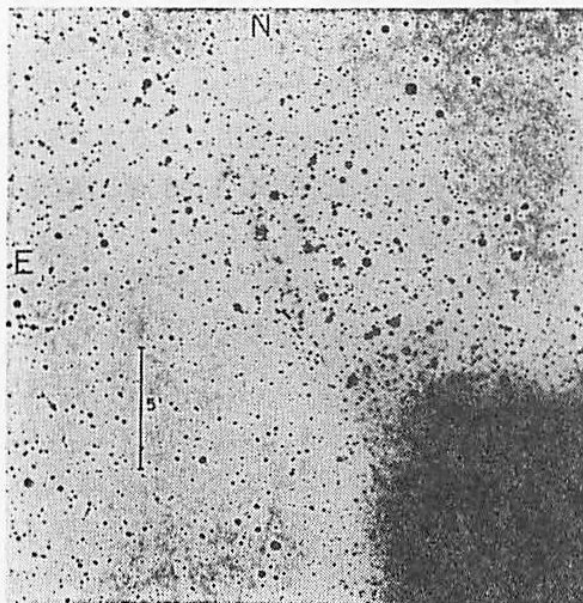


図 4.38 M. V. ブランコ
達 (1975) の外部ジ
ェット.

Figure 4.38 The outer jet of V. M. Blanco et al. (1975). N is marked at the top and E at the left. A 5' scale bar is at the left center.

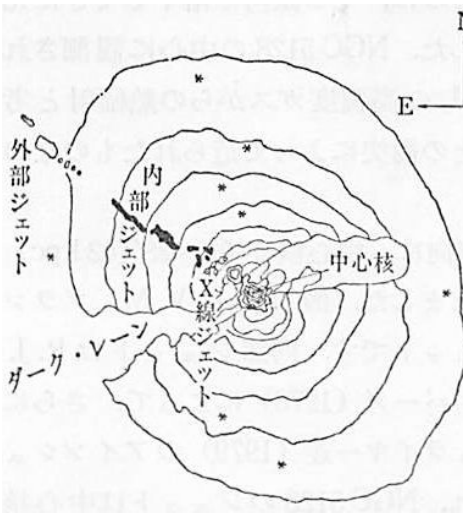


図 4.39 X線ジェット. (E. J. シュ
라이어達 1979).

Figure 4.39 The X-ray jet. (E. J. Schreier et al. 1979). Labels in the schematic: outer jet, inner jet, X-ray jet, nucleus, dark lane. Orientation N (up), E (left) at upper right. The positions of the outer jet are marked with asterisks.

The nucleus of NGC 5128 is covered by the dark lane, but it can be seen in infrared photographs (Figure 4.40). Its size is $\sim 4''$ (100 pc). No Seyfert-like spectrum is seen in the nucleus. Within the infrared nucleus identified by W. E. Kunkel and H. V. Bradt (1971), a compact radio source and an X-ray source have been discovered. In the observations of K. I. Kellermann (1974) at 31.5 and 89 GHz (9.5 and 3.4 mm), the size of the radio source is ~ 0.5 milliarcsecond (0.01 pc), and it also shows intensity variations. The X-ray source is powerful, its 0.3–3 keV luminosity being 2.8×10^{42} erg/s and its 0.1–100 keV luminosity reaching as much as 1.7×10^{43} erg/s. The X-ray intensity varies, and the size of the X-ray source is estimated to be $l \leq 10^{16}$ cm.

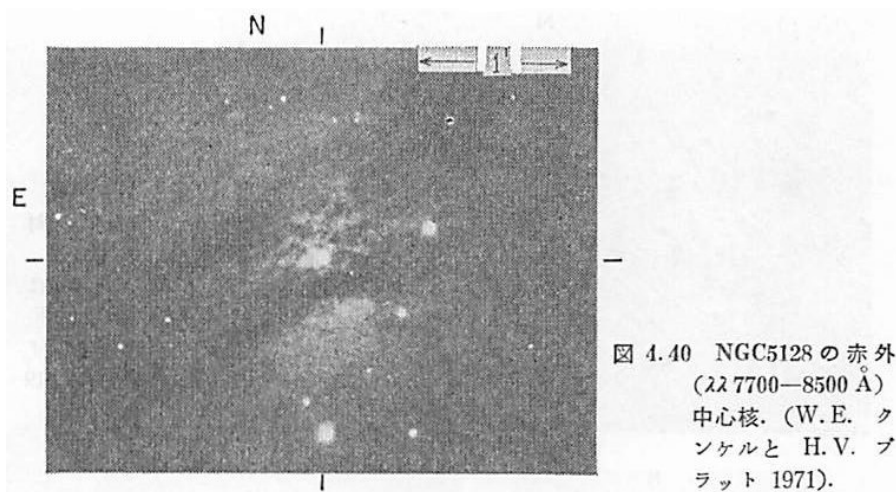


Figure 4.40 The infrared ($\lambda\lambda 7700\text{--}8500\text{ \AA}$) nucleus of NGC5128. (W. E. Kunkel and H. V. Bradt 1971). N is marked at the top and E at the left. A scale bar is at the top.

(2) NGC 1316

NGC 1316 is the double radio source Fornax A (Figure 4.41). If the distance is taken as 33 Mpc, the two radio sources are separated by 300 kpc. T. A. Matthews, W. W. Morgan and M. Schmidt (1964) classify NGC 1316 as D3-4.

Figure 4.42 is a series of photographs taken by F. Schweizer (1980) with the 4 m telescope at Cerro Tololo. The short-exposure photographs show the bright nucleus. As the exposure time is increased, the parent galaxy of NGC 1316 and the dark lane become distinct. Increasing the exposure still further brings out a huge box-shaped outermost region ($\geq 150 \times 220$ kpc), and within it many arc-shaped loops and ripples begin to appear (Figure 4.43). The photograph of Figure 4.44, made by superposing five plates taken with the Curtis Schmidt telescope, shows still more enormous loops ($\sim 110 \times 160$ kpc), extending well beyond the radio source.

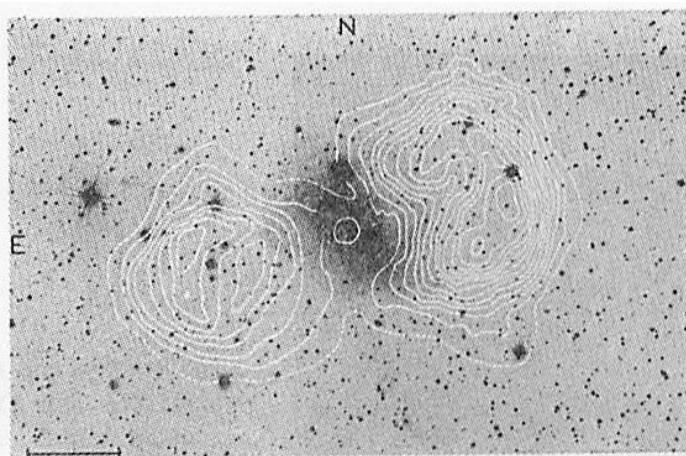


図 4.41 NGC 1316 の対状電波源。スケールは 100kpc。(F. シュヴァイツァー 1980)。

Figure 4.41 The double radio source of NGC 1316. The scale is 100 kpc. (F. Schweizer 1980). N is marked at the top and E at the left. Radio contours are superimposed on the photograph.

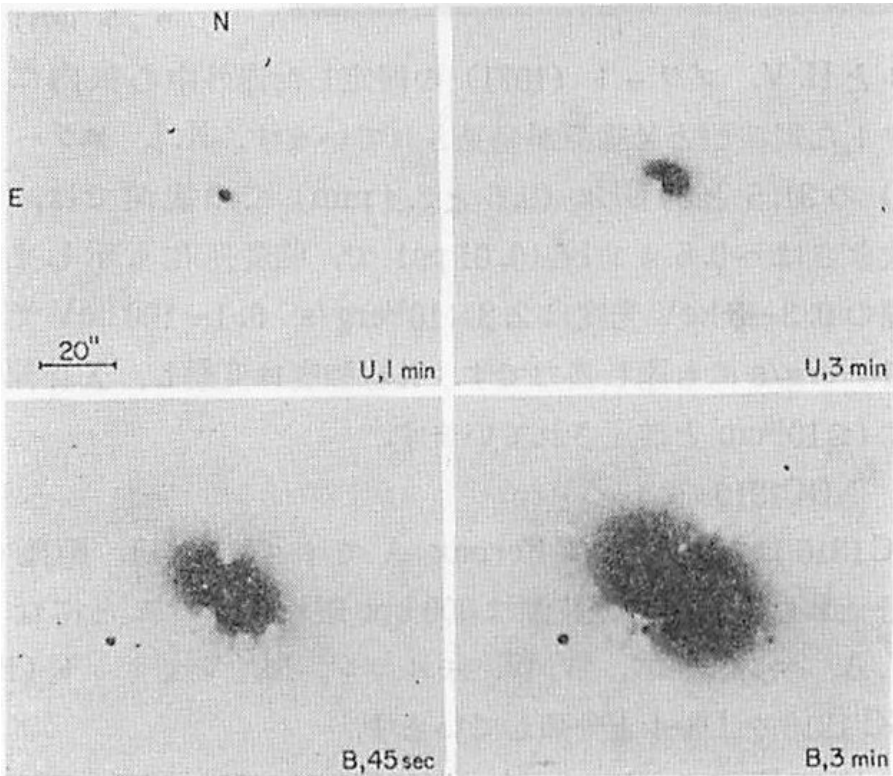


図 4.42 NGC1316. (F. シュヴァイツァー 1980).

Figure 4.42 NGC1316. (F. Schweizer 1980). Four panels: U, 1 min / U, 3 min / B, 45 sec / B, 3 min. N at upper left, E at left, with a 20" scale bar.

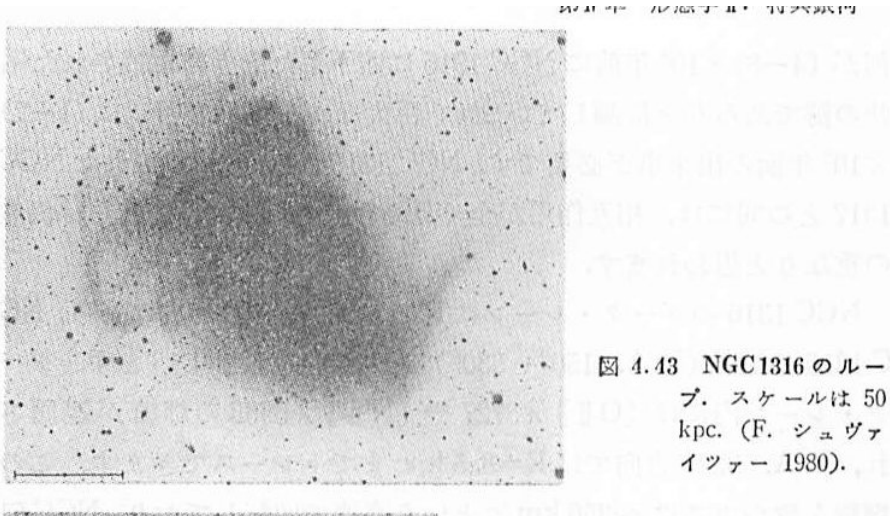


Figure 4.43 Loops of NGC 1316. The scale is 50 kpc. (F. Schweizer 1980).

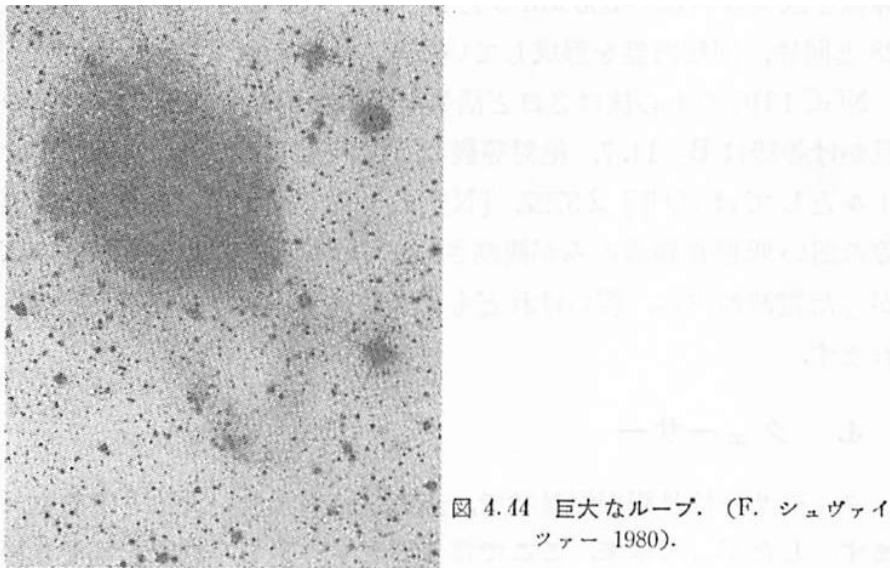


Figure 4.44 The giant loops. (F. Schweizer 1980).

Schweizer attempted spectroscopic observations of several of the loops and ripples, but no emission-line spectrum from ionized gas was seen. They are made of stars. Since the giant loops trace large arcs and appear to be connected to NGC 1316, he conjectured that they are the tail-like traces left behind when a galaxy fell into NGC 1316 $(4-8) \times 10^8$ years ago. Explaining the giant loops requires an event $(1-2) \times 10^9$ years ago. Since no interaction whatever is seen between NGC 1316 and NGC 1317, 60 kpc away, these are thought to be a chance superposition.

The dark lane of NGC 1316 lies in the direction P. A. $160^\circ-340^\circ$, roughly coinciding with the minor axis of NGC 1316 (P. A. $150^\circ-330^\circ$). Within the dark lane the emission lines [O II] $\lambda 3727$ and [N II] $\lambda 6583$ are observed, and in the direction P. A. 322° they can be traced out to $R=8.5$ kpc. The gas emitting these lines rotates at the high speed of ~ 350 km/s and, as in NGC 5128, is thought to form a rotating disk.

The nucleus of NGC 1316 does not show particularly vigorous activity. The apparent magnitude of the nucleus is $B=14.7$ and its absolute magnitude $M_B = -17.9$. As for the emission-line spectrum, only weak low-excitation lines such as [O II] $\lambda 3727$, [N II] $\lambda 6583$ and [S II] $\lambda \lambda 6716, 6731$ are observed. In the radio, a weak core of 0.1 arcsecond (~ 16 pc) is observed within an extended radio source 3 kpc in diameter.

4. Quasars

Quasars are defined as objects that are stellar in appearance and have large redshifts. Properly speaking, therefore, they cannot be the subject of the morphological discussion given here; but since quasars occupy an important

position in the study of Seyfert galaxies, we shall briefly examine only those aspects relevant to us.

The quasar catalog of A. Hewitt and G. Burbidge (1980) lists 1549 quasars. Of these, 17 have redshifts $z < 0.1$ and 35 have $0.1 \leq z < 0.2$, and the smallest redshift is $z = 0.036$ for B 272 (Q 1301+375). Moreover, these 52 quasars include 8 that are cataloged as Seyfert galaxies (Table 4.1). On the other hand, 16 quasars have redshifts exceeding 3, and the largest redshift is $z = 3.53$ for OQ 172 (Q 1442+101). This corresponds to a recession velocity of 91% of the speed of light.

Table 4.1 Quasars that are also Seyfert galaxies

Quasar	Seyfert galaxy	Redshift z
0121-590	Fairall 9 ESO 113-IG 49	0.045
0119-013	II Zw 1	0.054
0051+124	I Zw 1	0.061
2139+099	II Zw 136	0.061
1312+041	Tololo 1312+041	0.071
0007+106	III Zw 2	0.089
1257+286	X Comae	0.092
1304+346	Mkn 64 B 340	0.184

If quasars are the nuclei of galaxies, it is easy to anticipate that around quasars of small redshift there may exist a group to which the quasar belongs, or member galaxies of a cluster. A. Stockton (1978) carried out a systematic search for group galaxies around quasars. For the 27 quasars in the quasar catalog of G. R. Burbidge, A. H. Crowne and H. E. Smith (1977) satisfying the conditions $z \leq 0.45$, $m_v < 19.12 + 5 \log z$ and $-15^\circ < \delta < +55^\circ$, he searched for galaxies within a radius of $45''$, corresponding to 1 Mpc, the typical size of a group. For 10 of the quasars none were found, but for the remaining 17 quasars he was able to discover 29 galaxies.

As a result of spectroscopic observations made with the 2.2 m telescope of Mauna Kea Observatory, it was found that 13 galaxies around 8 of the quasars have redshifts agreeing with the quasar to within 1,000 km/s. For the representative quasar 3C 273 as well, a group galaxy 300 kpc away ($m_B = 20.3$, $z=0.1575$) was subsequently discovered.

Quasars are defined as stellar objects, but more than ten quasars are known that have envelopes suggestive of galaxies. 3C 48 is the most famous example (Figure 4.45). This envelope has a size of $12'' \times 5''$, and if one assumes the distance of 2,200 Mpc corresponding to $z=0.367$, it becomes 240×100 kpc. On the northern side of the envelope, the emission-line spectrum [O III] $\lambda\lambda 5007, 4959$, [O II] $\lambda 3727$ and [Ne III] $\lambda 3869$ is observed, exactly like the outermost region of 3C 120 seen earlier. In the quasar 3C 273, which has a jet (Figure 1.5), background light thought to be a galaxy has also been detected by S. Wyckoff et al. (1980). Its radius is $\sim 15''$ (75 kpc) and its absolute magnitude $M_R \approx -24$. In the region $5''$ north of the center, the emission-line spectrum [O II] $\lambda 3727$ and [Ne III] $\lambda 3869$ is likewise observed. The jet emits only a continuous spectrum, and it can be seen in X-rays as well.

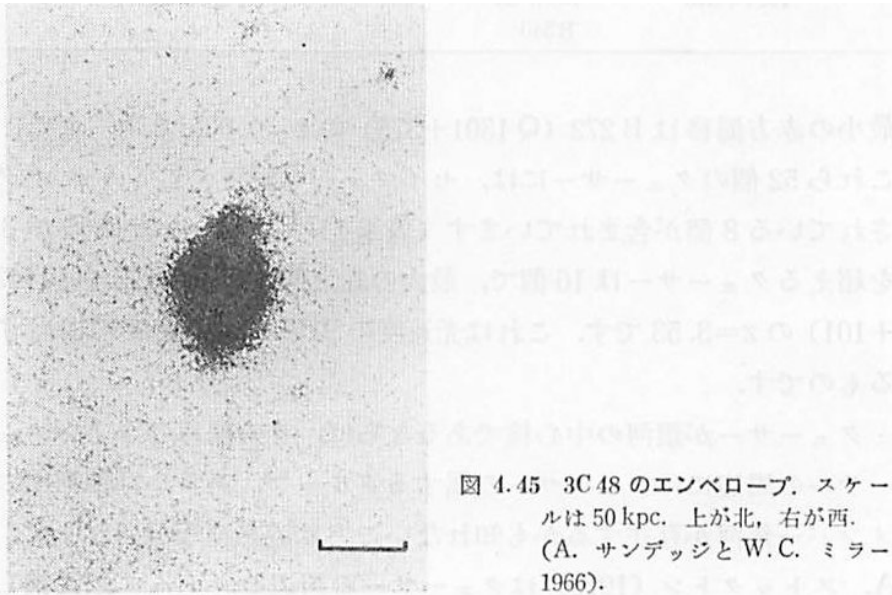


Figure 4.45 The envelope of 3C 48. The scale is 50 kpc. North is up and west is to the right. (A. Sandage and W. C. Miller 1966).

At present, ground-based observations cannot tell us what kind of galaxy morphology quasars have; but it is highly suggestive that the majority of quasars found by optical search methods are radio-quiet quasars, and that radio-loud quasars amount to no more than 5–10% of the total. This ratio agrees well with the fraction of radio galaxies found among Seyfert galaxies.

Chapter V. Morphology III. Characteristics of Seyfert Galaxies

In Chapter III we studied Seyfert galaxies, and in Chapter IV peculiar galaxies, from the morphological side. In doing so, I think their differences from normal galaxies, and the properties common to Seyfert galaxies, have become reasonably clear. Here we shall attempt to generalize those results, but we need to keep the following points firmly in mind. One is that the Seyfert galaxies we know of are not a statistically complete sample and may have a biased character. Differences in the quality of the data are also a major obstacle. In the nearest Seyfert galaxies $1''$ corresponds to 50–100 pc, but in 3C 120 it amounts to as much as 1 kpc, so these cannot be treated on an equal footing. As long as we rely on ground-based observations, we must regard it as regrettably close to impossible to discuss morphologically the structure of galaxies farther away than 200–300 Mpc.

(1) Do elliptical Seyfert galaxies exist?

The Seyfert galaxies we have examined are all spiral galaxies, except for the powerful radio sources NGC 1275, 3C 120 and 3C 390.3. NGC 1275 is clearly elliptical, but it is the central object of the Perseus cluster, and its radio-galaxy character — of the kind studied in Chapter IV — is stronger than that of a radio Seyfert galaxy such as 3C 120; there is therefore also the position that it is not a Seyfert galaxy at all. At present, when the essential nature of Seyfert galaxies has not been elucidated, we cannot exclude NGC 1275 from the Seyfert galaxies, but it is certain at least that it is not a typical radio Seyfert galaxy. Even if 3C 120 is not a spiral galaxy, it is an N or compact galaxy possessing a disk region, so it is not an

elliptical galaxy. The N galaxy 3C 390.3 is too distant for its morphology to be discussed.

Table 5.1 Seyfert galaxies that may be ellipticals

Galaxy	Redshift (km/s)	Comment
Mkn 352	4500	well-resolved amorphous envelope
NGC 1275	5200	peculiar “elliptical” radio galaxy
Mkn 50	6910	well-resolved amorphous envelope
Mkn 335	7500	not resolvable on the Palomar Sky Survey Atlas (no large-scale photograph)
Mkn 290	9240	well-resolved amorphous envelope
Mkn 509	10650	faint amorphous envelope
Mkn 464	15300	well-resolved amorphous envelope
Mkn 507	16750	small amorphous envelope (better photograph needed)
3 C 390.3	17100	barely resolved; radio galaxy
3 C 382	17580	amorphous envelope; radio galaxy
Ton 524 a	17940	barely resolved
Mkn 304	19950	barely resolved
Mkn 69	22870	barely resolved
Mkn 478	23700	compact envelope on good photographs
3 C 227	25650	barely resolved; radio galaxy
Mkn 64	55200	compact jet, or companion galaxy
3 C 287.1	64700	stellar; radio galaxy or quasar

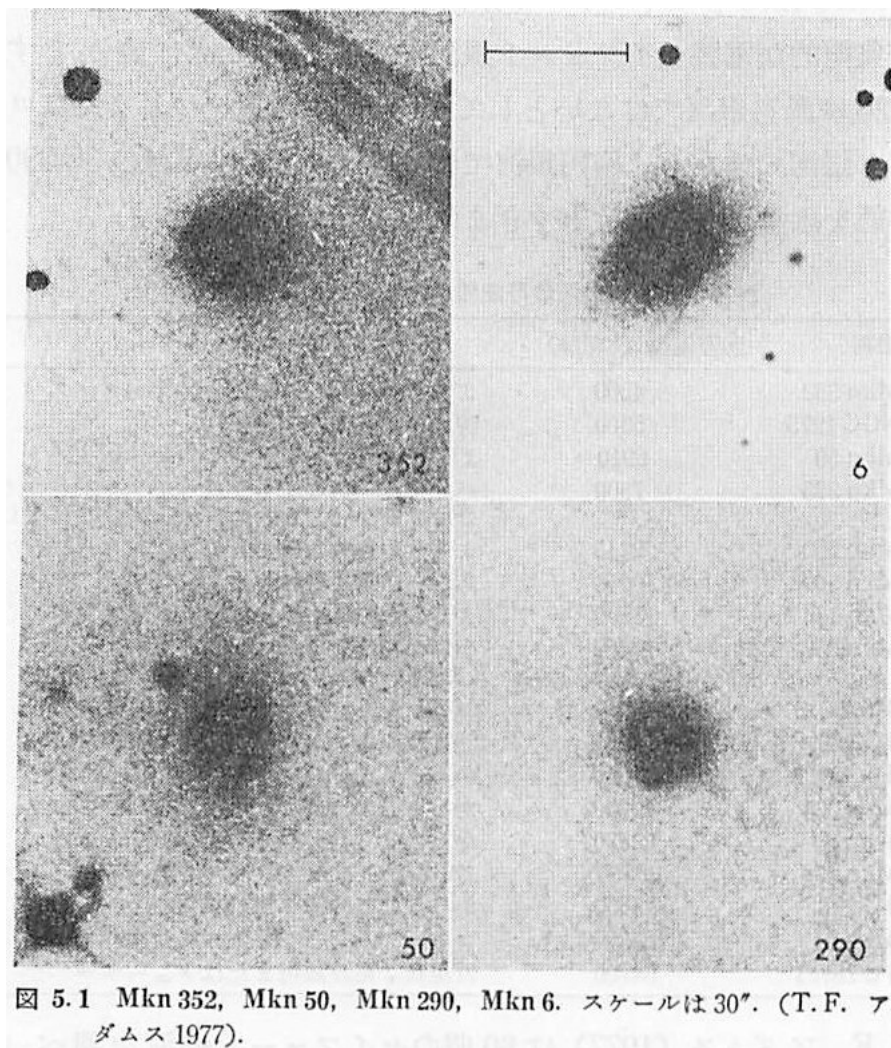


図 5.1 Mkn 352, Mkn 50, Mkn 290, Mkn 6. スケールは 30". (T. F. ア
ダムス 1977).

Figure 5.1 Mkn 352, Mkn 50, Mkn 290, Mkn 6. The scale is 30". (T. F. Adams 1977).
[Labels in the figure: 352, 6, 50, 290]

T. F. Adams (1977) examined 80 Seyfert galaxies and listed 17 as candidate ellipticals (Table 5.1). If, however, we restrict the distance to within 300 Mpc (15,000 km/s), the possibility of ellipticals becomes at most 10%. Figure 5.1 shows

Mkn 352, Mkn 50 and Mkn 290, all with $v < 10,000$ km/s, together with the SO-type Mkn 6. In Mkn 352 an outermost region similar to that of Mkn 6 can be seen, and if NGC 1275 is regarded as a peculiar radio galaxy the possibility of ellipticals decreases further, to $\sim 5\%$. For normal galaxies, on the other hand, more than 15% are ellipticals, so elliptical galaxies are clearly lacking among the Seyfert galaxies. In particular, if we exclude the radio Seyfert galaxies and restrict ourselves to the radio-quiet group (radio-quiet Seyfert galaxy), it is not impossible to suppose that elliptical galaxies do not exist at all.

(2) Bar structure and ring structure

Spiral galaxies are classified into normal spirals (type SA) and barred spirals (type SB), and the intermediate type is designated SAB. As we saw in Chapter III, Seyfert galaxies are found in all of the types SA, SAB and SB. Figure 5.2 shows Mkn 10, of type SA(r)b. This galaxy is enormous: the outer spiral arms extend 30×90 kpc and the bright inner ring 8×22 kpc. Figure 5.3 shows NGC 6814, of type SAB(rs)bc. The arms divide into four, each arm has a relatively uniform surface brightness and becomes abruptly fainter on the outside, but there is a further outermost region. Mkn 79, of type SB(rs)c, is shown in Figure 5.4. Its bar region is 20 kpc long, and the whole system is a huge ~ 50 kpc.

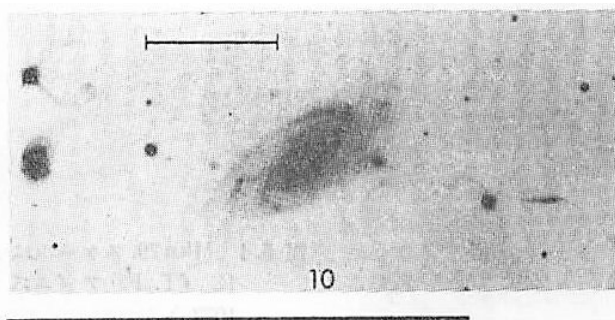


図 5.2 Mkn 10. スケールは $1'$ (T. F. アダムス)

Figure 5.2 Mkn 10. The scale is 1' (T. F. Adams) [Label in the figure: 10]



図 5.3 NGC 6814. (ハッブル・アトラス, A. サンデッジ 1961).

Figure 5.3 NGC 6814. (The Hubble Atlas, A. Sandage 1961).

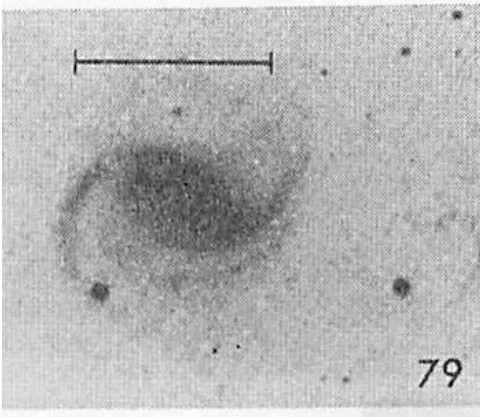


図 5.4 Mkn 79. スケールは 1'. (T. F. アダムス 1977.)

Figure 5.4 Mkn 79. The scale is 1'. (T. F. Adams 1977.) [Label in the figure: 79]

Spiral galaxies are also classified as types 0, a, b, c and d according to the form of their arms, and Seyfert galaxies are found in every type except d. NGC 3516 and

Mkn 6 are type 0, and NGC 5548 (Figure 5.5) is type 0/a. Of types a, ab, b, bc and c we have already seen a number of examples.

Now let us compare the morphological classification of Seyfert galaxies with that of normal galaxies. Table 5.2 gives the results obtained by S. M. Simkin, H. J. Su and M. P. Schwarz (1980), who examined 30 Seyfert galaxies in the southern and northern skies within 100 Mpc. Comparing with the galaxy catalogue RCBG II (Second Reference Catalogue of Bright Galaxies) of G. de Vaucouleurs, A. de Vaucouleurs and H. G. Corwin (1976) , the following morphological peculiarities are found.

Table 5.2 Morphological classification of Seyfert galaxies compared with normal galaxies

Morphological class	Seyfert galaxies (%)	Normal galaxies* (%)
[A / A B / B] (s)	23	29
[A B / B]	70	59
[A / A B / B] [(rs) / (r)]	57	35
[(R) / (R')] [A / A B / B]	43	8.2
[(R) / (R')] [A / A B / B] [(rs) / (r)]	30	3.2

* Galaxies with $v_R < 5,000$ km/s in RCBG II, excluding ellipticals

- (i) SAB and SB types with bar structure are relatively more common than among normal galaxies.
- (ii) Types (rs) and (r) with an internal ring-like structure are also somewhat more common.
- (iii) Objects with an outer ring (R) or pseudo-ring (R') are common.

(iv) Objects with ring structures both inside and outside, showing multiple structure, are overwhelmingly common.

Feature (i) was pointed out by J. L. Sersic (1973), but T. Heckman (1978) is skeptical. Neither analysis has a sufficient sample size, so here we merely note it as one possibility.

That ring structures, or multiple structures, are common is obvious. Systems with R/R' are found at five times the frequency of normal galaxies, and Seyfert galaxies with ring structures both inside and outside are even higher, at ten times. The fact that such structure is seen in every one of the spiral Seyfert galaxies studied in Chapter III — NGC 1068, NGC 4151, NGC 3516, NGC 3227 and NGC 7469 — also makes features (iii) and (iv) convincing.

Table 5.3 Seyfert galaxies with an annular main body

Galaxy	Seyfert type	Comment
Mkn 9	1	probably part of a spiral arm
Mkn 34	2	probably part of a spiral arm
Mkn 198	2	
Mkn 268	2	unresolvable spiral arm?
Mkn 279	1	unresolvable spiral arm?
Mkn 372	2	
Mkn 541	1	incomplete thin ring, or spiral arm.
Mkn 590		insufficiently resolved spiral arm?
NGC 5548	1	
II Zw 136	1	
Tololo 0109-381	1	

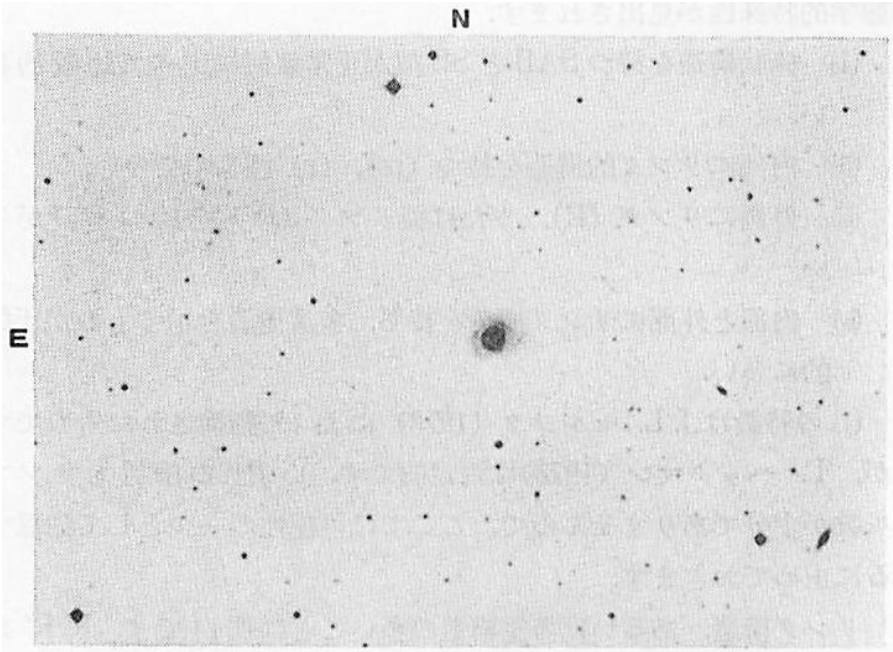


Figure 5.5 NGC 5548. (Palomar Sky Survey Atlas) [Labels in the figure: N (top), E (left)]

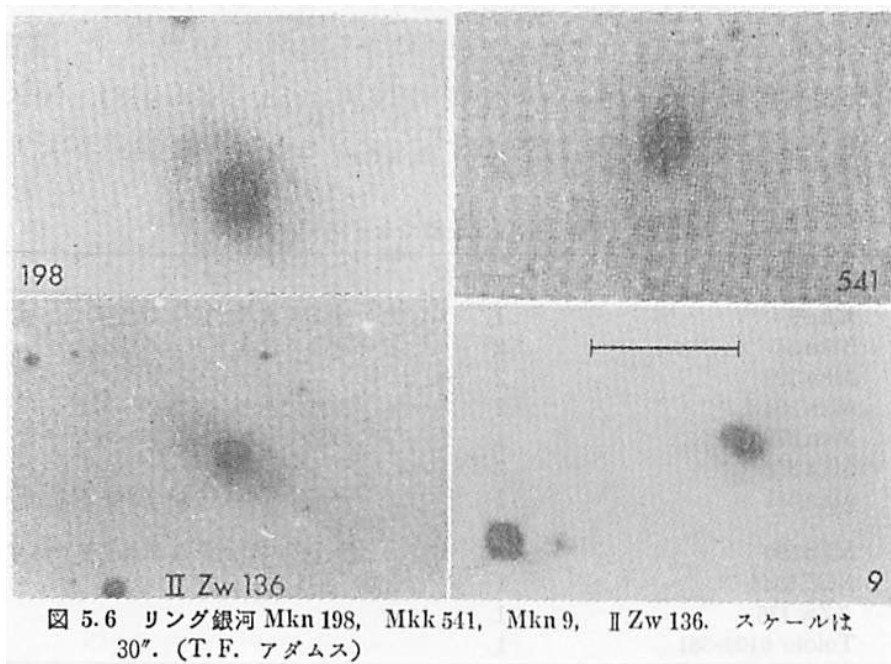


Figure 5.6 Ring galaxies Mkn 198, Mkn 541, Mkn 9, II Zw 136. The scale is 30". (T. F. Adams) [Labels in the figure: 198, 541, II Zw 136, 9]

T. F. Adams (1977) has pointed out that galaxies possessing an annular main body, different from the rings and halos that accompany barred galaxies, are frequently seen among Seyfert galaxies (Table 5.3). NGC 5548 is the typical case (Figure 5.5). It is classified as Sa, (R') SA(s)O/a, g? S 1 pN, etc., and shows a bright core 10 kpc in diameter together with a ring structure. The ring is 25–30 kpc in diameter, but outside it there is an outermost region more than 60 kpc across. As examples of ring galaxies, Figure 5.6 shows Mkn 198, Mkn 541, Mkn 9 and II Zw 136.

(3) Interacting galaxies and disturbed galaxies

Among Seyfert galaxies one relatively often sees systems in which two or more galaxies are interacting with one another, or galaxies possessing jets, filaments or tails, or greatly disturbed galaxies (disturbed galaxy) (Table 5.4).

Table 5.4 Disturbed galaxies and interacting galaxies

Disturbed galaxy (type)		Interacting galaxy (type)	
Mkn 110*	(1)	Mkn 40	(1)
Mkn 231	(1)	Mkn 176	(2)
Mkn 273	(2)	Mkn 374*	(1)
Mkn 298	(2)	III Zw 55	(2)
Mkn 463*	(1)	NGC 3227	(1/2)
NGC 985	(1)	NGC 7603	(1)
NGC 1275	(2?)		

* Probably a double nucleus.

Among the classical Seyfert galaxies, NGC 3227 and NGC 7469 are interacting galaxies, and NGC 7603 is also an interacting galaxy in appearance. VV 144 and VV 150 are shown in Figure 2.5, and III Zw 55 in Figure 2.4. Figure 5.7 shows Mkn 374, in which interaction is visible; it has two nuclei. Mkn 279, Mkn 348 and Mkn 506 are double galaxies in appearance, but no bridges, tails, filaments or the like indicating interaction can be seen (Figure 5.8).



図 5.7 相互作用銀河 Mkn 374. スケールは30". (T.F. アダムス 1977).

Figure 5.7 The interacting galaxy Mkn 374. The scale is 30". (T. F. Adams 1977).
[Label in the figure: 374]

(M 5. 0).

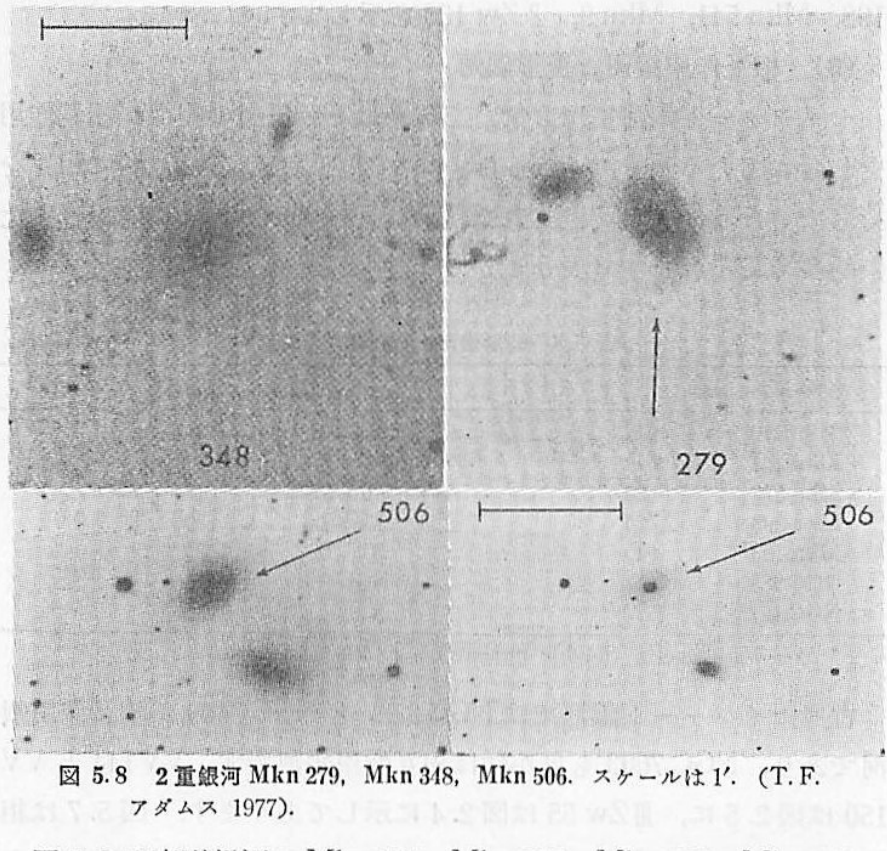


Figure 5.8 The double galaxies Mkn 279, Mkn 348, Mkn 506. The scale is 1'. (T. F. Adams 1977). [Labels in the figure: 348, 279, 506, 506]

Figure 5.9 shows the disturbed galaxies Mkn 110, Mkn 273, Mkn 231 and Mkn 463. Mkn 110 has a jet about 50 kpc long extending to the northwest from the nucleus, and the nucleus appears double. In Mkn 273 too a jet of about 50 kpc can be seen. Mkn 463 has two nuclei, and one can see an inner part resembling a portion of a ring together with disturbed arms. On the outside of Mkn 231 there is a

single arm. Figure 5.10 shows the disturbed ring galaxy NGC 985 (VV 285). It is not a Seyfert galaxy, but several other galaxies of this ring-like kind are known.

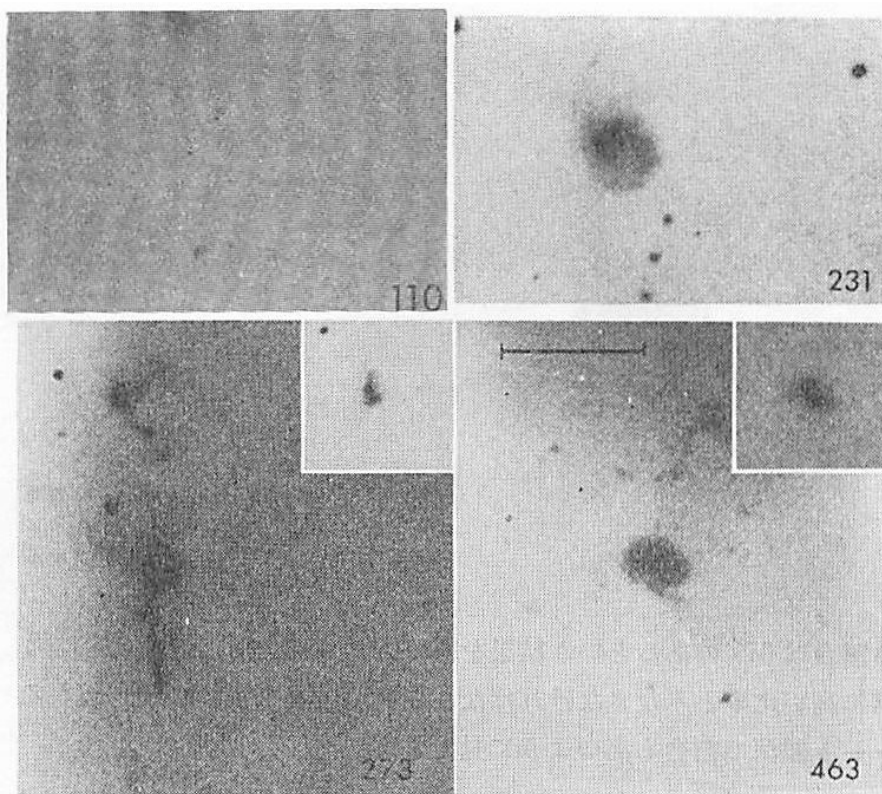


図 5.9 変形銀河 Mkn 110, Mkn 273, Mkn 231, Mkn 463. スケールは Mkn 273 のみ $30''$, 他は $1'$. (T.M. アダムス 1977).

Figure 5.9 The disturbed galaxies Mkn 110, Mkn 273, Mkn 231, Mkn 463. The scale is 30" for Mkn 273 only, and 1' for the others. (T. F. Adams 1977). [Labels in the figure: 110, 231, 273, 463]

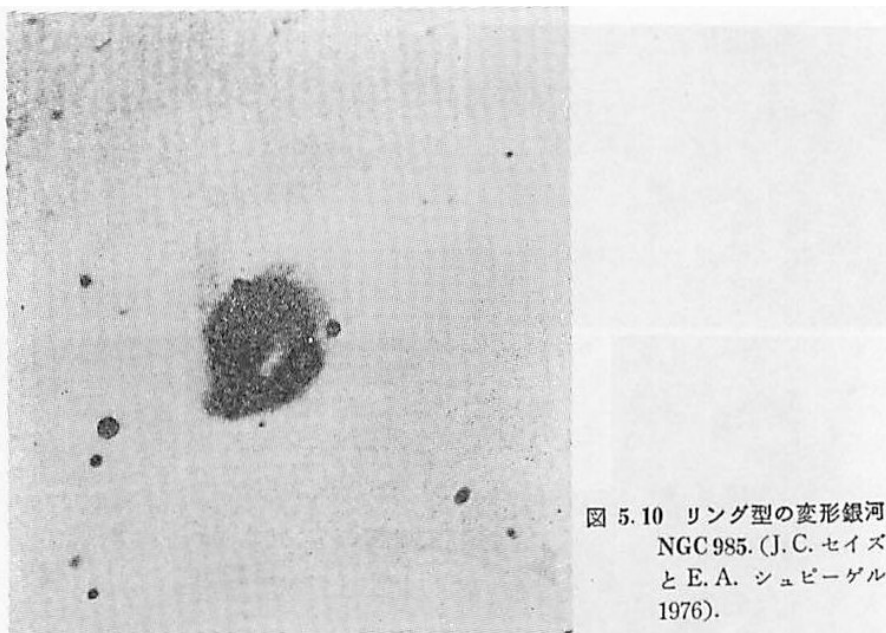


Figure 5.10 The ring-type disturbed galaxy NGC 985. (J. C. Theys and E. A. Spiegel 1976).

The interacting/disturbed galaxies of Table 5.4 make up 16% of the Seyfert galaxies examined by T. F. Adams (1977). H. Arp and B. F. Madore (1975) obtained the result that peculiar galaxies of all kinds account for 6% of southern galaxies, so the 16% above must be regarded as an abnormally high proportion. In Table 5.4 the proportion of type 2 Seyfert galaxies also appears to be high.

(4) N galaxies

N galaxies are frequently seen among the Seyfert galaxies. The classical Seyfert galaxies NGC 4051 (f? S 3 N), NGC 4151 (gSk 4 pN), NGC 5548 (g?S 1 pN) and NGC 7469 (g? S 3:pN) are all N galaxies. Figures 5.11 and 5.12 show NGC 4051 photographed with the 120 cm Schmidt telescope of Palomar Observatory and with the 188 cm telescope at Okayama. It is also classified as Sb/Sbc and SAB(rs)bc. The bright central spiral region measures 10×12 kpc. The northeastern arm splits into two or three sub-arms and is far broader than the southwestern arm, and many knots of ionized hydrogen regions are scattered along this northeastern arm. The faint outermost region measures 15×20 kpc. The shape of the arms is certainly Sb/Sbc-like, but in the central region only a quasi-stellar nucleus can be recognized. As a stellar system NGC 4051 is extremely poor, and it is precisely an N galaxy.

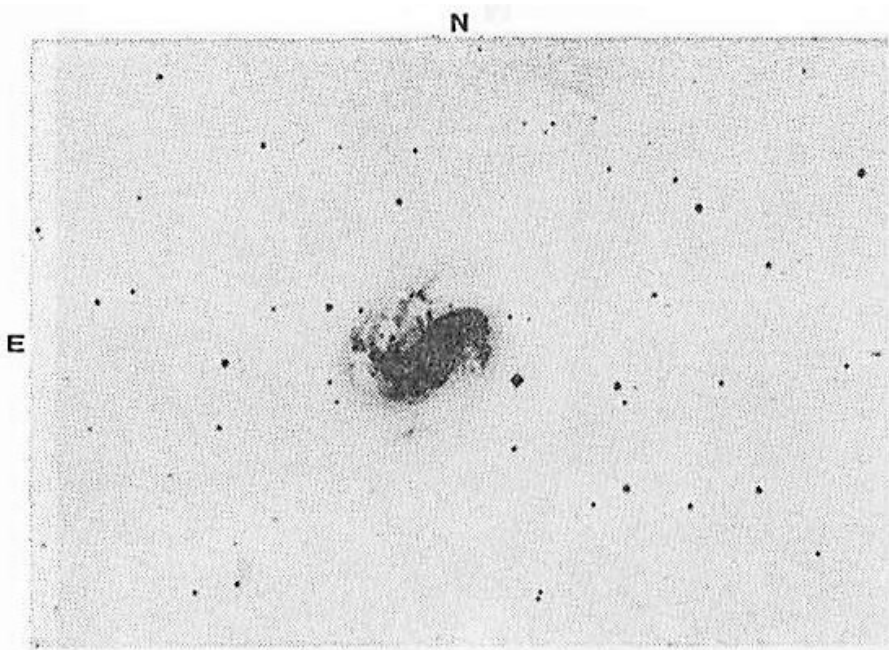


Figure 5.11 NGC 4051. (Palomar Sky Survey Atlas) [Labels in the figure: N (top), E (left)]

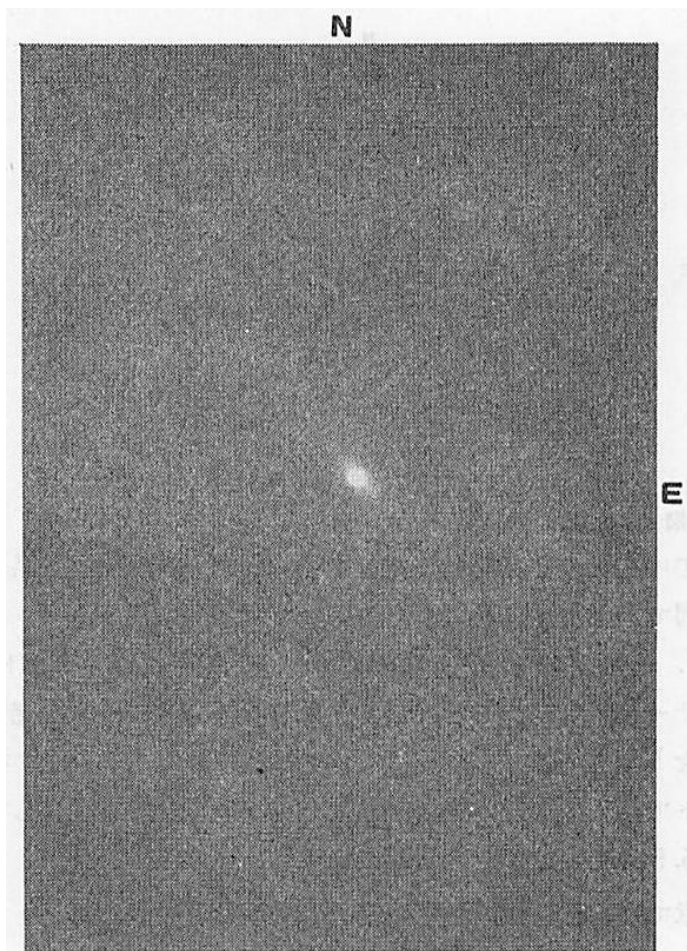


図 5.12 NGC 4051. (東京天文台岡山天体物理観測の 188 cm 望遠鏡で撮影)

Figure 5.12 NGC 4051. (Photographed with the 188 cm telescope of the Okayama Astrophysical Observatory, Tokyo Astronomical Observatory) [Labels in the figure: N (top), E (right)]

W. W. Morgan (1972) introduced, for Seyfert galaxies, compact galaxies and quasars, a morphological classification in which — besides the standard N galaxy — N galaxies with well-developed spiral arms are type NS, objects that are of N type though not markedly so are type N^- , and compact galaxies of high surface brightness are type C. Table 5.5 lists the objects that serve as its standards.

Let us also note the connection between N galaxies and radio sources described in Chapter II (Table 2.3). Broad type 1 emission-line profiles are overwhelmingly common among N-type radio galaxies.

Table 5.5 Morgan’s classification

Class	Seyfert galaxies	Quasars
Type N	NGC 5548 III Zw 2 3 C 120 Mkn 9 Zw 0039.5+4003 NGC 7469	3 C 48 III Zw 2 B 264
Type NS	NGC 7469 Mkn 10	
Type N^-	NGC 4051	
Type C	NGC 3516	Ton 256 B 264

(5) Ionized gas clouds and filament systems

A good many of the Seyfert galaxies studied in Chapter III, and the peculiar galaxies of Chapter IV, were accompanied by ionized gas clouds, filament systems or jets not seen in normal galaxies. NGC 1068 has an [O III] gas cloud, NGC 4151

an [O III] gas disk, and a huge [O III] nebulosity has been discovered in 3C 120 as well. H_α filament systems are found in NGC 1275, M 82 and M 87; dark lanes thought to be rotating gas disks are seen in NGC 5128 and NGC 1316; and jets exist in M 87 and NGC 5128. In NGC 1275, NGC 5128 and NGC 1316, galaxies in collision, or traces of collision, have also been observed. If individual galaxies are observed in detail, such examples will no doubt increase further.

Let us note that some are observed in [O III] $\lambda\lambda 4959, 5007$ and others show up clearly in H_α . Since [O III] $\lambda\lambda 4959, 5007$ are emission lines radiated by doubly ionized oxygen, the former and the latter may also be described as high-excitation and low-excitation objects respectively. Interestingly, there is a tendency for high-excitation ionized gas clouds/nebulosities to be common in Seyfert galaxies, and for low-excitation H_α filaments to be common in NGC 1275 and in radio galaxies (Table 5.6.).

Table 5.6 Nebulosities of active galaxies

Galaxy	Nebulosity, etc.
NGC 1068	[O III] gas cloud
NGC 4151	[O III] gas disk
NGC 3516	H_α filaments [O III] ionized gas
3 C 120	[O III] filaments
3 C 48	nebulosity
NGC 1275	H_α filaments
M 82	H_α filaments
M 87	jet H_α filaments
NGC 5128	dark lane jet
NGC 1316	dark lane loops/ripples

As to their origin, an ejection hypothesis and an infall hypothesis are under discussion. Clearly the H_α filaments of NGC 1275, M 82 and M 87 appear to be due to infalling gas, while the jets of M 87 and NGC 5128 must have been ejected from the nucleus. J. A. Baldwin and colleagues (1980) consider that the nebulosity of 3C 120 is due to ejection from the nucleus, since this galaxy belongs to no cluster or group. There is also the possibility that interstellar gas within 3C 120 is being excited by the strong radiation from the nucleus, but they judged that the gas motions are too disturbed for this. M.-H. Ulrich and D. Péquignot (1980) likewise regard the spectroscopic properties of the nebulosity of NGC 3516 as indicating ejection, so for high-excitation nebulosities the ejection hypothesis seems to have the upper hand.

(6) Clusters and groups of galaxies

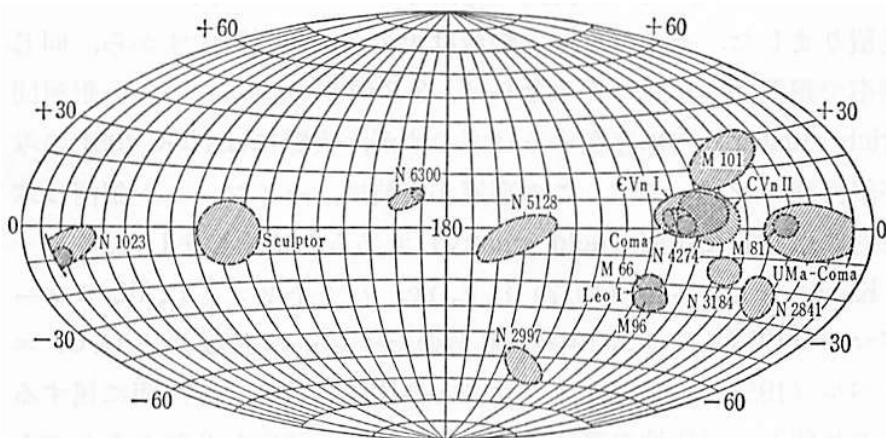
Seyfert galaxies show a tendency not to belong to clusters of galaxies. Among the classical Seyfert galaxies only NGC 1275 is a cluster member, and even this is widely held not to be a typical Seyfert galaxy.

Table 5.7 lists the Seyfert galaxies in the Shapley–Ames catalogue. Here cluster membership is indicated by + and –. NGC 1068 forms the NGC 1068 group together with at least six galaxies (Figure 5.13b). Near this group there is the NGC 1052 group, centered on the peculiar elliptical galaxy NGC 1052, and together these are called the Cetus I cloud. Its size is $12^\circ \times 9^\circ$ (4×3 Mpc). S. van den Bergh (1975) regards it as a cluster with few member galaxies (poor cluster) $\pm$. NGC 4051 is a member of the Canes Venatici II cloud (Figure 5.13a). There is also the view that, together with the Canes Venatici I cloud, which contains M 94 (NGC 4736) and NGC 4258, and the M 101 group, which contains M 101 (NGC 5457) and M 51 (NGC 5194), it forms the Canes Venatici cluster. Van den Bergh estimated the probability that cD, E+SO and S+Irr galaxies are found in clusters as

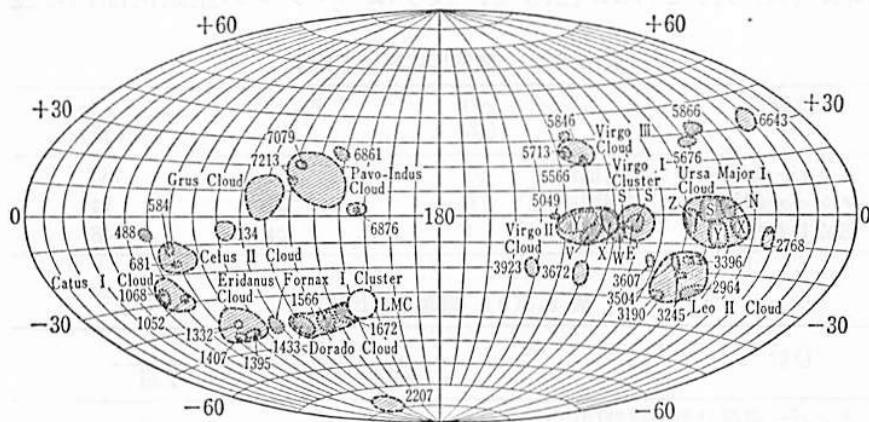
shown in Table 5.8. Since most Seyfert galaxies are spirals, if they were found in clusters with the same probability, 3.8 of them ought to lie within rich clusters; in fact only NGC 4051 is a cluster member. From this fact he concluded that Seyfert galaxies are essentially isolated galaxies (field galaxy).

Table 5.7 Seyfert galaxies in the Shapley–Ames catalogue

NGC	Cluster member
1068	±
1566	...
3227	–
3516	–
3783	–
4051	+
4151	–
5548	–
6814	–
7469	–



(a)



(b)

図 5.13 銀河のグループ, (G. ド・ヴォクルール 1975)

Figure 5.13 Groups of galaxies. (G. de Vaucouleurs 1975) The figure consists of two all-sky distribution maps (elliptical projection in galactic coordinates). The grid is marked +60, +30, 0, -30, -60 and 180. [Object names in (a): N 1023, Sculptor, N 6300, N 5128, N 2997, CVn I, CVn II, M 101, Coma, M 66, Leo I, M 96, N 4274, M 81, N 3184, N 2841, UMa-Coma] [Object names in (b): Cetus I Cloud, 488, 584, 681, 1068, 1052, 1332, 1407, 1395, 134, Cetus II Cloud, Grus Cloud, 7079, 7213, 6861, Pavo-Indus Cloud, 6876, Eridanus Cloud, Fornax I Cluster, 1566, 1433, 1672, Dorado Cloud, LMC, 2207, 5846, 5713, 5566, 5049, Virgo III Cloud, 5866, 5676, 6643, Virgo I Cluster, Virgo II Cloud, Ursa Major I Cloud, 3923, 3672, 3607, 3504, 3190, 3245, Leo II Cloud, 2964, 3396, 2768. In addition, the single letters V, W, X, Y, Z, E, N, S mark subdivisions within the clouds]

K.-H. Schmidt (1977) attempted a comparison of the 60 Seyfert galaxies in the list of E. Ye. Khachikian and D. W. Weedman (1974) with the cluster catalogue of G. O. Abell (1958), and obtained two objects belonging to clusters and three more with a high probability. One of the two certain objects is the well-known NGC 1275, and the other is the disturbed galaxy Mkn 298 (IC 1182) in the Hercules cluster. Compared with Table 5.8, Seyfert galaxies within clusters do indeed appear to be few. Of the five found by Schmidt, four are type 2 Seyfert galaxies, so if we restrict ourselves to type 1 Seyfert galaxies their isolation becomes still more certain.

Table 5.8(a) Probability of belonging to a cluster

Location	cD (%)	E+SO (%)	S+Ir (%)
In clusters with many member galaxies	93	56	38
In clusters with few member galaxies	6	20	14
Isolated galaxies	1	24	48

Table 5.8(b) Comparison with observation

Location	Number of galaxies (observed)	Number of galaxies (expected)
In clusters with many member galaxies	1	3.8
In clusters with few member galaxies	1	1.4
Isolated galaxies	7	3.8

Correlations with cluster membership are also seen in the properties of radio galaxies. According to the analysis of M. S. Longair and M. Seldner (1979), radio galaxies with complex radio structure and with no emission-line spectrum, or only a weak one, often belong to clusters, whereas radio galaxies that are double radio sources and moreover show strong emission-line spectra have a strong tendency to be isolated systems.

As H. Arp (1970) emphasized, quasars too show a weak tendency to belong to clusters and are thought to be essentially isolated systems.* We can therefore imagine that, morphologically, quasars are not the D/cD galaxies often seen within clusters but are probably isolated, N-galaxy-like objects.

Avoiding speculation, we shall confine ourselves here to pointing out the fact that a correlation is seen between Seyfert-type activity accompanied by strong emission-line spectra and the isolation of the galaxy. This also tells us that even a galaxy is a member of galactic society, and that its character is conditioned by its environment.

* Recently a number of quasars belonging to clusters have been discovered, such as 3C 206 ($z=0.200$, $m_V = 15.7$) (S. Wyckoff and colleagues 1980).

Chapter VI. Emission-Line Spectra

1. Emission-line spectra of type 1 and type 2

(1) NGC 1068 and the type 2 Seyfert galaxies

NGC 1068 is apparently the brightest and the most representative type 2 Seyfert galaxy. For this reason NGC 1068 has been observed repeatedly by many researchers. In the early spectroscopic observations the method adopted was to record the spectrum on hypersensitized photographic plates, but at present, with the adoption of techniques that convert the light directly into an electrical signal by means of image intensifiers, photomultiplier tubes or semiconductor detectors, the accuracy of the observational material has improved dramatically.

Figure 6.1 shows the result obtained by G. A. Shields and J. B. Oke (1975), who attached a multichannel spectrometer to the 5 m telescope and observed the nuclear region of NGC 1068, 7" (700 pc) in diameter. About 500 points, measured with a bandwidth of 10 Å in the blue region ($\lambda\lambda 3,300 - 5,790\text{Å}$) and 20 Å in the red region ($\lambda\lambda 5,790 - 11,090\text{Å}$) are plotted with the logarithm of the radiation flux as the vertical axis and the logarithm of the frequency as the horizontal axis. On the upper panel the horizontal axis is also labelled with wavelength in angstroms.

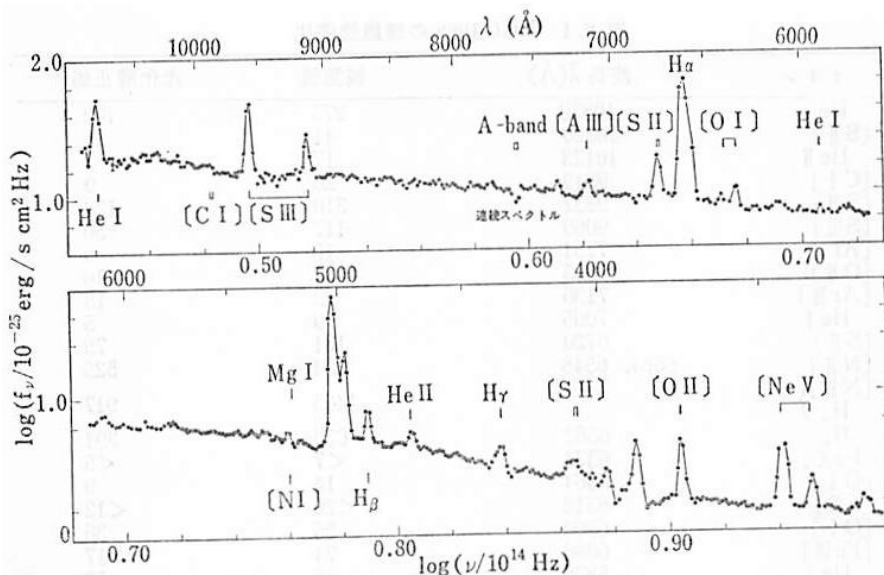


Figure 6.1 The spectrum of NGC 1068. (G. A. Shields and J. B. Oke 1975). Vertical axis: $\log(f_\nu/10^{-25}\text{erg/s cm}^2\text{ Hz})$. Horizontal axis: $\log(\nu/10^{14}\text{Hz})$. Upper axis of the top panel: λ (Å) (10000, 9000, 8000, 7000, 6000). Lines marked in the top panel (from left): He I, [C I], [S III], continuous spectrum, A-band, [A III], [S II], [O I], He I, H_α . Lines marked in the lower panel (from left): [N I], Mg I, H_β , He II, H_γ , [S II], [O II], [Ne V]. Horizontal scale of the lower panel: 0.70, 0.80, 0.90 (with 6000, 5000, 4000 Å marked along the top).

Many emission lines are seen in the spectrum of NGC 1068. The Balmer series of hydrogen, H_α , H_β and H_γ , appear at wavelengths 6563, 4861 and 4340 Å respectively. These Balmer lines are emission lines released when a hydrogen atom, having been ionized by the absorption of ultraviolet light of wavelength shorter than 912 Å or by an inelastic collision with a charged particle, recombines with a free electron; they are the representative examples of permitted lines. In the latter case, collisional excitation to the upper energy levels also becomes important. In the ultraviolet the Lyman series, and in the infrared the Paschen series and others, are emitted as permitted lines of hydrogen. He I $\lambda 5876$ of neutral helium and He II $\lambda 4686$ of singly ionized helium are likewise permitted lines emitted upon

recombination. The brackets $[\]$ denote a forbidden line. Such an emission line is emitted in association with a transition between metastable energy levels caused by collisions with free electrons, and the electron temperature and electron density of the gas are determined from the analysis of these collisionally excited lines. In Figure 6.1 a smooth curve descending to the right has been drawn tracing the observed points. This is the continuous spectrum emitted by the stars and gas within the $7''$ -diameter region together with the nucleus itself.

The relative intensities of the emission lines of NGC 1068 are given in Table 6.1. Here the intensity of H_{β} is set to 100. The total luminosity of the observed emission lines reaches 1.66×10^{43} erg/s, about 80% of which is contributed by forbidden lines (Table 6.2). The reddening correction is examined in Section 4.

Table 6.1 Emission-line intensity ratios of NGC 1068

Ion	Wavelength $\lambda(\text{\AA})$	Observed	Reddening-corrected※
He	10830	275	102
[S II]	10320	41	16
He II	10123	17	7
[C I]	9849	20	9
[S III]	9532	310	128
[S III]	9069	117	50
[Ar III]	7751	10	5
[O II]	7325	27	16
[Ar III]	7136	32	18
He I	7065	9	5
[S II]	6720	131	79
[N II]	6584, 6548	834	525
{ [N II], H_{α} }		1455	917
H_{α}	6562	620	391
[Fe X]	6374	<7	<5
[O I]	6364	14	9
[S III]	6312	<20	<12
[O I]	6300	55	36
[Fe VII]	6086	24	17
He I	5876	16	12
[N II]	5755	12	10
[Fe VII]	5721	12	10
[Cl III]	5538	10	9
[Ca V]	5309	12	12
[N I]	5199	14	14
[Fe VII]	5158	6	6
[O III]	5007, 4959	1500	1500
H_{β}^*	4861	100	100
[Ar IV]	4740	14	14

Ion	Wavelength $\lambda(\text{\AA})$	Observed	Reddening-corrected※
He II	4686	41	44
N III	4640	7	9
{ [O III], H_γ }	4363, 4340	44	52
[O III]	4363	10	13
{ H_δ , [S II] }	4101, 4072	48	64
[S II]	4072	24	31
He I	4026	11	14
{ [Ne III], H_ϵ }	3968, 3970	29	36
{ [Ne III], H_ζ }	3869, 3889	96	140
He I	3889	<13	<20
{ [Fe VII], O III }	3760, 3759	8	12
[O II]	3727	89	138
O III	3444	<6	<12
[Ne V]	3425	115	198
[Ne V]	3346	31	57
He II	3203	20	36

* $L(H_\beta) = 3 \times 10^{41} \text{erg/s}$ ($H_0 = 50 \text{km/s Mpc}$)

※ $E_B - V = 0.4$

Table 6.2 Emission-line luminosities of NGC 1068

Emission line	Observed (erg/s)	Reddening-corrected (erg/s)
H_β	3×10^{41}	11×10^{41}
All Balmer lines	23×10^{41}	64×10^{41}
He I + He II	12×10^{41}	24×10^{41}
[O III] $\lambda\lambda 4959, 5007$	47×10^{41}	160×10^{41}
All forbidden lines	130×10^{41}	440×10^{41}
All emission lines	170×10^{41}	530×10^{41}

As part of the spectroscopic observing programme of Seyfert galaxies and radio galaxies begun in 1973 by the Lick Observatory group, A. T. Koski (1978) carried out a systematic study of 28 type 2 Seyfert galaxies and NL radio galaxies. The spectra of the type 2 Seyfert galaxies resemble that of NGC 1068, and no difference from the NL radio galaxies is seen either. The mean relative intensities of the emission lines agree well with those of NGC 1068 (Table 6.3).

The emission-line spectrum of a type 2 Seyfert galaxy is basically similar to that of the highly excited planetary nebula NGC 7027, but it differs in several respects. One is that the forbidden lines of neutral atoms and singly ionized ions — [O I] $\lambda 6300$, [O II] $\lambda 3727$, [N I] $\lambda 5199$, [N II] $\lambda 6583$, [S II] $\lambda 6724$ — are very strong in type 2 Seyfert galaxies. Compared with NGC 7027 they are about 10 times stronger, and in this respect a similarity with the Crab Nebula is seen. Another is that the forbidden lines of highly ionized ions such as [Ne V] $\lambda\lambda 3346, 3426$ and [Fe VII] $\lambda 6086$, which are relatively weak in planetary nebulae, are strong. [Fe X] $\lambda 6374$ and [Fe XI] $\lambda 7892$, which are never observed in planetary nebulae, are also present in Seyfert galaxies. To ionize iron 9 to 10 times requires an ionization potential energy exceeding 200 eV. Since an energy of 1 eV corresponds to a temperature of $T=11,600^\circ\text{K}$, we must suppose that, in addition to ordinary ionized gas, there coexists low-temperature gas that is neutral or singly ionized together with high-temperature gas exceeding a million degrees, like the solar corona. The gas within the nucleus is in a wide range of ionization states, and is presumably far more inhomogeneous than in a planetary nebula.

Table 6.3 Mean intensity ratios of type 2 Seyfert galaxies

Ion	Wavelength $\lambda(\text{\AA})$	Type 2 Seyfert galaxies	Crab Nebula	NGC 7027
[Ne V]	3426	1	0.5	1.3
[O II]	3727	3	12.5	0.4
[Ne III]	3869	1.5	1.9	1
[S II]	4071	0.2	0.6	0.1
[O III]	4363	0.2	0.2	0.3
He II	4686	0.3	0.7	0.5
H_{β}	4861	1.0	1.0	1.0
[O III]	5007	11.	12.	11.
[N I]	5199	0.1	—	0.01
He I	5876	0.1	0.8	0.1
[Fe VII]	6087	0.1	—	0.01
[O I]	6300	0.5	1.2	0.1
[N II]	6583	2.3	6.2	1
[S II]	6724	1.5	14.1	0.05
[Ar III]	7136	0.2	—	0.2

(2) NGC 4151 and the type 1 Seyfert galaxies

NGC 4151 shows a typical type 1 spectrum. Figure 6.2 is the spectrum of the nuclear region of NGC 4151 ($1'' \times 3'' \approx 100 \times 300$ pc) observed by A. Boksenberg et al. (1975) with the 2.5 m Isaac Newton Telescope. Since the image photon counting system they developed was used for the observation, the vertical axis of the figure is the photon count.

In NGC 4151 almost all the forbidden lines identified in NGC 1068 are observed, and their relative intensities are also very similar to those of NGC 1068 and to the mean values for type 2 Seyfert galaxies (Table 6.4). We may therefore consider that

the gas emitting the forbidden lines of NGC 4151 (a type 1 Seyfert galaxy) is in a physical state similar to that in type 2 Seyfert galaxies.

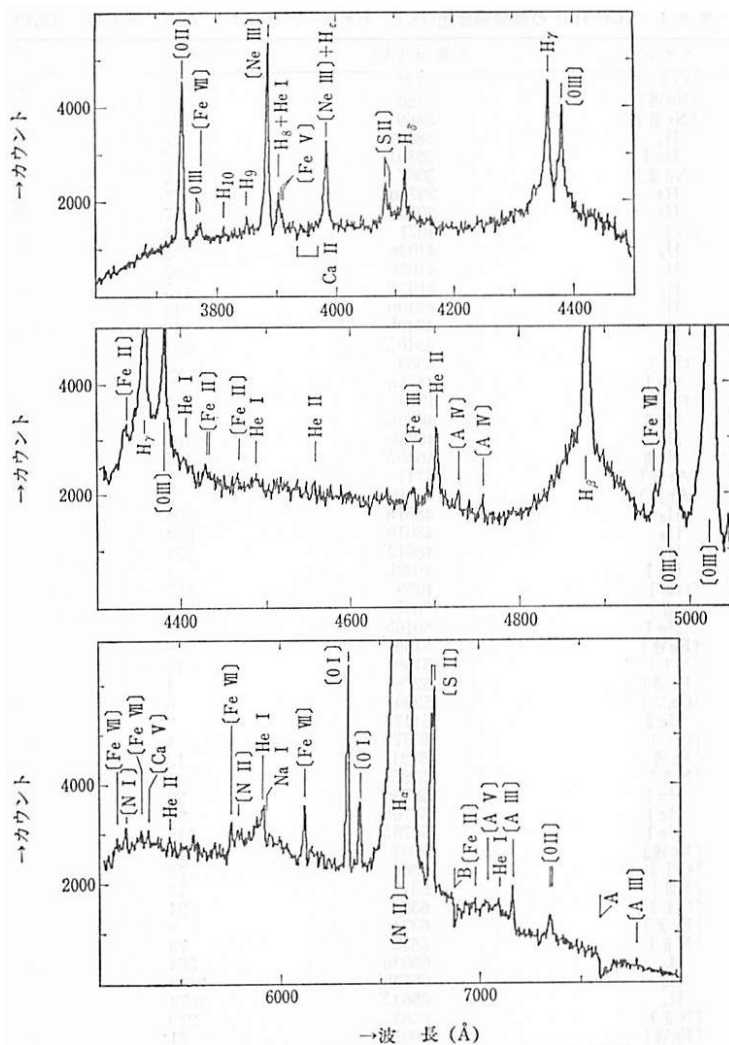


Figure 6.2 The spectrum of NGC 4151. (A. Boksenberg et al. 1975). Vertical axis: → counts (2000, 4000). Horizontal axis: → wavelength ($\text{\AA}$). Lines in the top panel ($\approx 3700\text{--}4500\text{ \AA}$): [O II], O III, H_{10} , H_9 , [Fe VII], [Ne III], $H_8 + He\text{ I}$, [Fe V], [Ne III] + H_ϵ , Ca II, [S II], H_δ , H_γ , [O III]. Lines in the middle panel ($4300\text{--}5050\text{ \AA}$): [Fe II], H_γ , [O III], He I, [Fe II], [Fe II], He I, He II, [Fe III], He II, [A IV], [A IV], H_β , [Fe VII], [O III], [O III]. Lines in the bottom panel ($\approx 5300\text{--}7400\text{ \AA}$): [N I], [Fe VII], [Fe VII], [Ca V], He II, [N II], [Fe VII], He I, Na I, [Fe VII], [O I], [O I], H_α , [N II], [S II], B, [Fe II], [A V], He I, [A III], [O II], A, [A III].

Table 6.4 Emission-line intensity ratios of NGC 4151 (D. E. Osterbrock and A.

T. Koski 1976)

Ion	Wavelength λ (Å)	Intensity ratio
[O II]	3727	241
[Fe VII]	3760	23
[Ne III]	3869	138
{ H_{ζ} , He I }	3889, 3889	15
{ [Ne III], H_{ϵ} }	3967, 3970n	52
H_{ϵ}	3970b	57
[S II]	4071	38
H_{δ}	4102n	23
H_{δ}	4102b	92
H_{δ}	4102 Σ	115
H_{γ}	4340n	42
H_{γ}	4340b	185
H_{γ}	4340 Σ	227
[O III]	4363	38
He I	4471n	5:
[Fe III]	4658	2
He II	4686n	22
He II	4686b	103
He II	4686 Σ	125
[Ar IV]	4711	2
[Ar IV]	4740	3
H_{β}	4861n	100
H_{β}	4861b	634
H_{β}	4861 Σ	734
He I	4922b	6
[O III]	4959	457
[O III]	5007	1363
He I	5016b	15
[Fe VII]	5159	9
[N I]	5199	10

Ion	Wavelength λ (Å)	Intensity ratio
[Fe VII]	5278	4
[Ca V]	5309	6
He II	5412n	2:
[O I]	5577	1
[Fe VII]	5721	13
[N II]	5755	4
He I	5876n	22
He I	5876b	93
He I	5876 Σ	115
[Fe VII]	6087	15
[O I]	6300	75
[S III]	6312	12
[O I]	6364	24
[Fe X]	6374	8
[N II]	6548	73
H_{α}	6563n	364
H_{α}	6563b	2310
H_{α}	6563 Σ	2674
[N II]	6583	219
[Fe VII]	6601	31:
He I	6678n	7

Table 6.4 Emission-line intensity ratios of NGC 4151 (continued)

Ion	Wavelength λ (Å)	Intensity ratio
He I	6678b	47
He I	6678 Σ	54
[S II]	6716	95
[S II]	6731	111
[Ar V]	7006	2
He I	7065n	4
He I	7065b	52
He I	7065 Σ	56
[Ar III]	7136	26
[O II]	7320	21
[O II]	7330	14
[Ar III]	7751	5

n=narrow, b=broad, Σ = *total*

What makes the spectrum of NGC 4151 stand out is the wing component, spread out like a wing, seen in the Balmer lines. Even a rough estimate from Figure 6.2 shows that the wing component of H_{β} covers the 120 Å of $\lambda\lambda 4800 - 4920\text{Å}$. Converted into a Doppler velocity this corresponds to as much as about 7,000 km/s. Similar wing components are also recognized in the permitted lines He II $\lambda 4686$, He I $\lambda 5876$ and He I $\lambda 7065$. The forbidden lines, on the other hand, have no wing component; they have only the same line profile as the core component of the Balmer lines. Energetically too the wing component accounts for more than 80%, and the sum of the wing components of hydrogen and helium reaches nearly half of the total emission-line luminosity (Table 6.5). For the spectrum of a type 1 Seyfert galaxy, the wing component of the permitted lines is the more essential feature.

Table 6.5 Emission-line luminosities of NGC 4151 (erg/s)

Emission line	Core component	Wing component	Total (sum)
H_{β} $\lambda 4861$	5×10^{40}	24×10^{40}	29×10^{40}
All Balmer lines (H_{α} , H_{β} , H_{γ} , H_{δ})	18×10^{40}	126×10^{40}	144×10^{40}
He I + II			36×10^{40}
[O III] $\lambda\lambda 4959/5007$	84×10^{40}	—	84×10^{40}
All forbidden lines	168×10^{40}	—	168×10^{40}
Sum	—	—	348×10^{40}

There are also type 1 Seyfert galaxies that have almost no forbidden lines. Figure 6.3 is the spectrum of Mkn 106. Even [O III] $\lambda 5007$, the strongest forbidden line, is very weak compared with H_{β} , and [O II] $\lambda 3727$ is barely recognizable. In Mkn 376 this tendency is even stronger: all that is observed are broad Balmer lines, He I $\lambda 5876$, He II $\lambda 4686$ and the Fe II multiplets (D. E. Osterbrock 1976). As we shall see later, the greater the absolute luminosity of a type 1 Seyfert galaxy, the stronger this tendency becomes.

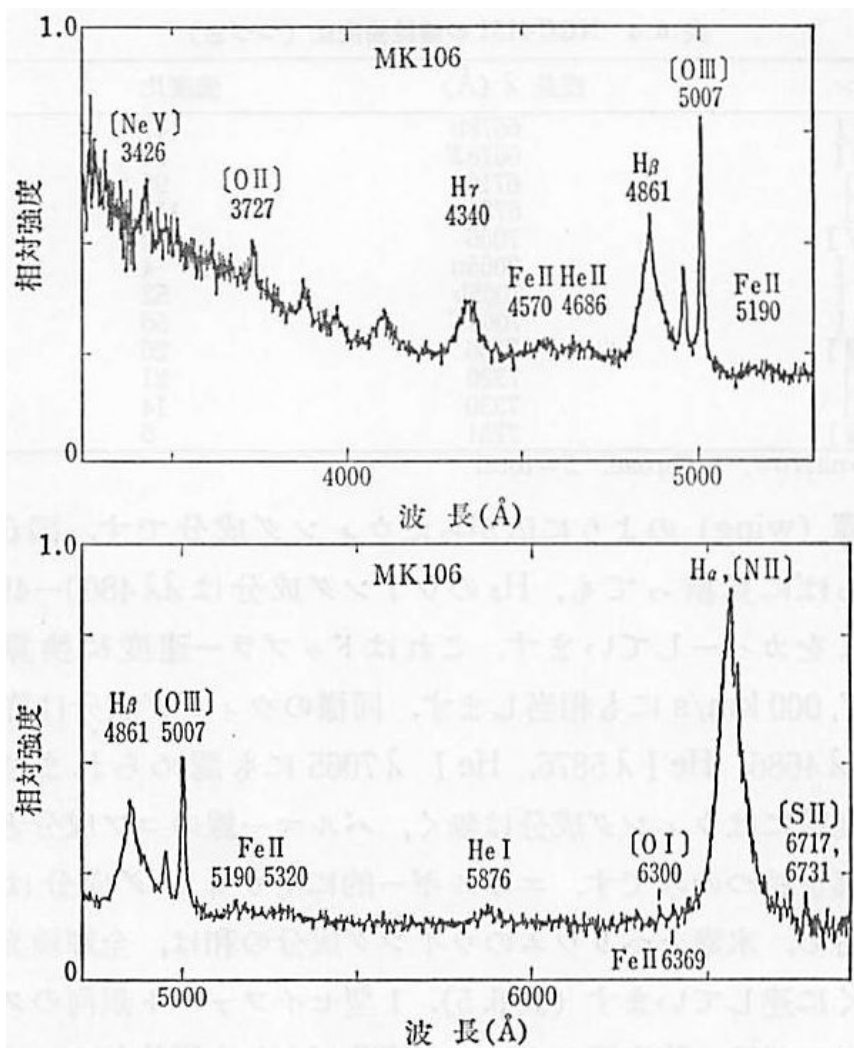


Figure 6.3 The spectrum of Mkn 106. (D. E. Osterbrock 1977). Top panel: MK 106. Vertical axis: relative intensity (0–1.0); horizontal axis: wavelength (Å) (4000, 5000). Lines marked: [Ne V] 3426, [O II] 3727, H_γ 4340, Fe II 4570, He II 4686, H_β 4861, [O III] 5007, Fe II 5190. Bottom panel: MK 106. Vertical axis: relative intensity (0–1.0); horizontal axis: wavelength (Å) (5000, 6000). Lines marked: H_β 4861, [O III] 5007, Fe II 5190 5320, He I 5876, Fe II 6369, [O I] 6300, H_α , [N II], [S II] 6717, 6731.

Regarding BL radio galaxies — that is, radio-loud type 1 Seyfert galaxies — D. E. Osterbrock (1979) has pointed out an interesting spectroscopic characteristic. 3C 120, shown in Figure 6.4, is a good example. Compared with non-radio type 1 Seyfert galaxies, the forbidden lines of BL radio galaxies are relatively strong and no strong Fe II multiplets are observed. Spectroscopically, BL radio galaxies also possess elements characteristic of type 2 Seyfert galaxies.

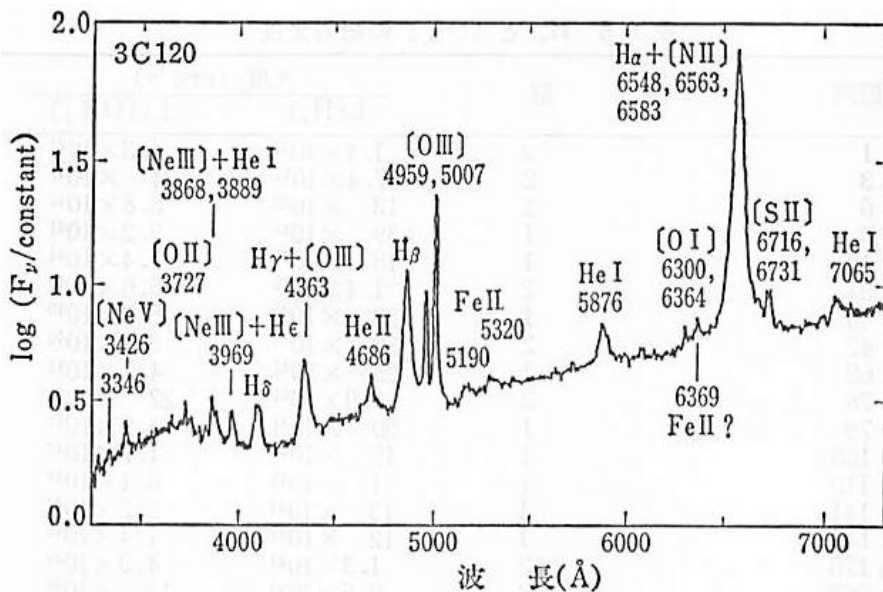


図 6.4 3C 120 のスペクトル. (M. M. フィリップスと D. E. オスターブロッック 1975).

Figure 6.4 The spectrum of 3C 120. (M. M. Phillips and D. E. Osterbrock 1975). Vertical axis: $\log (F_v/\text{constant})$ (0.0–2.0). Horizontal axis: wavelength ($\text{\AA}$) (4000, 5000, 6000, 7000). Lines marked: [Ne V] 3426, 3346; [O II] 3727; [Ne III] + H_ϵ 3969, H_δ ; [Ne III] + He I 3868, 3889; H_γ + [O III] 4363; He II 4686; [O III] 4959, 5007; H_β ; Fe II 5320 5190; He I 5876; 6369 Fe II ?; [O I] 6300, 6364; H_α + [N II] 6548, 6563, 6583; [S II] 6716, 6731; He I 7065.

2. Absolute luminosities of the emission lines

The absolute luminosities $L(H_\alpha)$ and $L([O\ III])$ of H_α and $[O\ III]\ \lambda\lambda 4959, 5007$ provide a measure of the scale of the ionized gas clouds that radiate the emission-line spectrum. For type 1 Seyfert galaxies in particular, the H_α luminosity provides a measure of the size of the region emitting the wing component of the Balmer lines (the BL = broad line region).

Table 6.6 summarizes the absolute luminosities of H_α and $[O\ III]\ \lambda\lambda 4959, 5007$. The emission-line luminosities are distributed over a wide range. The H_α luminosity of the brightest object, III Zw 2, reaches as much as ten thousand times that of the faintest, NGC 4051, and is comparable even to that of quasars. The H_α luminosity of 3C 273, one of the brightest quasars, is 8×10^{45} erg/s, and even 3C 48 gives 2×10^{45} erg/s, so these fall within ten times the value for the brightest Seyfert galaxies.

Table 6.6 Absolute luminosities of H_{α} and [O III]

Galaxy	Type	Luminosity (erg/s) $L(H_{\alpha})$	Luminosity (erg/s) $L([O III])$
Mkn 1	2	1.4×10^{41}	4.3×10^{41}
Mkn 3	2	7.4×10^{41}	24×10^{41}
Mkn 6	2	13×10^{42}	6.8×10^{42}
Mkn 9	1	39×10^{41}	3.2×10^{41}
Mkn 10	1	18×10^{41}	7.4×10^{41}
Mkn 34	2	1.4×10^{42}	5.6×10^{42}
Mkn 40	1	28×10^{40}	8.0×10^{40}
Mkn 42	2	59×10^{40}	5.1×10^{40}
Mkn 69	1	25×10^{41}	4.7×10^{41}
Mkn 78	2	7.0×10^{41}	22×10^{41}
Mkn 79	1	30×10^{41}	4.9×10^{41}
Mkn 106	1	15×10^{42}	1.7×10^{42}
Mkn 110	1	31×10^{41}	6.1×10^{41}
Mkn 141	1	13×10^{41}	2.2×10^{41}
Mkn 142	1	12×10^{41}	1.4×10^{41}
Mkn 176	2	1.3×10^{41}	4.3×10^{41}
Mkn 268	2	9.5×10^{40}	18×10^{40}
Mkn 270	2	2.5×10^{40}	7.8×10^{40}
Mkn 273	2	3.4×10^{41}	2.5×10^{41}
Mkn 279	1	37×10^{41}	3.3×10^{41}
Mkn 290	1	31×10^{41}	7.9×10^{41}
Mkn 291	1	4.5×10^{41}	1.3×10^{41}
Mkn 298	2	4.1×10^{41}	2.7×10^{41}
Mkn 304	1	18×10^{42}	2.0×10^{42}
Mkn 315	2	23×10^{41}	7.2×10^{41}
Mkn 348	2	1.0×10^{41}	3.8×10^{41}
Mkn 352	1	46×10^{42}	2.7×10^{42}
Mkn 372	2	23×10^{41}	6.9×10^{41}
Mkn 374	1	26×10^{41}	4.6×10^{41}

Galaxy	Type	Luminosity (erg/s) $L(H_{\alpha})$	Luminosity (erg/s) $L([O III])$
Mkn 376	1	16×10^{42}	0.9×10^{42}
Mkn 478	1	28×10^{42}	2.1×10^{42}
Mkn 486	1	55×10^{41}	3.9×10^{41}
Mkn 504	1	43×10^{41}	4.1×10^{41}
Mkn 506	1	14×10^{41}	3.2×10^{41}
Mkn 509	1	20×10^{42}	2.3×10^{42}
Mkn 541	1	27×10^{41}	3.4×10^{41}
Mkn 618	1	30×10^{41}	4.8×10^{41}
Mkn 700	2	38×10^{40}	8.3×10^{40}
NGC 1068	2	1.9×10^{42}	4.7×10^{42}
NGC 1275	2p	17×10^{41}	7.4×10^{41}
NGC 1566	1	4.5×10^{40}	2.4×10^{40}
NGC 3227	1/2	9.5×10^{40}	4.2×10^{40}
NGC 3516	1	63×10^{40}	4.2×10^{40}
NGC 3783	1	9.1×10^{40}	4.4×10^{40}
NGC 4051	1	13×10^{39}	6.2×10^{39}
NGC 4151	1	11×10^{41}	8.4×10^{41}
NGC 5548	1	4.0×10^{42}	1.1×10^{42}
NGC 7469	1	3.7×10^{42}	1.2×10^{42}
NGC 7603	1	19×10^{41}	2.0×10^{41}
IC 4329A	1	14×10^{42}	1.0×10^{42}
I Zw 1	1	38×10^{42}	5.0×10^{42}
I Zw 92	2	2.2×10^{42}	7.1×10^{42}

Table 6.6 Absolute luminosities of H_α and [O III] (continued)

Galaxy	Type	Intensity (erg/s) $L(H_\alpha)$	Intensity (erg/s) $L([O III])$
II Zw 136	1	32×10^{42}	4.1×10^{42}
III Zw 2	1	1.0×10^{43}	1.3×10^{43}
3C 120	1	11×10^{42}	2.9×10^{42}
3C 227	1	6.5×10^{42}	1.6×10^{42}
3C 382	1	20×10^{42}	3.4×10^{42}
3C 390.3	1	16×10^{42}	3.6×10^{42}
3C 445	1	8.4×10^{42}	3.3×10^{42}
Akn 120	1	43×10^{42}	1.6×10^{42}
Eso 141-G55	1	11×10^{42}	0.63×10^{42}
Fairall 9	1	59×10^{42}	3.6×10^{42}

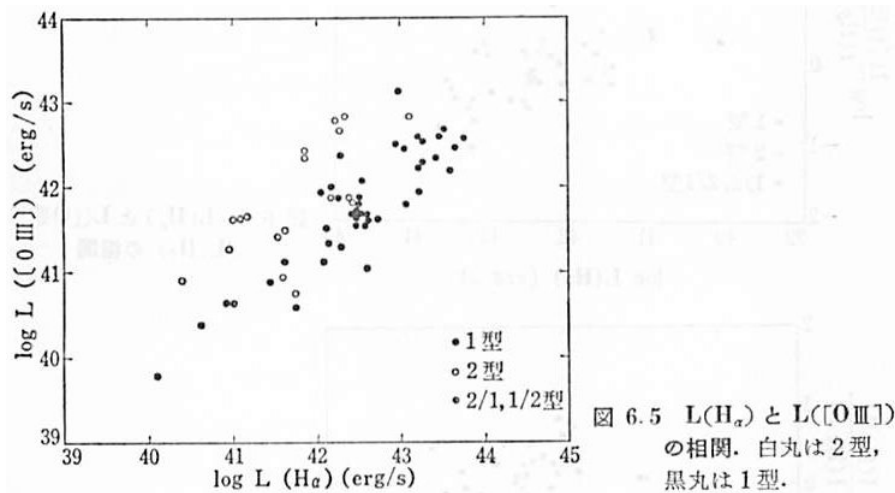


Figure 6.5 The correlation between $L(H_\alpha)$ and $L([O III])$. Open circles are type 2, filled circles type 1. Vertical axis: $\log L([O III])$ (erg/s) (39–44). Horizontal axis: $\log L(H_\alpha)$ (erg/s) (39–45). Legend: ● type 1, ○ type 2, ◐ type 2/1, 1/2.

Figure 6.5 shows the correlation between $L(H_\alpha)$ and $L([O III])$. A proportional relation is seen for type 1 and type 2 separately. For type 1, $L(H_\alpha) > L([O III])$

holds, and for type 2, $L(H_\alpha) < L([O III])$ holds; this is due to the contribution of the wing component in type 1 Seyfert galaxies. In $L(H_\alpha)$ there is a tendency for type 1 to be somewhat brighter, but no difference exists in $L([O III])$. Presumably the scale of the NL (narrow line) region that radiates the forbidden lines is roughly the same in type 1 and type 2.

Type 1 Seyfert galaxies show properties of the emission-line spectrum that correlate with absolute luminosity. Figure 6.6 plots the intensity ratio $I([O III])/I(H_\beta)$ of $[O III] \lambda\lambda 4959, 5007$ to H_β against $L(H_\alpha)$ on the horizontal axis. For type 2 the points scatter, but for type 1 one can discern a tendency for the ratio $I([O III])/I(H_\beta)$ to be smaller the larger $L(H_\alpha)$ is. It is thought that the brighter the type 1 Seyfert galaxy, the relatively larger the BL region is compared with the NL region. Figure 6.7 is a plot of $I(He II \lambda 4686)/I(He I \lambda 5876)$ against $L(H_\alpha)$ for type 1 Seyfert galaxies. Although it is not very clear-cut, if one accepts the correlation that this intensity ratio is smaller for objects with brighter H_α , then there exists a tendency for the ionization state of the gas to be lower in brighter type 1 Seyfert galaxies. The low-ionization Fe II multiplets tend to be observed more strongly in type 1 Seyfert galaxies of higher absolute luminosity, and this too appears to support the paradoxical property noted above.

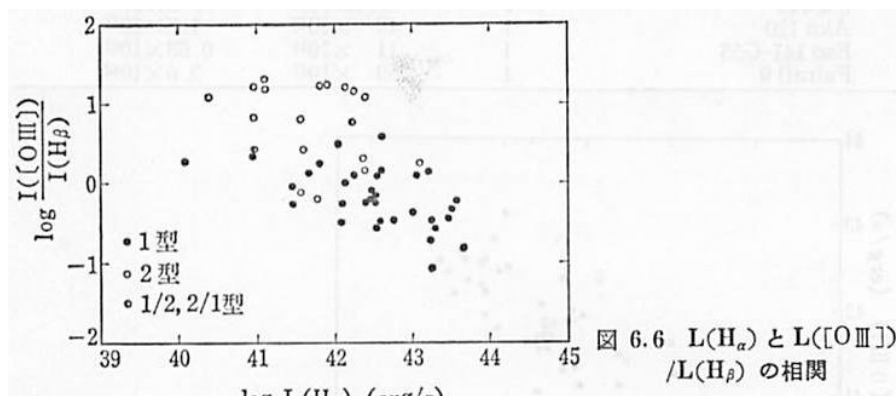


図 6.6 $L(H_\alpha)$ と $L([O III])$ / $L(H_\beta)$ の相関

Figure 6.6 The correlation between $L(H_\alpha)$ and $L([O III])/L(H_\beta)$ Vertical axis: $\log I([O III])/I(H_\beta)$ (-2 to 2). Horizontal axis: $\log L(H_\alpha)$ (erg/s) (39–45). Legend: ● type 1, ○ type 2, ● type 1/2, 2/1.

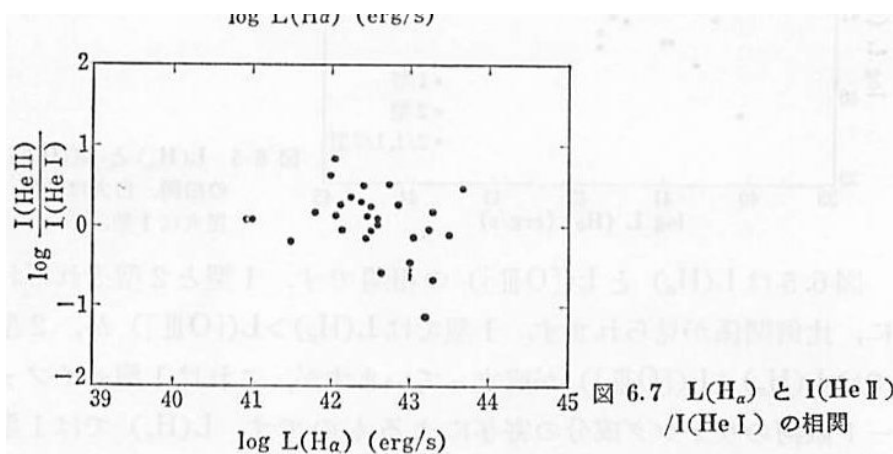


Figure 6.7 The correlation between $L(H_\alpha)$ and $I(He II)/I(He I)$ Vertical axis: $\log I(He II)/I(He I)$ (-2 to 2). Horizontal axis: $\log L(H_\alpha)$ (erg/s) (39–45).

3. Interpretation of the emission-line spectrum

(1) Reddening and the Balmer decrement

Because dust grains in the interstellar medium extinguish light of shorter wavelength more strongly, the observed spectrum of a celestial object is generally reddened. This phenomenon is called reddening. For stars inside a gaseous nebula the dust grains within the nebula also contribute, so the spectrum suffers still stronger reddening. The amount of extinction due to reddening is defined as the difference between the absorption A_B in the B magnitude and A_V in the V magnitude,

$$E_{B-V} = A_B - A_V$$

and for interstellar absorption the following relation holds.

$$A_V = 3E_{B-V}$$

The ratio A_λ/E_{B-V} of the absorption A_λ at an arbitrary wavelength λ to E_{B-V} is called the extinction curve, and for interstellar absorption it takes the values in Table 6.7.

Direct evidence that the emission-line spectra of Seyfert galaxies suffer strong reddening was provided by J. S. Miller (1968) and E. J. Wampler (1968). Because [S II] $\lambda 10320$ and [S II] $\lambda 4072$ of sulphur are forbidden lines emitted when the ion makes a transition from the same level 3 to levels 2 and 1 respectively (Figure 6.9), their intensity ratio $I(\lambda 10320)/I(\lambda 4072)$ should take a fixed value of 0.55 determined only by the transition probabilities. Miller's suggestion — that if the emission-line spectra of Seyfert galaxies are reddened, then an intensity ratio larger than the theoretical value should be observed — was immediately confirmed by observations carried out by Wampler. According to the results of the observations he repeated in 1971, the reddening of NGC 1068 is $E_{B-V} = 0.4$.

Table 6.7 Extinction curve (A. D. Code et al. 1976)

Wavelength	$A_\lambda/E_B - V$	Wavelength	$A_\lambda/E_B - V$	Wavelength	$A_\lambda/E_B - V$
1100	11.70	2600	6.82	5500	3.09
1200	10.20	2700	6.41	5700	2.95
1300	9.19	2800	6.10	5900	2.80
1400	8.54	2900	5.85	6100	2.65
1500	8.29	3000	5.65	6300	2.50
1600	8.03	3300	5.16	6500	2.36
1700	7.85	3500	4.92	6700	2.25
1800	7.90	3700	4.70	6900	2.15
1900	8.38	3900	4.51	7100	2.05
2000	9.05	4100	4.35	7300	1.96
2100	9.90	4300	4.14	7500	1.87
2160	10.10	4500	3.94	7700	1.76
2200	9.85	4700	3.76	7900	1.69
2300	8.75	4900	3.57	8100	1.62
2400	7.92	5100	3.40	8300	1.55
2500	7.30	5300	3.24	8500	1.49

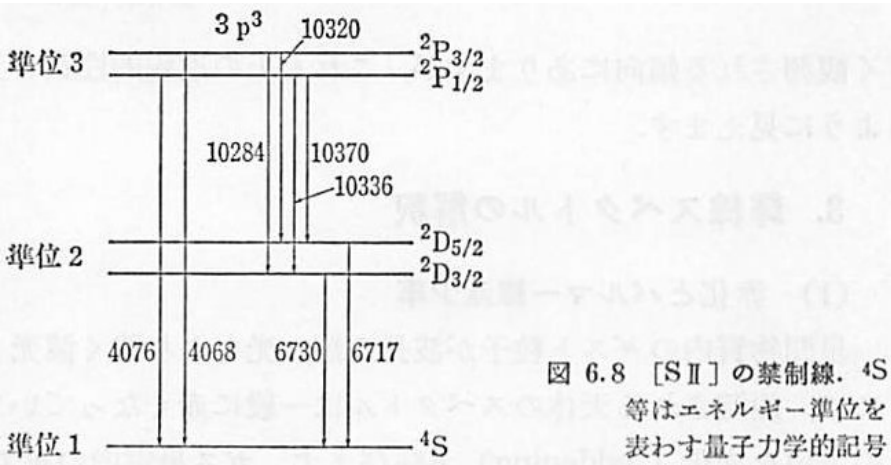


Figure 6.8 The forbidden lines of [S II]. 4S and the like are quantum-mechanical symbols denoting the energy levels Level 3: $3p^3\ ^2P_{3/2},\ ^2P_{1/2}$. Level 2: $^2D_{5/2},\ ^2D_{3/2}$. Level 1: 4S . Transition wavelengths: 10320, 10284, 10370, 10336 (level 3 $\rightarrow$ 2); 4076, 4068 and 6730, 6717 (level 2 $\rightarrow$ 1).

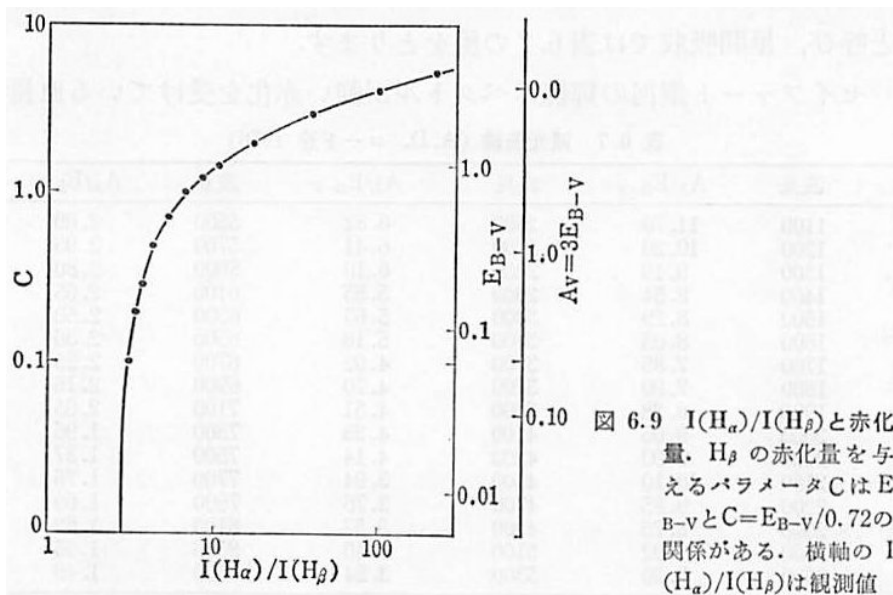


Figure 6.9 $I(H_\alpha)/I(H_\beta)$ and the amount of reddening. The parameter C , which gives the reddening of H_β , is related to $E_B - V$ by $C = E_B - V/0.72$. The $I(H_\alpha)/I(H_\beta)$ on the horizontal axis is the observed value. Vertical axis: C (0–10). Right-hand axis: $E_B - V$, $A_V = 3E_B - V$ (0.01–1.0). Horizontal axis: $I(H_\alpha)/I(H_\beta)$ (1–100).

Ordinarily the reddening is determined from the Balmer lines, which are easy to observe. If hydrogen atoms are ionized by ultraviolet radiation and the Lyman series is optically thick, the intensity ratios of the Balmer lines depend only weakly on temperature, and

$$I(H_\alpha) : I(H_\beta) : I(H_\gamma) = 2.9 : 1.0 : 0.47$$

Table 6.8 Balmer decrements

Balmer line	Electron temperature	Electron temperature	Electron temperature
	$T_e(^{\circ}\text{K})$ 5,000	$T_e(^{\circ}\text{K})$ 10,000	$T_e(^{\circ}\text{K})$ 20,000
H_{α}	3.05	2.87	2.76
H_{β}	1.00	1.00	1.00
H_{γ}	0.45	0.47	0.47
H_{δ}	0.25	0.26	0.26
H_{ϵ}	0.15	0.16	0.16

results (Table 6.8). This ratio is called the Balmer decrement. In actual Seyfert galaxies, however, the Balmer decrement is steeper than the theoretical value. For example, in NGC 1068,

$$I(H_{\alpha}) : I(H_{\beta}) : I(H_{\gamma}) = 6.2 : 1.0 : 0.33$$

(Table 6.1). If this discrepancy between the theoretical and observed values is interpreted as due to reddening, we obtain $E_B - V \approx 0.6$, close to the reddening derived from [S II] (Figure 6.9). Even in the results of G. Neugebauer et al. (1980) for NGC 1068, which examined the ultraviolet and infrared emission lines as well, the reddening is $E_B - V \approx 0.4$ over the wide wavelength range from 1,000 Å to 2μ (Table 6.9). The Balmer decrement can therefore be used to estimate the reddening. This conclusion also means, at the same time, that the steep Balmer decrement of Seyfert galaxies is not due to collisional excitation or to self-absorption of the Balmer lines.

Table 6.9 The reddening of NGC 1068

Emission-line ratio	Observed	Theoretical	$E_B - V(mag)$
$L_\alpha \lambda 1215/H_\beta \lambda 4861$	5.2 ± 1.1	35	0.32 ± 0.04
$H_\alpha \lambda 6563/H_\beta \lambda 4861$	5.3 ± 1.1	2.8	0.54 ± 0.15
$P_\alpha \lambda 18751/H_\beta \lambda 4861$	1.2 ± 0.3	0.34	0.41 ± 0.07
$B_\gamma \lambda 21656/H_\beta \lambda 4861$	0.12 ± 0.03	0.027	0.50 ± 0.08
He II $\lambda 1640$ /He II $\lambda 4686$	1.6 ± 0.7	6.8	0.38 ± 0.07
[S II] $\lambda 10320$ /[S II] $\lambda 4072$	1.9 ± 0.3	0.55	0.40 ± 0.05
Mean			0.38 ± 0.03

The above conclusions about reddening must be qualified in the case of type 1 Seyfert galaxies. The reason is that when the observed values of $I(H_\alpha)/I(H_\beta)$ and $I(H_\gamma)/I(H_\beta)$ are plotted, type 2 Seyfert galaxies (Figure 6.10) show a distribution that follows the reddening direction comparatively well, whereas for type 1 Seyfert galaxies (Figure 6.11) the scatter is large and no such tendency is seen. As we shall examine in the next chapter, dust absorption at $\lambda 2175\text{\AA}$ is observed in the ultraviolet for several type 1 Seyfert galaxies. This, however, is due to interstellar absorption within the Milky Way Galaxy. The reddening within the nucleus of a type 1 Seyfert galaxy is small enough to be negligible. On the other hand, in the type 2 galaxy NGC 1068 the emission-line spectrum suffers a reddening of $E_B - V \approx 0.4$, yet no absorption at $\lambda 2175\text{\AA}$ is observed. The reddening in this type 2 Seyfert galaxy is occurring inside the gas clouds that radiate the emission lines. The conclusion of T. F. Adams and D. W. Weedman (1975) — that the emission-line spectra of type 2 Seyfert galaxies suffer strong reddening but those of type 1 do not — is thought to be basically correct.

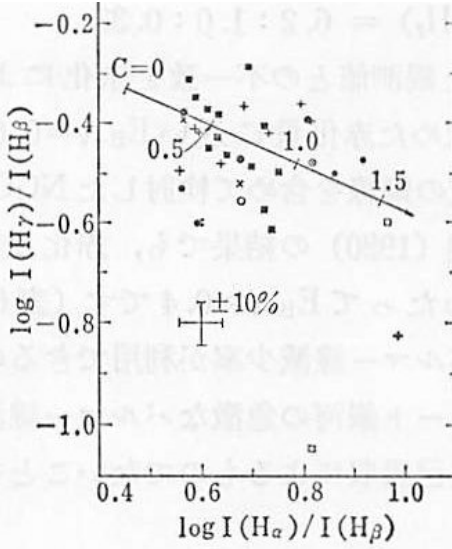


図 6.10 2型セイファート銀河に対する $H_\alpha/H_\beta/H_\gamma$ 比. 各シンボルは,
 ■ 2型セイファート銀河
 + NL電波銀河
 × Cygnus A
 ○ 1型と2型の中間的セイファート銀河のコア成分
 ● 中間型のウィング成分.
 × Fe IIの強いセイファート銀河
 — 赤化方向
 (A. T. コスキー 1978).

Figure 6.10 The $H_\alpha/H_\beta/H_\gamma$ ratios for type 2 Seyfert galaxies. The symbols are: ■ type 2 Seyfert galaxy + NL radio galaxy × Cygnus A ○ Core component of Seyfert galaxies intermediate between type 1 and type 2 ● Wing component of the intermediate types. × Seyfert galaxies with strong Fe II — reddening direction (A. T. Koski 1978). Vertical axis: $\log I(H_\gamma)/I(H_\beta)$ (-1.0 to -0.2). Horizontal axis: $\log I(H_\alpha)/I(H_\beta)$ (0.4–1.0). The scale marks $C=0, 0.5, 1.0, 1.5$ and a $\pm 10\%$ error bar are shown in the figure.

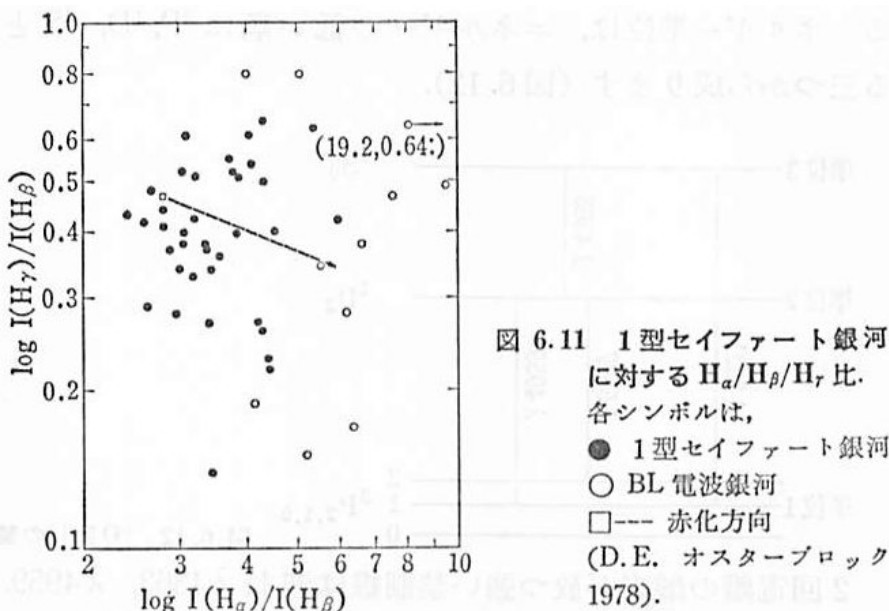


Figure 6.11 The $H_\alpha/H_\beta/H_\gamma$ ratios for type 1 Seyfert galaxies. The symbols are: ● type 1 Seyfert galaxy ○ BL radio galaxy □— reddening direction (D. E. Osterbrock 1978). Vertical axis: $\log I(H_\gamma)/I(H_\beta)$ (0.1–1.0). Horizontal axis: $\log I(H_\alpha)/I(H_\beta)$ (2–10). The point (19.2, 0.64) is marked in the figure.

(2) Electron temperature and electron density

Let us take the forbidden lines [O III] of doubly ionized oxygen as an example and consider the intensity ratios of forbidden lines. The doubly ionized oxygen ion has six electrons, and the two lowest-energy electrons are in the inner K shell. The remaining four are in the L shell, and of these the two of lower energy take a closed configuration. The optical electrons that take part in the spectrum are the two electrons of higher energy. In the ground state the energy levels formed by these electrons consist of three, called, in order of increasing energy, 3P , 1D and 1S (Figure 6.12).

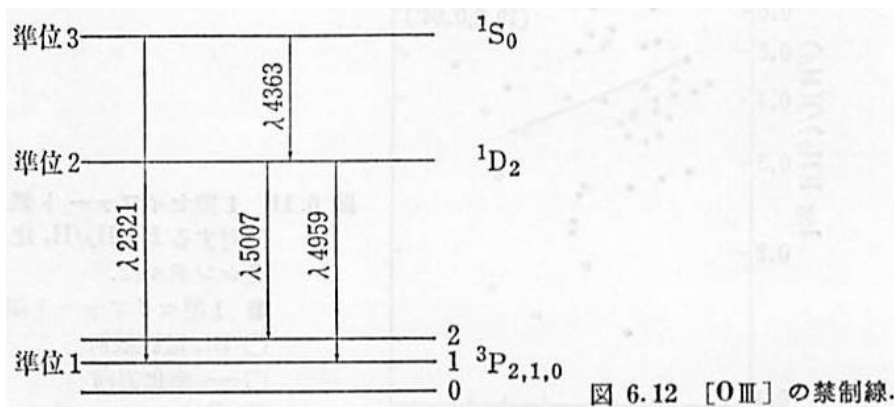


Figure 6.12 The forbidden lines of [O III]. Level 3: $1S_0$. Level 2: $1D_2$. Level 1: $3P_{2,1,0}$ (2, 1, 0). Transition wavelengths: $\lambda 4363$ (level 3 $\rightarrow$ 2); $\lambda 2321$ (leftmost, level 2 $\rightarrow$ 1); $\lambda 5007$, $\lambda 4959$.

The strong forbidden lines emitted by doubly ionized oxygen are the three lines at wavelengths $\lambda 4363$, $\lambda 4959$ and $\lambda 5007$, together with the ultraviolet line $\lambda 2321$. The three energy levels involved in the forbidden lines are called metastable levels and have very long lifetimes. Even the shortest, $\lambda 4363$, requires 0.6 seconds, and $\lambda 5007$ requires as long as 48 seconds. In order for a forbidden line to be radiated, the electron must remain in the excited state (levels 2 and 3) without suffering a collision from a free electron for a time longer than the lifetime required for the transition between the metastable levels. For if a collision occurs, the excited electron has the energy it should have radiated as a forbidden line taken away by the free electron, and falls to a lower level without being able to radiate the forbidden line, or, in some cases, receives energy from the free electron and is excited to a higher level.

Now, excitation from level 1 to levels 2 and 3 occurs by collisions with free electrons. Excitation from level 2 to level 3 can generally be neglected. Level 2 is populated not only by collisional excitation from level 1 but also by transitions

from level 3 to level 2, but this contribution is not large either. If we neglect the collisional de-excitation (“knocking down”) of excited electrons, then, as a result of the balance among these excitation and transition processes, the intensity ratio of $\lambda\lambda 4959 + 5007$ to $\lambda 4363$ is

$$\frac{I(\lambda\lambda 4959 + 5007)}{I(\lambda 4363)} = \frac{8.32 \exp(3.29 \times 10^4 / T_e)}{1 + 4.5 \times 10^{-4} N_e / T_e^{1/2}}$$

This expression is a good approximation for electron densities $N_e \leq 10^5 / \text{cm}^3$, and it is used to determine the electron temperature T_e (Figure 6.13). The reason the ratio in (6.3) becomes smaller at higher temperatures is that level 3 is excited more strongly, so that $\lambda 4363$ is relatively enhanced. Figure 6.14 shows the ratio at the high densities where collisions become important. Because level 2 has a longer lifetime than level 3, collisional de-excitation acts more strongly on $\lambda\lambda 4959 + 5007$, and because collisional excitation from level 2 to level 3 strengthens $\lambda 4363$, the ratio $I(\lambda\lambda 4959 + 5007)/I(\lambda 4363)$ decreases relative to (6.3) as N_e increases.

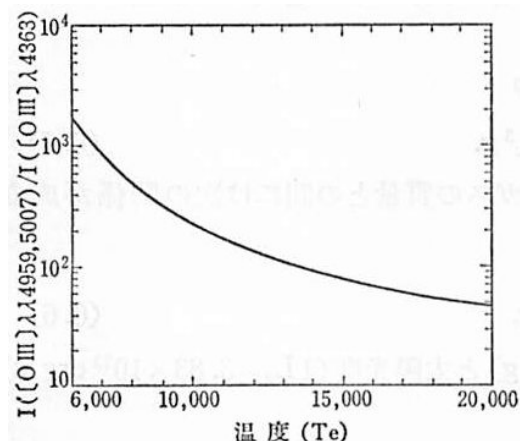


図 6.13 温度 T_e と $I([\text{O III}]\lambda\lambda 4959, 5007)/I([\text{O III}]\lambda 4363)$ の関係. 低密度 ($N_e \rightarrow 0$) で成立つ. (D. E. オスターブロック 1974).

Figure 6.13 Relation between the temperature T_e and $I([\text{O III}]\lambda\lambda 4959, 5007)/I([\text{O III}]\lambda 4363)$. It holds at low density ($N_e \rightarrow 0$). (D. E. Osterbrock 1974). Vertical axis: $I([\text{O III}]\lambda\lambda 4959, 5007)/I([\text{O III}]\lambda 4363)$ ($10 - 10^4$, logarithmic); horizontal axis: temperature (T_e) (6,000 / 10,000 / 15,000 / 20,000).

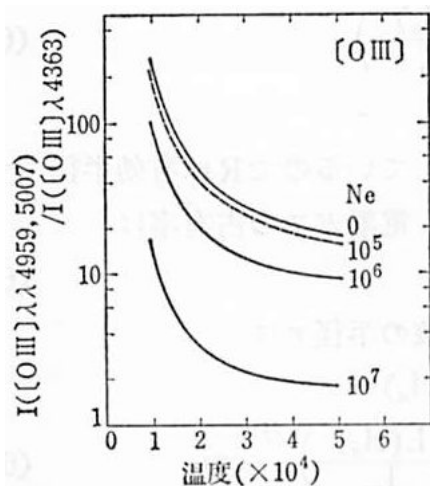


図 6.14 N_e の効果. (D. E. オスターブロック 1970).

Figure 6.14 The effect of N_e . (D. E. Osterbrock 1970). Vertical axis: $I([O III] \lambda \lambda 4959, 5007)/I([O III] \lambda 4363)$ (1 – over 100, logarithmic); horizontal axis: temperature ($\times 10^4$) (0–6). Symbol in the figure: [O III]. Curve labels: $N_e = 0, 10^5, 10^6, 10^7$.

The mass of the ionized gas is calculated from the luminosity of the Balmer lines. Assuming $T_e = 10,000^\circ\text{K}$,

$$\begin{aligned} L(H_\alpha) &= 1.5 \times 10^{-24} N_e^2 R^3 \\ &= 4.4 \times 10^{31} N_e^2 R_{\text{pc}}^3 \text{ erg/s} \end{aligned}$$

Here a sphere of uniform density is assumed. R and R_{pc} are its radius in units of cm and of pc respectively. The mass is obtained simply by multiplying the volume $(4/3)\pi R^3$ by the number density N_e and the mass of the hydrogen atom $M_H = 1.67 \times 10^{-24} \text{g}$, and can be expressed by the following equation.

$$\begin{aligned} M &= 7.0 \times 10^{-24} N_e R^3 \\ &= 2.0 \times 10^{32} N_e R_{\text{pc}}^3 \text{ g}. \end{aligned}$$

Therefore the following relation holds between the H_α luminosity and the mass of the ionized gas.

$$M = 4.6L(H_\alpha)/N_e g.$$

Taking the solar mass ($1 M_\odot = 1.99 \times 10^{33} \text{g}$) and the solar luminosity ($1 L_\odot = 3.83 \times 10^{33} \text{erg/s}$) as units,

$$(M/M_\odot) = 8.8 \cdot (1/N_e)(L(H_\alpha)/L_\odot)$$

Since the ionized gas is represented by a sphere of radius R , R is an effective radius. If the nucleus is approximated by a sphere of radius r , the filling factor of the ionized gas is defined as

$$f = (R/r)^3$$

Thus the radius r of the nucleus is

$$\begin{aligned} r &= 8.7 \times 10^7 f^{-1/3} N_e^{-2/3} L(H_\alpha)^{1/3} \\ &= 1.4 \times 10^{19} f^{-1/3} N_e^{-2/3} (L(H_\alpha)/L_\odot)^{1/3} \text{cm}, \end{aligned}$$

and in units of parsecs (pc) it can be written

$$\begin{aligned} r_{\text{pc}} &= 2.8 \times 10^{-11} f^{-1/3} N_e^{-2/3} L(H_\alpha)^{1/3} \\ &= 4.4 f^{-1/3} N_e^{-2/3} (L(H_\alpha)/L_\odot)^{1/3} \text{pc}, \end{aligned}$$

(3) The physical state of type 2 Seyfert galaxies

Let us determine the electron density, electron temperature, mass and effective radius of the ionized gas from the intensity ratios of the forbidden lines and from the H_α luminosity. It goes without saying, of course, that a correction for reddening is required for this purpose. Table 6.2 gives the reddening-corrected intensity ratios of NGC 1068, and the mean relative intensities of Table 6.4 have also been corrected for reddening.

In the observations of G. A. Shields and J. B. Oke (1975) (Table 6.2), the ratio $I(\lambda\lambda 4959 + 5007)/I(\lambda 4363)$ for NGC 1068 is 115. In the observations of A. T.

Koski (1978) it is 75. Assuming $N_e < 10^5/\text{cm}^3$, these give $T_e = 12,500$ and $10,000$ °K respectively. To obtain the physical state in more detail one uses not only [O III] but also the intensity ratios of other forbidden lines. Shields and Oke derive $T_e \approx 12,000^\circ\text{K}$, $N_e \approx 2 \times 10^5/\text{cm}^3$ for the highly ionized region that radiates [O III] and [Ar IV], and $T_e \approx 1 \times 10^4^\circ\text{K}$, $N_e \approx 800/\text{cm}^3$ for the low-ionization region of [S II] and [O II]. Table 6.10 gives the electron temperatures and electron densities of type 2 Seyfert galaxies determined by Koski. On average we obtain $T_e \approx 15,000^\circ\text{K}$, $N_e \approx 2,000/\text{cm}^3$.

It is of interest to examine how the physical state (N_e , T_e) of type 2 Seyfert galaxies is related to the H_α luminosity. When N_e and T_e are plotted against $L(H_\alpha)$, however, no dependence on $L(H_\alpha)$ is seen at all. There is simply no tendency for brighter objects to have higher temperatures or higher densities.

Let us examine the mass and effective radius of the ionized gas. The

Table 6.10 Electron temperatures and electron densities of type 2 Seyfert galaxies and NL radio galaxies

Object	T_e	N_e	Object	T_e	N_e
Mkn 176	20,000	4,000:	I Zw 81	—	LDL
3 C 33	12,500	800	Mkn 298	16,000	630
Mkn 3	12,500	3,000	Mkn 507	50,000:	3,000:
NGC 1068	10,000	16,000	Mkn 700	—	1,600
Mkn 573	12,500	2,000	NGC 6764	16,000	1,600
Mkn 78	10,000	1,600	Mkn 378	—	400:
Mkn 348	16,000	2,000	Mkn 6	16,000	800
Mkn 34	12,500	1,600	Mkn 315	25,000	2,000
Mkn 1	12,500	5,000:	Mkn 372	20,000	2,500
3 C 184.1	12,500	3,000	Mkn 42	63,000:	5,000:
3 C 433	16,000	250	5 C 3.100	50,000:	LDL
Mkn 270	16,000	2,500	Cyg A	10,000	1,000
III Zw 55	12,500	3,000	3 C 98	20,000	4,000
3 C 452	16,000	125	3 C 178	—	1,600:
Mkn 198	12,500	400	3 C 192	20,000	LDL
Mkn 268	20,000	1,000	3 C 327	20,000	1,600
Mkn 273	20,000	LDL	PKS 2322-12	30,000:	125

H_α luminosity of NGC 1068 is $L(H_\alpha) \approx 4 \times 10^{42} \text{erg/s}$, so for $N_e = 16,000/\text{cm}^3$ we obtain $M \approx 5 \times 10^5 M_\odot$. The H_α luminosities of type 2 Seyfert galaxies lie for the most part in the range $L(H_\alpha) \approx 10^{41} - 10^{44} \text{erg/s}$, so if we assume $N_e = 10^3/\text{cm}^3$ there is $M \approx 2 \times 10^5 - 2 \times 10^8 M_\odot$ of ionized gas within the nucleus, and if we assume $N_e = 10^4 \text{cm}^{-3}$, $M \approx 2 \times 10^4 - 2 \times 10^7 M_\odot$.

The effective radius of NGC 1068 is $R \approx 7 \text{ pc}$. For $L(H_\alpha) = 10^{41} - 10^{44} \text{erg/s}$ we obtain $R = 13 - 130 \text{ pc}$ when $N_e = 10^3/\text{cm}^3$, and $R = 3 - 30 \text{ pc}$ when $N_e = 10^4/\text{cm}^3$. These results are astonishing, because the radius $R = 7 \text{ pc}$ of NGC 1068 is extremely small compared with what is observed. As we saw in Chapter III, the

nucleus of NGC 1068 was as large as several hundred pc. Even if we estimate the radius of the nucleus as $r = 100$ pc, the filling factor is $f \approx 3.4 \times 10^{-4}$, and if $r = 200$ pc then $f \approx 4.3 \times 10^{-5}$ — meaning that the ionized gas occupies only about one hundred-thousandth of the volume. We must conclude that the ionized gas within the nucleus is scattered as many small gas clouds, or else has a filamentary form.

(4) The physical state of type 1 Seyfert galaxies

Since the forbidden-line spectra of type 1 Seyfert galaxies resemble those of type 2, the physical state of the NL region is expected to be similar to that of type 2 as well. In the case of NGC 4151, $I(\lambda\lambda 4959 + 5007)/I(\lambda 4363) \approx 50$ gives $T \approx 2 \times 10^4$ K for $N_e \leq 10^5/\text{cm}^3$. From a more detailed analysis, J. B. Oke and W. L. W. Sargent (1968) derive $T_e = 2 \times 10^4$ K, $N_e = 5,000/\text{cm}^3$, while A. Boksenberg and colleagues (1975) derive $T_e = 12,500^\circ\text{K}$, $N_e = 2 \times 10^4/\text{cm}^3$ for the high-ionization region and $T_e = 14,500^\circ\text{K}$, $N_e = 5,000/\text{cm}^3$ for the low-ionization region. Figure 6.15 shows the distribution of the [O III] ratio for type 1 Seyfert galaxies. The ratio peaks at ~ 20 , and if $N_e \leq 10^5/\text{cm}^3$ then $T_e \sim 5 \times 10^4$ K is obtained. This temperature, however, is too high for gas ionized by ultraviolet light. It is more natural to assume $T_e \sim 10^4$ K and interpret the result as $N_e \sim 10^6/\text{cm}^3$.

In type 1 Seyfert galaxies one must take only the core component as the H_α luminosity of the NL region. The H_α luminosities lie over the wide range 10^{40} – 10^{44} erg/s, but in the bright objects more than 90% is in the wing component, so the H_α luminosity of the NL region is estimated as $L(H_\alpha) = 10^{40}$ – 10^{43} erg/s. Assuming $T_e \sim 10^4$ K and $N_e \sim 10^4/\text{cm}^3$, the mass and effective radius are $M \approx 2 \times 10^3 - 2 \times 10^6 M_\odot$, $R \approx 1.3$ – 13 pc; if $N_e \sim 10^6/\text{cm}^3$, the result is $M = 20 - 2 \times 10^4 M_\odot$, $R \approx$

0.06–0.6 pc. Presumably the NL region of type 1 Seyfert galaxies is more compact and denser than that of type 2.

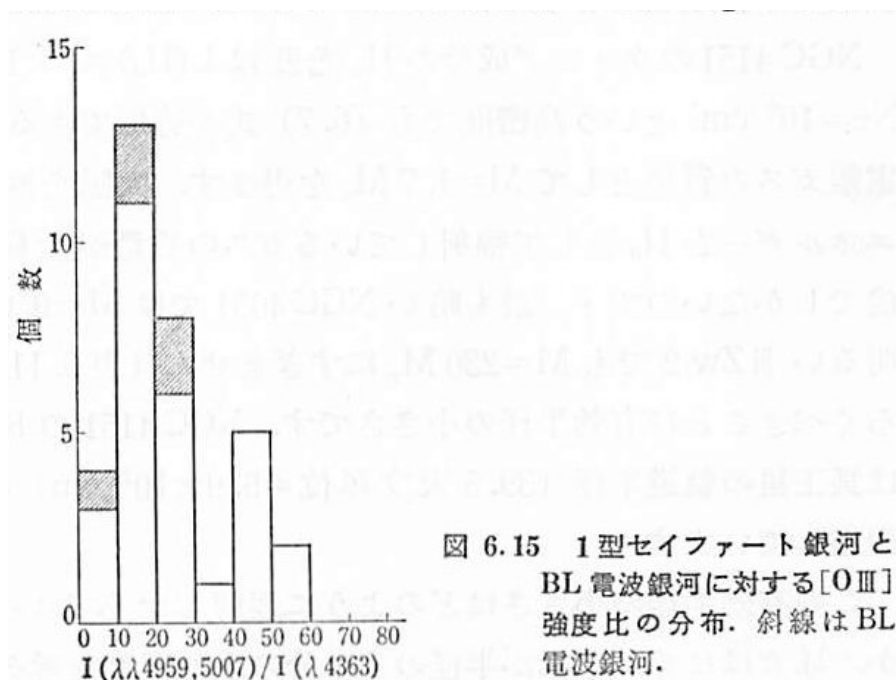


Figure 6.15 Distribution of the [O III] intensity ratio for type 1 Seyfert galaxies and BL radio galaxies. The hatched areas are BL radio galaxies. Vertical axis: number (0–15); horizontal axis: $I(\lambda\lambda 4959, 5007)/I(\lambda 4363)$ (0–80).

The interest of type 1 Seyfert galaxies lies in the BL region. From the constraint that no forbidden lines are emitted, a lower limit $N_e \geq 10^8/\text{cm}^3$ is set on the density of the BL region. In the ultraviolet region of type 1 Seyfert galaxies and quasars the semi-forbidden line C III] $\lambda 1909$ is observed with the same width as the Balmer-line wings, but for this to be radiated one must have $N_e \leq 10^{10}/\text{cm}^3$. Thus the density of the BL region lies in the range $N_e = 10^8\text{--}10^{10}/\text{cm}^3$, and $N_e \approx 10^9/\text{cm}^3$.

is considered a reasonable value. Since there is no good method of determining the temperature, $T_e \approx 1 \times 10^4$ K is generally assumed for the BL region.

The H_α luminosity of the wing component of NGC 4151 is $L(H_\alpha) \approx 2 \times 10^8 L_\odot$. If equation (6.7) can be applied even at a density as high as $N_e = 10^9/\text{cm}^3$, we obtain $M = 1.7M_\odot$ for the mass of the ionized gas. The mass of gas radiating 200 million times the solar luminosity in H_α is only 1.7 times the mass of the Sun. In the faintest case, NGC 4051, $M = 0.02M_\odot$, and even in the brightest, III Zw 2, M is no more than $230M_\odot$ (Table 6.11). Still more astonishing is the smallness of the effective radius. The $R = 0.0025$ pc of NGC 4151 corresponds to about 10 times the orbital radius of Pluto (39.5 astronomical units $= 5.9 \times 10^{14}$ cm).

How should we understand this smallness of the effective radius? Even if we consider not a sphere but a disk whose thickness is one hundredth of its radius, its

Table 6.11 BL gas in type 1 Seyfert galaxies

Galaxy	$L(H_\alpha)$ (erg/s)	Mass $M(M_\odot)$	Effective radius R (pc)
NGC 4051	1×10^{40}	0.02	0.0006
NGC 4151	7×10^{41}	1.7	0.0025
Mkn 79	7×10^{42}	17	0.0053
III Zw 2	1×10^{44}	230	0.013

$N_e = 10^9 \text{cm}^{-3}$ assumed.

radius would only be $R_{\text{disk}} \approx 3.2 R_{\text{sphere}}$. Nor can we suppose that it is distributed in gas clouds or filaments with an extremely small filling factor, as in the NL region. The reason is that, as we shall consider later, intensity variations of the Balmer lines are observed on time scales of one month to one year, so the size of the BL region can hardly exceed 10^{17} – 10^{18} cm (0.03–0.3 pc). The typical size of the BL region (0.1 pc $\sim 3 \times 10^{17}$ cm) is comparable to that of a planetary nebula. For a

body of gas that emits as much as $10^7\text{--}10^{11}L_{\odot}$ of energy in emission lines, this is a smallness that defies imagination.

From the BL region, besides the hydrogen Balmer lines and the Lyman-series L_{α} $\lambda 1216$, everything from high-ionization emission lines such as C IV $\lambda 1550$ and He II $\lambda 4686$ down to low-ionization lines such as the Fe II multiplets and Mg II $\lambda 2798$ is radiated; these cannot be regarded as radiation from one and the same uniform region. Small though the BL region is, it possesses a very complex internal structure.

J. A. Baldwin (1977) discovered that the intensity ratio of L_{α} to H_{β} in quasars is $I(L_{\alpha})/I(H_{\beta}) \sim 3$, no more than one tenth of the recombination-theory value (~ 40); the same property is observed in type 1 Seyfert galaxies as well (Table 6.10). As C. C. Wu, A. Boggess and T. R. Gull (1980a) showed, these cannot be explained as reddening of the recombination-theory value. The peculiarity that the L_{α} to H_{β} intensity ratio is a few times to more than ten times smaller than the theoretical value is common to type 1 Seyfert galaxies and quasars. This also means that type 1 Seyfert galaxies and quasars are in a physical state fundamentally different from that of ordinary gaseous nebulae.

Table 6.10 L_α in Seyfert galaxies and quasars

Galaxy	$I(L_\alpha)/I(H_\beta)$	$I(H_\alpha)/I(H_\beta)$
NGC 1068	5.2	5.3
Mkn 9	8.1	3.7
Mkn 10	3.9	2.4
Mkn 335	7.0	2.60
I Zw 1	5.7	4.86
Fairall 9	11.8	2.51
NGC 985	9.7	3.48
3C 120	4.8	5.08
Mkn 78	19.6	5.31
Mkn 79	2.2	4.65
NGC 3783	3.3	2.78
NGC 4151	4.5	2.91
NGC 5548	5.9	4.21
Mkn 478	13.0	4.32
3C 390.3b	2.4	6.31
3C 390.3 n	26.5	4.18
ESO 141-G 55	8.2	3.67
Mkn 509	4.8	2.83
II Zw 136	3.5	3.63
NGC 7469	2.8	3.88
MCG 2-58-22	3.6	2.68
3C 273*	5.6	3.15
MR 2251-178*	16.4	4.27

* Quasar

In a high-density region with $N_e \sim 10^9/\text{cm}^3$, collisional excitation and the collisional de-excitation of the reverse process become important. The gas becomes opaque, and the process of self-absorption, in which Balmer-line photons are absorbed again, also operates. Many model calculations taking these effects into

account have been attempted in order to interpret the emission-line spectrum of the BL region, but unfortunately they have not yet reached the point of prescribing the properties of the BL region.

(5) Chemical composition

Since emission-line intensity ratios are proportional to the relative abundances of the elements, the chemical composition of the radiating gas can be determined from their analysis. Helium gives recombination lines and has properties very similar to those of hydrogen. In a uniform ionized gas cloud in which hydrogen and helium coexist, the proportionalities

$$N(\text{He}^+)/N(\text{H}^+) \propto I(\text{HeI}\lambda 5876)/I(\text{H}_\beta),$$

$$N(\text{He}^{++})/N(\text{H}^+) \propto I(\text{HeII}\lambda 4686)/I(\text{H}_\beta),$$

hold, and the ratio of the number densities of hydrogen and helium can be estimated from

$$N(\text{He})/N(\text{H}) \approx (N(\text{He}^+) + N(\text{He}^{++}))/N(\text{H}^+)$$

The observed values for Seyfert galaxies correspond to $N(\text{He})/N(\text{H}) \approx 0.08\text{--}0.15$, and the mean value agrees well with the helium abundance of the Sun and of planetary nebulae. We may therefore conclude that the helium abundance of Seyfert galaxies is $N(\text{He})/N(\text{H}) \approx 0.1$, that is, normal. The scatter is probably due not so much to anomalies in chemical composition as to the complexity of the structure within the nucleus and to differences in the spectrum of the ionizing photons.

Since the forbidden lines are emission lines excited by collisions with free electrons, they depend strongly on the electron density N_e and the electron temperature T_e ; taking oxygen as an example,

$$N(O^+)/N(H^+) \propto I([OII]\lambda 3727)/I(H_\beta),$$

$$N(O^{++})/N(H^+) \propto I([OIII]\lambda 5007)/I(H_\beta),$$

hold, so the ratio of the number densities of oxygen and hydrogen can be approximated as follows.

$$N(O)/N(H) \approx (N(O^+) + N(O^{++}))/N(H^+)$$

Since nitrogen has an ionization potential energy very similar to that of oxygen,

$$N(N)/N(O) \approx N(N^+)/N(O^+) \propto I([NII]\lambda 6584)/I([OII]\lambda 3727)$$

allows its number density to be estimated.

In Seyfert galaxies the range of ionization is extremely wide and the filling factor is very small, so the gas is thought to be in a state far removed from a uniform distribution. Consequently, a method is also used in which the ionization structure within the gas cloud is calculated and a chemical composition is selected that matches the observations.

Table 6.13 shows the chemical compositions of NGC 1068 (G. A. Shields and J. B. Oke 1975), NGC 3516 (D. Péquignot 1980), and the NL radio galaxy Cygnus A (D. E. Osterbrock and J. S. Miller 1975). For comparison the chemical compositions of the Sun and of planetary nebulae are also given. The Sun and planetary nebulae are Population I objects, rich in heavy elements (elements other than hydrogen and helium). In globular clusters, which are representative of Population II, this heavy-element abundance is only one tenth to one hundredth of that of Population I, so it is clear that the gas within the nuclei of Seyfert galaxies corresponds to Population I.

Table 6.13 Chemical composition

	NGC 1068	NGC 3516	Cyg A	Sun	Planetary nebulae
H	10000	10000	10000	10000	10000
He	1300	1000	1000	1000	1300
N	4	1	1	1.1	8
O	7	6	4	6.8	8
Ne	4	3.5	1	0.28	0.8
S	0.5	0.5	0.3	0.16	0.8
Fe	0.6	—	≤ 0.1	0.25	—

4. Emission-line profiles

(1) Emission-line profiles of type 2 Seyfert galaxies

In type 2 Seyfert galaxies the forbidden lines and the permitted lines have identical emission-line profiles. Figure 6.16 shows the high-dispersion emission-line profile of [O III] $\lambda\lambda 4959, 5007$ obtained by D. Pelat and D. Alloin (1980) with the 152 cm telescope of the Haute-Provence Observatory. This asymmetric, irregular structure can be reproduced as the superposition of eight components with Gaussian profiles and one broad component. The broad emission-line profile of NGC 1068 can therefore be interpreted as being produced by the motions of many gas clouds having internal motions of ~ 100 km/s. Pelat and Alloin's components 2 and 3 correspond respectively to Walker's gas clouds III and IV, and component 7 to I+II. The broad component of 2,000 km/s (FWHM) contains about 50% of the total light and even appears to resemble the wing component of type 1 Seyfert galaxies.

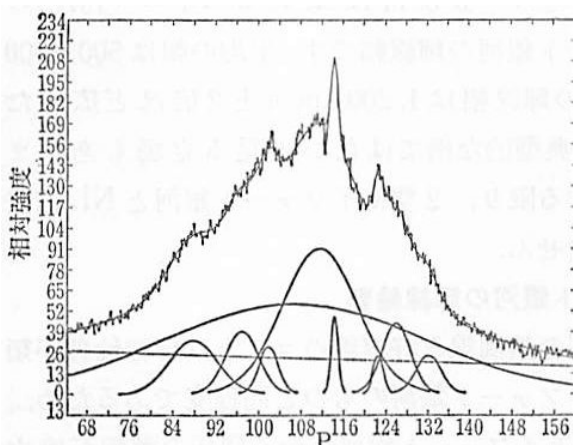


図 6.16 NGC 1068 の [O III]
 $\lambda\lambda 4959, 5007$. 横軸は
 $\lambda = (0.05943 \times p + 4958.3) \text{ \AA}$
 で波長に変換される.
 (D. ペラと D. アロ
 アン 1980).

Figure 6.16 [O III] $\lambda\lambda 4959, 5007$ of NGC 1068. The horizontal axis is converted to wavelength by $\lambda = (0.05943 \times p + 4958.3) \text{ \AA}$. (D. Pelat and D. Alloin 1980). Vertical axis: relative intensity (ticks 13, 26, 39, 52, 65, 78, 91, 104, 117, 130, 143, 156, 169, 182, 195, 208, 221, 234); horizontal axis: p (68, 76, 84, 92, 100, 108, 116, 124, 132, 140, 148, 156).

The emission-line profiles of other type 2 Seyfert galaxies have hardly been studied, but as with NGC 1068, it is thought that profiles with widths of 500–1,000 km/s (FWHM) are produced because many gas clouds with internal motions of ~ 100 km/s are in random motion, or in expansion/infall motion, at velocities of several hundred km/s. Table 6.14 gives the emission-line widths of type 2 Seyfert galaxies determined by A. T. Koski (1978). The mean width is 500–600 km/s. The emission-line width of NGC 1068 is 1,200 km/s, about twice as broad, so there is also a view that NGC 1068 is not a typical example of type 2. Moreover, as far as emission-line width is concerned, there is no difference between type 2 Seyfert galaxies and NL radio galaxies.

Table 6.14 Emission-line widths of type 2 Seyfert galaxies and NL radio galaxies

Galaxy	FWHM (km/s)	Galaxy	FWHM (km/s)
Mrk 176	750±150	Mrk 198	350±150
3C 33	450±100	Mrk 268	750±100
Mrk 3	900±150	Mrk 273	700±100
NGC 1068	1200±150	I Zw 81	225±200
Mrk 573	350±150	Mrk 298	350±100
Mrk 78	1100±150	Mrk 507	800±200
Mrk 348	400± 50	Mrk 700	350±150
Mrk 34	450±100	NGC 6764	400±100
Mrk 1	600±150	Mrk 378	300±150
3C 184.1	350±100	Mrk 6	700±100
3C 433	700±100	Mrk 315	500±100
Mrk 270	500±100	Mrk 372	400±100
III Zw 55	670±100	Mrk 42	550±100
3C 452	650±100	5C 3.100	450±150

(2) Emission-line profiles of type 1 Seyfert galaxies

In type 1 Seyfert galaxies the emission-line profiles of the forbidden lines and of the cores of the permitted lines are similar, and their widths are also comparable to those of type 2 Seyfert galaxies, so it is thought that exactly the same interpretation as for type 2 Seyfert galaxies holds for the NL component. Accordingly, in the case of type 1 Seyfert galaxies the wings of the permitted lines constitute the essential problem. Indeed, when one speaks simply of the emission-line profile of a Seyfert galaxy, one means the wing component of type 1.

Let us begin with the profiles of the Balmer lines. Figure 6.17 shows the H_{α} emission-line profiles of NGC 4151 and NGC 5548 obtained by K. S. Anderson (1971). In NGC 4151 smooth wings extend relatively symmetrically about the core.

In NGC 5548, however, H_α shows an asymmetric profile skewed by as much as 2,000 km/s toward shorter wavelengths. The H_β of IC 4329 A (Figure 6.18), which is often cited as an asymmetric profile, has on the contrary a shoulder of 1,000–3,000 km/s on the long-wavelength side (Figure 6.19). In H_α , however, no such clear asymmetry is seen. In 3C 445 the profile is not only asymmetric but also differs from line to line among H_α , H_β and H_γ (D. E. Osterbrock, A. T. Koski, M. M. Phillips 1976). Such asymmetric profiles are observed in 20–40% of type 1 Seyfert galaxies. Looking at it the other way round, one may equally say that 60–80% of type 1 Seyfert galaxies have symmetric emission-line profiles.

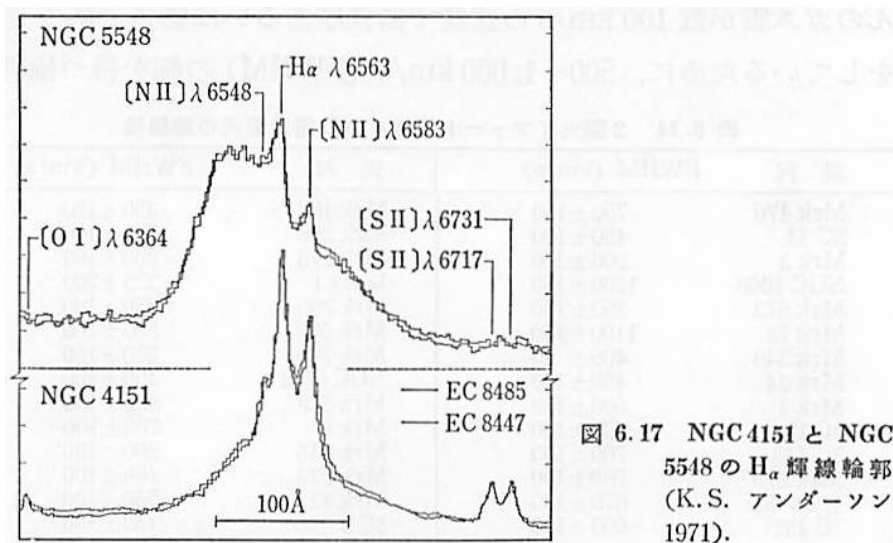


Figure 6.17 H_α emission-line profiles of NGC 4151 and NGC 5548. (K. S. Anderson 1971). Upper panel NGC 5548, lower panel NGC 4151. Lines identified in the figure: [O I] λ 6364, [N II] λ 6548, H_α λ 6563, [N II] λ 6583, [S II] λ 6717, [S II] λ 6731. Key in the lower panel: EC 8485 / EC 8447. Horizontal scale bar: 100 Å.

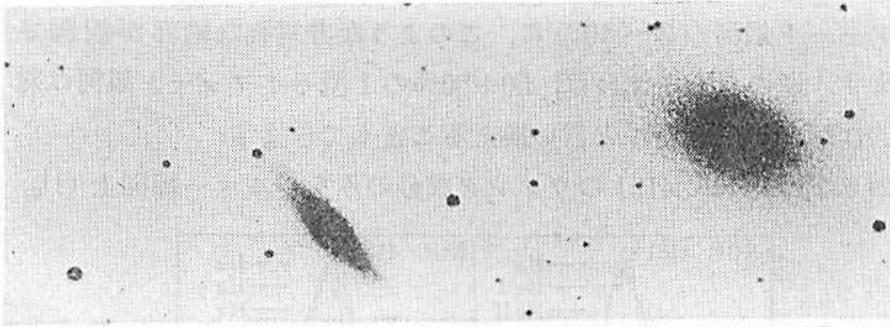


図 6.18 IC 4329 A. 右が IC 4329A, 左がセイファート銀河の IC 4329 A. (M. J. ディズニー 1973).

Figure 6.18 IC 4329 A. On the right is IC 4329A, on the left the Seyfert galaxy IC 4329 A. (M. J. Disney 1973).

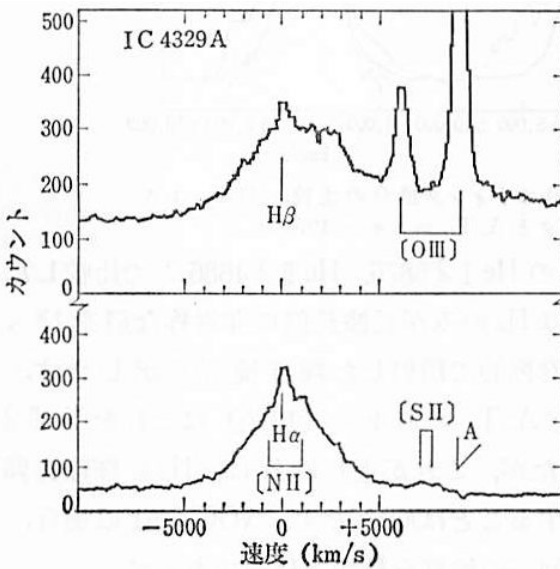


図 6.19 IC 4329 A の H_{α} , [O III] と H_{β} . (A. S. ウィルソンと M. V. ペンストン 1979).

Figure 6.19 H_{α} , [O III] and H_{β} of IC 4329 A. (A. S. Wilson and M. V. Penston 1979). Upper panel: vertical axis counts (100–500), with H_{β} and [O III] identified. Lower panel: vertical axis counts (0–400), with H_{α} , [N II], [S II] and A identified. Horizontal axis: velocity (km/s) (–5000, 0, +5000).

Figure 6.20 compares only the wing components of NGC 4151 among the Balmer lines themselves (H_α , H_β , H_γ , H_δ) and with the helium lines He I $\lambda 5876$ and He II $\lambda 4686$. Among the Balmer lines only H_β has an asymmetric shoulder on the long-wavelength side; the other three show symmetric and mutually similar emission-line profiles. D. E. Osterbrock and A. T. Koski (1976) interpreted this as the contribution of Fe II $\lambda 4924$, and if that is correct, it is dangerous to judge asymmetry from the H_β profile alone. In the case of NGC 4151 we may conclude that the Balmer-line wings have identical profiles.

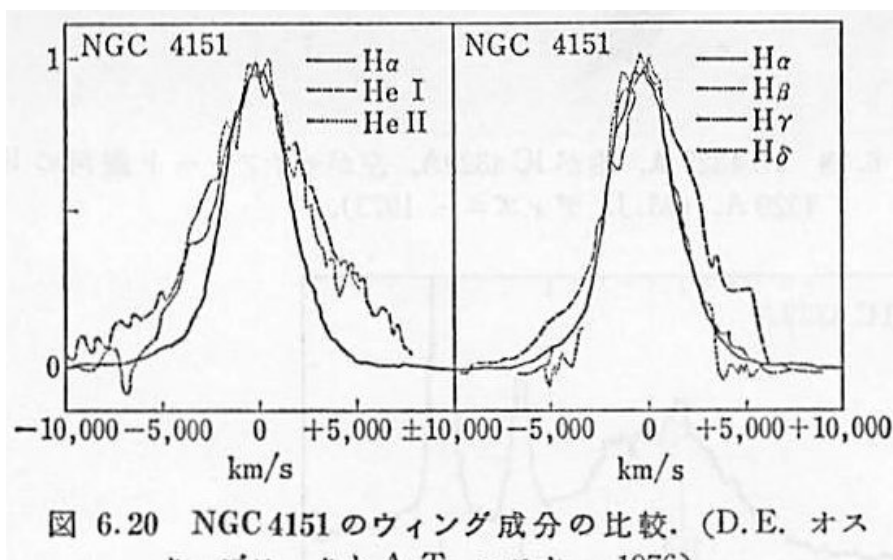


Figure 6.20 Comparison of the wing components of NGC 4151. (D. E. Osterbrock and A. T. Koski 1976). Key, left panel: H_α /He I / He II. Key, right panel: H_α / H_β / H_γ / H_δ . Vertical axis: 0–1; horizontal axis: km/s (–10,000, –5,000, 0, +5,000, ±10,000, –5,000, 0, +5,000, +10,000).

In contrast, He I $\lambda 5876$ and He II $\lambda 4686$ in NGC 4151 form wings far broader than that of H_α . The wing widths (FWHM) of H_α , He I $\lambda 5876$ and He II $\lambda 4686$ are 3,900, 5,500 and 5,900 km/s respectively. In 3C 120 too the emission-line profiles

of H_α and He I $\lambda 5876$ agree comparatively well, but He II $\lambda 4686$ has a wing broader than these (M. M. Phillips and D. E. Osterbrock 1975). Hence in NGC 4151 and 3C 120 the inequality

$$w(\text{Balmer lines}) \leq w(\text{He I}) < w(\text{He II})$$

holds for the emission-line widths, and a tendency is seen for lines of higher ionization potential to have broader profiles. This suggests that even the compact BL region possesses a distinct internal structure.

The ultraviolet emission lines Mg II $\lambda 2798$, C III] $\lambda 1909$, C IV $\lambda 1550$ and L_α $\lambda 1215$ also show broad profiles. Figure 6.21 shows IUE satellite observations of NGC 4151 (M. V. Penston and colleagues, 1979) and 3C 120 (J. B. Oke and B. Zimmerman 1979). The L_α of NGC 4151 is extremely asymmetric, but this is due to absorption. C IV $\lambda 1550$ can be traced out to at least $\pm 4,000$ km/s, in good agreement with the width (FWOI) of H_β , 8,000 km/s.

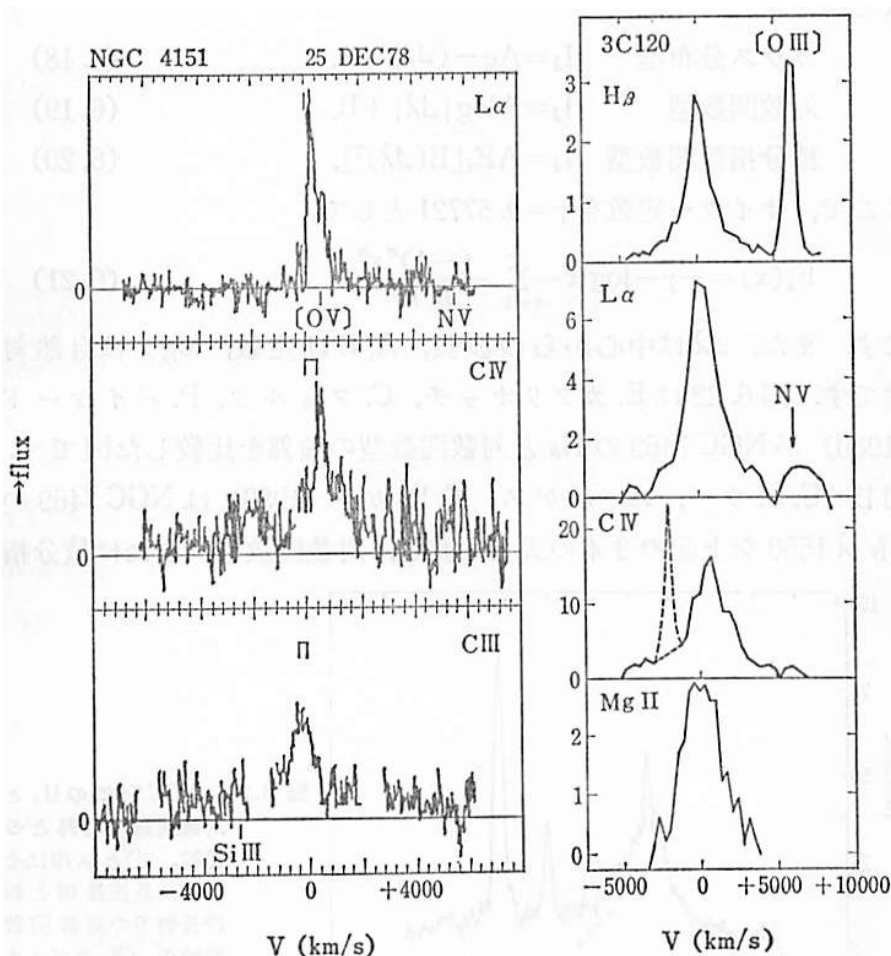


図 6.21 NGC 4151 と 3C 120 の紫外スペクトル. (M. V. ペンストン達 1979; J.B. オークと B. ツィンメルマン 1979).

Figure 6.21 Ultraviolet spectra of NGC 4151 and 3C 120. (M. V. Penston and colleagues 1979; J. B. Oke and B. Zimmerman 1979). Left (NGC 4151, 25 DEC 78): vertical axis $\rightarrow$ flux. Top panel $L\alpha$, with [O V] and N V identified. Middle panel C IV. Bottom panel C III, with Si III identified. Horizontal axis: V (km/s) (-4000, 0, +4000). Right (3C 120): from the top, $H\beta$ and [O III] (0-3); $L\alpha$ (0-6, with N V marked by an arrow); C IV (0-20, with a dashed curve also shown); Mg II (0-3). Horizontal axis: V (km/s) (-5000, 0, +5000, +10000).

To express emission-line profiles quantitatively, the following three theoretical formulae have been tried.

Gaussian $I_\lambda = A e^{-(\Delta\lambda)^2/B}$

Logarithmic $I_\lambda = A \log|\Delta\lambda| + B$

Exponential-integral $I_\lambda = A E_i[B(\Delta\lambda)^2]$

where, with Euler's constant $\gamma = 0.57721$,

$$E_i(x) = -\gamma - \log x - \sum_{n=1}^{\infty} \frac{(-1)^n x^n}{n \cdot n!}$$

Here $\Delta\lambda$ is the wavelength measured from the line center, A and B are constants, and $\log x$ is the natural logarithm. Figure 6.22 is the diagram in which E. Capriotti, C. Foltz and P. Byard (1980) compared the H_β of NGC 7469 with a logarithmic profile. Likewise, C. C. Wu, A. Boggess and T. R. Gull (1980) compared the C IV $\lambda 1550$ of NGC 7469 with the three formulae above and confirmed that the logarithmic or exponential-integral profiles reproduce the observations comparatively well, but that the agreement with a Gaussian profile is poor.

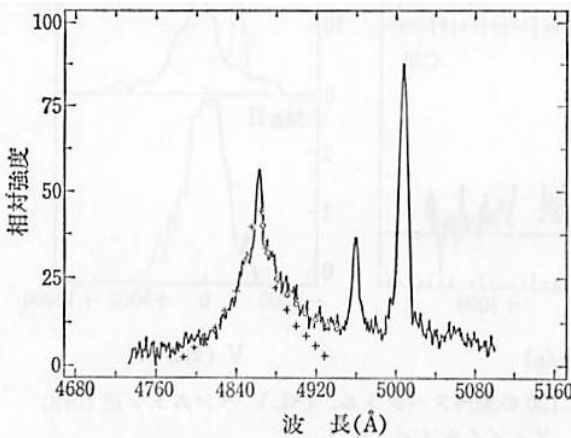


図 6.22 NGC 7469 の H_β と対数関数型輪郭との比較. ○と×印はそれぞれ長波長側と短波長側での対数関数型輪郭. (E. カプリotti, C. フォルツ P. バイヤード 1980).

Figure 6.22 Comparison of the H_{β} of NGC 7469 with a logarithmic profile. The $\circ$ and $\times$ marks are the logarithmic profiles on the long-wavelength and short-wavelength sides respectively. (E. Capriotti, C. Foltz P. Byard 1980). Vertical axis: relative intensity (0, 25, 50, 75, 100); horizontal axis: wavelength ($\text{\AA}$) (4680, 4760, 4840, 4920, 5000, 5080, 5160).

Table 6.15 summarizes the Balmer-line widths (FWHM and FWOI) of type 1 Seyfert galaxies; what characterizes the profiles of type 1 Seyfert galaxies is the FWOI. Since the contributions of the core and the wing differ from galaxy to galaxy, the FWHM gives no measure of the width of the wing.

Table 6.15 Emission-line widths of type 1 Seyfert galaxies

Galaxy	H_{β} FWHM	H_{β} FWOI	H_{α} FWHM	H_{α} FWOI	H I FWHM	H I FWOI
Mk 10	2400	9300	2400	15300	2400	12300
Mk 40	2000	13300	1900	9100	2000	11200
Mk 64	2930	11000				
Mk 69	1500	11100	1500	8200	1500	9600
Mk 79	5200	12200	3300	17100	4200	14600
Mk 106	3700	15700	3300	14200	3500	15000
Mk 110	2500	13000	2200	13200	2400	13100
Mk 124	1400	9800	1400	7500	1400	8600
Mk 141	5300	12300	2300	14900	3800	13600
Mk 142	1700	12300	1100	9100	1400	10700
Mk 236	4900	13000	3700	15100	4300	14000
Mk 279	6200	18500	4100	16900	5200	17700
Mk 290	2500	13000	2500	13000	2500	13000
Mk 291	1100	8300	500	5200	800	6800
Mk 304	5900	15400	4700	22100	5300	18800
Mk 335	1700	10500	1400	9500	1600	10000
Mk 352	3800	12500	3100	14300	3400	13400
Mk 358	2000	7500	1300	8200	1600	7800
Mk 374	4600	10600	3100	15800	3800	13200
Mk 376	5900	18100	4900	20200	5400	19200
Mk 382	1500	7400	1400	6900	1400	7200
Mk 478	1700	10200	1400	9700	1600	10000
Mk 486	2000	14200	1900	12700	2000	13400
Mk 504	2300	13900	1900	11900	2100	12900
Mk 506	3400	12500	3600	11300	3500	12000
Mk 509	3600	15100	2900	12900	3200	14000
Mk 541	3300	10200	2600	10000	2900	10100
Mk 590	3700	9300	3100	13000	3400	11200
Mk 618	2200	10500	2100	8700	2200	9600
Mk 830	8630	20000				

Galaxy	H_{β} FWHM	H_{β} FWOI	H_{α} FWHM	H_{α} FWOI	H I FWHM	H I FWOI
Mk 854	2000	11000				
Mk 876	6170	21000				
NGC 3227	2500	11800	2400	11400	2400	11600
NGC 3516	6800	14800	4300	15500	5600	15200
NGC 5548	3700	15400	3300	14900	3500	15100
NGC 7469	1900	8500	1700	7800	1800	8200
I Zw 1	1400	9600	1200	8200	1300	8900
II Zw 1	1500	11200	1900	12600	1700	11900

Table 6.15 Emission-line widths of type 1 Seyfert galaxies (continued)

Galaxy	H_{β} FWHM	H_{β} FWOI	H_{α} FWHM	H_{α} FWOI	H I FWHM	H I FWOI
II Zw 136	2300	11400	2200	10100	2200	10800
III Zw 2	5700	15800	4100	17400	4900	16600
3 C 120					2000	15000
3 C 227					2500	14000
3 C 382					18000	25000
3 C 390.3					13000	18000
3 C 445					3000	14000
3 C 234	1000	3600	890	13000		
3 C 287.1	1000	4300	2200	13000		
3 C 332	1600	2400	990	3100		
3 C 381	740	1600	790	6000		
PKS 0353+027	1200	10000	...	...		
PKS 1417–19	1900	8800	1600	12000		
PKS 2349–01	5500	23000	5000	27000		
4 C 29.06	1100	22000	1200	22000		
4 C 35.37	1900	5900	...	...		
IVZw 29	950	11000	2500	16000		

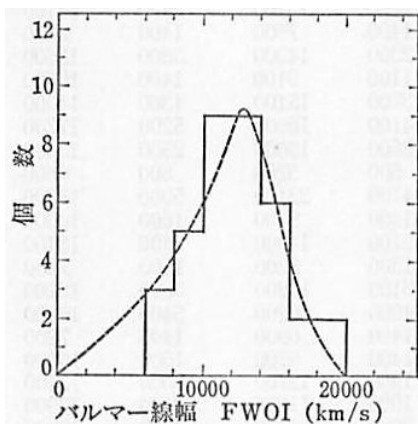


図 6.23 1 型セイファート銀河に対するバルマー線幅 (FWOI) の分布. 波線は回転円盤が無秩序な方向に回転軸を持ち, 回転速度も適当な分布を持つと仮定して計算された理論値. (D. E. オスターブロック 1977).

Figure 6.23 Distribution of Balmer-line widths (FWOI) for type 1 Seyfert galaxies.

The dashed curve is the theoretical value calculated on the assumption that rotating disks have their rotation axes in random directions and that the rotational velocities also have a suitable distribution. (D. E. Osterbrock 1977). Vertical axis: number (0–12); horizontal axis: Balmer-line width FWOI (km/s) (0, 10000, 20000).

Figure 6.23 is the distribution of the FWOI. On average they have widths (FWOI) of 10,000–15,000 km/s, but the widths of 3 C 382, PKS 2349-01, 4C 29.06, Mkn 830 and Mkn 876 exceed 20,000 km/s.

Searching for observable quantities that correlate with the emission-line width is one clue to understanding what property the emission-line profile expresses. Figure 6.24 shows the correlation between the emission-line width (FWOI) of type 1 Seyfert galaxies and the H_{α} luminosity. There is considerable scatter, but one can see a tendency for the emission-line width to be broader the brighter the H_{α} luminosity. The larger the scale of the nucleus, the broader the wings it presumably has.

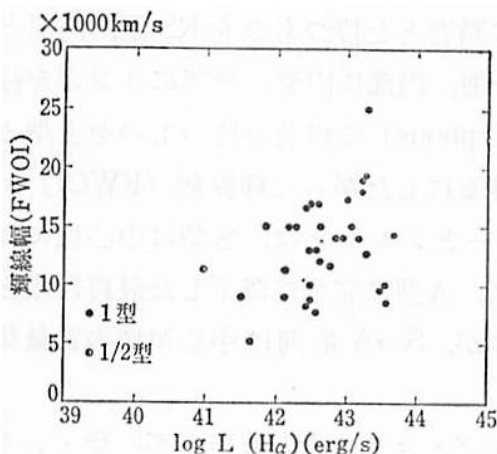


図 6.24 1 型セイファート銀河
に対する $L(H\alpha)$ と輝線
幅 (FWOI).

Figure 6.24 $L(H\alpha)$ versus emission-line width (FWOI) for type 1 Seyfert galaxies. Vertical axis: line width (FWOI) ($\times 1000$ km/s, 0–30); horizontal axis: $\log L(H\alpha)$ (erg/s) (39–45). Key: $\bullet$ type 1, $\circ$ type 1/2.

The correlation between emission-line width and galaxy morphology was clarified by H. J. Su and S. M. Simkin (1980). If one classifies galaxies that have only spiral structure as type S, those with an inner ring and outer spiral as type RS, those with both inner and outer rings as type RR, those with an inner disk and an outer ring as type DR, and those with amorphous structure as type A, then the emission-line width (FWOI) becomes broader in going from type S to type A (Figure 6.25). Su and Simkin suggest an evolutionary sequence in which type S is the early stage where gas has just begun to fall into the nucleus and type A is the final stage after it has fallen in completely; but the $S \rightarrow A$ sequence can equally be regarded as a sequence of mass concentration in the central region.

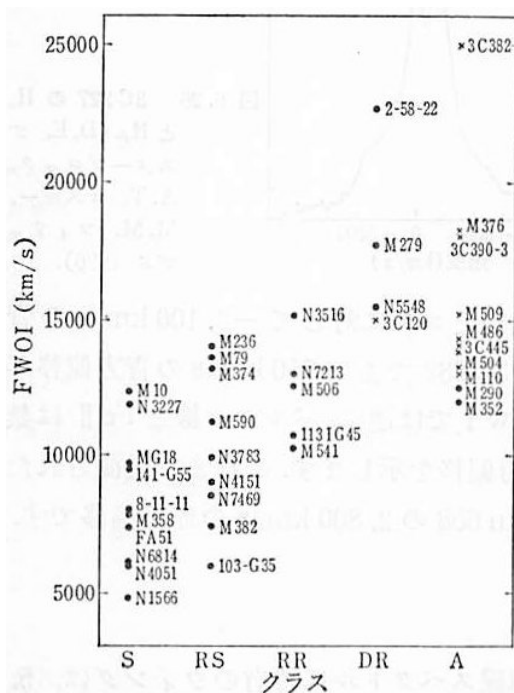


図 6.25 銀河の形態と輝線幅.
(H. J. スーと S. M. シム
キン 1980).

Figure 6.25 Galaxy morphology and emission-line width. (H. J. Su and S. M. Simkin 1980). Vertical axis: FWOI (km/s) (5000–25000); horizontal axis: class (S, RS, RR, DR, A). Objects plotted in the figure (in decreasing order of the vertical axis, grouped approximately by class): Class A — ×3C382, ×M376, 3C390-3, ×M509, M486, ×3C445, M504, M110, M290, M352 Class DR — 2-58-22, M279, N5548, ×3C120 Class RR — N3516, N7213, M506, 113 IG45, M541 Class RS — M236, M79, M374, M590, N3783, N4151, N7469, M382, 103-G35 Class S — M10, N3227, MG18, 141-G55, 8-11-11, M358, FA51, N6814, N4051, N1566

Concerning emission-line profiles, there is the fact that the redshifts of the wings and of the core do not agree. In the $H\alpha$ and $H\beta$ of 3C 227 shown in Figure 6.26 there are two peaks, and the wings show a blueshift of $-2,100$ km/s relative to the forbidden lines and the core. Similarly, a blueshift of -750 km/s is observed in 3C 382 as well. In I Zw 1, however, the opposite occurs: the Balmer lines and Fe II

show a redshift of 600 km/s relative to the forbidden lines. The largest difference observed so far is the redshift of 2,800 km/s in OQ 208 = Mkn 668.

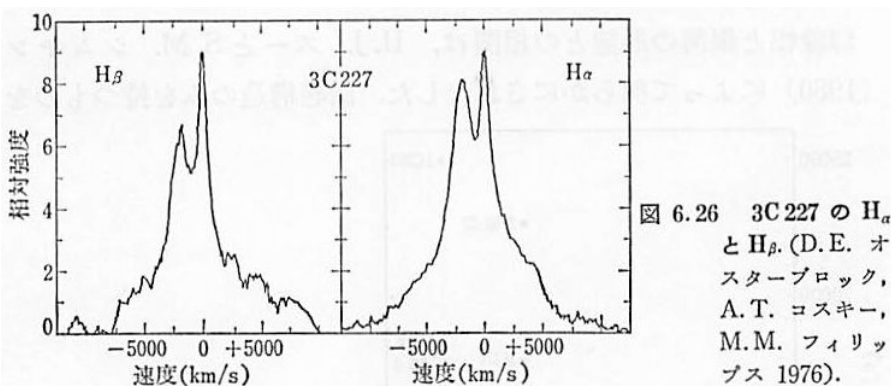


Figure 6.26 $H\alpha$ and $H\beta$ of 3C 227. (D. E. Osterbrock, A. T. Koski, M. M. Phillips 1976). Left panel $H\beta$, right panel $H\alpha$. Vertical axis: relative intensity (0–10); horizontal axis: velocity (km/s) (–5000, 0, +5000).

5. The broadening mechanism

The wings characteristic of the emission-line spectra of type 1 Seyfert galaxies have widths (FWOI) of as much as 5,000–25,000 km/s. Their astonishing speed can be appreciated from the fact that at such velocities it would take only 2.5–0.5 seconds to cross the Earth, whose diameter is 12,740 km.

(1) The gas-cloud motion hypothesis

If, as we saw in NGC 1068, the NL components of type 2 Seyfert galaxies and of type 1 Seyfert galaxies are broadened by the Doppler effect due to the motions of many gas clouds or filaments, then it is conceivable that the wings are broadened by the same mechanism. This motion hypothesis is the broadening mechanism advocated by E. M. Burbidge, G. R. Burbidge and K. H. Prendergast (1959) and by

E. A. Dibai, B. F. Esipov and V. I. Pronik (1968). The latter in particular explained the core-wing structure of the emission lines in terms of two kinds of gas cloud with different densities. In their interpretation, gas clouds produced by a recent explosion have high density ($N_e \gtrsim 10^7/\text{cm}^3$) and moreover high velocity ($v \gtrsim$ several 1,000 km/s), and so produce the wing component, while gas clouds that have expanded sufficiently and slowed down emit the core component and the forbidden lines. If the gas-cloud motion hypothesis is correct, the irregular structure seen in the emission-line profiles of NGC 1068 (Figure 6.16) ought also to appear in the profiles of the wings. A. Boksenberg and H. Netzer (1977) suggest the b component seen in the $H\alpha$ of NGC 3516 as just such observational evidence (Figure 6.27).

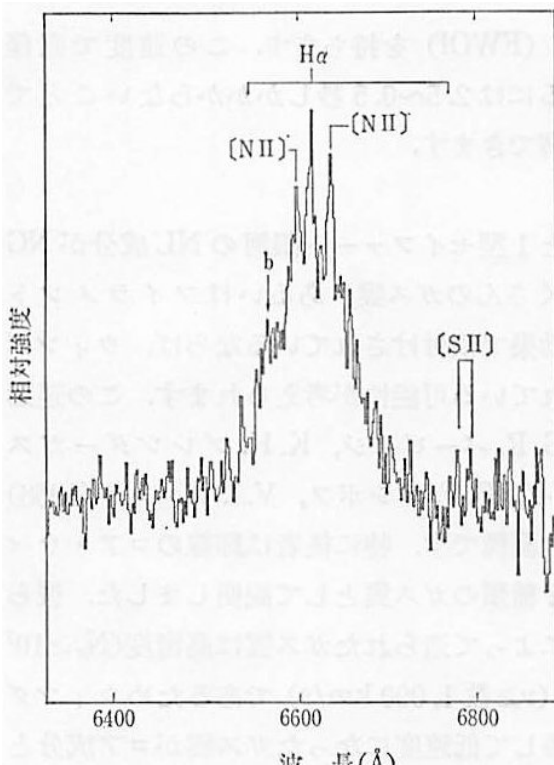


図 6.27 NGC 3516 の $H\alpha$.
(A. ボクセンバーグと
H. ネットァー 1975).

Figure 6.27 *H α of NGC 3516.* (A. Boksenberg and H. Netzer 1975). Vertical axis: relative intensity; horizontal axis: wavelength ($\text{\AA}$) (6400, 6600, 6800). Lines identified in the figure: *H α* , [N II], [N II], b, [S II].

As forms of gas-cloud motion one may consider random motion bound by the gravity of the nucleus, outflow from the nucleus, and infall toward the nucleus. Rotational motion is considered separately. In the case of random motion the emission-line profile becomes the Gaussian distribution of (6.18). G. R. Blumenthal and W. G. Mathews (1975, 1979) have shown that when gas clouds are accelerated by the strong radiation pressure from the nucleus and continue to flow outward, the emission-line profile takes the logarithmic form of (6.19). E. Capriotti, C. Foltz and P. Byard (1980) have further shown that when gas clouds are ejected ballistically from the nucleus and simply flow outward, the emission-line profile can be expressed by the exponential-integral form of (6.20). As compared in Figure 6.22, the emission-line profiles are well approximated by a logarithmic function or by an exponential integral, so random motion can be excluded as the form of gas-cloud motion. With random motion, collisions between gas clouds also become a problem. If collisions occurred frequently at relative velocities of several 1,000 km/s, the gas clouds would be heated to more than 10^8 K and could not remain at $T_e = 1-2 \times 10^4$ K.

From comparison with (6.18)–(6.20) alone one cannot distinguish between outflow and infall, but researchers who advocate the motion hypothesis regard asymmetric emission-line profiles as strong evidence for outflow. E. Capriotti, C. Foltz and P. Byard (1979) explain it as follows. Since a high-density gas cloud in the BL region is ionized only over a thickness of $\sim 10^{13}$ cm on the side facing the nucleus, if the gas clouds are flowing outward at velocities of several 1,000 km/s, then the blueshifted light approaching the observer is weakened because it passes through the neutral region. The redshifted light, on the other hand, is emitted from the

ionized region facing the observer and so suffers no absorption; as a result, an emission-line profile skewed toward longer wavelengths is formed.

It takes 7 years to traverse a radius $R = 10^{17}$ cm at a velocity $v = 5,000$ km/s, so if the gas clouds really are flowing outward the BL region would be emptied in about 10 years. Since, however, no case of an extreme change in emission-line profile has been known since the discovery of Seyfert galaxies, if the outflow model is correct it is essential that high-density gas continue to be supplied to the BL region from the nucleus at a rate of $1\text{--}100M_{\odot}$ per 10 years. If this supply continued throughout the 10^8 years thought to be the lifetime of a Seyfert galaxy, the mass would reach as much as $10^7\text{--}10^9M_{\odot}$.

(2) The rotation hypothesis

The motivation of L. Woltjer (1959), who first proposed the rotation hypothesis, was to construct a nuclear model that could exist stably over the long span of 10^8 years. He erred, however, in taking the apparent size of $\sim 1''$ to be the true radius of the nucleus, and was consequently forced to estimate the mass of the nucleus as $10^{10}\text{--}10^{11}M_{\odot}$.

In the black-hole hypothesis, which is the most promising candidate for the energy source, the rotation of a disk or of a system of gas clouds provides the broadening mechanism. Figure 6.28 is the nuclear model of D. E. Osterbrock (1979). The mass of the black hole is $4 \times 10^7M_{\odot}$, the size of the BL region is 0.1 pc, and its mass is $100M_{\odot}$. The NL region is taken to extend to ~ 100 pc, with a mass of $10^6\text{--}10^7M_{\odot}$. In the equatorial plane the ionizing photons are absorbed, so it becomes a region of neutral atoms and singly ionized ions. The highly ionized region is formed in the polar direction.

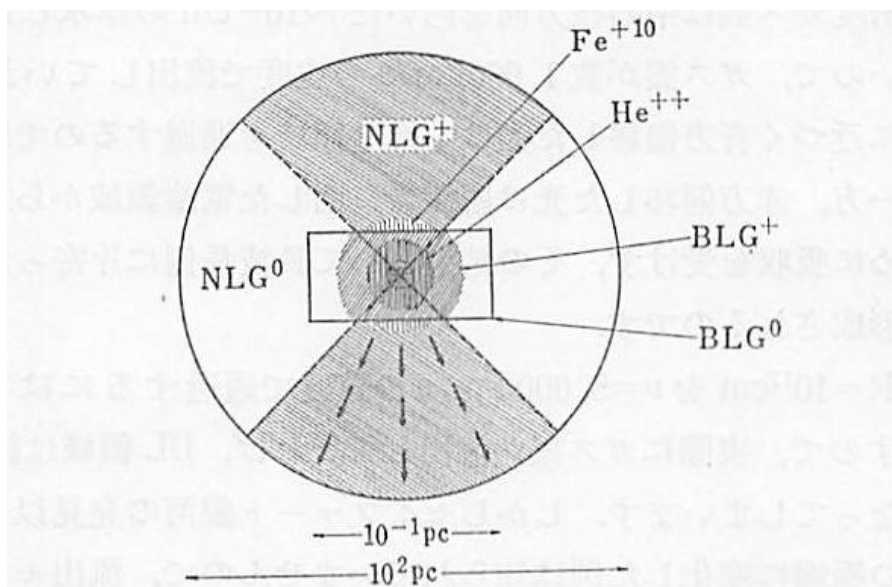


図 6.28 回転円盤モデル. BLG^0 と BLG^+ は BL ガスの中性と電離領域, NLG^0 と NLG^+ は NL ガスの中性と電離領域を意味する. BLG^0 が回転円盤領域で, 中心にはエネルギー源をかこんで He の 2 回電離領域 He^{++} , 鉄の 10 回電離領域 Fe^{+10} , BLG^+ がある. (D. E. オスターブロック 1979).

Figure 6.28 The rotating-disk model. BLG^0 and BLG^+ denote the neutral and ionized regions of the BL gas, and NLG^0 and NLG^+ the neutral and ionized regions of the NL gas. BLG^0 is the rotating-disk region, and at the center, surrounding the energy source, there are the doubly ionized helium region He^{++} , the ten-times ionized iron region Fe^{+10} , and BLG^+ . (D. E. Osterbrock 1979). Scales shown in the figure: 10^{-1} pc (inner), 10^2 pc (outer).

In the rotation model the width of the emission lines appears different depending on the direction of observation. For example, viewed from the equatorial plane the width is twice the rotation velocity, whereas in the polar direction the line-of-sight component of the rotation velocity is zero and no broadening occurs. In Figure 6.23 the distribution of emission-line widths obtained on the assumption that the rotation

axes point in random directions is drawn as a dashed curve. The theoretical distribution appears to reproduce the observations, but below 6,000 km/s it does not fit at all. For this reason Osterbrock supposed that, in addition to a representative rotation velocity of 5,000 km/s, the gas clouds have a turbulent velocity of $\sim 2,000$ km/s. However, the emission-line profile of the turbulent rotation model obtained by E. Capriotti, C. Foltz and P. Byard (1980) deviates considerably from a logarithmic function.

If the plane of rotation of the BL region lay in the same plane as the disk region of the galaxy, one would expect a correlation such that the more inclined the Seyfert galaxy, the broader the emission lines. But in the results of H. J. Su and S. M. Simkin (1980), who examined 32 type 1 Seyfert galaxies, no such correlation exists at all. One must conclude either that the plane of rotation of the BL region is not coplanar with the galactic plane, or that a spherically symmetric broadening mechanism is at work.

(3) The electron-scattering hypothesis

An electron has only $1/1840$ the mass of a proton. Since the equipartition of energy holds between the two in a plasma, electrons move at 43 times the velocity of protons. In a plasma at ten thousand degrees the electron velocity reaches ~ 600 km/s, and if emission-line photons are scattered by these electrons, a wavelength shift of at most ± 600 km/s results.

This electron-scattering hypothesis was proposed by G. B. Field (1958), but he could not explain the core-wing structure. In response, the Burbidges together with F. Hoyle and C. R. Lynds (1966), and J. B. Oke and W. L. W. Sargent (1968), argued that permitted lines such as the Balmer lines must, because of resonance scattering, travel a distance longer than the radius of the nucleus before escaping from the gas within the nucleus, and therefore undergo sufficient electron

scattering. The present author and Hiroshi Ohtani (1968), on the other hand, proposed a two-component-structure model in which, besides the low-density nebular region (the NL region) within the nucleus that radiates the forbidden lines and the cores of the Balmer lines, there is a region (the BL region) so dense that it does not permit the emission of forbidden lines, and the wings of the Balmer lines are formed by electron scattering within this high-density region.

Figure 6.29 is a comparison of the electron-scattering profile for $\tau_{es} = 10$ computed by R. J. Weymann (1970) with the Balmer-line profile of NGC 5548. The smooth wings are well reproduced. The relation between the optical depth of electron scattering,

$$\tau_{es} = 6.65 \times 10^{-25} N_e l$$

and the emission-line width is shown in Figure 6.30. Here N_e (cm^{-3}) is the electron density and l (cm) is the size of the scattering gas. If l is taken as the effective radius, then $\tau_{es} \approx 5$ for NGC 4151 and as much as $\tau_{es} \approx 20$ for III Zw 2. If $T_e = 10^4$ K, then $\text{FWOI} = 10,000$ km/s corresponds to $\tau_{es} \approx 17$, and if the BL region is an atmosphere surrounding the energy source, electron scattering looks promising as a broadening mechanism.

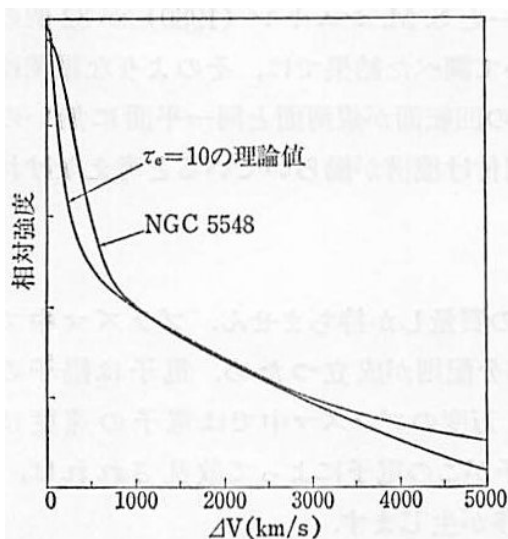


図 6.29 NGC 5548 のバルマー線と電子散乱輪郭との比較。(R. J. ワイマン 1970).

Figure 6.29 Comparison of the Balmer lines of NGC 5548 with an electron-scattering profile. (R. J. Weymann 1970). Vertical axis: relative intensity; horizontal axis: ΔV (km/s) (0–5000). Curves: “theoretical value for $\tau_e = 10$ ” and “NGC 5548”.

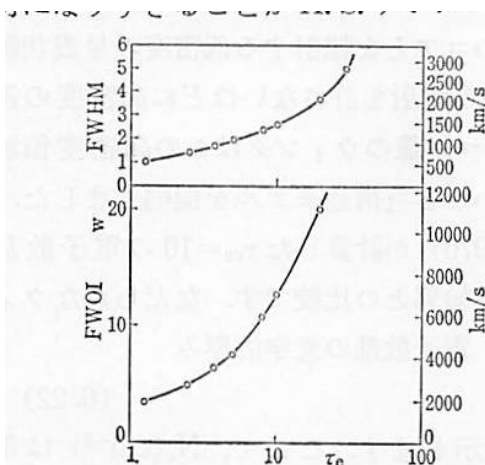


図 6.30 電子散乱輪郭の幅と光学的厚み. 10^4 Kを単位とする温度 $t_4 = T_e/10^4$, 1000 km/s を単位とする速度 $v_8 = V/10^8$ を使えば, 縦軸 w は $w = 1.82 v_8 / \sqrt{t_4}$ と書ける. 右軸の速度は $t_4 = 1$ を仮定.

Figure 6.30 Width of the electron-scattering profile and the optical depth. Using the temperature $t_4 = T_e/10^4$ in units of 10^4 K and the velocity $v_8 = V/10^8$ in units of 1000 km/s, the vertical axis w can be written $w = 1.82 v_8/\sqrt{t_4}$. The velocities on the right-hand axis assume $t_4 = 1$. Upper panel vertical axis: FWHM (1–6), right-hand axis km/s (500–3000). Lower panel vertical axis: FWOI (w , 0–20), right-hand axis km/s (2000–12000). Horizontal axis: τ_e (1–100).

However, K. S. Anderson (1970) pointed out that in such a model the Balmer lines become too optically thick. If electron scattering with $\tau_{es} \gg 1$ occurs, the propagation velocity of light becomes apparently c/τ_{es} , so the electron-scattering hypothesis is also incompatible with short-timescale light variation. There is also indirect evidence that the BL gas clouds cover only about $\sim 10\%$ of the energy source. Furthermore, the polarization spectroscopy of NGC 4151 by G. D. Schmidt and J. S. Miller (1980) is fatal to the electron-scattering hypothesis (Figure 7.27). Unless the BL region is a perfect sphere, the wings should show polarization if they had undergone electron scattering with $\tau_{es} \sim 10$. Yet in their observational results the wings are not polarized at all.

(4) The hypothesis of Ptak and Stoner

R. Ptak and R. E. Stoner (1973, 1975), and R. E. Stoner and R. Ptak (1974, 1977), explained the broadening mechanism in terms of the interaction between high-energy protons ejected from the nucleus and the large amount of partially ionized gas clouds surrounding the nucleus. In this mechanism, the broadened emission lines are radiated by protons that have captured electrons from the partially ionized gas clouds. However, the hypothesis of Ptak and Stoner cannot explain the fundamental property that the emission-line width is nearly the same regardless of the kind of atom. The greatest difficulty of this model lies in its requiring a flux of high-energy protons of 10–100 KeV.

Of the four broadening mechanisms considered above, we may regard the electron-scattering hypothesis and the Ptak–Stoner hypothesis as unlikely. In the end, then, we must return to either the gas-cloud motion hypothesis or the rotation hypothesis, but neither explanation is adequate. More detailed observations, and theoretical analysis based on them, are needed.

6. Variability of the line spectrum

(1) The emission-line spectrum

NGC 3516 is the first Seyfert galaxy in which variability of the emission-line spectrum was discovered. Y. Andrillat and S. Souffrin (1968) compared a spectrum taken in 1967 with Seyfert's observations and noticed that $H\beta$ had weakened extremely relative to $[\text{O III}] \lambda\lambda 4959, 5007$ (Figure 6.31). By 1970 $H\beta$ had strengthened again, and its profile could be traced clearly. A. Boksenberg and H. Netzer (1977) observed variability on an even shorter timescale. In spectra obtained on 7 February and 16 March 1975, $H\beta$ showed a decrease of 30% and $H\alpha$ of 7%, accompanying a decrease in the continuum. During this interval the intensity of $[\text{O III}] \lambda\lambda 4959 + 5007$ remained constant, and the variability occurred only in the Balmer lines (Table 6.16). The correlation between the intensity changes of the Balmer lines and of the continuum was confirmed by A. M. Cherepashchuk and V. M. Lyutyi (1973) (Figure 6.32).

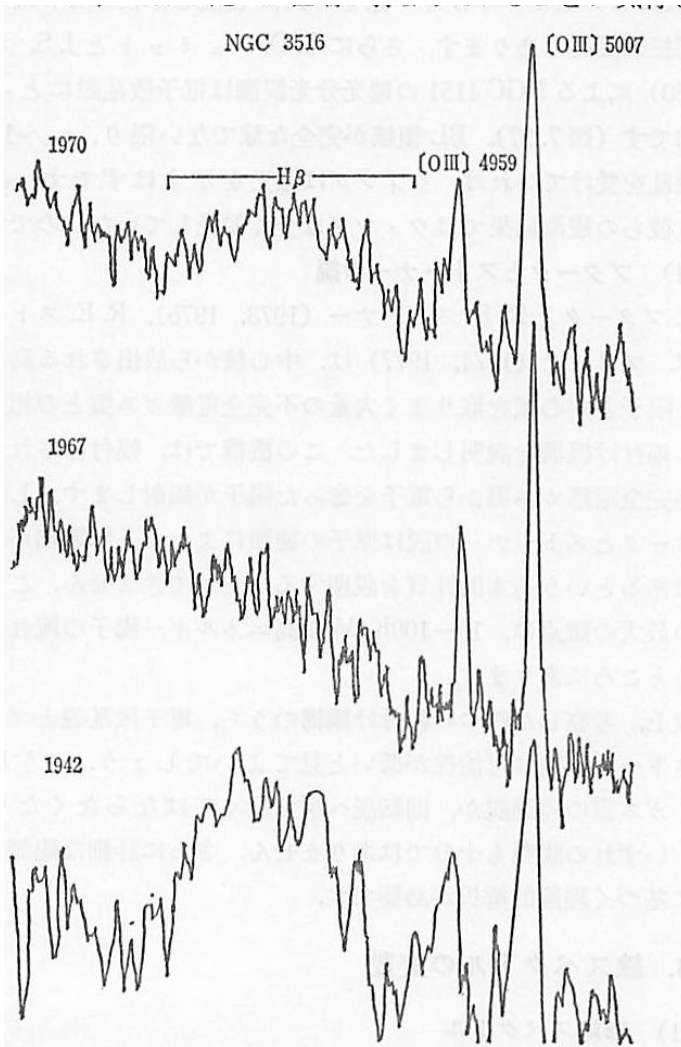


Figure 6.31 Variability of $H\beta$ in NGC 3516. (Y. Andrillat and S. Souffrin 1968). Three spectra (from top: 1970, 1967, 1942). Lines identified in the figure: $H\beta$, $[O III] 4959$, $[O III] 5007$.

Table 6.16 Changes in the emission-line intensities of NGC 3516

Observer	Year	[O III] $\lambda\lambda 4959, 5007$ ($\times 10^{-13}$ erg/s cm ²)	$H\beta$	$H\alpha/H\beta$
Andrillat and Souffrin	1967	7.2	~ 2.9	
Souffrin et al.	1970	6.1	11.5	
Anderson	1970	6.2	3.3	5.06
Adams and Weedman	1974	5.75	5.37	6.31
Boksenberg and Netzer	1975 Feb. 4–7	6.3	12.1	4.5
	1975 Mar. 16	6.3	8.9	5.8

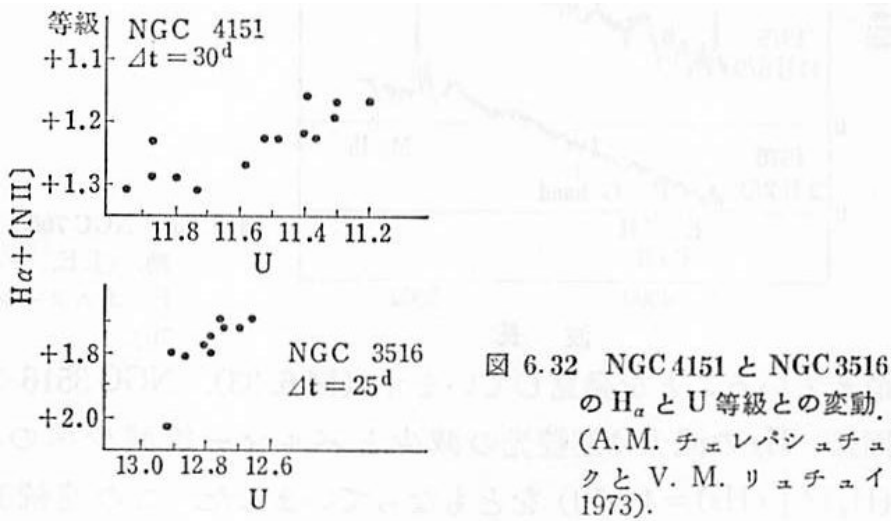


Figure 6.32 Variation of $H\alpha$ against U magnitude for NGC 4151 and NGC 3516. (A. M. Cherepashchuk and V. M. Lyutyi 1973). Upper panel: NGC 4151, $\Delta t = 30^d$. Vertical axis $H\alpha + [N II]$ magnitude (+1.1, +1.2, +1.3); horizontal axis U (11.8, 11.6, 11.4, 11.2). Lower panel: NGC 3516, $\Delta t = 25^d$. Vertical axis $H\alpha + [N II]$ magnitude (+1.8, +2.0); horizontal axis U (13.0, 12.8, 12.6).

J. E. Tohline and D. E. Osterbrock (1976) discovered that although $H\beta$ in NGC 7603 was clearly recognizable in 1974, it had almost disappeared by 1975 (Figure 6.33). As in the case of NGC 3516, the decrease of $H\beta$ was accompanied by a decrease of the continuum and an increase of the Balmer decrement ($I(H\alpha)/I(H\beta) = 4 \rightarrow 10$). This increase of the Balmer decrement accompanying a decrease of the continuum has also been observed in NGC 7469 by A. G. de Bruyn (1980).

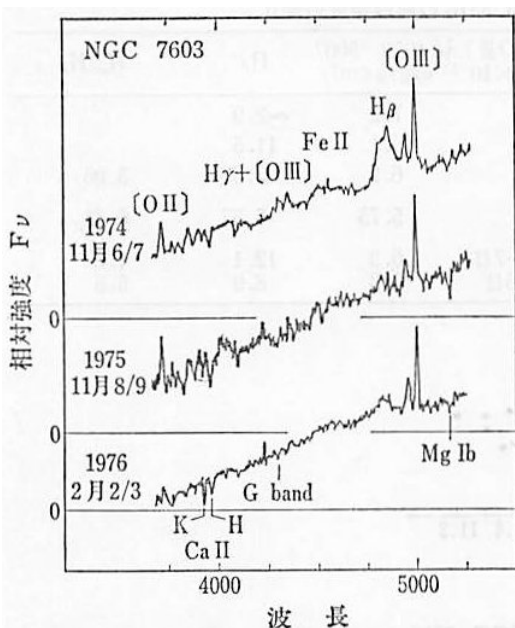


図 6.33 NGC 7603 の $H\beta$ の変動。(J. E. トーリンと D. E. オスターブロッック 1976).

Figure 6.33 Variability of $H\beta$ in NGC 7603. (J. E. Tohline and D. E. Osterbrock 1976). Vertical axis: relative intensity F_ν ; horizontal axis: wavelength (4000, 5000). Three spectra: 1974 Nov. 6/7, 1975 Nov. 8/9, 1976 Feb. 2/3. Lines identified in the figure: [O II], $H\gamma + [O III]$, Fe II, $H\beta$, [O III], Mg Ib, G band, Ca II K, H.

Since the intensity changes of the Balmer lines are due to variability of the wings, the timescale of the variability provides one measure of the size of the BL region. This is because even if variability occurred on intervals shorter than the time

required for light to cross the BL region, such variability would be smoothed out over the BL region as a whole. If the time over which variability can be clearly distinguished is t seconds, the radius of the BL region can be expressed as $R \approx ct$. Here the velocity of light is $c = 3 \times 10^{10}$ cm/s. Taking for NGC 3516 the five weeks found by Bokserberg and Netzer as t gives $R \sim 10^{17}$ cm; and regarding the 25-day lag Δt in the variability found by Cherepashchuk and Lyutyi as the propagation time from the nucleus to the BL region also gives $R \sim 10^{17}$ cm. Here lies the basis for taking ~ 0.1 pc as the representative size of the BL region.

Because the emission coefficient of the Balmer lines does not depend strongly on temperature, their luminosity is proportional to the product of the electron and proton densities, $N_e N_p \approx N_e^2$, and to the volume V of the BL gas clouds. Since the mass of the BL gas clouds can be written $M \propto N_e V$, the luminosity of the Balmer lines can be expressed as

$$L(\text{Bal}) \propto N_e M$$

Accordingly, variability of the Balmer lines arises either because (i) N_e changes while M stays constant, or (ii) M has changed; but it is difficult to alter the density of the whole BL region greatly in a short time. Probably the BL region contains a considerable amount of neutral or partially ionized gas, which is ionized by an increase in the ultraviolet light, thereby strengthening the Balmer lines.

(2) The absorption-line spectrum

In NGC 4151 there is an absorption line near $\lambda 3880\text{\AA}$. This had already been pointed out in 1934 by N. D. Mayall, but he took it to be CN absorption ($\lambda 3835$). K. S. Anderson and R. P. Kraft (1969) observed it and concluded that, as O. C. Wilson had suggested, it is the $\lambda 3889$ absorption arising from the metastable state (2^3S) of neutral helium. Figure 6.34 is the spectrum they obtained. Between [Ne III] $\lambda 3869$ and He I + H_γ $\lambda 3889$ there are three absorption lines, shifted by -280 , -550 and

−840 km/s respectively. In H_γ and H_β a further absorption line blueshifted by −970 km/s can be seen. Note also that strong absorption on the short-wavelength side was seen in L_α and C IV $\lambda 1550$ of NGC 4151 (Figure 6.21).

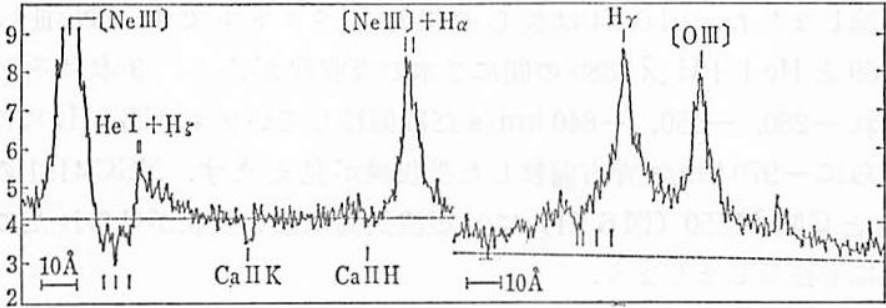


Figure 6.34 Absorption lines of NGC 4151. (K. S. Anderson and R. P. Kraft 1969). Vertical axis: 3–9. Lines identified in the figure: [Ne III], He I + H_z , [Ne III] + H_α , H_γ , [O III], Ca II K, Ca II H. Scale bar: 10 Å.

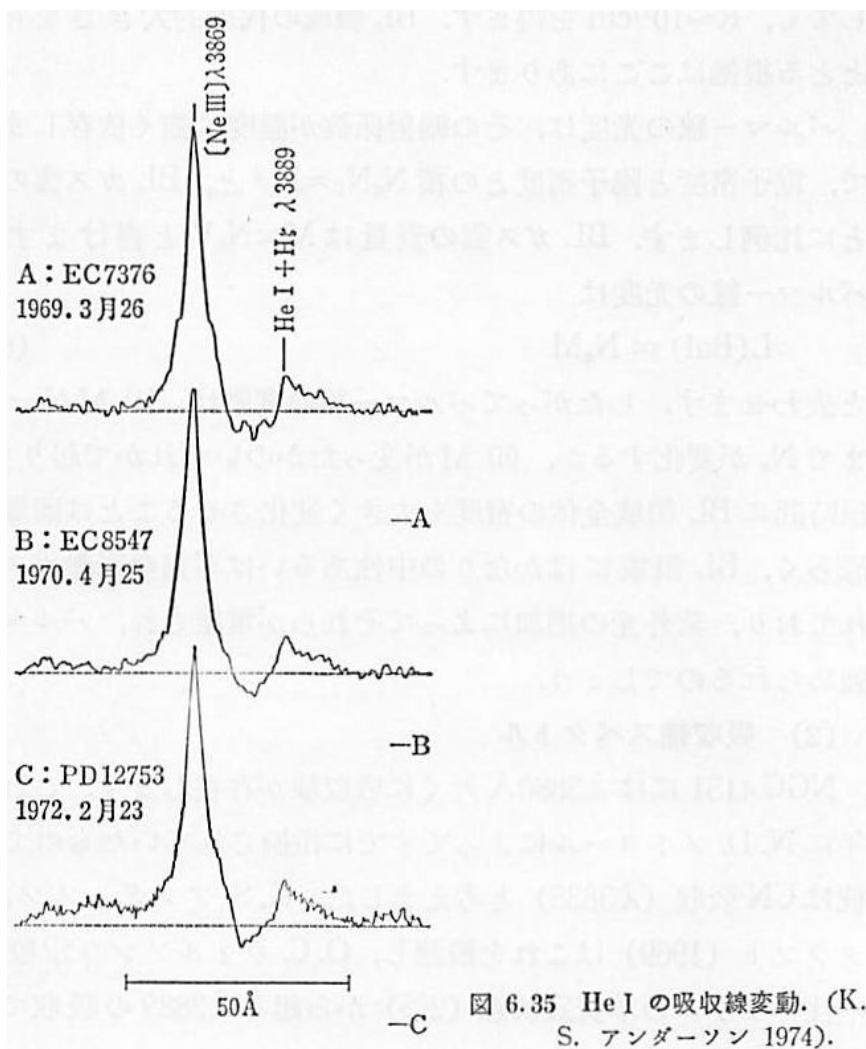


Figure 6.35 Variability of the He I absorption line. (K. S. Anderson 1974). A: EC7376, 1969 Mar. 26 / B: EC8547, 1970 Apr. 25 / C: PD12753, 1972 Feb. 23. Lines identified in the figure: [Ne III] $\lambda 3869$, He I + H_{ϵ} $\lambda 3889$. Scale bar: 50 Å.

The absorption lines of He I and of the Balmer lines vary on timescales of several months to a year. R. Cromwell and R. E. Weymann (1970) compared their spectra

obtained in 1969 and 1970 with observations already published and confirmed that in 1956, 1962 and 1968 the $H\beta$ absorption line had disappeared. Figure 6.35 shows the He I observations of K. S. Anderson (1974). Between 1969, 1970 and 1972 the He I absorption line changed greatly. Similarly, variability of the absorption line seen in $H\beta$ of 3C 390.3 has been reported by D. E. Osterbrock et al. (1976).

One possible cause of the variability of the absorption lines is that a gas cloud crosses in front of the BL region, just like a solar eclipse; but even running for three months at a velocity of $V = 1,000$ km/s gives only $l \sim 10^{15}$ cm. It is thought that either gas was ejected intermittently from the nucleus, or the physical state of the absorbing gas clouds changed in step with the light variation of the nucleus. R. E. Weymann and R. Cromwell (1972) and K. S. Anderson (1974) suggest that the equivalent width of the absorption lines of NGC 4151 weakens as the continuum increases, but unfortunately there have been no subsequent observations.

Chapter VII. Visible and Ultraviolet Continuum

1. Spectral Distribution

(1) Broadband Photometry and the Two-Color Diagram

The spectral distribution of the continuum can be determined by broadband photometry. This measures the intensity of light in a target wavelength range using a combination of a photomultiplier tube and color filters. The most representative photometric systems are summarized in Table 7.1. Here U, B, V, R, I are the initials of ultraviolet, blue, visible, red, and infrared respectively. The radiative flux f_ν ($\text{W}/\text{m}^2\text{Hz}$) and the absolute magnitude M_λ at wavelength λ are connected by the following relation.

Table 7.1 Broadband photometric systems

Filter photometric band	Central wavelength $\lambda(\mu)$	Bandwidth $\Delta\lambda(\mu)$	Flux at 0 mag $\text{W}/\text{m}^2\text{Hz}$
U	0.36	0.066	1.88×10^{-23}
B	0.44	0.098	4.44×10^{-23}
V	0.55	0.087	3.81×10^{-23}
R	0.70	0.207	3.01×10^{-23}
I	0.90	0.231	2.43×10^{-23}
J	1.25	0.297	1.77×10^{-23}
H	1.60		1.08×10^{-23}
K	2.20	0.578	6.80×10^{-24}
L	3.40	0.701	3.00×10^{-24}
M	5.00	1.128	1.80×10^{-24}
N	10.20	4.330	4.30×10^{-25}
Q	22.00	7.500	1.02×10^{-25}

$$M_{\lambda} = -2.5 \log \left(\frac{f_{\nu}}{\text{flux at 0 mag}} \right)$$

Here c is the speed of light with $c = \lambda \nu$, and $\log$ is the common logarithm. Note that the flux values at zero magnitude are not the same in each band. For example, B is 17% larger than V. For this reason the AB magnitude, which does not depend on wavelength or frequency,

$$AB = -2.5 \log f_{\nu} - 56.10$$

is also used. It is defined so that $AB(\lambda 5450) \approx V$.

Differences between magnitudes measured in different bands give the slope of the spectral distribution. The most commonly used are (U–B) and (B–V), which are called color indices. If the spectral distribution is approximated by a power law $f_{\nu} \propto \nu^{-\alpha}$, the relation between the spectral index α and (U–B), (B–V) is expressed as

$$\begin{aligned} (U - B) &= 0.22\alpha - 0.90 \\ (B - V) &= 0.24\alpha + 0.10 \end{aligned}$$

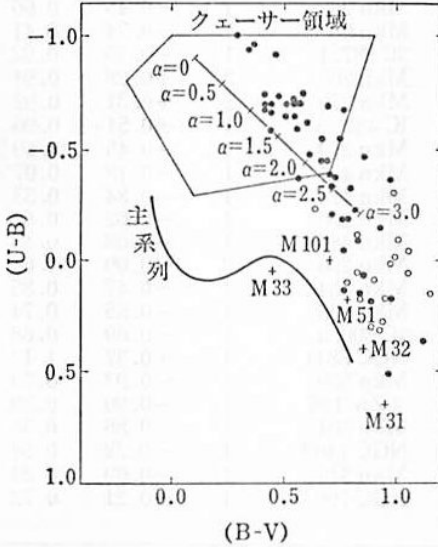


図 7.1 セイファート銀河の2色図。白丸が2型，黒丸が1型，+印は正常銀河。

Figure 7.1 Two-color diagram of Seyfert galaxies. Open circles are type 2, filled circles are type 1, and plus signs are normal galaxies. Vertical axis (U-B): -1.0 to 1.0 (negative upward); horizontal axis (B-V): 0.0 to 1.0. Annotations in the figure are “quasar region” and “main sequence”, together with $\alpha = 0$, $\alpha = 0.5$, $\alpha = 1.0$, $\alpha = 1.5$, $\alpha = 2.0$, $\alpha = 2.5$, $\alpha = 3.0$ marked along the mixing line. Normal galaxies shown as plus signs are M 101, M 33, M 51, M 32, M 31.

Let us plot Seyfert galaxies on a two-color diagram. A two-color diagram is drawn with (U-B) and (B-V) as the vertical and horizontal axes respectively; in Figure 7.1 the list of D. W. Weedman (1977) (Table 7.2) is used. Representative normal galaxies are also plotted for comparison. The first thing the two-color diagram shows is that, compared with normal galaxies, the continuum of Seyfert galaxies is blue — in other words, it has a flatter spectral distribution. The difference between type 1 and type 2 is also clear. Type 1 Seyfert galaxies are very blue and many of them lie in the quasar region, whereas type 2 Seyfert galaxies have relatively steep spectral distributions, and some of them even show colors similar to those of normal galaxies.

Table 7.2 Color indices of Seyfert galaxies

Galaxy	Type	U–B	B–V	Galaxy	Type	U–B	B–V
Mkn 335	1	–0.70	0.41	NGC 3516	1	–0.18	0.77
III Zw 2	1	–0.70	0.52	VV 144	1	–0.23	0.82
Mkn 348	2	+0.17	0.95	Mkn 176	2	+0.30	0.89
I Zw 1	1	–0.80	0.36	NGC 3783	1	–0.70	0.56
Mkn 352	1	–0.66	0.44	Mkn 42	1	–0.19	0.79
Mkn 1	2	+0.09	0.90	NGC 4051	1	–0.38	0.73
II Zw 1	1	–0.42	0.57	NGC 4151	1	–0.72	0.53
Mkn 358	1	–0.32	0.79	Mkn 231	1	+0.15	0.84
NGC 985	1	–0.95	0.36	Mkn 236	1	–0.45	0.66
NGC 1068	2	–0.01	1.00	Mkn 64	1	–0.74	0.41
Mkn 372	2	–0.03	1.05	3C 287.1	1	–0.15	0.92
NGC 1275	2?	–0.23	0.64	Mkn 268	2	+0.28	0.94
III Zw 55	2	+0.17	0.84	Mkn 270	2	+0.31	0.92
NGC 1566	1	–0.04	0.76	IC 4329A	1	+0.51	0.96
3C 120	1	–0.75	0.58	Mkn 279	1	–0.45	0.69
Mkn 3	2	+0.15	1.15	Mkn 474	1	–0.18	0.97
Mkn 6	1/2	+0.02	0.97	Mkn 478	1	–0.84	0.33
Mkn 374	1	–0.38	0.70	Mkn 290	1	–0.62	0.60
Mkn 376	1	–0.58	0.55	Mkn 486	1	–0.68	0.43
Mkn 9	1	–0.64	0.54	Mkn 298	2	–0.09	1.01
Mkn 78	2	–0.31	0.99	Mkn 504	1	–0.47	0.85
Mkn 79	1	–0.74	0.47	Mkn 506	1	–0.55	0.74
Mkn 10	1	–0.55	0.67	3C 390.3	1	–0.69	0.68
Mkn 382	1	–0.63	0.51	NGC 6814	1	+0.37	1.12
Mkn 110	1	–0.67	0.76	Mkn 509	1	–0.93	0.23
3C 227	1	–0.36	0.98	II Zw 136	1	–0.90	0.29
Mkn 124	1	–0.47	0.61	Mkn 304	1	–0.86	0.36
Mkn 141	1	–0.32	0.71	NGC 7469	1	–0.72	0.54
NGC 3227	2/1	–0.11	0.82	Mkn 315	1	–0.09	0.82
Mkn 142	1	–0.58	0.44	NGC 7603	1	–0.21	0.72

Galaxy	Type	U-B	B-V	Galaxy	Type	U-B	B-V
Mkn 34	2	+0.07	1.06				

(2) The Spectral Distribution of the Continuum

Broadband photometry is well suited to the purpose of observing large numbers of objects quickly, but its bandwidth ($\Delta\lambda \approx 1,000\text{\AA}$) is too wide to allow an accurate spectral distribution to be obtained. Recently, in its place, accurate observations covering a wide wavelength range using spectrophotometers have come to be carried out. For example, with the multichannel spectrophotometer used at the Hale Observatories, the wavelength range $\lambda\lambda 3,100 - 12,000\text{\AA}$ is measured simultaneously with 33 photomultiplier tubes. The bandwidth of each channel is chosen from 20, 40, 80, 160, or $320\text{\AA}$ according to the purpose.

The spectral distributions of classical Seyfert galaxies measured by K. S. Anderson (1970) are shown in Figure 7.2. A 2.5 m telescope and a multichannel spectrophotometer were used for the observations, and the aperture was 8" in diameter (14" for NGC 3516 only). The peak on the left is H_α $\lambda 6563$, and the two strong lines in the center together with the peak to their right are [O III] $\lambda\lambda 5007, 4959$ and H_β $\lambda 4861$. Removing such emission lines and smoothing what remains gives the continuum spectrum. A more detailed continuum spectrum of NGC 1068 has already been seen in Figure 6.2. As is clear from a comparison with the continuum spectra of M 31 and M 32, in Seyfert galaxies the ultraviolet light is far stronger and the spectrum is flatter. This is the "blue" property seen in the two-color diagram.

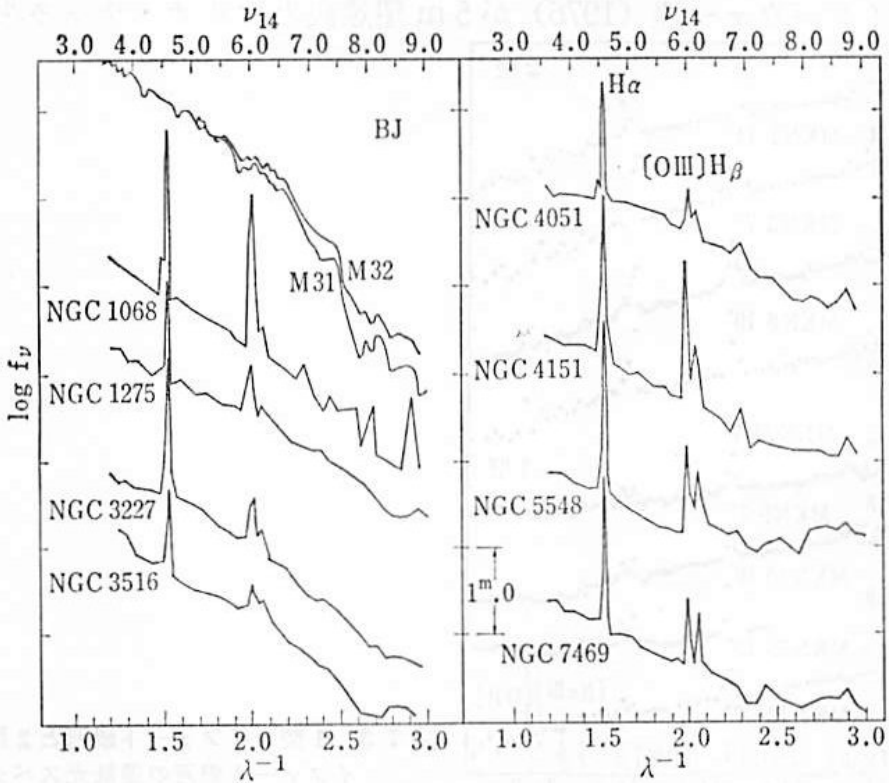


Figure 7.2 Continuum spectra of classical Seyfert galaxies (K. S. Anderson 1970). Vertical axis $\log f_\nu$; horizontal axis λ^{-1} (1.0–3.0); upper axis ν_{14} (3.0–9.0). Objects in the left panel, from the top: NGC 1068, NGC 1275, NGC 3227, NGC 3516, with M 31, M 32 and BJ shown for comparison. Objects in the right panel, from the top: NGC 4051, NGC 4151, NGC 5548, NGC 7469. Line identifications: H_α , $[O III] H_\beta$. A scale bar of $1^m.0$ is at the lower left of the right panel.

NGC 1068 and NGC 1275 are classified as type 2. NGC 3227 is classified as either type 2 or type 1. If the spectra of Figure 7.2 are divided into type 1 and type 2, one notices that type 1 is flatter, and that NGC 4151, NGC 5548 and NGC 7469 have strong ultraviolet excesses. Figure 7.3 shows continuum spectra observed by G. Neugebauer et al. (1976) with the 5 m telescope and the multichannel

spectrophotometer. Mkn 1, Mkn 3, Mkn 6 and Mkn 34 are type 2, while Mkn 9, Mkn 10, Mkn 79 and Mkn 124 are type 1; comparing the two groups shows that, again, type 1 Seyfert galaxies have flatter spectra. In II Zw 136, which has an extremely flat spectrum, there is a minimum at 4,000–5,000Å with the flux rising on both sides (J. B. Oke and G. A. Shields 1976).

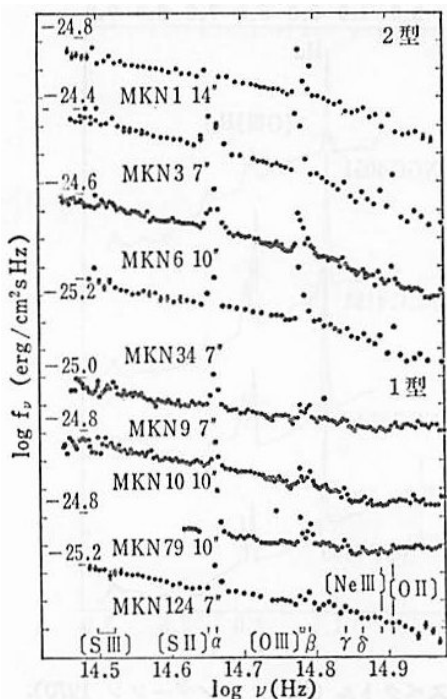


図 7.3 1型セイファート銀河と2型セイファート銀河の連続光スペクトル。(G. ノイゲbauer達 1976)。

Figure 7.3 Continuum spectra of type 1 and type 2 Seyfert galaxies. (G. Neugebauer et al. 1976). Vertical axis $\log f_\nu$ ($\text{erg}/\text{cm}^2 \text{s Hz}$); horizontal axis $\log \nu$ (Hz) (14.5–14.9). “type 2” is marked in the upper part and “type 1” in the middle. Object names, from the top: MKN 1 14”, MKN 3 7”, MKN 6 10”, MKN 34 7”, MKN 9 7”, MKN 10 10”, MKN 79 10”, MKN 124 7”. The ordinate values marked, from the top: -24.8, -24.4, -24.6, -25.2, -25.0, -24.8, -24.8, -25.2. Line identifications along the bottom: [S III], [S II], α (H_α), [O III], β , γ , δ , [Ne III], [O II].

(3) Absolute Luminosity and Spectral Distribution of the Continuum

Since the continuum is characterized both by the relative shape of its spectrum and by its absolute brightness, dealing only with the relative spectral distribution risks losing sight of an important aspect. Table 7.3 gives the absolute radiative flux $F_\nu(U)$ at $3,600\text{\AA}$, corresponding to the central wavelength of the U magnitude, obtained from the observational data of A. G. de Bruyn and W. L. W. Sargent (1978), together with the spectral index defined between $3,600\text{\AA}$ and $9,000\text{\AA}$, the latter corresponding to the central wavelength of the I magnitude:

$$\alpha(U - I) = -\frac{\log F_\nu(U) - \log F_\nu(I)}{\log \nu(U) - \log \nu(I)}$$

Here $\nu(U)$ and $\nu(I)$ are the frequencies of light at wavelengths $3,600\text{\AA}$ and $9,000\text{\AA}$. The observations of de Bruyn and Sargent cover the wide wavelength range $\lambda 3,140 - 10,680\text{\AA}$; the bandwidth of each channel is $20\text{\AA}$ in the blue region ($\lambda \leq 5,720\text{\AA}$) and $40\text{\AA}$ in the red region ($\lambda \geq 5,720\text{\AA}$), and the aperture used for the observations was $10''$ in diameter.

Table 7.3 Absolute radiative flux $F_\nu(U)$ and spectral index $\alpha(U - I)$

Galaxy	$F_\nu(U)$ $\times 10^{28} \text{erg/sHz}$	$\alpha(U - I)$	Galaxy	$F_\nu(U)$ $\times 10^{28} \text{erg/sHz}$	$\alpha(U - I)$
Type 2: Mkn 1	0.57	2.7	Type 1: Mkn 290	15	0.7
Mkn 3	0.98	3.6	Mkn 291	5.0	1.3
Mkn 6	2.7	2.5	Mkn 304	80	0.6
Mkn 34	5.6	2.5	Mkn 335	36	0.2
Mkn 42	1.6	2.0	Mkn 352	3.1	1.0
Mkn 78	2.6	3.3	Mkn 358	4.2	2.2
Mkn 176	1.8	2.9	Mkn 374	18	1.2
Mkn 198	1.9	2.6	Mkn 376	49	1.1
Mkn 268	3.8	3.1	Mkn 391	0.81	2.6
Mkn 270	0.32	3.3	Mkn 464	6.3	0.8
Mkn 273	3.6	2.7	Mkn 471	4.3	2.5
Mkn 315	6.3	2.4	Mkn 474	3.2	2.5
Mkn 348	0.20	4.1	Mkn 478	110	0.7
Mkn 372	1.4	3.5	Mkn 486	19	0.8
Mkn 463	10	3.7	Mkn 506	2.4	2.3
NGC 1068	1.0	2.8	Mkn 509	62	0.4
NGC 1275	9.8	1.8	Mkn 618	16	1.1
I Zw 92	9.5	0.8	NGC 3516	3.1	2.1
III Zw 55	1.4	3.0	NGC 4051	0.10	2.2
NGC 3227	0.086	3.3	NGC 4151	1.9	0.8
			NGC 5548	6.1	1.4
Type 1: Mkn 9	18	1.1	NGC 7469	15	1.2
Mkn 10	7.5	1.6	NGC 7603	5.5	2.5
Mkn 40	0.65	2.5	NGC 6814	0.13	3.3
Mkn 50	3.2	1.5	I Zw 1	68	1.2
Mkn 69	18	1.1	II Zw 136	66	0.6
Mkn 79	12	1.0	III Zw 2	150	0.6
Mkn 110	10	0.8	III Zw 77	6.0	0.9

Galaxy	$F_{\nu}(U)$ $\times 10^{28} \text{erg/sHz}$	$\alpha(U-I)$	Galaxy	$F_{\nu}(U)$ $\times 10^{28} \text{erg/sHz}$	$\alpha(U-I)$
Mkn 141	8.8	1.6	3C 120	19	1.3
Mkn 142	8.1	1.0	3C 382	45	1.2
Mkn 205	15	0.4	3C 390.3	23	1.2
Mkn 231	12	2.7	MCG 8-11-11	3.1	1.8
Mkn 279	26	0.9	PKS 2349-0	1220	0.4

Figure 7.4 is a plot of Table 7.3. Open and filled circles are type 2 and type 1 Seyfert galaxies respectively. The property that brighter objects have flatter spectra is seen for the sample as a whole, including both type 1 and type 2, but a clear tendency is also recognized for type 1 to occupy the flat, bright region and type 2 the steeper, fainter region, with the boundary at $\alpha(U-I) \sim 2$.

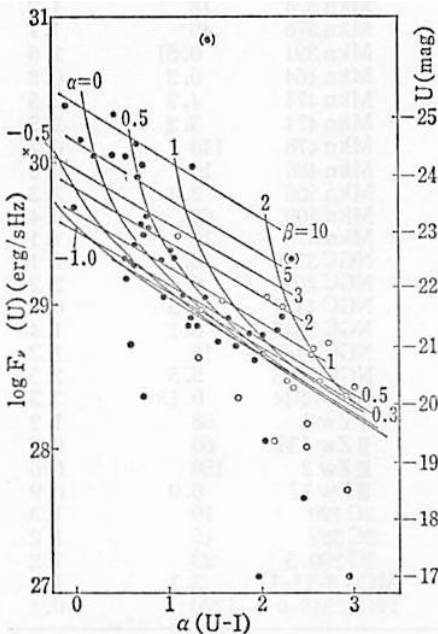


図 7.4 絶対流速 $F_{\nu}(U)$ とスペクトル指数 $\alpha(U-I)$ のプロット。●印は中間型、あるいは1型とも2型とも分類される NGC 3227 と Mkn6. 曲線は銀河光とスペクトル指数 α^* を持つ中心核連続光との混合曲線. β は $\lambda=0.9 \mu$ での銀河光 $f_{\nu}(G)$ に対する中心核光 f_{ν}^* の比: $\beta=f_{\nu}^*/f_{\nu}(G)$. (山本将史と橋場孝の卒業研究 1980)

Figure 7.4 Plot of the absolute flux $F_\nu(U)$ against the spectral index $\alpha(U-I)$. The half-filled symbols are NGC 3227 and Mkn 6, which are of intermediate type, or are classified as either type 1 or type 2. The curves are mixing curves of galaxy light with nuclear continuum light having spectral index α . β is the ratio of the nuclear light f_ν to the galaxy light $f_\nu(G)$ at $\lambda = 0.9\mu$: $\beta = f_\nu^*/f_\nu(G)$. (Graduation research of Yamamoto, M. [山本将史] and Hashiba, T. [橋場孝] 1980) Vertical axis $\log F_\nu(U)$ (erg/sHz): 27 to 31; right-hand vertical axis $U(\text{mag})$: -17 to -25; horizontal axis $\alpha(U-I)$: 0 to 3. The values marked on the mixing curves are $\alpha = 0, 0.5, 1, 2$ and $\beta = 10, 5, 3, 2, 1, 0.5, 0.3$.

A suggestive fact for considering the meaning of such a correlation has been pointed out by J. B. Oke (1972). It is as follows.

- (1) In galaxies with a steep slope, $\alpha > 2.1$, the stellar absorption lines H and K are always observed.
- (2) In galaxies with relatively flat spectra, $2.1 > \alpha > 1.4$, the H and K lines are sometimes seen and sometimes not, depending on the luminosity and the spectral index.
- (3) In flat spectra with $\alpha < 1.4$, the H and K lines are not observed.

In other words, it is thought that in the steep spectra with $\alpha > 2.1$ a considerable amount of starlight is mixed in, whereas the flat spectra with $\alpha < 1.4$ contain almost no starlight. Oke uses a spectral index α defined between 4,000 and 10,000Å, but it can be identified with our $\alpha(U-I)$. Figure 7.4 can therefore be interpreted as meaning that the brighter the object, the smaller the degree of contamination by light from the stars making up the galaxy. Put another way, because of the contamination by starlight, the observed spectral distribution is not the true spectral distribution of the nucleus.

Before analyzing the true spectral distribution of the nucleus, let us examine the correlation between the absolute brightness of the continuum and the emission-line spectrum. Figure 7.5 shows $F_\nu(U)$ against $L(H_\alpha)$, with type 1 and type 2

distinguished by filled and open circles respectively. Type 2 shows a large scatter, but for type 1 a relatively good proportionality holds. As expected from Figure 6.24, a relation is also seen in which the brighter the continuum, the broader the emission lines. The property that the correlation scatters relatively widely for type 2 Seyfert galaxies is one we have already seen in the emission-line spectra, and is presumably due to an inhomogeneous nuclear structure. The good correlation seen in type 1 Seyfert galaxies implies a self-similar structure of the nucleus, and at the same time suggests that the gas radiating the emission lines is ionized by the ultraviolet continuum.

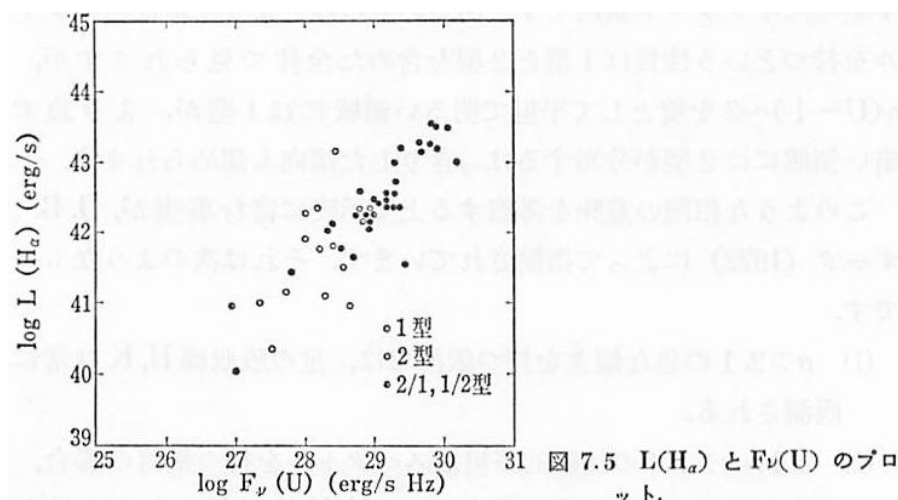


Figure 7.5 Plot of $L(H_\alpha)$ against $F_\nu(U)$. Vertical axis $\log L(H_\alpha)$ (erg/s): 39 to 45; horizontal axis $\log F_\nu(U)$ (erg/s Hz): 25 to 31. Legend: type 1 (open circles), type 2 (filled circles), types 2/1 and 1/2.

2. The Nuclear Continuum

(1) Background Light

The background light that interferes with determining the spectral distribution of the nuclear light consists of the light of stars within the galaxy and the continuum radiated by the ionized gas within the nucleus.

Galaxy light When observing the continuum, the aperture diameter of the photometer is usually chosen to be around $10''$. This angle of $10''$ corresponds to 1 kpc even for nearby galaxies such as NGC 1068 and NGC 4151, and to as much as 10 kpc for 3C 120, so that it covers a major part of the galaxy. Taking the Andromeda galaxy M31 as an example, the region 1 kpc in diameter emits $\sim 1 \times 10^9 L_{\odot}$ and the 10 kpc region $6 \times 10^9 L_{\odot}$ (Figure 7.6).

The continuum spectrum of M31 has a maximum around $\lambda = 1.5\mu$ in the infrared and decreases sharply toward shorter wavelengths (Table 7.4, Figure 8.1). Contamination by starlight is therefore particularly important on the long-wavelength side ($\lambda \gtrsim 5,000\text{\AA}$). On the short-wavelength side, $\lambda \lesssim 3,000\text{--}4,000\text{\AA}$, the contamination by starlight is thought to be relatively small. For quasars with large redshifts, starlight can presumably be neglected.

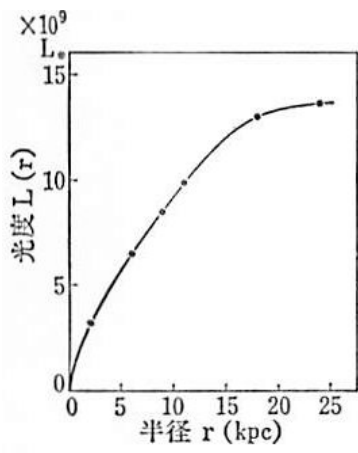


図 7.6 M31 の光度 $L(r)$ と半径 r の関係.

Figure 7.6 Relation between the luminosity $L(r)$ of M31 and the radius r . Vertical axis luminosity $L(r)$ ($\times 10^9 L_{\odot}$, 0 to 15); horizontal axis radius r (kpc) (0 to 25).

Table 7.4 The continuum of M31

Wavelength λ	$AB(\lambda) - AB(V)$	$F_{\nu}/F_{\nu}(V)$
1550 Å	4.15	0.0219
1800 Å	4.23	0.0203
2200 Å	3.82	0.0297
2500 Å	4.09	0.0231
3300 Å	1.81	0.189
B	0.92	0.429
V	0	1.00
R	-0.60	1.74
I	-1.40	3.63
H	-1.75	5.01
K	-1.40	3.63
L	-0.95	2.40

1550Å–V: C. C. Wu et al. (1980) R–L : A. R. Sandage, E. E. Becklin, G. Neugebauer (1969).

Continuum radiation of ionized hydrogen Ionized hydrogen gas emits, in addition to the emission-line spectrum, a continuum. There are three kinds of this. The first is free–free transition radiation (bremsstrahlung), emitted when a free electron is accelerated by a proton. The second is free–bound transition radiation, emitted upon recombination; that emitted when an electron falls from the free state to the ground level 1 is called the Lyman continuum ($\lambda \leq 912\text{\AA}$), while those emitted on falling to levels 2 and 3 are called the Balmer continuum ($912 < \lambda \leq 3,646\text{\AA}$) and the Paschen continuum ($3,646 < \lambda \leq 8,204\text{\AA}$) respectively. The discontinuities at $\lambda = 3,646\text{\AA}$ and so on are called the Balmer jump and so on. In general, the hydrogen continuum means the sum of the free–free and free–bound transition radiation. Figure 7.7 and Table 7.5 give the emission coefficient of the hydrogen continuum, $\gamma_\nu(H)\text{erg cm}^3/\text{sHz}$. Using this emission coefficient, the continuum radiative energy emitted by hydrogen gas with electron density N_e/cm^3 , proton density N_p/cm^3 and volume $V\text{ cm}^3$ is expressed as

$$F_\nu(H) = \gamma(H)N_eN_pV\text{erg/sHz}$$

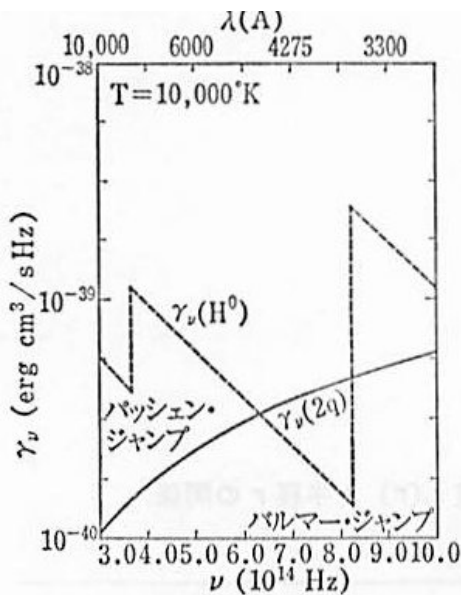


図 7.7 水素の連続光輻射係数

Figure 7.7 Continuum emission coefficient of hydrogen Vertical axis γ_ν (erg cm³/s Hz): 10⁻⁴⁰ to 10⁻³⁸; horizontal axis ν (10¹⁴Hz): 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0; upper axis λ (Å): 10,000 / 6000 / 4275 / 3300. Labels in the figure: $T = 10,000^\circ\text{K}$, $\gamma_\nu(H^0)$, $\gamma_\nu(2q)$, Paschen jump, Balmer jump.

Table 7.5 Continuum emission coefficients of hydrogen

$\lambda(\text{\AA})$	$\nu(10^{14}\text{Hz})$	T 5000°	T 10,000°	T 15,000°	T 20,000°
10,000	2.998	6.23	5.86	5.35	4.98
8204+	3.654–	3.30	4.31	4.35	4.25
8204–	3.654+	25.36	11.54	8.31	6.81
7000	4.283	13.51	8.67	6.87	5.90
5696	5.263	5.17	5.52	5.09	4.70
4500	6.662	1.388	2.88	3.29	3.40
4000	7.495	0.653	1.946	2.54	2.79
3646+	8.224–	0.343	1.380	2.017	2.35
3646–	8.224+	71.7	24.8	14.89	10.65
3122	9.603	17.83	13.19	9.81	7.84
2600	11.530	2.857	5.39	5.43	5.07

* In units of $10^{-40}\text{ergcm}^3/\text{sHz}$.

At low densities, with electron density $N_e \leq 10^4/\text{cm}^3$, the third kind of continuum — the two-photon continuum — is radiated. Energy level 2 of the hydrogen atom consists of the two states 2^2S and 2^2P , but the transition from 2^2S to the ground state (1^1S) is forbidden. If the density is high, collisions with protons and free electrons cause the $2^2S \rightarrow 2^2P$ transition, and an L_α photon is radiated on the fall to the ground state; but at $N_e \leq 10^4/\text{cm}^3$ the electron cannot move to 2^2P even after the lifetime of the 2^2S state (0.12 s) has elapsed. The electron in the 2^2S state therefore falls to the ground state by emitting two photons, just as though there were a P level between level 2 and the ground state. Since the energy of that P level is determined probabilistically, this two-photon emission forms a continuum, whose peak appears at $1,620\text{\AA}$. Table 7.6 gives the emission coefficient of the two-photon continuum, $\gamma_\nu(2q)\text{erg cm}^3/\text{sHz}$. The two-photon continuum becomes

important in the ultraviolet region at low densities, but can be neglected in the high-density BL region ($N_e \approx 10^9/\text{cm}^3$).

Table 7.6 Two-photon continuum emission coefficients of hydrogen

Wavelength $\lambda(\text{\AA})$	$\gamma_y(\times 10^{-40}\text{ergcm}^3/\text{sHz})$	Wavelength $\lambda(\text{\AA})$	$\gamma_y(\times 10^{-40}\text{ergcm}^3/\text{sHz})$
1216	0.000	2400	7.32
1220	0.459	2600	6.74
1230	1.43	2800	6.23
1250	3.04	3000	5.76
1300	5.76	4000	4.08
1400	8.32	5000	3.05
1500	9.24	6000	2.37
1600	9.49	7000	1.91
1800	9.21	8000	1.57
2000	8.60	9000	1.31
2200	7.95	10000	1.12

* T = 10,000°K assumed (C. M. Gaskell 1980).

(2) The Nuclear Continuum Spectrum

Since the active nucleus that is our object of study is no more than 0.1 pc in size, when a nuclear region of about 10'' is observed we have

observed continuum = continuum of the active nucleus + starlight within the aperture
+ continuum of the ionized hydrogen gas within the nucleus

Therefore, to obtain the continuum spectrum of the active nucleus, the starlight and the hydrogen continuum must be subtracted.

The contribution of the ionized hydrogen gas can be obtained from the following equation using the Balmer-line luminosity.

$$F_{\nu}(\text{H}) = 1.08 \times 10^{18} \left(\frac{L(\text{H}\alpha)}{L_{\odot}} \right) \left(\frac{\gamma_{\nu}(\text{H})}{10^{-40}} \right) \text{erg s}^{-1} \text{Hz}^{-1}$$

If we take $L(H_{\alpha})/L_{\odot} = 10^{10}$, the hydrogen continuum is of order $F_{\nu}(H) \approx 10^{28} \text{erg/sHz}$. On the other hand, Figure 7.5 shows that for $L(H_{\alpha})/L_{\odot} = 10^{10}$ the observed continuum is of order $F_{\nu}(U) \approx 10^{32} - 10^{33} \text{W/m}^2 \text{Hz}$, that is, $10^{29} - 10^{30} \text{erg/sHz}$. We may therefore consider that in Seyfert galaxies the continuum of ionized hydrogen gas, including two-photon emission, does not make a large contribution. The problem is how to subtract the starlight of the background.

The first attempt to subtract the starlight was made by A. G. Pacholczyk and W. Z. Wisniewski (1967). Regarding all the $9,000\text{\AA}$ light of NGC 1068 as starlight, they subtracted an average galaxy light and found ultraviolet and infrared excesses similar to those of quasars. The separation methods tried so far can be broadly divided as follows.

- (i) Assuming color indices (U–B), (B–V) for the nuclear light and the background light, or for one of them, and comparing with the observed color indices.
- (ii) Adding nuclear light of the form $f_{\nu} \propto \nu^{-\alpha}$ to the continuum spectrum of a normal galaxy and comparing with the observations.
- (iii) Interpolating the background light around the nucleus and subtracting it from the observed values.
- (iv) Using light variation or polarization, which are characteristic of the nuclear light.

Method (i), which assumes color indices, was used by A. Sandage (1973) in his analysis of N galaxies and quasars; he assumed $(B - V)_N = 0.0$, $(U - B)_N = -0.80$ for the nuclear light and $(B - V)_G = 0.95$, $(U - B)_G = 0.62$ for the background light. Figure 7.8 is the two-color diagram of M. V. Penston et al. (1974) for eight classical Seyfert galaxies. They observed each galaxy with different apertures, regarded the light of the annulus not containing the nucleus as the background light, and adopted the color indices $(B - V)_G = 0.9$, $(U - B)_G = 0.4$. The color indices assumed for the nuclear light are $(B - V)_N = 0.0$, $(U - B)_N = -1.0$. The corresponding mixing curves are drawn in Figure 7.8, and, apart from NGC 1275, all the objects are distributed very well along the mixing curves.

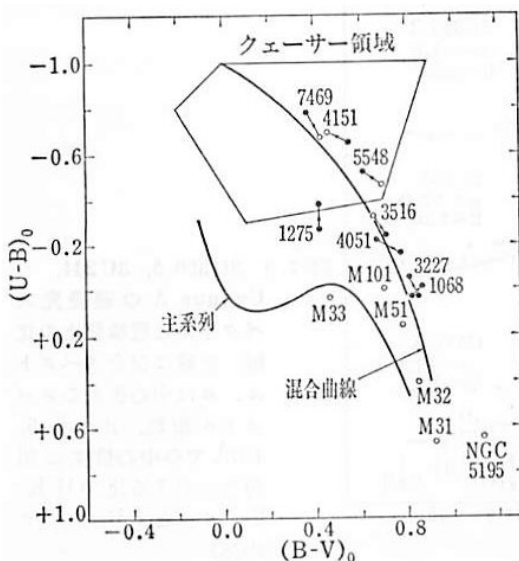


図 7.8 古典セイファート銀河の
2 色図と混合曲線。(M. V.
ペンストン達 1974)。

Figure 7.8 Two-color diagram of classical Seyfert galaxies with mixing curves. (M. V. Penston et al. 1974). Vertical axis $(U - B)_0$: -1.0 to $+1.0$; horizontal axis $(B - V)_0$: -0.4 to 0.8 . Annotations in the figure: “quasar region”, “main sequence”, “mixing curve”. The Seyfert galaxies shown are 7469, 4151, 5548, 3516, 1275, 4051, 3227, 1068, and the normal galaxies are M 101, M 33, M 51, M 32, M 31, NGC 5195.

Table 7.7 Fraction of nuclear light

Galaxy	Nuclear light within 3 kpc (%)
NGC 1068	4.5
NGC 1275	38
NGC 3227	7.5
NGC 3516	35
NGC 4051	15
NGC 4151	48
NGC 5548	59
NGC 7469	86

Table 7.7 gives the fraction of nuclear light relative to the light within 3 kpc as derived by them. It is relatively small for NGC 1068 and NGC 3227, but for the bright type 1 objects NGC 4151, NGC 5548 and NGC 7469 about half of the B magnitude is nuclear light.

Method (i) is also effective for variable galaxies. Assuming that the spectral distribution of the nuclear light remains unchanged even when it varies, T. F. Adams (1974) derived $(B - V)_N = 0.22$, $(U - B)_N = -0.96$ for the nuclear light of 3C 390.3.

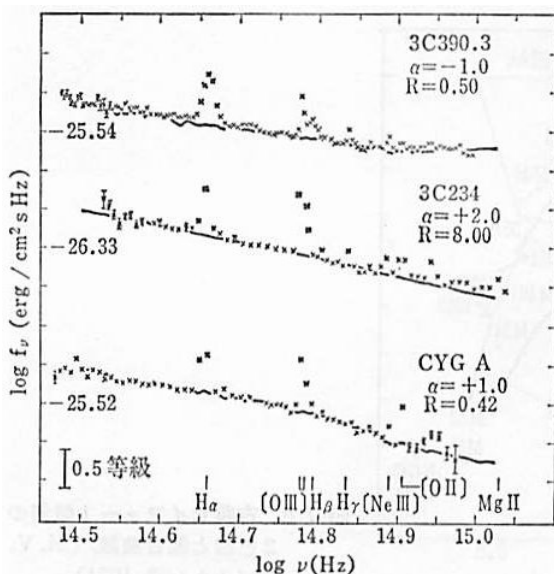


図 7.9 3C 390.3, 3C 234, Cygnus A の連続光スペクトルと理論値との比較. 実線は混合スペクトル. α は中心核光のスペクトル指数, R は $\lambda=5,450\text{\AA}$ での中心核光の銀河光に対する比. (H. K. C. イーと J. B. オーク 1978).

Figure 7.9 Comparison of the continuum spectra of 3C 390.3, 3C 234 and Cygnus A with theoretical values. The solid lines are the mixed spectra. α is the spectral index of the nuclear light and R the ratio of the nuclear light to the galaxy light at $\lambda = 5,450\text{\AA}$. (H. K. C. Yee and J. B. Oke 1978). Vertical axis $\log f_\nu$ (erg / cm² s Hz); horizontal axis $\log \nu$ (Hz): 14.5 to 15.0. Labels on each spectrum: 3C 390.3 ($\alpha = -1.0$, $R = 0.50$, -25.54), 3C 234 ($\alpha = +2.0$, $R = 8.00$, -26.33), CYG A ($\alpha = +1.0$, $R = 0.42$, -25.52). A 0.5 magnitude scale bar is at the lower left. Line identifications along the bottom: H_α , [O III], H_β , H_γ , [Ne III], [O II], Mg II.

Method (ii) is used in analyzing continuum spectra observed with spectrophotometers. Figure 7.9 shows the results of H. K. C. Yee and J. B. Oke (1978). 3C 390.3 and 3C 234 are radio Seyfert galaxies (BL radio galaxies) and Cygnus A (3C 405) is an NL radio galaxy, and each of the observations is well reproduced as a mixture of nuclear light ($f_\nu \propto \nu^{-\alpha}$) and the continuum of an elliptical galaxy. Note, however, that the spectral index α of the nuclear light shown in Figure 7.9 and the ratio R of the nuclear light to the galaxy light at $\lambda = 5,450\text{\AA}$ differ greatly from galaxy to galaxy. For example, for 3C 390.3 $\alpha = -1.0$ and $R =$

0.50, whereas for 3C 234 $\alpha = 2.0$ and $R = 8.0$. From A. T. Koski's (1978) analysis of type 2 Seyfert galaxies and NL radio galaxies, the mean spectral index of the nuclear light is $\langle\alpha\rangle = 1.0 \pm 0.5$, and the mean fraction accounted for by galaxy light at $\lambda = 4,861\text{\AA}$ is $71 \pm 17\%$. Since the above methods contain both the ratio of nuclear light to galaxy light and the spectral index α of the nuclear light as freely adjustable parameters, a unique solution cannot be obtained, just as with method (i). As Yee and Oke state, by suitably choosing the parameter R , every galaxy can be reproduced with any spectral index in the range $\alpha = 0.0\text{--}2.0$. In order to obtain the true continuum spectrum of an active nucleus, an accurate determination of the galaxy light is absolutely necessary.

On the basis of data in which NGC 4151 was measured with apertures from $8''$ to $124''$ in diameter, M. V. Penston et al. (1971) assumed that the galaxy light has the same spectral distribution as M31 and that the luminosity distribution is proportional to a power of the aperture diameter D , and separated out the nuclear light by least squares. The nuclear-light spectrum obtained was astonishingly flat ($\alpha \approx 0$), with $f_\nu = 3 \times 10^{-28} \text{W/m}^2\text{Hz}$. The present author (1980) likewise made use of the fact that the surface-brightness distribution of NGC 4151 follows the quarter-power law (Figure 3.15) to subtract the galaxy light and attempt the separation of the nucleus (Figure 7.10). Here the spectrum of M51* is used for the galaxy light. Except for the observations of K. S. Anderson (1970), in agreement with the results of Penston et al., the nuclear light shows a spectral distribution that is flat, or rather rises toward shorter wavelengths, and despite variations of a factor of several the slope of the spectrum remains almost constant.

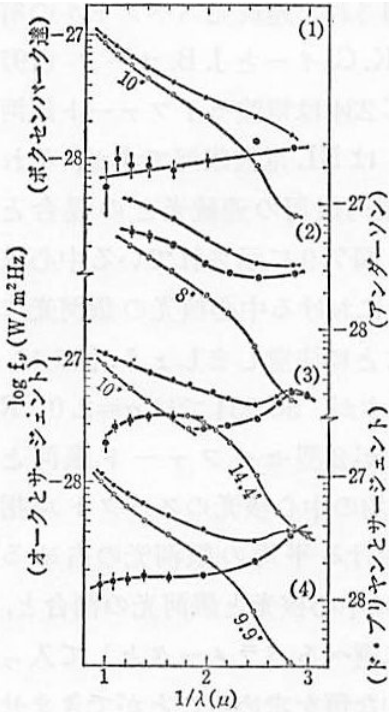


図 7.10 NGC 4151 の中心核光の分離。波線は銀河光スペクトル (M 51), 細い実線は観測, 太い実線は中心核光。(1) A. ボクセンバーグ達 (1975), (2) K.S. アンダーソン (1970), (3) J.B. オークと W.L.W. サージェント (1968), (4) A.G. ド・ブリヤンと W.L.W. サージェント (1978). (兼古昇 1980).

Figure 7.10 Separation of the nuclear light of NGC 4151. The dashed line is the galaxy-light spectrum (M 51), the thin solid line the observations, and the thick solid line the nuclear light. (1) A. Boksenberg et al. (1975), (2) K. S. Anderson (1970), (3) J. B. Oke and W. L. W. Sargent (1968), (4) A. G. de Bruyn and W. L. W. Sargent (1978). (Kaneko, N. 1980). Vertical axis $\log f_v$ ($\text{W}/\text{m}^2\text{Hz}$) (each panel marked -27, -28); horizontal axis $1/\lambda(\mu)$: 1 to 3. Labels outside the left-hand axis: (Boksenberg et al.), (Oke and Sargent); outside the right-hand axis: (Anderson), (de Bruyn and Sargent). Apertures marked on the curves: 10'', 8'', 10'', 14.4'', 9.9''.

* Against this, G. H. Rieke and M. J. Lebofsky (1981) point out that the contribution of starlight has been overestimated.

The property that the spectrum of the nuclear light is flat is also obtained from analyses that make use of light variation. If the nuclear light varies without changing its spectral distribution, its radiative flux can be written $a(t)\varepsilon_\nu$. Here ε_ν is the spectral distribution and $a(t)$ a quantity proportional to the intensity at time t . Writing the galaxy light as g_ν , the observed value at time t is

$$f_\nu(t) = g_\nu + a(t)\varepsilon_\nu$$

Taking the difference of the radiative fluxes at two different times t_1, t_2 observed with the same aperture,

$$\Delta f_\nu = f_\nu(t_1) - f_\nu(t_2) = a(t_1) - a(t_2)\varepsilon_\nu \propto \varepsilon_\nu$$

gives the spectral distribution of the nucleus. As an example, Figure 7.11 shows the results of A. G. de Bruyn's (1980) analysis of NGC 3516 and NGC 5548. As with NGC 4151, these type 1 Seyfert galaxies also give $\alpha(U-I) \approx 1-2$ as observed, but when the contaminating background light is removed, the spectral index of the nuclear light becomes $\alpha \approx 0$.

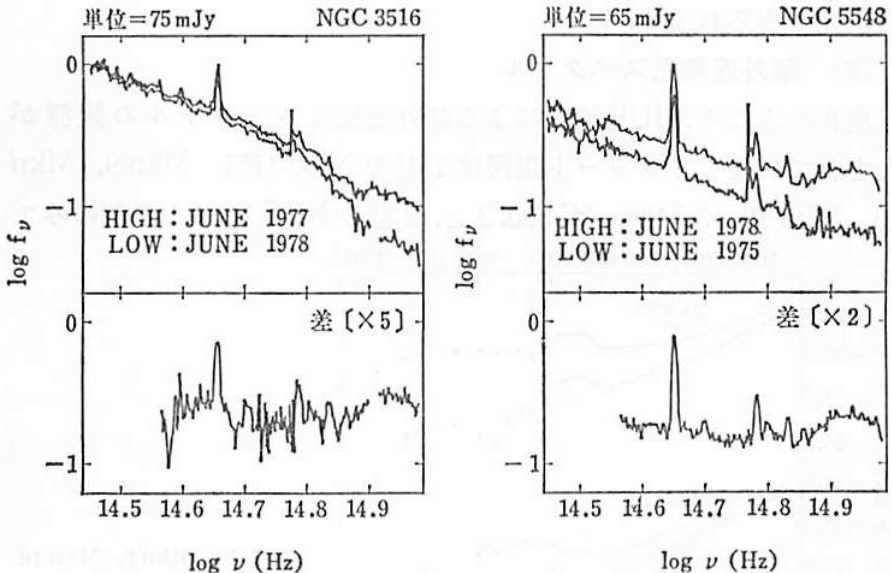


Figure 7.11 The nuclear light of NGC 3516 and NGC 5548. (A. G. de Bruyn 1980). Left panel NGC 3516: unit = 75 mJy, HIGH: JUNE 1977, LOW: JUNE 1978; the lower panel is the difference [$\times 5$]. Right panel NGC 5548: unit = 65 mJy, HIGH: JUNE 1978, LOW: JUNE 1975; the lower panel is the difference [$\times 2$]. Vertical axis $\log f_\nu$ (0 to -1); horizontal axis $\log \nu$ (Hz): 14.5 to 14.9.

In the method that uses polarization, it is assumed that the degree of polarization of the nuclear light is constant. In the results of N. Visvanathan and J. B. Oke (1968), who analyzed NGC 1068 using the continuum spectrum of M 31, a flat nuclear-light spectrum polarized by 7–8% is obtained (Figure 7.12). Applying the same method to NGC 4151 gives nuclear light with $\alpha = 0.33$ –0.37.

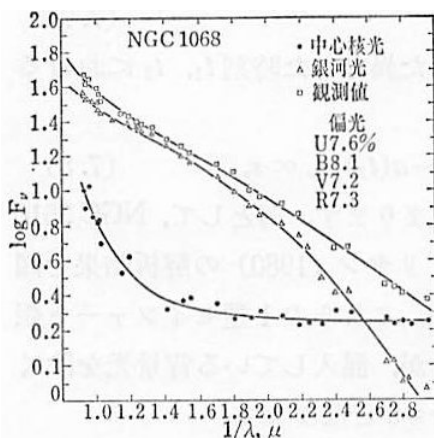


図 7.12 NGC1068 の偏光を利用した中心核光の分離. (N. ヴィスヴァナサンと J. B. オーク 1968).

Figure 7.12 Separation of the nuclear light of NGC 1068 using polarization. (N. Visvanathan and J. B. Oke 1968). Vertical axis $\log F_\nu$: 0 to 2.0; horizontal axis $1/\lambda, \mu$: 1.0 to 2.8. Legend: nuclear light (filled circles), galaxy light (triangles), observed values (open squares). Polarization values: U 7.6%, B 8.1, V 7.2, R 7.3.

(3) The Ultraviolet Continuum Spectrum

At present the only Seyfert galaxies for which the ultraviolet continuum spectrum has been observed with the IUE satellite are seven objects: the type 1 galaxies

NGC 4151, Mkn 9, Mkn 10, Mkn 79, 3C 120 and 3C 390.3, and the type 2 galaxy NGC 1068. The telescope carried on this satellite has an aperture of 45 cm, and an f/15 Cassegrain focus is used.

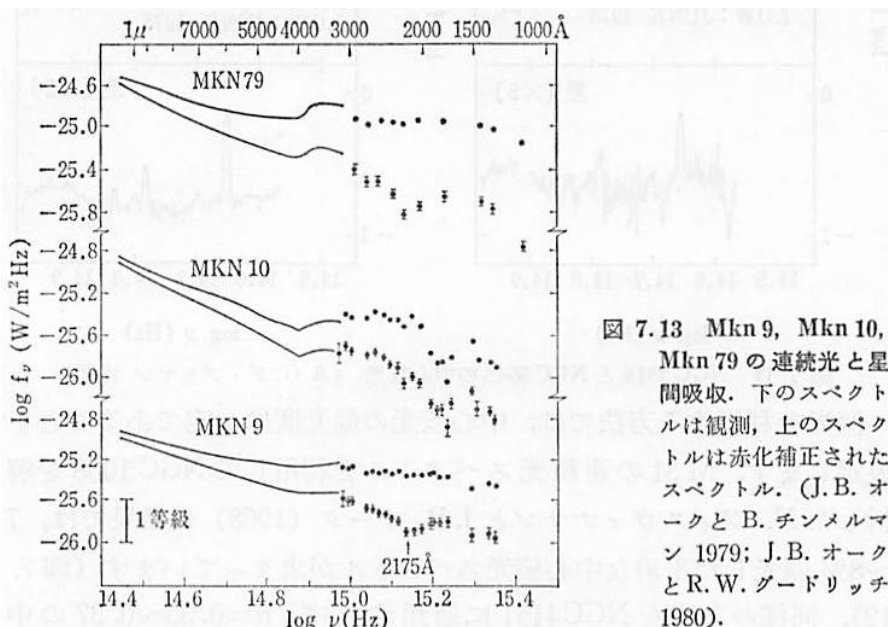


図 7.13 Mkn 9, Mkn 10, Mkn 79 の連続光と星間吸収. 下のスペクトルは観測, 上のスペクトルは赤化補正されたスペクトル. (J. B. オークと B. チンメルマン 1979; J. B. オークと R. W. グードリッチ 1980).

Figure 7.13 The continuum of Mkn 9, Mkn 10 and Mkn 79 and interstellar absorption. The lower spectra are the observations, the upper spectra are corrected for reddening. (J. B. Oke and B. Zimmerman 1979; J. B. Oke and R. W. Goodrich 1980). Vertical axis $\log f_\nu$ ($\text{W}/\text{m}^2\text{Hz}$) (MKN 79: -24.6 to -25.8 ; MKN 10: -24.8 to -26.0 ; MKN 9: -24.8 to -26.0); horizontal axis $\log \nu$ (Hz): 14.4 to 15.4 ; upper axis wavelengths 1μ , 7000 , 6000 , 5000 , 4000 , 3000 , 2000 , 1500 , $1000\text{\AA}$. The position of the $2175\text{\AA}$ absorption and a 1-magnitude scale bar are marked in the figure.

Besides the interest of being an extension of the nuclear light, the ultraviolet continuum spectrum is important for determining the amount of reddening the continuum has suffered. As briefly described in the previous chapter, the $\lambda 2175\text{\AA}$ absorption observed in Mkn 9 and other objects shows no redshift, and this

absorption is thought to be due to interstellar absorption within the Milky Way Galaxy (Figure 7.13). If the absorption occurred within the nucleus of Mkn 9, the center of the absorption should lie not at $\lambda 2,175\text{\AA}$ ($\log \nu = 15.14$) but at $\lambda 2,260\text{\AA}$ ($\log \nu = 15.12$). The same fact has been confirmed for Mkn 10, Mkn 79, 3C 120 and 3C 390.3 as well, so we must consider that within the nuclei of these type 1 Seyfert galaxies the reddening of the continuum is negligibly small. According to the observations of A. Boksenberg et al. (1978), the $\lambda 2,175\text{\AA}$ absorption in NGC 4151 is likewise extremely weak, only $E(B-V) \approx 0.06$ (Figure 7.14).

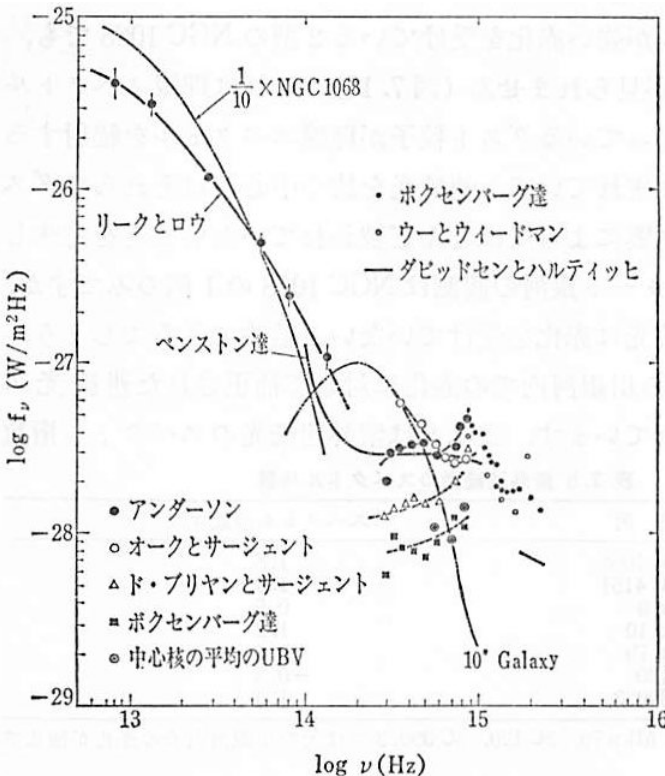


図 7.14 NGC 4151
の連続光スペ
クトル. (兼
古昇 1980).

Figure 7.14 The continuum spectrum of NGC 4151. (Kaneko, N. 1980). Vertical axis $\log f_\nu$ ($\text{W}/\text{m}^2\text{Hz}$): -29 to -25 ; horizontal axis $\log \nu$ (Hz): 13 to 16 . Annotations in the figure: $1/10 \times \text{NGC 1068}$, Rieke and Low, Penston et al., Boksenberg et al., Wu and Weedman, Davidsen and Hartig, $10''$ Galaxy. Legend: Anderson ($\bullet$), Oke and Sargent ($\circ$), de Bruyn and Sargent ($\triangle$), Boksenberg et al. ($\blacksquare$), mean UB V of the nucleus ($\odot$).

Even in NGC 1068, a type 2 object whose emission-line spectrum is strongly reddened, no $\lambda 2,175\text{\AA}$ absorption is seen (Figure 7.15). This means that the dust grains responsible for the reddening of the emission-line spectrum are contained within the gas clouds that radiate the emission-line spectrum themselves, and that the nucleus emitting the continuum is hardly covered at all by those dust-bearing gas clouds. Observations of type 2 Seyfert galaxies amount to the single case of NGC 1068, but we may conclude that, as with type 1, the continuum is not reddened.

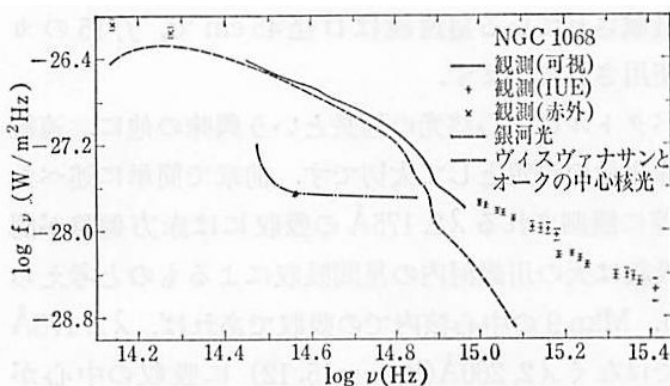


図 7.15 NGC 1068 の連続光スペクトル. (G. ノイゲバウアー達 1980).

Figure 7.15 The continuum spectrum of NGC 1068. (G. Neugebauer et al. 1980). Vertical axis: $\log f_\nu$ ($\text{W}/\text{m}^2\text{Hz}$) (-26.4 to -28.8); horizontal axis: $\log \nu$ (Hz) (14.2 to 15.4). Legend: observed (visible) / observed (IUE) / observed (infrared) / galaxy light / nuclear light of Visvanathan and Oke.

Figure 7.13 shows continuum spectra corrected for reddening within the Milky Way Galaxy. Table 7.8 gives the spectral indices of the ultraviolet continuum. In

the observations the slope is fairly steep, $\alpha = 1-2$, but the corrected mean value is flat, $\langle \alpha \rangle \approx 0.6$.

Table 7.8 Spectral indices of the ultraviolet continuum

Galaxy	Spectral index α
NGC 1068	1.8
NGC 4151	1.0
Mkn 9	0.5
Mkn 10	1.2
Mkn 79	0.6
3C 120	-0.3
3C 390.3	1.0

For Mkn 9, Mkn 10, Mkn 79, 3C 120 and 3C 390.3 the reddening within the Milky Way Galaxy has been corrected for.

As is clear if one compares the visible and ultraviolet light of the three Markarian Seyfert galaxies in Figure 7.13, the visible continuum at $\lambda \lesssim 4,000\text{\AA}$ and the ultraviolet light appear to be one and the same radiation component. The cause of the increase toward longer wavelengths at $\lambda \gtrsim 4,000\text{\AA}$ is presumably contamination by the starlight of the background. In the case of NGC 4151 the correspondence between the visible nuclear light and the ultraviolet light is not clear because of the light variation, but apart from the peak at $\lambda \approx 3,000\text{\AA}$, the spectrum from $1,000\text{\AA}$ to 1μ can be approximated by $\alpha \approx 0-0.5$. In NGC 1068 as well, the nuclear light derived by Visvanathan and Oke and the ultraviolet continuum join continuously. In 3C 390.3, however, the spectral indices of the nuclear light and of the ultraviolet continuum differ enormously. According to Yee and Oke, $\alpha = -1.0$ (Figure 7.9), whereas in the ultraviolet region $\alpha = 1.0$. A more detailed examination of 3C 390.3 will be needed.

Finally, let us compare briefly with the continuum spectra of quasars. According to the 85 observations of D. O. Richstone and M. Schmidt (1980), the spectral index scatters widely from -0.3 to 2.5 , but the mean value is $\langle \alpha \rangle \approx 0.5$, in good agreement with that of Seyfert galaxies. Figure 7.16 shows the continuum spectra of six quasars with $z=0.23-2.04$ observed with the IUE satellite by R. F. Green et al. (1980). The mean spectral index is $\langle \alpha \rangle \approx 0.5$, but a break is seen at $\lambda = 1,200\text{\AA}$ ($\log \nu = 15.4$), and shortward of this the index tends to become $\alpha \approx 2.3$. The same holds for OQ 172, the quasar with the largest redshift ($z=3.53$). According to the preliminary IUE satellite observations of R. Wilson, D. J. Carnochan and P. M. Gondhalekar (1979), the ultraviolet continuum of the $z=3.18$ quasar Q 2204-408 extends with $\alpha = 1.5 \pm 0.3$ all the way to $\sim 300\text{\AA}$. If the above properties hold also for the nuclear light of type 1 Seyfert galaxies, then the continuum has an extremely flat spectral distribution ($\alpha \approx 0-0.5$) at least from $\lambda = 1\mu$ to $\lambda = 1,200\text{\AA}$, and beyond $\lambda = 1,200\text{\AA}$ it is thought to fall off steeply ($\alpha \approx 1.5-2.5$).

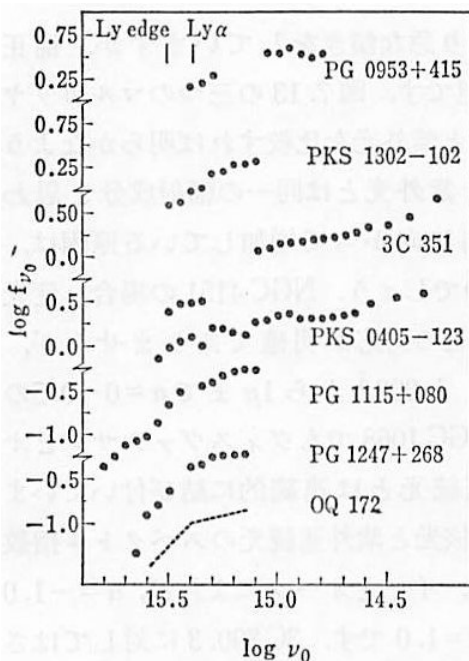


図 7.16 クェーサーの IUE 衛星観測. (R. F. グリーン達 1980).

Figure 7.16 IUE satellite observations of quasars. (R. F. Green et al. 1980). Vertical axis: $\log f_{\nu_0}$; horizontal axis: $\log \nu_0$ (15.5 to 14.5). The positions of the Ly edge and Ly α are marked at the top. From top to bottom: PG 0953+415, PKS 1302-102, 3C 351, PKS 0405-123, PG 1115+080, PG 1247+268, OQ 172.

It must be emphasized that this conclusion is incompatible with the interpretation advanced by W. A. Stein and D. W. Weedman (1976) and by G. Neugebauer et al. (1976), which is still widely believed today. On their interpretation, the continuum of type 1 Seyfert galaxies can be represented from the $\lambda = 10\mu$ infrared region right through to the ultraviolet by a synchrotron spectrum $f_\nu \propto \nu^{-\alpha}$ ($\alpha = 1.3 - 1.7$). In the next chapter, however, we shall see that this interpretation also contradicts the observational facts about the infrared radiation.

3. Light Variation

(1) Light curves

Light variation, the phenomenon that most vividly demonstrates nuclear activity, was first discovered in NGC 4151 by W. S. Fitch, A. G. Pacholczyk and R. J. Weymann (1967). Following this, T. G. Barnes (1968), B. A. Peterson (1969) and D. M. Selove (1969) discovered the variation of NGC 1275, and T. D. Kinman (1968) and K. Takayanagi [高柳和智] (1968) that of 3C 120.

Systematic monitoring of light variation by photoelectric photometry has been carried out by M. V. Penston et al. (1971, 1974), G. V. Zaitseva and V. M. Lyutyi (1968), V. M. Lyutyi (1973, 1977) and others. Lyutyi's observations in particular were continued by the same method for ten years and provide the most valuable material on light variation. Figures 7.17 and 7.18 are his light curves.

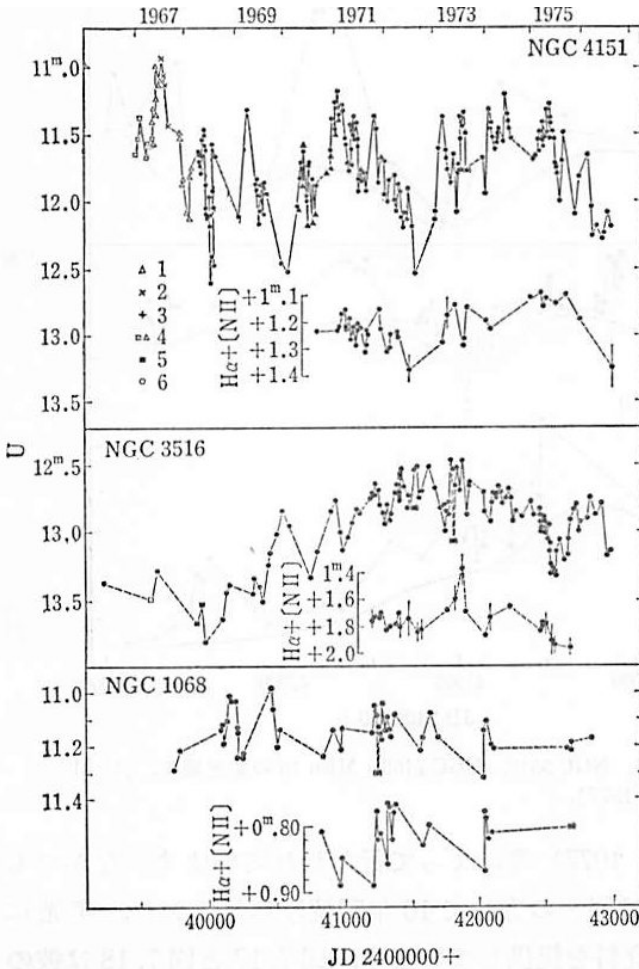


図 7.17 NGC 1068, NGC 3516, NGC 4151 の変光観測. (V. M. リュチュイ 1977).

Figure 7.17 Light-variation observations of NGC 1068, NGC 3516 and NGC 4151. (V. M. Lyutyi 1977). Vertical axis: U magnitude; horizontal axis: JD 2400000+ (about 39500–43000, with the years 1967, 1969, 1971, 1973, 1975 marked along the top). Each panel also shows the variation of the $H\alpha + [N II]$ emission-line intensity (NGC 4151: +1^m.1 to +1^m.4; NGC 3516: +1^m.4 to +2.0; NGC 1068: +0^m.80 to +0.90). Legend: 1, 2, 3, 4, 5, 6 (symbols for the different observers/instruments).

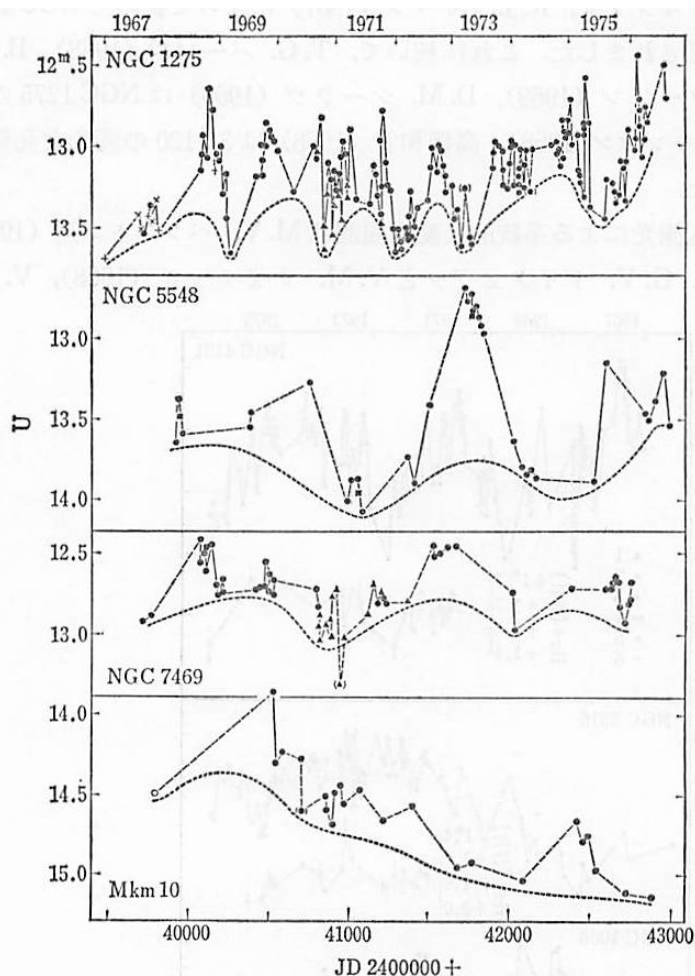


図 7.18 NGC 1275, NGC 5548, NGC 7469, Mkn 10 の変光観測. (V. M. リュチュイ 1977).

Figure 7.18 Light-variation observations of NGC 1275, NGC 5548, NGC 7469 and Mkn 10. (V. M. Lyutyi 1977). Vertical axis: U magnitude; horizontal axis: JD 2400000+ (years 1967–1975 marked along the top). The dashed curves are the first component.

As is clear from Figure 7.17, NGC 1068, of type 2, shows no light variation. Variation has also been confirmed in NGC 3227, NGC 4051 and NGC 6814, so it is

believed that all type 1 classical Seyfert galaxies exhibit the phenomenon of light variation. For type 1 Seyfert galaxies, light variation is a universal phenomenon. In Figure 7.17 the variations of the $H_\alpha + [N\text{ II}]$ emission-line intensity are also plotted for NGC 1068, NGC 3516 and NGC 4151; note too that 1967, the year in which S. Souffrin and Y. Andrillat discovered a large intensity change in H_β of NGC 3516, fell exactly at the epoch of continuum minimum.

The smallest time scale seen in the light curves places one constraint on the size of the continuum source, that is, of the nucleus. In Lyutyi's light curves, variations on time scales of a month or less are recognized in every Seyfert galaxy except NGC 1068. However, when A. Lawrence et al. (1981) observed the V and K magnitudes of NGC 4151 for the week of 14–21 May 1979, no variation exceeding 0.05 mag was found on any time scale from a few minutes to one week. Taking these into account, the minimum time scale of light variation can be estimated at around ~ 10 days. Since the distance light travels in one day is $1\sim 2.6 \times 10^{15}$ cm, the size of the nucleus is estimated to be $R \approx (2 - 3) \times 10^{16}$ cm.

For the radio Seyfert galaxies NGC 1275 and 3C 120, variations on time scales of a few days have been reported. According to M. J. Geller et al. (1979), the 4,000–6,000Å continuum of NGC 1275 changed by 30% in six nights. The simultaneous visible, infrared and radio observations carried out by E. E. Epstein and 21 co-authors (1972) also suggest variation of 3C 120 over a few days; if these can be confirmed, the size of the continuum sources of NGC 1275 and 3C 120 would be $R \lesssim 1 \times 10^{16}$ cm.

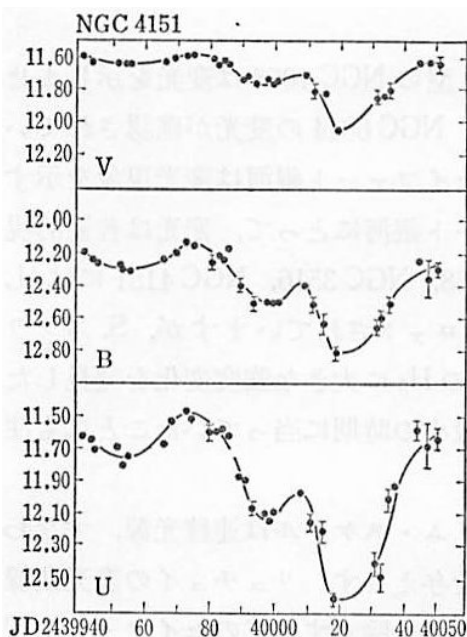


図 7.19 NGC 4151 の UBV 変光曲線。
(G. V. ザイツェヴァと V. M. リ
ュチユイ 1969)。

Figure 7.19 UBV light curves of NGC 4151. (G. V. Zaitseva and V. M. Lyutyi 1969).

From top: V (11.60–12.20), B (12.00–12.80), U (11.50–12.50). Horizontal axis: JD 2439940, 60, 80, 40000, 20, 40, 40050.

In general, light variation has a wavelength dependence. Figure 7.19 gives the U, B, V light curves of NGC 4151. In U it varies with an amplitude of $\Delta U \sim 1$ mag, but the amplitude of variation decreases with increasing wavelength: $\Delta B \sim 0.7$, $\Delta V \sim 0.4$. In other words, the object becomes bluer as it brightens. This wavelength dependence, however, is not an intrinsic property of the nuclear light. If the starlight of the background is subtracted, then despite variations of more than a factor of several, the color indices of the nuclear light of NGC 4151 remain $(U-B) \sim -1.1$ and $(B-V) \sim -0.2$ (Figure 7.20). Moreover, at its faintest the nuclear light comes to coincide with the sum of the emission lines and the continuum of ionized hydrogen. The wavelength dependence is due to contamination by starlight,

and the variation occurs with a large amplitude without changing the spectral distribution.

(2) Periodicity

Because the periodicity of light variation is intimately related to the radiation mechanism of the continuum and to the structure of the nucleus, analyses have been attempted for representative Seyfert galaxies and quasars. The results, however, are not very clear-cut. As we shall see below, it is better to regard the light curves as showing quasi-periodic variations.

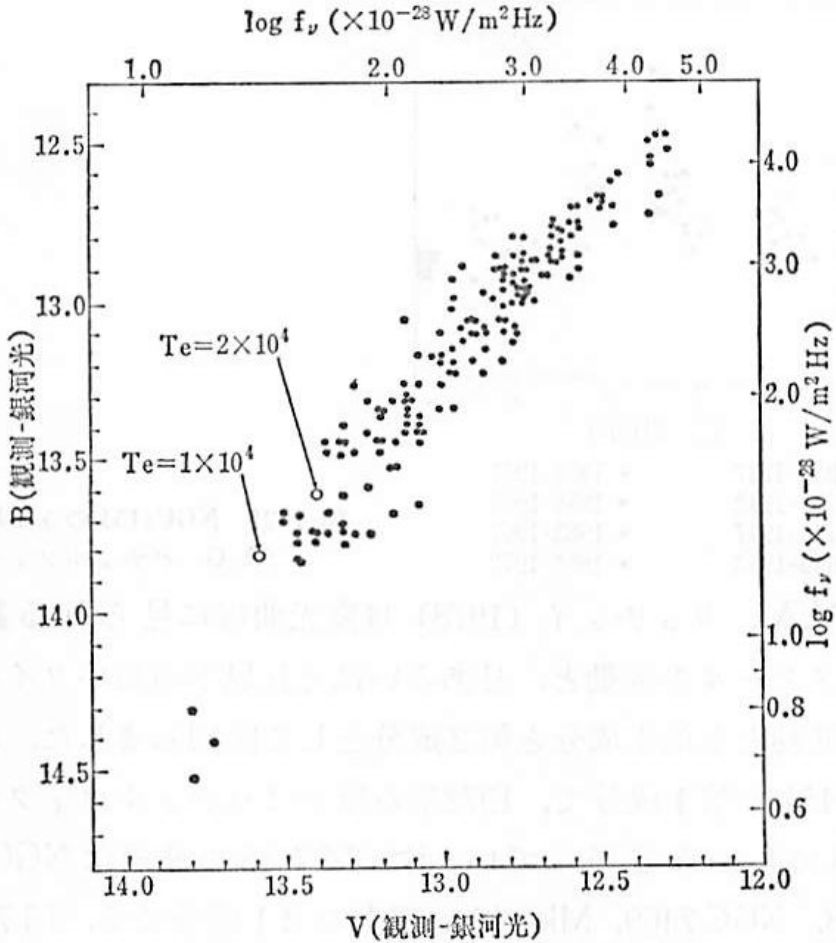


図 7.20 NGC4151 の中心核光の変光. 白丸は電離水素ガスの連続光と輝線の和. (兼古昇 1980).

Figure 7.20 Light variation of the nuclear light of NGC 4151. The open circles are the sum of the continuum of the ionized hydrogen gas and the emission lines. (N. Kaneko 1980). Vertical axis: B (observed – galaxy light) (12.5–14.5) and $\log f_{\nu}$ ($\times 10^{-23}$ W/m²Hz); horizontal axis: V (observed – galaxy light) (14.0–12.0) and $\log f_{\nu}$ ($\times 10^{-23}$ W/m²Hz) (1.0–5.0). The open circles are labeled $T_e = 1 \times 10^4$ and $T_e = 2 \times 10^4$.

A. G. Pacholczyk (1971) analyzed photographic plates taken at the Harvard Observatory and the Steward Observatory between 1932 and 1968 and suggested that NGC 4151 varies with a period of 5.1 years. Figure 7.21 is the light curve with eight periods folded together. The minima occur in the years $1932+5n$ ($n=0, \pm 1, \pm 2, \dots$).

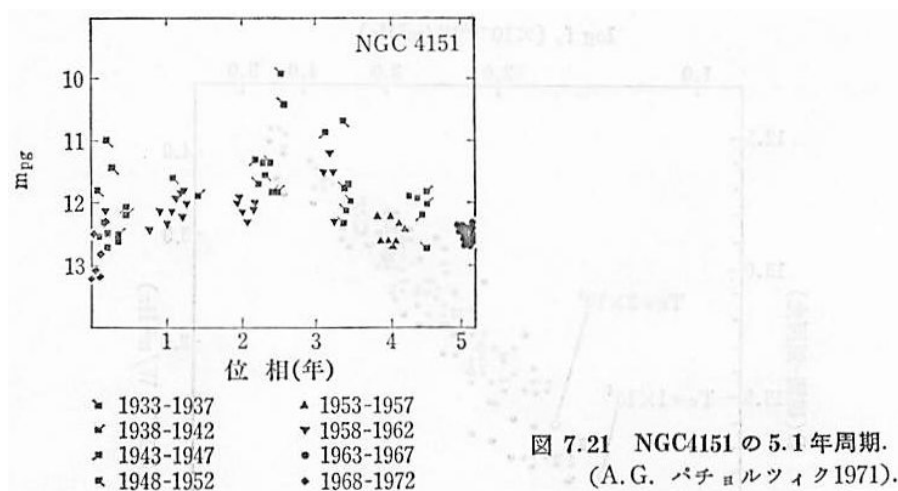


Figure 7.21 The 5.1-year period of NGC 4151. (A. G. Pacholczyk 1971). Vertical axis: m_{pg} (10–13); horizontal axis: phase (years) (1–5). Legend: 1933–1937, 1938–1942, 1943–1947, 1948–1952, 1953–1957, 1958–1962, 1963–1967, 1968–1972.

V. M. Lyutyi (1977) and E. T. Belokon, M. K. Babazhanyants and V. M. Lyutyi (1978) distinguished the variations on time scales of several years seen in the light curves from those on the short time scales of a month or less, calling them the first and second components respectively. Figure 7.22 shows the first component of NGC 4151; the minimum of 1972 falls exactly on $n=8$ as suggested by Pacholczyk. The dashed curves in Figure 7.18 are the first components of the variations of NGC 1275, NGC 5548, NGC 7469 and Mkn 10.

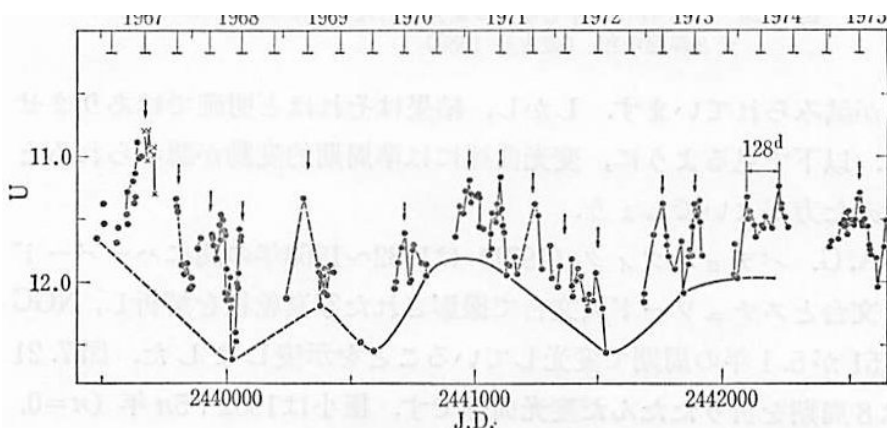


図 7.22 NGC 4151 の変光の第 1 成分. 下の波線と実線が第 1 成分. 上のマークは 130 日の第 2 成分. (E. T. ペロコン, M. K. ババザンヤンツ, V. M. リュチュイ 1978).

Figure 7.22 The first component of the light variation of NGC 4151. The lower dashed and solid curves are the first component. The marks at the top are the 130-day second component. (E. T. Belokon, M. K. Babazhanyants, V. M. Lyutyi 1978). Vertical axis: U (11.0–12.0); horizontal axis: J.D. (2440000, 2441000, 2442000; years 1967–1975 marked along the top). An interval of 128^d is indicated in the figure.

In Figure 7.22 the peaks of the 130-day period of the second component are marked, and folding them together gives Figure 7.23. Thus NGC 4151 turns out to possess two (quasi-)periods, $P=5.1$ years and $P=130$ days. A similar periodicity has been reported for 3C 120 as well. According to measurements by I. Jurkevich et al. (1971) of Harvard patrol plates taken over 60 years, there exist a short period of 350 days and a long period of 22.5 years.

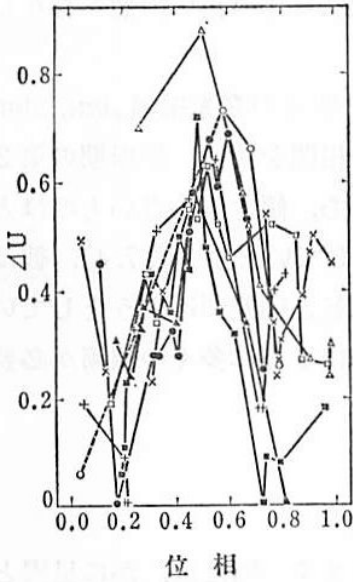


図 7.23 NGC 4151 の 130 日周期 (第 2 成分).
(E. T. ベロコン, M. K. ババザンヤンツ, V. M. リュチュイ 1978).

Figure 7.23 The 130-day period of NGC 4151 (second component). (E. T. Belokon, M. K. Babazhanyants, V. M. Lyutyi 1978). Vertical axis: ΔU (0–0.8); horizontal axis: phase (0.0–1.0).

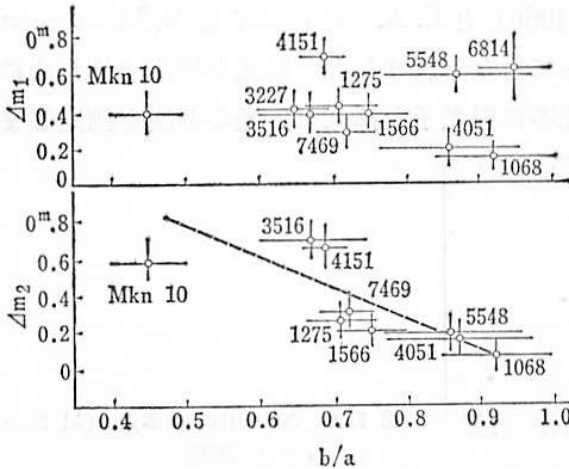


図 7.24 第 1 成分と第 2 成分の変光振幅と銀河の軸比. (V. M. リュチュイ 1977).

Figure 7.24 The light-variation amplitudes of the first and second components and the axial ratio of the galaxy. (V. M. Lyutyi 1977). Upper panel vertical axis: Δm_1 (0–0^m.8); lower panel vertical axis: Δm_2 (0–0^m.8); horizontal axis: b/a (0.4–1.0). Galaxies plotted: Mkn 10, 3227, 3516, 4151, 7469, 1566, 1275, 5548, 6814, 4051, 1068.

V. M. Lyutyi (1977) examined the correlation between the light-variation amplitudes Δm_1 and Δm_2 of the first and second components and the axial ratio b/a, which is a measure of the inclination of the galaxy, and found that for the short-period second component the larger b/a is — that is, the smaller the inclination — the smaller the amplitude Δm_2 tends to be (Figure 7.24). He seeks to relate the cause of this short-period variation to rotation of the nucleus, but many more observations will be needed to establish the correlation firmly.

4. Polarization

Polarization observations often play an important role. For example, the strong polarization discovered in the Crab Nebula and in the M 87 jet demonstrated that the light from them is synchrotron radiation, while conversely the H_α polarization of M 82 established conclusively that the filaments shine not by synchrotron radiation but by scattering off dust grains.

NGC 1068 is the Seyfert galaxy in which polarization was first discovered. The observations were made by M. F. Walker (1966) and by E. A. Dibay and N. M. Shakhovskoy (1966). To observe polarization one inserts a polarizer into the photometer or the spectrograph and measures the intensity of the light. Figure 7.25 shows the result of M. F. Walker's (1968) observation of NGC 1068. Maximum intensity is obtained at a position angle of 98°. The degree of polarization is defined in terms of the maximum intensity $I_{\max}$ and the minimum intensity $I_{\min}$ by

$$P = (I_{\max} - I_{\min}) / (I_{\max} + I_{\min}) \times 100(\%)$$

and for NGC 1068 it is $P(\text{UV})=8.8\%$.

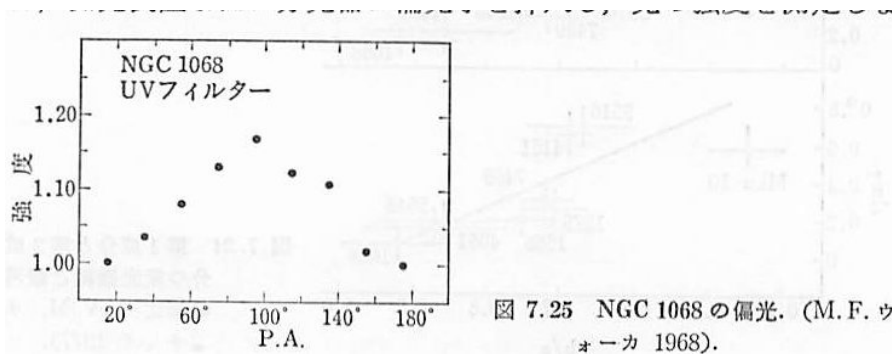


図 7.25 NGC 1068 の偏光. (M. F. ウォーカー 1968).

Figure 7.25 Polarization of NGC 1068. (M. F. Walker 1968). Vertical axis: intensity (1.00–1.20); horizontal axis: P.A. (20°–180°). Labeled in the figure: “NGC 1068 UV filter”.

The Seyfert galaxies for which polarization observations including spectropolarimetry have been made are, at present, six: NGC 1068, NGC 3227, NGC 3516, NGC 4151, Mkn 3 and Mkn 231. In addition, in the survey of 47 Seyfert galaxies by J. Maza et al., polarization has been detected in Mkn 348, Mkn 376, Mkn 486 and IC 4329A. Figure 7.26 shows the result of observations by J. R. P. Angel et al. (1976), who used the 2.3 m telescope of the Steward Observatory to observe the 2"-diameter nuclear region of NGC 1068. The degree of polarization of the continuum shows a strong wavelength dependence — 11% at $\lambda = 3,200\text{\AA}$ and 0.6% at $8,000\text{\AA}$ — and can be approximated by $P \propto \nu^3$. The position angle shows a slow increase from $\theta = 102^\circ$ to 94° , but may be regarded as essentially constant ($\theta = 98^\circ$). Figure 7.26 gives the degree of polarization and the position angle of NGC 4151 observed by G. D. Schmidt and J. S. Miller (1980) with the 3 m telescope of the Lick Observatory. The aperture used was 2".8 in diameter. The degree of polarization of the continuum is 2.5% at $\lambda = 4,000\text{\AA}$ and 1.2% at $7,000\text{\AA}$, and the mean position angle is 88° .

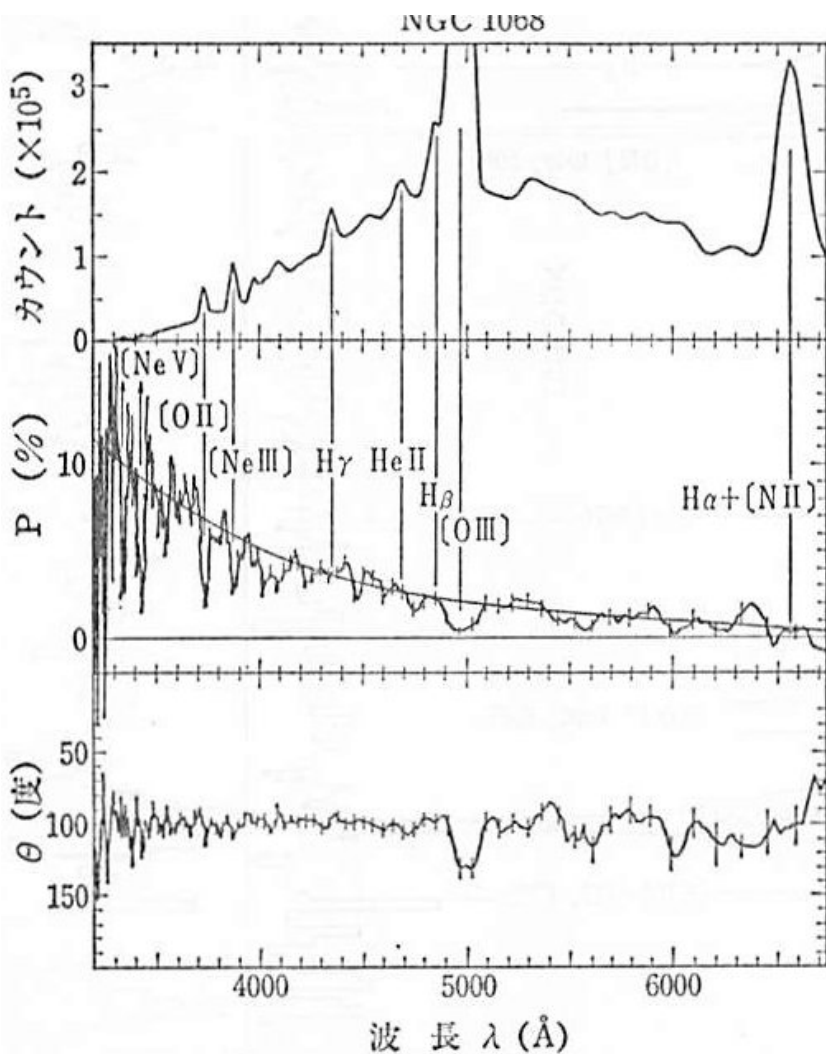


Figure 7.26 Spectropolarimetric observations of NGC 1068. (J. R. P. Angel et al. 1976). Upper panel vertical axis: counts ($\times 10^5$); middle panel vertical axis: P (%); lower panel vertical axis: θ (degrees) (50, 100, 150); horizontal axis: wavelength λ ($\text{\AA}$) (4000, 5000, 6000). Emission lines identified: [Ne V], [O II], [Ne III], H_γ , He II, H_β , [O III], $H_\alpha + [N II]$.

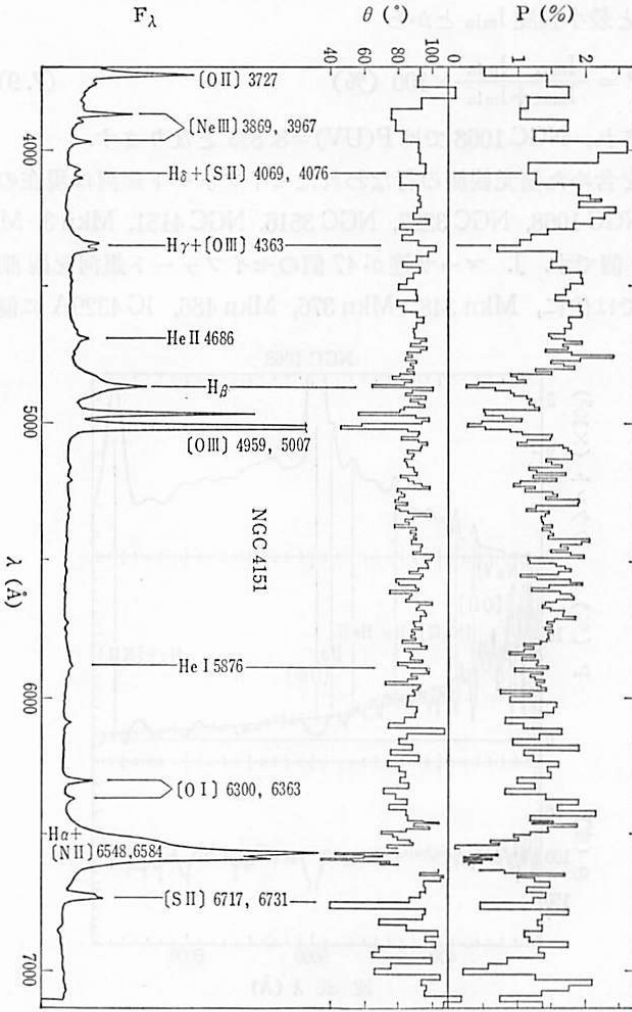


図 7.27 NGC4151 の分光偏光観測。

Figure 7.27 Spectropolarimetric observations of NGC 4151. Vertical axis: λ ($\text{\AA}$) (4000–7000); horizontal axes: F_λ , θ ($^\circ$) (40, 60, 80, 100), P (%) (0, 1, 2). Emission lines identified: [O II] 3727, [Ne III] 3869, 3967, $H_\delta + [S II]$ 4069, 4076, $H_\gamma + [O III]$ 4363, He II 4686, H_β , [O III] 4959, 5007, He I 5876, [O I] 6300, 6363, $H_\alpha + [N II]$ 6548, 6584, [S II] 6717, 6731.

Table 7.9 Polarization of Seyfert galaxies

Galaxy	$P(\lambda)(\%)$ U	$P(\lambda)(\%)$ B	$P(\lambda)(\%)$ V	Position angle θ (deg)	Aperture (arcsec)
NGC 1068	7.0	3.2	1.5	98	2.0
NGC 3227	2.8	2.1	1.2	130	4.6
NGC 3516	0.9	0.8	0.7	0	4.6
NGC 4151	2.6	2.0	1.7	88	2.8
Mkn 3	3.0	2.6	1.7	140	7.7
Mkn 231	9.0	5.5	3.3	95	5.2

The wavelength dependence whereby the degree of polarization is larger at shorter wavelengths is a property seen in every Seyfert galaxy in which polarization has been detected (Table 7.9). This, however, is not an intrinsic characteristic of the continuum; it is thought to arise because the starlight forming the background dilutes the degree of polarization more strongly the longer the wavelength.

Like the continuum, the emission lines are also polarized. In NGC 1068 of Figure 7.26, the Balmer lines H_α , H_β , H_γ and He II $\lambda 4686$ show the same degree of polarization and position angle as the continuum. On the other hand, the forbidden lines such as [O III] $\lambda\lambda 4959, 5007$ have a smaller degree of polarization than the continuum or the permitted lines, and their position angles differ as well. Probably the forbidden lines are radiated from a region farther out than the continuum and the permitted lines. In the case of NGC 4151, the forbidden lines and the cores of the Balmer lines show the same degree of polarization and position angle, but the wings of the Balmer lines are unpolarized. This is observational evidence supporting the interpretation that the cores and the wings are radiation from different regions. Table 7.10 summarizes the polarization of the emission-line spectrum. Here NGC 3227, NGC 3516, Mkn 3 and Mkn 231 are from the observations of I. Thompson et al. (1980).

Table 7.10 Polarization of the emission lines and the continuum

Galaxy	Emission line	Line P(%)	Line θ (deg)	Continuum P(%)	Continuum θ (deg)
NGC 1068	[O III]	0.5	143	2.3	99
	H_{α}	1.3	102	1.1	96
NGC 3227	[O III]	1.3	123	1.6	132
	H_{α}	0.8	122	1.3	130
NGC 3516	H_{α}	0.7	178	0.5	3
NGC 4151	[O III]	0.4	44	1.8	90
	H_{α} (core)	0.4	44		
	H_{α} (wing)	0	—	1.2	88
Mkn 3	[O III]	0.8	119	1.8	144
	H_{α}	1.7	156	1.3	135
Mkn 231	H_{α}	3.1	90	2.3	101
	Fe II	4.8	91	3.6	99

When polarization was first observed in NGC 1068, it was immediately interpreted as strong observational evidence that the continuum is synchrotron radiation. However, just as in the case of M 82, the emission lines of most Seyfert galaxies are polarized in the same way as the continuum, so we must conclude that scattering by dust grains is the principal cause of the polarization. In NGC 1068, besides the (linear) polarization examined so far, circular polarization — which can arise only through multiple scattering — has been observed, making the interpretation in terms of dust-grain scattering all the more certain.

In the case of NGC 4151, the position angles of the NL emission-line component and of the continuum differ by about 45° , and the degree of polarization is also larger for the continuum (Table 7.10). The dust grains polarizing the forbidden lines and the cores of the Balmer lines are presumably distributed within, or in the vicinity of, the gas clouds that radiate them. A. Kruszewski (1977), on the basis of his polarimetric photometry, states that the polarization of the continuum of NGC

4151 can be understood in terms of Serkowski's empirical law (Figure 7.28); but since the exact spectral distribution of the nuclear light cannot be obtained, the comparison is difficult. As one interpretation of the continuum polarization, scattering by gas clouds within the BL region surrounding the nucleus, or by dust grains distributed around it, is favored; but since the wings of the Balmer lines are not polarized, the possibility of synchrotron radiation cannot be ruled out either.

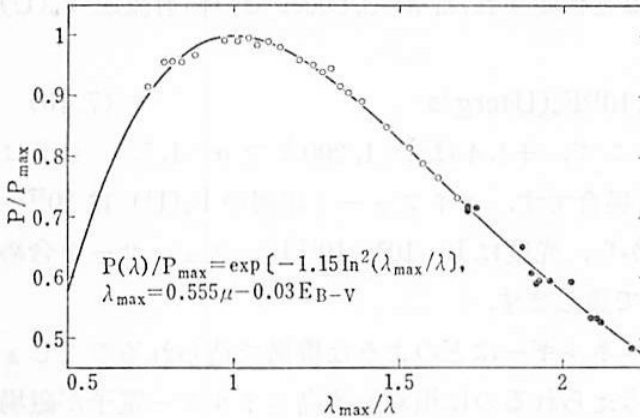


図 7.28 星間気体による偏光.

$P_{\max}$ と E_{B-V} とには, $P_{\max} \leq 9.0 E_{B-V}$ の関係がある (K. セルコフスキー, D. S. マシューソン, V. L. フォード 1975).

Figure 7.28 Polarization by the interstellar medium. $P_{\max}$ and E_{B-V} are related by $P_{\max} \leq 9.0 E_{B-V}$ (K. Serkowski, D. S. Mathewson, V. L. Ford 1975). Vertical axis: $P/P_{\max}$ (0.5–1); horizontal axis: $\lambda_{\max}/\lambda$ (0.5–2). Formula in the figure: $P(\lambda)/P_{\max} = \exp\{-1.15 \ln^2(\lambda_{\max}/\lambda)\}$, $\lambda_{\max} = 0.555\mu - 0.03 E_{B-V}$.

In general, strong polarization is not observed in quasars. In the recent observations of H. S. Stockman and J. R. P. Angel (1978) as well, 90% of quasars brighter than $V=17$ had $P \sim 2\%$ or less. Quasars showing strong polarization are limited to a small number of objects called OVV (Optically Violently Variable) quasars, which vary violently in the optical. In these, the degree of polarization and the position angle change along with the light variation. Interestingly, variations of polarization similar to those of OVV quasars have been reported in the radio Seyfert galaxies NGC 1275 and 3C 390.3. For example, according to the observations of NGC 1275

by P. G. Martin, J. R. P. Angel and J. Maza (1976), over the four days 4–7 January 1976 the degree of polarization varied irregularly between 3.0% and 3.5% and the position angle between 131° and 152° . Together with the light-variation observations of NGC 1275 by M. J. Geller et al. (1979), this appears to hint at a similarity to OVV quasars.

5. The Radiation Mechanism of the Continuum

If we assume that the continuum spectrum has the form $f_\nu \propto \nu^{-0.5}$ from $\lambda = 1\mu$ to $1,200\text{\AA}$ and falls off as $f_\nu \propto \nu^{-2.0}$ in the region shortward of this, then the luminosity L of the visible and ultraviolet continuum can be expressed, using the radiative flux $F_\nu(U)\text{erg/s Hz}$ at $\lambda = 3,600\text{\AA}$, as

$$L = 3.3^{+1.4}_{-0.5} \times 10^{15} F_\nu(U) \text{erg/s}$$

Here $+1.4$ corresponds to assuming $\alpha = 1.5$ at $\lambda \lesssim 1,200\text{\AA}$ and -0.5 to assuming $\alpha = 2.5$. Since $F_\nu(U)$ for Seyfert galaxies is $10^{27}\text{--}10^{30}\text{erg/s Hz}$, the luminosity is $L = 10^9\text{--}10^{12}L_\odot$, and including quasars it reaches as high as $\sim 10^{14}L_\odot$.

By what mechanism is this enormous radiant energy produced? The first thing that comes to mind is synchrotron radiation, emitted when relativistic high-energy electrons are accelerated by a magnetic field. If the energy spectrum of the high-energy electrons is proportional to the $-\gamma$ power of the energy E , then the spectral index of the synchrotron radiation is $\alpha = (\gamma - 1)/2$, and depending on the value of γ a spectral distribution of any slope can be obtained (Figure 7.29). It is therefore easy to explain the flat spectral distribution of the nuclear light. In the nuclear light of Seyfert galaxies, however, the strong polarization characteristic of synchrotron radiation is not observed. Furthermore, the acceleration mechanism for relativistic high-energy electrons is not clear either.

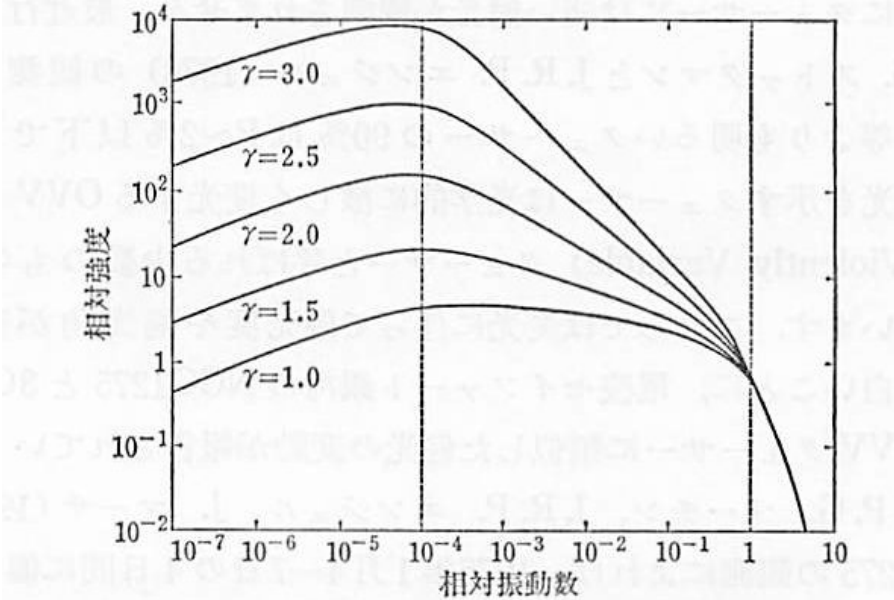


図 7.29 ベキ型のエネルギー分布を持つ高エネルギー電子からのシンクロトロン・スペクトル。2本の波線は電子の高エネルギーと低エネルギーのカット・オフ (cut off)。横軸の相対振動数は高エネルギー・カット・オフで規格化され、低エネルギー・カット・オフは 10^{-4} と仮定されている。(K. ケラーマン 1964)。

Figure 7.29 Synchrotron spectra from high-energy electrons with a power-law energy distribution. The two dashed lines are the high-energy and low-energy cut-offs of the electrons. The relative frequency on the horizontal axis is normalized to the high-energy cut-off, and the low-energy cut-off is assumed to be 10^{-4} . (K. Kellermann 1964). Vertical axis: relative intensity (10^{-2} to 10^4); horizontal axis: relative frequency (10^{-7} to 10). The curves are $\gamma = 1.0, 1.5, 2.0, 2.5, 3.0$.

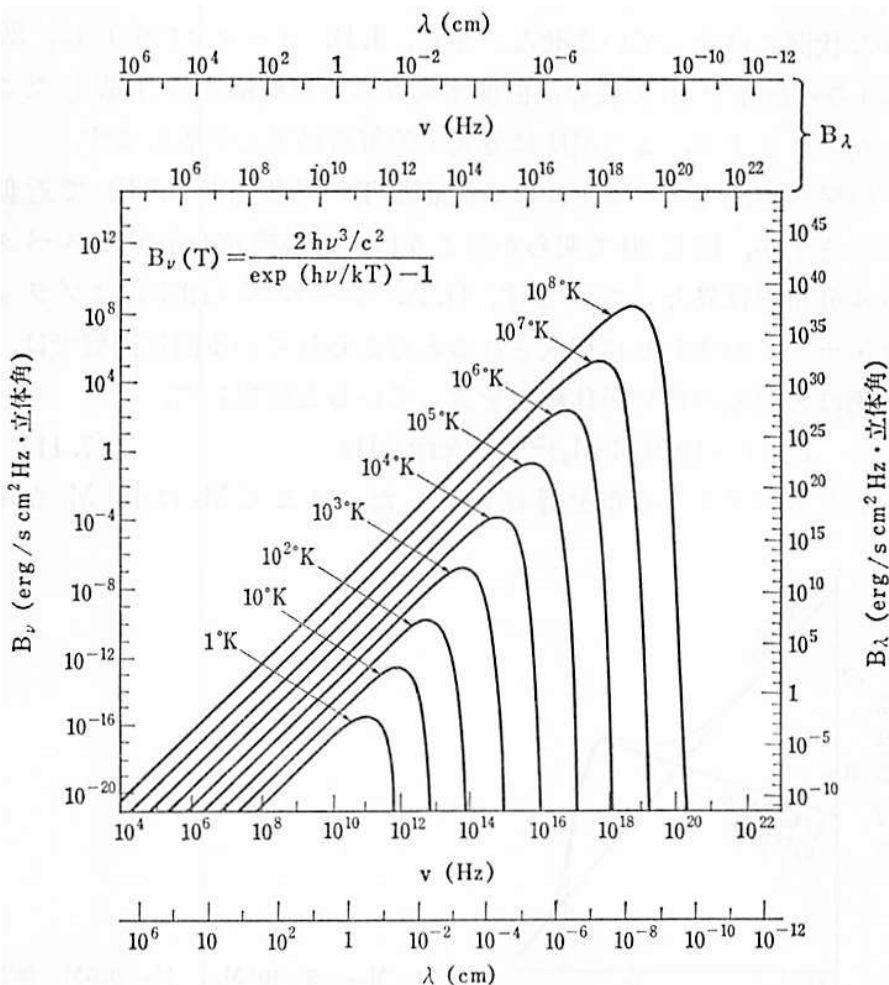


図 7.30 黒体輻射スペクトル. (J. D. クラウス 1966).

Figure 7.30 Black-body radiation spectra. (J. D. Kraus 1966). Vertical axes: B_ν (erg/s cm²Hz·steradian) (10^{-20} to 10^{12}) and B_λ (erg/s cm²Hz·steradian) (10^{-10} to 10^{45}); horizontal axes: ν (Hz) (10^4 to 10^{22}) and λ (cm) (10^6 to 10^{-12}). Formula in the figure: $B_\nu(T) = 2h\nu^3/c^2/(\exp(h\nu/kT) - 1)$. The curves are 1°K, 10°K, 10² K, 10³ K, 10⁴ K, 10⁵ K, 10⁶ K, 10⁷ K, 10⁸ K.

I. S. Shklovsky (1965) and K. Takarada [宝田克男] (1968, 1970) explained the ultraviolet continuum of quasars as light produced by inverse Compton scattering of infrared photons off relativistic electrons. As we shall see in the next chapter, however, the infrared light of Seyfert galaxies is very probably thermal radiation from dust grains that absorb ultraviolet light and re-emit it, and the situation required for inverse Compton scattering does not obtain. J. B. Oke (1965) also once argued that the continuum of 3C 273 is the continuous radiation of high-temperature hydrogen gas at 160,000 degrees, but this temperature contradicts the results of spectroscopic analysis.

The continuum spectrum of a star can be approximated by black-body radiation $B_\nu(T)$ at the surface temperature T , but as is clear from Figure 7.30 this differs from the flat spectral distribution of the nuclear light. G. A. Shields (1978) interpreted the rotating disk thought to form around a black hole as emitting black-body radiation of lower temperature the farther out one goes, and derived the spectral distribution

$$F_\nu = 6 \times 10^{29} (M_8 \dot{M}_0)^{2/3} \nu_{15}^{1/3} \text{ erg/sHz}$$

Here M_8 is the mass of the black hole in units of $10^8 M_\odot$, $\dot{M}_0$ is the mass of gas falling onto the black hole in one year in units of the solar mass, and ν_{15} is the frequency of the light in units of 10^{15} Hz . The spectrum of (7.11) is cut off at the frequency corresponding to the temperature of the inner part of the rotating disk,

$$\nu_c = 6 \times 10^{15} (M_8^{-1/2} \dot{M}_0^{1/4}) \text{ Hz}$$

Figure 7.31 shows the spectral distribution expected for $M_{\text{BH}} = 5 \times 10^9 M_\odot$ and $\dot{M}_0 = 0.5 M_\odot/\text{year}$. This appears to reproduce well the characteristics of the continuum spectra of Seyfert galaxies and quasars. It is not easy, however, to explain the violent light variation seen in NGC 4151 as thermal radiation.

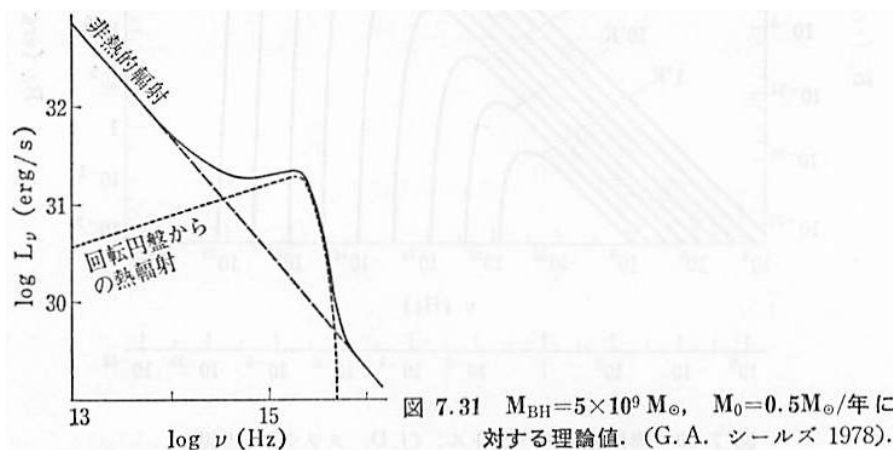


Figure 7.31 Theoretical values for $M_{\text{BH}} = 5 \times 10^9 M_{\odot}$, $M_0 = 0.5 M_{\odot}/\text{year}$. (G. A. Shields 1978). Vertical axis: $\log L_{\nu}$ (erg/s) (30–32); horizontal axis: $\log \nu$ (Hz) (13–15). Labels in the figure: non-thermal radiation; thermal radiation from the rotating disk.

Regrettably, our understanding of the continuum is quite inadequate. Observationally, contamination by the background light makes it impossible to determine the correct spectral distribution of the nucleus. Both the radiation mechanism and the cause of the light variation remain unknown.

Chapter VIII. Infrared Radiation

1. The Infrared Continuum

(1) Spectral distribution

The spectral distribution in the infrared is determined mainly from the broadband photometric observations described in the previous chapter. Because absorption by water vapor within the Earth's atmosphere is strong, telescopes installed on high mountains and telescopes carried aboard aircraft are also used for infrared observations. For example, on the summit of the volcano Mauna Kea in Hawaii, at an altitude of 4,200 m, the water-vapor content is reduced to 10% of that at ground level. Recently two telescopes dedicated to the infrared, of aperture 3.8 m and 3 m, were built there. In addition, the flying observatory named after G. P. Kuiper (KAO: Kuiper Airborne Observatory) carries a 91 cm telescope.

Figure 8.1 shows, for type 1 and type 2 Seyfert galaxies, the spectral distribution of the infrared light plotted in absolute luminosity together with the visible light. Comparison with the spectral distribution of the Andromeda galaxy M 31 shows that every Seyfert galaxy has a large infrared excess at $\lambda \gtrsim 2 - 3\mu$. This is the infrared continuum studied in this chapter.

In the spectral distributions of the type 2 objects Mkn 1, Mkn 3, Mkn 273 and the type 1 objects NGC 3227, NGC 6814, Mkn 50, one can see the infrared region separated from the short-wavelength region containing the visible light by a minimum near $\lambda \approx 2 - 3\mu$. As is clear from a comparison with M31, the maximum at $\lambda \approx 1.5\mu$ in the short-wavelength region is the contribution of starlight. These infrared continua are therefore thought to fall off sharply beyond $\lambda \approx 2\mu$. For the

type 2 objects NGC 1068 and Mkn 176, and for the majority of the type 1 objects, the spectral distribution is continuous and decreases comparatively monotonically from $\lambda \approx 10\mu$ to the visible region. As we examined in the previous chapter, however, the contamination by starlight cannot be neglected at $\lambda \lesssim 1\mu$ in either NGC 1068 or NGC 4151. Even in these Seyfert galaxies, which at first sight have spectral distributions of the form $f_\nu \propto \nu^{-\alpha}$, the infrared continuum at $\lambda \lesssim 2\mu$ appears to be decreasing rapidly, with a slope steeper than a spectral index of $\alpha \approx 2$. The $\lambda = 1 - 10\mu$ infrared continuum cannot be extrapolated into the visible and ultraviolet regions. The spectral distribution of NGC 4051, the faintest type 1 object, closely resembles those of NGC 4151 and the bright I Zw 1; but since this Seyfert galaxy has a peculiar morphology with no distinct central bulge, it is natural that the contribution of starlight should be small. NGC 4051 and I Zw 1 differ in brightness by about a factor of 100, yet the fraction of contaminating starlight is presumably the same.

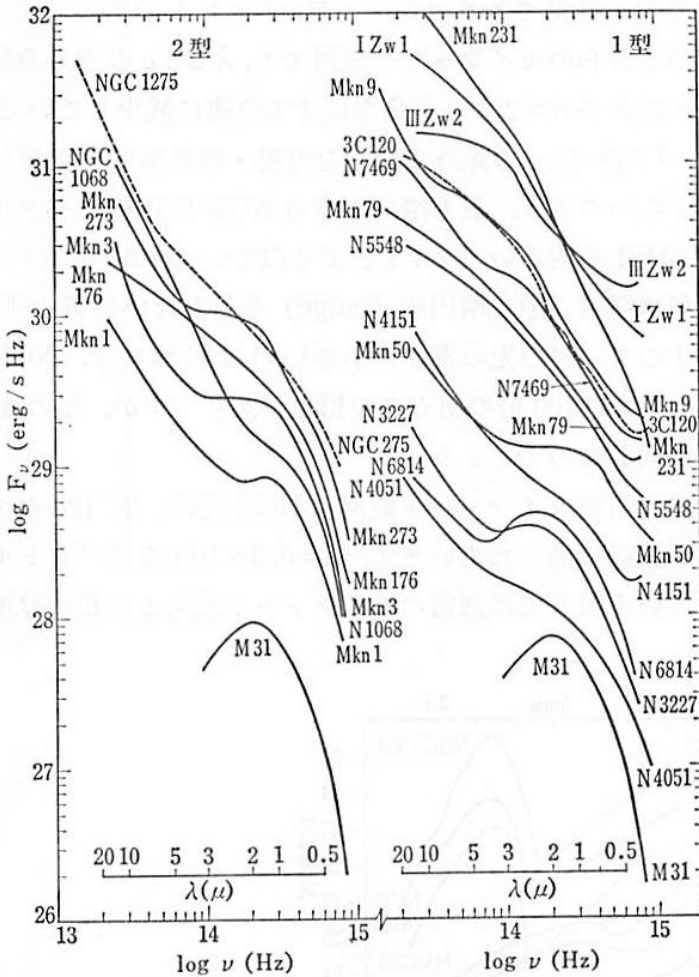


図 8.1 1 型と 2 型セイファート銀河の赤外・可視光スペクトル。
M31 のスケールは任意.

Figure 8.1 Infrared and visible spectra of type 1 and type 2 Seyfert galaxies. The scale for M31 is arbitrary. Ordinate: $\log F_\nu$ (erg/s Hz). Abscissa: $\log \nu$ (Hz) (13–15). Secondary scale $\lambda(\mu)$: 20, 10, 5, 3, 2, 1, 0.5. Curves in the left (“type 2”) panel: NGC 1275 (dashed), NGC 1068, Mkn 273, Mkn 3, Mkn 176, Mkn 1, N 3227, NGC 1275, N 6814, N 4051, Mkn 273, Mkn 176, Mkn 3, N 1068, Mkn 1, M 31. Curves in the right (“type 1”) panel: I Zw 1, Mkn 231, Mkn 9, III Zw 2, 3C 120, N 7469, Mkn 79, N 5548, N 4151, Mkn 50, III Zw 2, I Zw 1, N 7469, Mkn 79, Mkn 9, 3C 120, Mkn 231, N 5548, Mkn 50, N 4151, N 6814, N 3227, N 4051, M 31.

In Figure 8.1 the spectral distributions of the radio Seyfert galaxies NGC 1275 and 3C 120 are drawn as dashed lines. So long as one compares only the spectral distribution over $\lambda = 0.3 - 10\mu$, the difference from ordinary Seyfert galaxies is not clear; but once the $\lambda \sim 100\mu$ far infrared and the millimeter- and centimeter-wave radio emission are taken into account, the difference between the two becomes obvious (Figure 8.2). Whereas the infrared light of the radio-quiet NGC 1068, NGC 4151 and Mkn 231 peaks at $\lambda \approx 100\mu$ and falls off sharply toward the millimeter region, the infrared continuum of the radio Seyfert galaxies NGC 1275 and 3C 120 extends with a slope of $\alpha \approx 0.5$ into the millimeter- and centimeter-wave region and shows a break due to synchrotron self-absorption. Infrared spectra similar to that of NGC 1068 are also observed in M 82 and NGC 253 (Figure 8.3). It is established that this infrared light is thermal radiation from dust grains. The infrared and radio spectra of NGC 1275 and 3C 120 share features in common with the quasar 3C 273 and with the BL Lac objects BL Lac and OJ 287, which resemble the OVV quasars; hence it is inferred that their infrared light originates in synchrotron radiation.

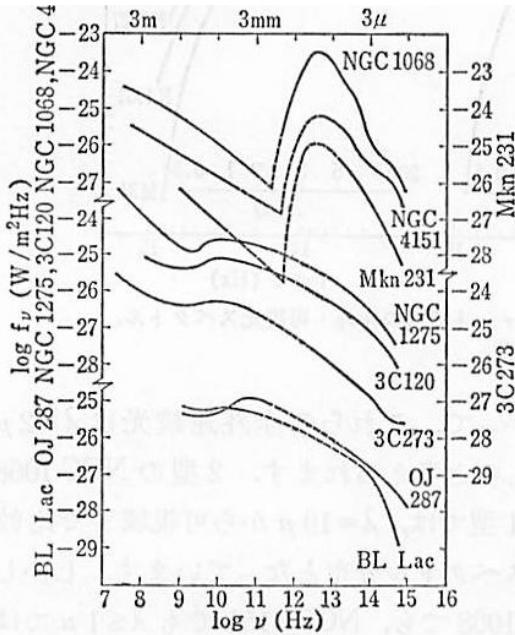


図 8.2 電波・赤外光のスペクトル.

Figure 8.2 Radio and infrared spectra. Ordinate: $\log f_\nu$ ($\text{W}/\text{m}^2\text{Hz}$) (the left-hand axis serves BL Lac, OJ 287, NGC 1275, 3C 120, NGC 1068, NGC 4151; the right-hand axis serves Mkn 231, 3C 273). Abscissa: $\log \nu$ (Hz) (7–16). Wavelength scale along the top: 3 m, 3 mm, 3μ . Curve labels: NGC 1068, NGC 4151, Mkn 231, NGC 1275, 3C 120, 3C 273, OJ 287, BL Lac.

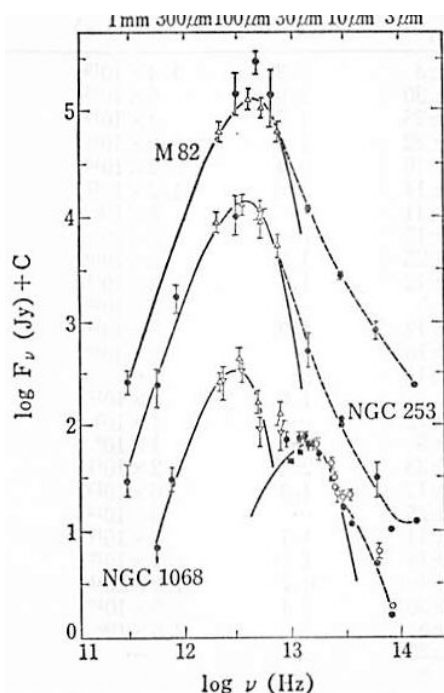


図 8.3 NGC 1068, NGC 253, M 82 の
赤外光スペクトル. (C. M. テレ
スコと D. A. ハーバー 1980).

Figure 8.3 Infrared spectra of NGC 1068, NGC 253 and M 82. (C. M. Telesco and D. A. Harper 1980). Ordinate: $\log F_\nu$ (Jy) + C. Abscissa: $\log \nu$ (Hz) (11–14). Wavelength scale along the top: 1 mm, 300 μm , 100 μm , 30 μm , 10 μm , 3 μm .

Thus it is very likely that the radiation mechanism of the infrared light is entirely different in ordinary Seyfert galaxies and in radio Seyfert galaxies (BL radio galaxies), and in this sense it is important to analyze the two separately.

(2) Luminosity

Table 8.1 gives the infrared observational data of G. H. Rieke (1978). The 1.5 m and 2.3 m telescopes were used for the observations, with apertures of 5".7 and 3".9 respectively. One millijansky (mJy), the unit used for the radiative flux at $\lambda = 10.6\mu$, corresponds to $f_\nu = 1 \times 10^{-29} \text{W/m}^2\text{Hz}$. The spectral index α is defined

between $\lambda = 1\mu$ and 10μ . The luminosity L refers to the wavelength range $\lambda = 1 - 30\mu$. The data of G. H. Rieke (1978) are used in Figure 8.1.

Table 8.1 Infrared radiation of Seyfert galaxies

Galaxy	Type	$F_{\nu}(10.6\mu)$ (mJy)	α (1–10 μ)	$L_{\text{IR}}(L_{\odot})$
Mrk 1	2	61±8	2.3	1.4×10^{10}
Mrk 3	2	290±30	2.9	6×10^{10}
Mrk 6	1	160±25	1.7	4×10^{10}
Mrk 9	1	146±22	1.0	2×10^{11}
Mrk 10	1	18±10	0.4	2×10^{10}
Mrk 34	2	55±14	2.2	1.2×10^{11}
Mrk 50	1	24±11	...	8×10^9
Mrk 78	2	40±17	...	8×10^9
Mrk 79	1	185±25	1.2	8×10^{10}
Mrk 124	1	74±12	1.1	2×10^{11}
Mrk 141	1	17±9	...	2×10^{10}
Mrk 176	2	79±12	1.3	5×10^{10}
Mrk 198	2	69±18	...	6×10^{10}
Mrk 205	1	–3±11	...	...
Mrk 231	1	1420	1.6	2×10^{12}
Mrk 268	2	–1±12	...	1×10^9
Mrk 270	2	17±9	...	1×10^9
Mrk 273	2	98±23	2.4	1.2×10^{11}
Mrk 279	1	76±12	1.4	6×10^{10}
Mrk 290	1	48±25	...	3×10^{10}
Mrk 304	1	73±11	1.1	3×10^{11}
Mrk 315	1	68±14	1.8	7×10^{10}
Mrk 335	1	210±40	0.7	1.2×10^{11}
Mrk 348	2	300±30	2.4	5×10^{10}
Mrk 352	1	17±8	...	2.5×10^9
Mrk 358	1	17±25	...	...
Mrk 372	2	14±8	...	...

Table 8.1 Infrared radiation of Seyfert galaxies (continued)

Galaxy	Type	$F_{\nu}(10.6\mu)$ (mJy)	$\alpha(1 - 10\mu)$	$L_{\text{IR}}(L_{\odot})$
Mrk 374	1	25±17	...	3×10^{10}
Mrk 376	1	77±13	0.5	3×10^{11}
Mrk 391	1	36±13	...	4×10^9
Mrk 471	1	14±20	...	...
Mrk 478	1	86±19	1.0	5×10^{11}
Mrk 486	1	62±15	0.8	6×10^{10}
Mrk 506	1	-6±10	...	...
Mrk 509	1	140±20	0.6	2×10^{11}
NGC 1068	2	18000	2.2	3×10^{11}
NGC 1275	2	770	1.5	2.5×10^{11}
NGC 3227	1	280±35	2.5	4×10^9
NGC 3516	1	230±30	...	1×10^{10}
NGC 3783	1	440±60	1.3	3×10^{10}
NGC 4051	1	260±30	1.5	1×10^9
NGC 4148	1	1400	1.45	1.0×10^{10}
NGC 5584	1	210±20	1.0	5×10^{10}
NGC 6764	2	150±21	3.5	2×10^{10}
NGC 6814	1	56±15	2.2	1.4×10^9
NGC 7469	1	600	1.4	1.7×10^{11}
NGC 7603	1	77±14	1.7	5×10^{10}
IC 4329A	1	770±70	...	1.5×10^{11}
3C 120	1	220±30	1.0	2.4×10^{11}
Zw 0039.5	1	13±13	...	...
I Zw 1	1	310±30	1.2	9×10^{11}
II Zw 136	1	140±30	1.0	4×10^{11}
III Zw 2	1	44±9	0.4	4×10^{11}
III Zw 55N	2	...	...	...

The most striking characteristic of the infrared light is its enormous radiated energy. The infrared luminosity of Mkn 231, the brightest object in the infrared, reaches $L_{\text{IR}} = 2 \times 10^{12} L_{\odot}$ (8×10^{45} erg/sec), an energy comparable to — or even surpassing — the ultraviolet luminosity of the brightest quasars. The infrared luminosity of NGC 1068 is also very large, $L_{\text{IR}} = 3 \times 10^{11} L_{\odot}$, accounting for more than 90% of the total radiated energy. The infrared luminosities of NGC 4051 and NGC 4151 are $L_{\text{IR}} = 1 \times 10^9 L_{\odot}$ and $1 \times 10^{10} L_{\odot}$ respectively, corresponding to energies of the same order as the visible and ultraviolet luminosities obtained from equation (7.10).

In Figure 8.4 we plot the absolute flux of the nuclear light at $\lambda = 3,600 \text{Å}$, $F_{\nu}(U)$, against the infrared luminosity L_{IR} . Types 1 and 2 are distinguished by filled and open circles respectively. Considerable scatter is seen among the type 2 Seyfert galaxies, but for the type 1 Seyfert galaxies a comparatively good proportionality holds between the two quantities. As can be seen by drawing the line along which the infrared luminosity equals the visible-plus-ultraviolet luminosity, the infrared luminosity of type 1 Seyfert galaxies is of the same order as their visible and ultraviolet luminosity. As one would expect from the relations $F_{\nu}(U) \propto L(H_{\alpha}) \propto L([O \text{ III}])$ and $F_{\nu}(U) \propto L_{\text{IR}}$, a proportionality is also found between the infrared luminosity and the emission-line luminosity of type 1 Seyfert galaxies. The scatter seen among the type 2 Seyfert galaxies presumably reflects their inhomogeneous character.

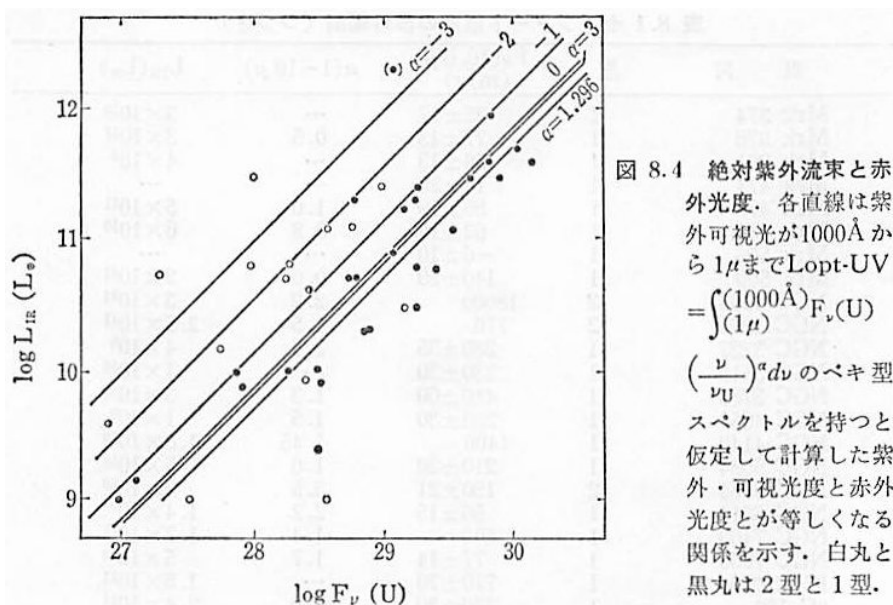


Figure 8.4 Absolute ultraviolet flux and infrared luminosity. Each straight line shows the relation along which the infrared luminosity equals the ultraviolet-plus-visible luminosity, calculated on the assumption that the ultraviolet-visible light from 1000Å to 1μ has a power-law spectrum $L_{\text{opt-UV}} = \int_{(1\mu)}^{(1000\text{\AA})} F_{\nu}(U) (\nu/\nu_U)^{\alpha} d\nu$. Open and filled circles denote types 2 and 1. Ordinate: $\log L_{\text{IR}} (L_{\odot})$ (9–12). Abscissa: $\log F_{\nu}(U)$ (27–30). Line labels: $\alpha = -3, -2, -1, 0, \alpha = 3, \alpha = 1.296$.

2. Emission Lines and Si Absorption

NGC 1068, apparently the brightest object in the infrared, is a good target for infrared spectroscopy. Figure 8.5 shows the spectrum around 2.2μ observed by R. I. Thompson, M. J. Lebofsky and G. H. Rieke (1978), who attached an interferometric spectrometer to the 2.3 m telescope of the Steward Observatory. Identified in it are the hydrogen Brackett-series emission line B_{γ} , neutral helium He I, and two emission lines of molecular hydrogen H_2 . The strength of B_{γ} , together with the P_{α} observed by G. Neugebauer et al. (1980), is used to determine the

amount of reddening (Table 6.9). The mass of molecular hydrogen gas calculated from the molecular hydrogen lines is $6,000M_{\odot}$.

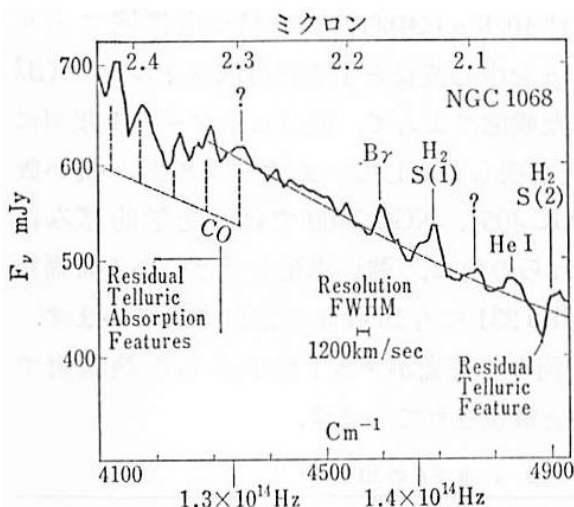


図 8.5 NGC 1068 の 2.2μ 周辺の赤外スペクトル。
(R. I. トムソン,
M. J. レボフスキー,
G. H. リーク 1978).

Figure 8.5 Infrared spectrum of NGC 1068 around 2.2μ . (R. I. Thompson, M. J. Lebofsky, G. H. Rieke 1978). Ordinate: F_{ν} mJy (400–700). Abscissa: cm^{-1} (4100–4900), with a micron scale along the top (2.4, 2.3, 2.2, 2.1) and $1.3 \times 10^{14}\text{Hz}$, $1.4 \times 10^{14}\text{Hz}$ below. Annotations in the figure: NGC 1068, CO, $B\gamma$, H_2 S(1), H_2 S(2), He I, ?, Residual Telluric Absorption Features, Resolution FWHM 1200 km/sec, Residual Telluric Feature.

Figure 8.6 shows the $8\text{--}13\mu$ spectrum of NGC 1068 observed by D. E. Kleinmann, F. G. Gillett and E. L. Wright (1976) with the 2.1 m and 4 m telescopes of Kitt Peak National Observatory. Besides the forbidden line of neon $[\text{Ne II}] \lambda 12.8\mu$, one sees the $\lambda = 9.7\mu$ absorption of silicon Si, first detected by G. H. Rieke and F. J. Low (1975). This corresponds to an absorption of optical depth $\tau(9.7\mu) \approx 0.4 - 1.2$. By an ingenious observation using a broadband filter centered on 10.6μ ($\Delta\lambda = 5\mu$) and a narrowband filter centered on 10.4μ ($\Delta\lambda = 1.3\mu$), M. J. Lebofsky and G. H. Rieke (1979) have shown that Si absorption is present in other Seyfert galaxies as well (Table 8.2). In NGC 3227, NGC 4051 and NGC 7469, which show strong absorption, the optical depth exceeds 0.2. Besides these, Si absorption has also

been reported in Mkn 231, the peculiar type 1 Seyfert galaxy that suffers strong reddening. The Si absorption is interpreted as meaning that the infrared light of Seyfert galaxies is thermal radiation from dust grains.

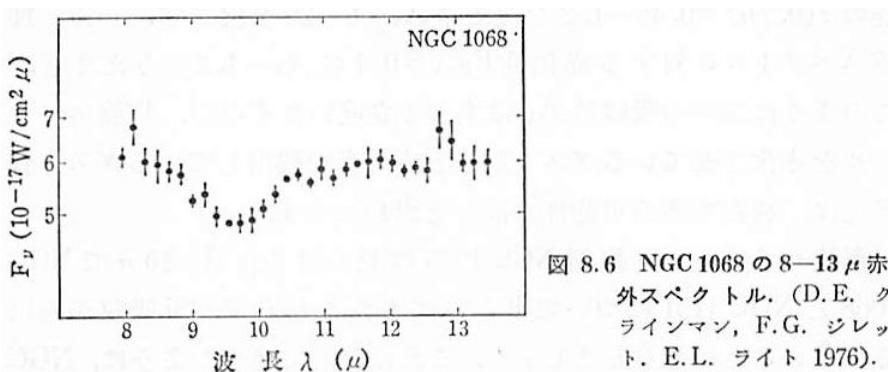


Figure 8.6 The 8–13 μ infrared spectrum of NGC 1068. (D. E. Kleinmann, F. G. Gillett, E. L. Wright 1976). Ordinate: F_ν ($10^{-17} \text{ W/cm}^2 \mu$). Abscissa: wavelength λ (μ) (8–13).

Table 8.2 Si absorption at $\lambda = 9.7\mu$

Galaxy	I (narrowband filter) / I (broadband filter)	Optical depth τ_{Si}
NGC 1068	0.88 ± 0.02	0.18
NGC 1275	1.01 ± 0.06	≤ 0.15
NGC 3227	0.77 ± 0.06	0.50
NGC 4051	0.85 ± 0.07	0.25
NGC 4151	1.02 ± 0.04	≤ 0.09
NGC 7469	0.87 ± 0.04	0.20
I Zw 1	0.91 ± 0.15	0.11

Between the absorption A_V in the V magnitude and the optical depth of the Si absorption $\tau(9.7\mu)$ there holds the relation $A_V/\tau(9.7\mu) \approx 14 - 22$. Adopting for NGC 1068 the value $\tau(9.7\mu) = 0.18$ from Table 8.2 gives $A_V \approx 2.5 - 4$, while using Kleinmann et al.'s $\tau(9.7\mu) = 0.45 - 1.2$ gives $A_V \approx 6 - 26$. On the other

hand, the reddening $E_B - V = 0.4$ for the emission-line spectrum gives $A_V = 1.2$. Since these two values of the absorption A_V differ so greatly, it seems very likely that the dust grains that redden the emission-line spectrum and the dust grains that radiate the infrared light are different things.

It should be noted that although the radio Seyfert galaxy NGC 1275 is apparently the third brightest object at $\lambda = 10\mu$ after NGC 1068 and NGC 4151, no Si absorption is detected in it. As stated in the previous section, this is a fact favorable to interpreting the infrared light of NGC 1275 as non-thermal synchrotron radiation.

3. Light Variation and Polarization

(1) Infrared variability

At present the evidence for light variation at $\lambda = 10\mu$ is negative. G. H. Rieke and E. J. Low (1972) reported detecting $\lambda = 10\mu$ variability in NGC 1068, NGC 4151 and 3C 273; but W. A. Stein, F. G. Gillett and K. M. Merrill (1974) compared these with $\lambda = 11\mu$ observations of NGC 1068 and NGC 4151 made during the same period, and showed that the variation claimed by the former was not seen in NGC 4151 and that NGC 1068 did not vary at all (Figure 8.7). Stein et al. conclude that, while leaving open the possibility of 50% variation at $\lambda = 11\mu$ in NGC 4151 on a time scale of about 100 days, no variability exists at $\lambda \approx 10\mu$.

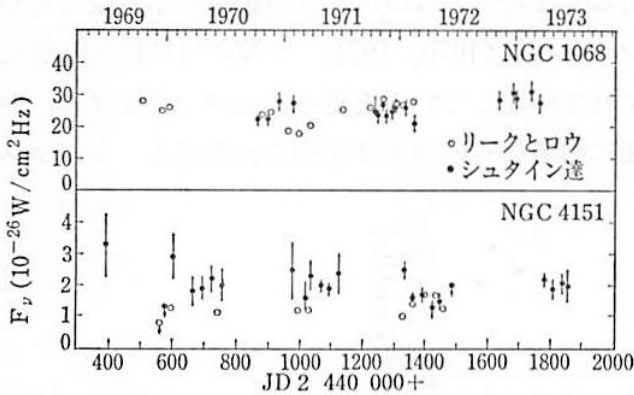


図 8.7 NGC 1068
と NGC 4151
の赤外変光モ
ニター. (W.
A. シュタイ
ン, F.C. ジ
レット, M. メ
リル 1974).

Figure 8.7 Infrared variability monitoring of NGC 1068 and NGC 4151. (W. A. Stein, F. C. Gillett, M. Merrill 1974). Ordinate: F_ν ($10^{-26}\text{W}/\text{cm}^2\text{Hz}$). Abscissa: JD 2 440 000+ (400–2000), with years along the top (1969, 1970, 1971, 1972, 1973). Legend: $\circ$ Rieke and Low, $\bullet$ Stein et al. Upper panel NGC 1068, lower panel NGC 4151.

Recently M. J. Lebofsky and G. H. Rieke (1980) discovered that the K (2.2μ) magnitudes of III Zw 2, NGC 4151, NGC 5548, NGC 1275 and 3C 120, which vary with large amplitude, fluctuate on time scales of years (Figure 8.8). The amplitude of the infrared variation is 20–30% for III Zw 2, NGC 4151 and NGC 5548, but the fluctuations are larger for the powerful radio sources NGC 1275 and 3C 120; in particular, 3C 120 shows a dimming of more than 0.6 magnitude from 1972 to 1980.

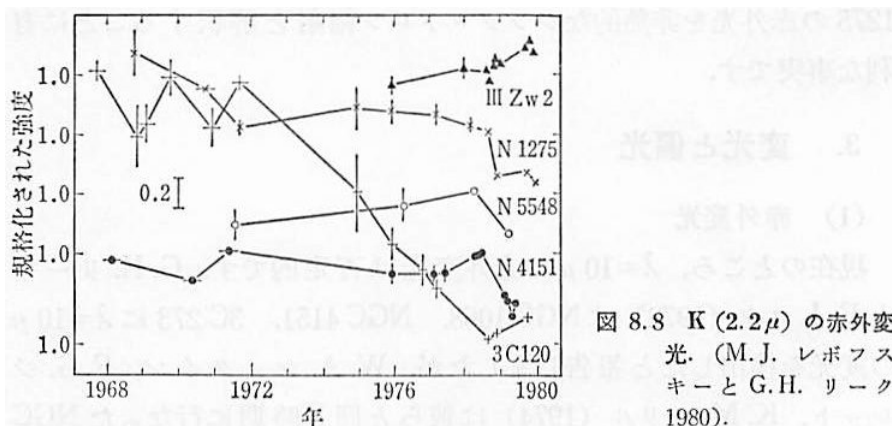


Figure 8.8 Infrared variation of K (2.2μ). (M. J. Lebofsky and G. H. Rieke 1980). Ordinate: normalized intensity (each series referred to 1.0; a bar of scale 0.2 is shown). Abscissa: year (1968, 1972, 1976, 1980). Curve labels: III Zw 2, N 1275, N 5548, N 4151, 3C 120.

Figure 8.9 gives the result of M. J. Lebofsky and G. H. Rieke (1980), who observed the B and K magnitudes of III Zw 2 simultaneously. Over the two years 1978 and 1979 the object brightened in K magnitude while it faded in B magnitude. In the observations of NGC 4151 by M. V. Penston et al. (1970, 1974) the two can be regarded as being in step with a phase lag of a few months, but no clear correspondence is found between the U-magnitude and K-magnitude variations. Lebofsky and Rieke interpreted the observational facts for III Zw 2 as strong evidence that the infrared light is thermal radiation from dust grains. The reason is that if the visible and infrared light were one and the same synchrotron radiation, the K-magnitude variation ought to be synchronized with the B magnitude. The hot dust grains that efficiently radiate the $\lambda \approx 2\mu$ infrared light are distributed in a region of radius $r \approx 0.1-1$ pc. It takes about a year for the varying ultraviolet light to reach this dust region, so the infrared variation need not necessarily be in phase with the visible and ultraviolet variation. Moreover, because the dust region is

comparatively large, the fluctuations are smoothed out and a large variability amplitude cannot be expected; but the 20–30% amplitude of III Zw 2, NGC 4151 and NGC 5548 is not inconsistent with the calculations carried out by the present author with K. Toyama and M. Nishimura (1972) (Figure 8.10).

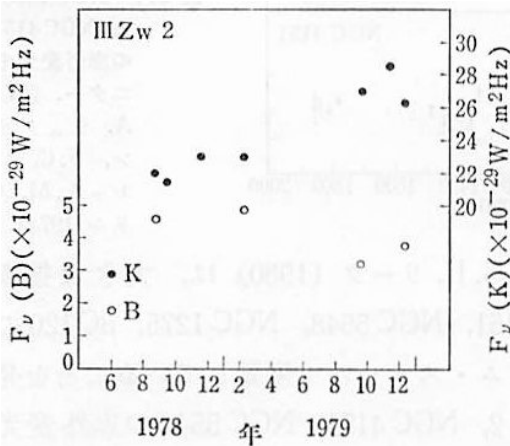


図 8.9 III Zw 2 の B 等級と K 等級.

Figure 8.9 B and K magnitudes of III Zw 2. Left ordinate: $F_v(B)(\times 10^{-29} \text{ W/m}^2\text{Hz})$. Right ordinate: $F_v(K)(\times 10^{-29} \text{ W/m}^2\text{Hz})$. Abscissa: year (1978: months 6, 8, 10, 12; 1979: months 2, 4, 6, 8, 10, 12). Legend: $\bullet$ K, $\circ$ B.

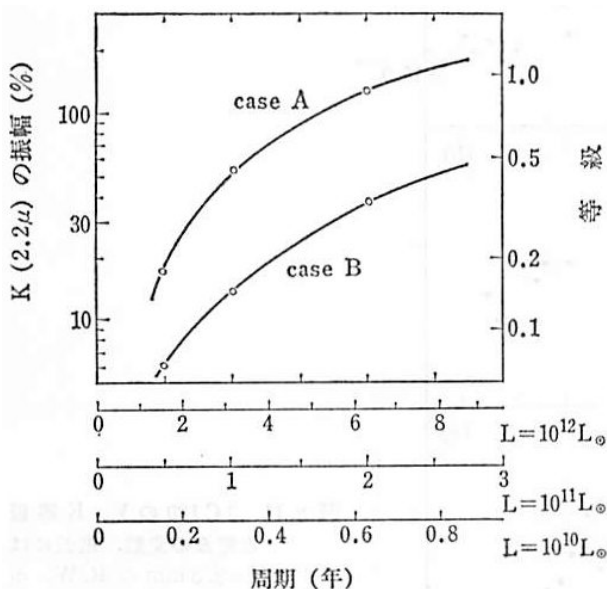


図 8.10 赤外交光の振幅と周期。Aは紫外光が100%変動，Bは50%変動する場合。（兼古昇，外山清高，西村雅樹 1972）。

Figure 8.10 Amplitude and period of the infrared variation. A is the case in which the ultraviolet light varies by 100%, B by 50%. (Kaneko, N., Toyama, K., Nishimura, M. 1972). Ordinate: amplitude of K (2.2μ) (%) (10, 30, 100). Right ordinate: magnitude. Abscissa: period (years) — 0–8 for $L = 10^{12}L_{\odot}$, 0–3 for $L = 10^{11}L_{\odot}$, 0–0.8 for $L = 10^{10}L_{\odot}$. Curve labels: case A, case B.

For NGC 1275 and 3C 120, whose spectra appear continuous from the infrared all the way to the centimeter- and millimeter-wave radio region, the interpretation that the infrared light is thermal radiation from dust grains must be held in reserve. In the case of 3C 120, the V magnitude, the K magnitude, and the radio intensities at $\lambda = 3.3\text{mm}$ and 2.8 cm all show a declining trend over twelve years (Figure 8.11). Whether these are due to one and the same radiation mechanism, or merely reflect a decline in the activity of 3C 120, cannot be decided; but from the standpoint that attaches importance to a non-thermal radiation mechanism for radio Seyfert galaxies these are interesting observational facts.

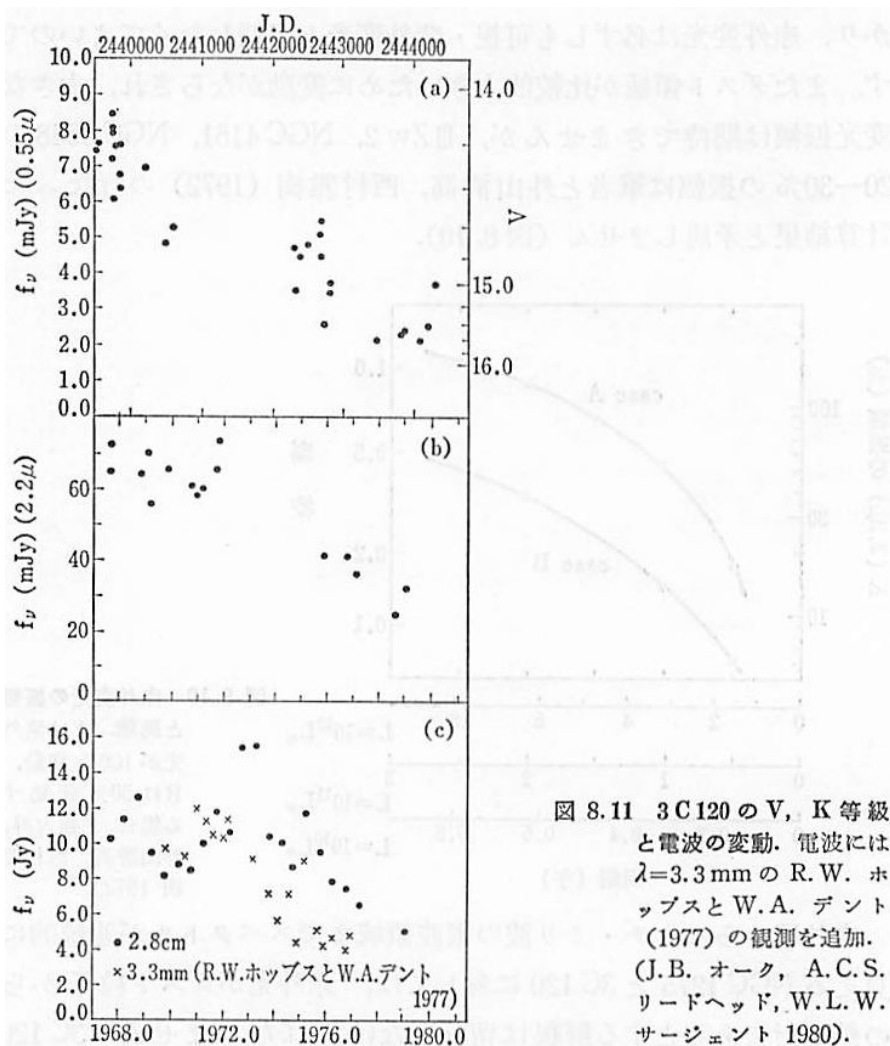


Figure 8.11 Variation of the V and K magnitudes and the radio emission of 3 C 120.

The $\lambda = 3.3\text{mm}$ observations of R. W. Hobbs and W. A. Dent (1977) have been added to the radio data. (J. B. Oke, A. C. S. Readhead, W. L. W. Sargent 1980). (a) Ordinate: f_ν (mJy) (0.55μ) (0.0–10.0), with V magnitude on the right axis (14.0, 15.0, 16.0). (b) Ordinate: f_ν (mJy) (2.2μ) (0–80). (c) Ordinate: f_ν (Jy) (0.0–16.0). Legend: ● 2.8 cm, × 3.3 mm (R. W. Hobbs and W. A. Dent 1977). Abscissa: 1968.0–1980.0, with J.D. along the top (2440000, 2441000, 2442000, 2443000, 2444000).

(2) Infrared polarization

In general the infrared light of Seyfert galaxies is thought to be unpolarized. In the results of J. C. Kemp et al. (1977), observed at $\lambda = 2.2\mu$, NGC 1275, NGC 4151, Mkn 231 and the quasar 3C 273 show only very small degrees of polarization, 0.1–0.6%.

In NGC 1068, however, strong infrared polarization is observed. Figure 8.12 shows the infrared polarization of NGC 1068 observed by M. J. Lebofsky, G. H. Rieke and J. C. Kemp (1978) with the 2.3 m telescope of the Steward Observatory. The degree of polarization of this galaxy (Figure 7.26, Table 7.9) was ~10% in the ultraviolet and decreased rapidly with increasing wavelength to ~0.5% at $\lambda \approx 8,000\text{\AA}$; but in the infrared region it increases again, to 3–4%, and the position angle of polarization is also different. In the case of NGC 1068, the possibility must be considered that, besides the infrared thermal radiation from dust grains, strongly polarized non-thermal radiation is also present.

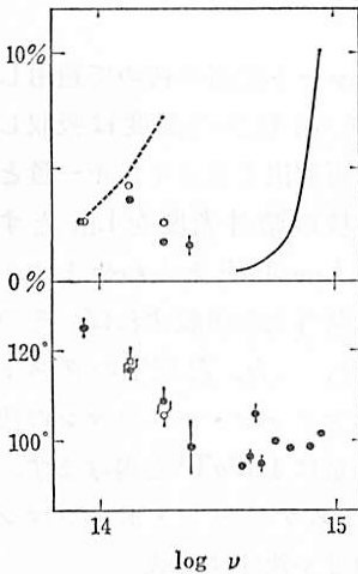


図 8.12 NGC 1068 の赤外偏光. (M. J. レボフスキー, G. H. リーク, J. C. ケンプ 1978).

Figure 8.12 Infrared polarization of NGC 1068. (M. J. Lebofsky, G. H. Rieke, J. C. Kemp 1978). Upper ordinate: degree of polarization (0%–10%). Lower ordinate: position angle (100°, 120°). Abscissa: $\log \nu$ (14–15).

4. The Radiation Mechanism of the Infrared Light

Now, from the studies above we have obtained evidence sufficient to convince us that, apart from the radio sources, the infrared light of Seyfert galaxies is thermal radiation from dust grains. To recapitulate:

- (1) The $\lambda = 10\mu$ infrared light of NGC 1068 is radiation from a region of ~ 100 pc, not from the compact region ($\lesssim 0.1$ pc) that synchrotron radiation would require (Chapter III, Section 1);
- (2) The infrared spectral distributions of NGC 1068 and NGC 4151 resemble those of the peculiar galaxies M 82 and NGC 253, for which a thermal origin is

established, and those of infrared sources within the Milky Way galaxy (planetary nebulae, gaseous nebulae) (Figure 8.2; Figure 8.3);

(3) Si absorption is present at $\lambda = 9.7\mu$ (Figure 8.6; Table 8.2);

(4) Infrared variation is observed only at $\lambda = 2.2\mu$, and moreover in III Zw 2 it is not synchronized with the visible and ultraviolet variation (Figure 8.8; Figure 8.9).

The first to apply the theory of thermal radiation from dust grains to Seyfert galaxies were M. J. Rees et al. (1969). The temperature of a dust grain is determined by requiring that the energy of the ultraviolet light it absorbs equal the energy it re-emits as infrared light. If the ultraviolet luminosity of the nucleus is L_{UV} , the radiative flux at a point a distance d away can be written $L_{UV}/4\pi d^2$. If a spherical dust grain of radius a absorbs the ultraviolet light completely, the energy absorbed is $\pi a^2 \cdot L_{UV}/4\pi d^2$. On the other hand, if a dust grain at temperature T radiates as a blackbody, the energy of the infrared light re-emitted can be written, from the Stefan–Boltzmann law, as $4\pi a^2 \sigma T^4$. Here $\sigma = 5.67 \times 10^{-5} \text{ erg/cm}^2 \text{ sec deg}^4$ is the Stefan–Boltzmann constant. Equating the two, we obtain the equation determining the temperature,

$$L_{UV}/(4\pi d^2) \cdot \pi a^2 = \sigma T^4 \cdot 4\pi a^2$$

If temperature, distance and luminosity are measured in units of 100°K , 1 pc and $10^{10}L_\odot$ respectively, equation (8.1) can be expressed as follows:

$$(T/100)^4 \approx (15/d_{\text{pc}}^2)(L_{UV}/10^{10}L_\odot).$$

That is, the temperature of a dust grain falls in inverse proportion to the square root of the distance. Since the dependence on the ultraviolet luminosity is weak,

assuming $L_{UV} = 10^{11}L_{\odot}$ gives $T=1,100^{\circ}\text{K}$ (827°C) and 350°K (77°C) for $d=0.1$ and 1 pc respectively, and $T=110^{\circ}\text{K}$ (-163°C) and 35°K (-238°C) for $d=10$ and 100 pc.

A dust grain at temperature T can be regarded as emitting blackbody radiation (Figure 7.30) with maximum intensity at the wavelength λ_m given by Wien's displacement law,

$$\lambda_m T = 0.51 \text{cm}^{\circ}\text{K}$$

The values $T=1,100^{\circ}\text{K}$ and 350°K obtained above correspond to $\lambda_m \approx 4.6\mu$ and 15μ , and $T=110^{\circ}\text{K}$ and 35°K to $\lambda_m = 46\mu$ and 150μ . The infrared spectrum of NGC 1068 (Figure 8.3) peaks around $\lambda \approx 100\mu$, and the dust-grain temperature is estimated at $T=30-40^{\circ}\text{K}$. As T. W. Jones et al. (1977) showed, in order to explain the energy $L \sim 1.5 \times 10^{11}L_{\odot}$ of this $30-300 \mu$ far-infrared light, one must suppose the radiation comes from a region of several kpc corresponding to the inner region. Figure 8.3 also shows another spectrum peaking at $\lambda \sim 20-30 \mu$. This is thermal radiation at $T \sim 170^{\circ}\text{K}$ (-103°C), and corresponds to the infrared source of diameter 100 pc observed at $\lambda = 10\mu$ by E. E. Becklin et al. (1973).

The total mass of the dust grains, with ρ the specific gravity and N the total number, is

$$M = (4/3)\pi a^3 \rho N$$

Assuming blackbody radiation, the infrared luminosity is

$$L_{IR} = 4\pi a^2 \cdot \sigma T^4 \cdot N$$

so the above expression can be rewritten as

$$M = (a\rho/3) \cdot (L_{\text{IR}}/\sigma T^4)$$

Taking $a\rho/3 = 1 \times 10^{-5} \text{g/cm}^2$, the mass can be written

$$M/M_{\odot} = 34(L_{\text{IR}}/10^{10}L_{\odot})(100/T)^4$$

Substituting $L_{\text{IR}} = 1.5 \times 10^{11}L_{\odot}$ and $T=30\text{--}40^{\circ}\text{K}$ for NGC 1068 gives $M \approx (2 - 6) \times 10^4 M_{\odot}$. Since equation (8.5) does not allow for the radiative efficiency, however, the mass in (8.7) must be regarded as a lower limit. For NGC 1068, C. M. Telesco and D. A. Harper (1980) obtain $2 \times 10^7 M_{\odot}$ and R. H. Hildebrand et al. (1977) obtain $1 \times 10^8 M_{\odot}$. These amount to $\sim 1\%$ of the total mass of gas contained in the inner region of NGC 1068.

We have already seen that the infrared light of Seyfert galaxies accounts for more than half of the total radiated energy. This means that more than half of the ultraviolet light is absorbed by dust grains and converted into infrared light. In NGC 1068 we must suppose that more than 90% is converted into infrared light. The nuclear light analyzed in Chapter VII must be affected by this, and we are forced to recognize afresh how difficult it is to determine the true spectral distribution of the nuclear light.

The infrared radiation of the powerful radio sources NGC 1275 and 3C 120 is of a character that should be discussed as a fundamental problem of radio galaxies rather than of Seyfert galaxies. Finally, let us mention that S. A. Colgate (1967) once considered infrared radiation from a turbulent plasma, and F. J. Low (1970) once supposed that the continuous creation of matter and antimatter takes place within infrared sources called “irtrons.”

Chapter IX. Radio

1. Continuous Spectrum

In general, half of all spiral galaxies and 15% of elliptical galaxies emit radio waves originating in synchrotron radiation strong enough to be received at centimeter and decimeter wavelengths. In fewer than half of these, however, is the nucleus the radio source, as it is in Seyfert galaxies. According to P. C. van der Kruit (1973), the fraction of ordinary spiral galaxies that possess a radio nucleus is less than 20%.

In observations made by A. G. de Bruyn and A. S. Wilson (1976) at 1,415 MHz (21.2 cm), radio emission was detected in 36 of the 56 Seyfert galaxies excluding the radio Seyfert galaxies (Table 9.1). The observations were carried out with the radio interferometer composed of twelve 25 m parabolic antennas at Westerbork in the Netherlands (WSRT = Westerbork Synthesis Radio Telescope), and the detection limit was 4 mJy ($1 \text{ mJy} = 10^{-29} \text{ W/m}^2 \text{ Hz}$). Radio emission has also been detected from Mkn 506, Mkn 533, Mkn 668 (OQ 208), MCG 8-11-11, NGC 6764, and others. Those for which the size or structure of the radio source has been observed are limited to nearby Seyfert galaxies, but their sizes lie in the range of a few hundred pc to a few kpc, less than one-tenth the size of the galaxy. The radio sources of Seyfert galaxies agree well with the nuclear region that radiates the emission-line spectrum.

Table 9.1 Radio intensities of Seyfert galaxies

Galaxy Mkn	Galaxy other name	V_r (km/s)	Type	Spectral index at 1415 MHz	Radio intensity $P_{1415\text{MHz}}$ 10^{21}W/Hz • sr	Radio size (kpc)
1	NGC 449	4800	2	-0.60 ± 0.07	6	< 0.5
3		4110	2	-0.80	68	< 0.4
6	IC 450	5920	2	-0.94 ± 0.05 (total) -0.98 ± 0.15 (core)	36	34 (halo) < 0.2 (core)
34		15300	2		15	< 30
78		11260	2		16	67
79		6580	1		3.2	< 10
110		10800	1		5	< 31
124		16970	1		8	< 49
176	VV 150	8080	2		5.2	< 16
198		7220	2		1.2	< 21
205		21180	1		5.1	< 41
231		12300	1	-0.54 ± 0.06 (total) -0.52 ± 0.1 (core)	150	72 (halo) < 1 (core)
268		12300	2		21	< 18
270		2700	2		0.4	< 4
273		11400	2	-0.59 ± 0.08	66	< 1
279		9220	1		6.8	< 11
290		9240	1		1.7	< 27
298	IC 1182	10350	2		1.8	< 30
335		11830	1		12	< 23
348	NGC 262	4200	2	(~ 0.0)	23	< 0.4
374		13200	1		9	< 38
463		15140		-1.02 ± 0.15	300	

Galaxy Mkn	Galaxy other name	V_r (km/s)	Type	Spectral index at 1415 MHz	Radio intensity $P_{1415\text{MHz}}$ 10^{21}W/Hz • sr	Radio size (kpc)
	NGC 1068	1090	2	-0.75 ± 0.03 (total) -0.25 ± 0.07 (core)	20	1 kpc (halo) $0.2\text{pc} < d < 32\text{pc}$ (core)
	1275	5290	2	(~ 0.0)	(2000)	multi- component
	1566	1170	1	-0.70 ± 0.06	1.5	15
	3227	1000	2	-0.84 ± 0.1 -0.2	0.4	< 0.4
	3516	2780	1		0.7	< 2
	4051	700	1	-0.40 ± 0.2	0.04	0.7
	4151	990	1	-0.74 ± 0.05	1.3	0.3
	5548	4990	1		3	< 4
	6764	2650	2	-1.05 ± 0.25	5	
	6814	1590	1		< 0.05	
	7469	5020	1	-0.85 ± 0.25	19	1.5
	IC 4329A	4140	1		16	
	I Zw 1	18280	1		13	< 53
	III Zw 2	26930	1		(800)	
	3 C 120	9900	1	(-0.1)	(2000)	multi- component
	227	25600	1	-0.82 ± 0.02	1.7×10^4	440
	287.1	64700	1	-0.51 ± 0.07	4×10^4	395
	390.3	17100	1	-0.78 ± 0.03	1.3×10^4	350 (total) < 5 (core)
	PKS 2349-01	52200	1	-0.8 ± 0.1	1.6×10^4	86
	NGC 5506	1800	1	-0.49 ± 0.03	3.9	< 4

(1) Structure of the radio sources

The structures of the radio sources of NGC 1068 (Figures 3.9; 3.10), NGC 3227 (Figure 3.27), NGC 7469 (Figure 3.30), and of the radio sources NGC 1275 (Figures 3.34; 3.45), 3C 120 (Figure 3.50) and 3C 390.3 (Figure 3.54) were already examined in Chapter III. In NGC 1068 there is a halo of about 1 kpc and a core of 0.2–32 pc, and the radio source of NGC 7469 likewise consists of a halo 2 kpc in diameter and a core smaller than 150 pc. In Mkn 6 (Figure 5.1) and Mkn 231 (Figure 5.9), still larger halos are observed (Figure 9.1). Their diameters are 34 kpc and 72 kpc respectively, and the radio halo of Mkn 231 extends in the same direction as the outermost region seen in visible light. Note also that Mkn 6 has a character intermediate between type 1 and type 2, and that Mkn 231 is a strongly reddened type 1 deformed galaxy.

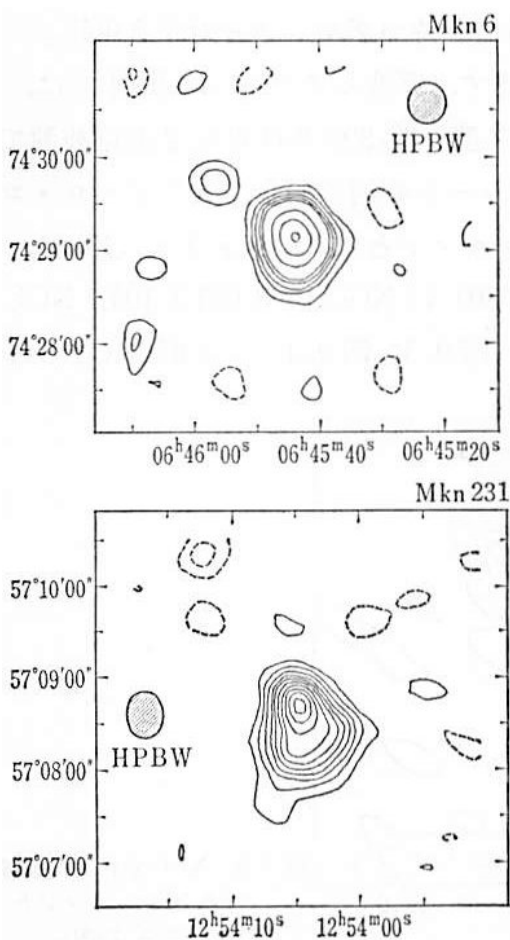


図 9.1 Mkn 6 と Mkn 231 の電波構造. (A. G. フ・ブリヤンと A. S. ウィルソン 1976).

Figure 9.1 Radio structure of Mkn 6 and Mkn 231. (A. G. de Bruyn and A. S. Wilson 1976). Upper panel, Mkn 6: vertical axis (declination) 74°28'00", 74°29'00", 74°30'00". Horizontal axis (right ascension) 06^h45^m20^s, 06^h45^m40^s, 06^h46^m00^s. HPBW shown hatched at upper right. Lower panel, Mkn 231: vertical axis (declination) 57°07'00", 57°08'00", 57°09'00", 57°10'00". Horizontal axis (right ascension) 12^h54^m00^s, 12^h54^m10^s. HPBW shown hatched at lower left.

In the radio Seyfert galaxies NGC 1275 and 3C 120 there exist core components smaller than 1 pc that show changes in radio intensity, and according to the

observations of P. C. Crane (1979), NGC 3227, NGC 7469, Mkn 1 and Mkn 348 also possess compact radio sources smaller than 1 pc. Mkn 348 is classified as type 2, but it is a peculiar Seyfert galaxy in which variations of radio intensity are observed.

Radio galaxies are broadly divided into a group with halo–core structure and a group with paired double radio sources. Among the radio Seyfert galaxies, NGC 1275 and 3C 120 are of the halo–core type, while 3C 390.3 is a paired double radio source. In the case of ordinary, radio-quiet Seyfert galaxies most show halo–core structure, but A. S. Wilson and A. G. Willis (1980), and A. S. Wilson et al. (1980), maintain that paired double radio sources exist in the three Seyfert galaxies NGC 1068 (Figure 3.10), NGC 5548 (Figures 9.2; 5.5) and Mkn 3 (Figures 9.3; 9.4). Compared with the paired double radio sources of 3C 390.3 (Figure 3.54), NGC 5128 (Figure 4.32) and NGC 1316 (Figure 4.41), however, these are on a very much smaller scale: the northern and southern radio sources of NGC 1068 lie 750 pc from the center, and the northern and southern sources of NGC 5548 lie 2.5 kpc and 1.6 kpc from the center respectively. The paired double radio source of Mkn 3 is separated by only 600 pc.

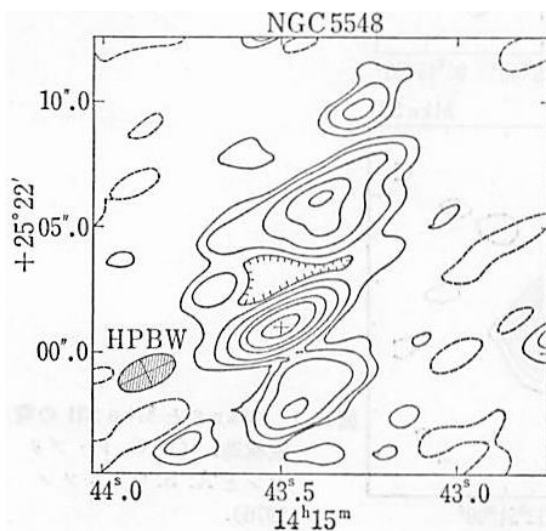


図 9.2 NGC 5548 の電波構造.
(A. S. ウィルソンと A. G. ウィリス 1980).

Figure 9.2 Radio structure of NGC 5548. (A. S. Wilson and A. G. Willis 1980). Vertical axis (declination) $+25^{\circ}22' 00''.0$, $05''.0$, $10''.0$. Horizontal axis (right ascension) $14^{\text{h}}15^{\text{m}} 43''.0$, $43''.5$, $44''.0$. HPBW shown hatched at lower left.

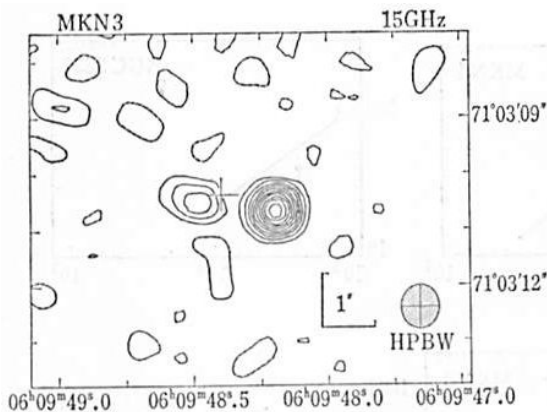


図 9.3 Mkn 3 の電波構造.
(A. S. ウィルソン達 1980).

Figure 9.3 Radio structure of Mkn 3. (A. S. Wilson et al. 1980). “MKN3” at upper left of the panel, “15GHz” at upper right. Vertical axis (declination) $71^{\circ}03'09''$, $71^{\circ}03'12''$. Horizontal axis (right ascension) $06^h09^m49^s.0$, $06^h09^m48^s.5$, $06^h09^m48^s.0$, $06^h09^m47^s.0$. A 1' scale bar and the HPBW are shown in the panel.

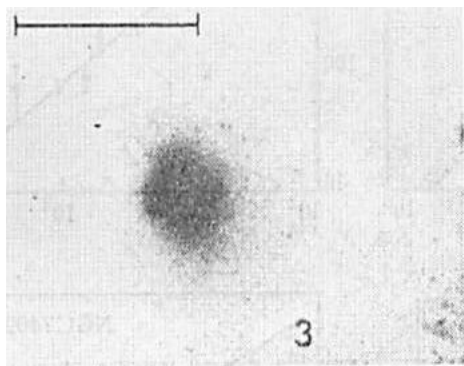


図 9.4 Mkn 3 の写真. スケールは $30''$. (T. F. アダムス 1977).

Figure 9.4 Photograph of Mkn 3. The scale is $30''$. (T. F. Adams 1977).

(2) Spectral distribution

The radio emission of Seyfert galaxies basically shows the spectral distribution of synchrotron radiation, $f_{\nu} \propto \nu^{-\alpha}$. Figure 9.5 shows the spectral distributions of the type 1 galaxies NGC 3227, NGC 4151 and NGC 7469, and of the type 2 galaxies Mkn 1, Mkn 3 and Mkn 273. Figure 9.6 gives the spectral distributions of NGC 1068 and Mkn 6, which have halo–core structure. In the case of NGC 1068 the observed spectral index is $\alpha = 0.8$, but the spectral distribution of the core component is very flat, with $\alpha = 0.25$. The spectral distributions of Mkn 231, Mkn 348 and III Zw 2, in which variations of radio intensity are seen, are very complex and cannot be represented by a single synchrotron spectrum (Figure 9.7). In the frequency region above $\sim 10,000$ MHz (10 GHz; 3 cm) the spectra show the self-absorption characteristic of synchrotron radiation, resembling the radio sources NGC 1275, 3C 120, 3C 273 and the like. It is inferred that within these nuclei there

exist active compact radio sources similar to NGC 1275 and 3C 120, though on a smaller scale.

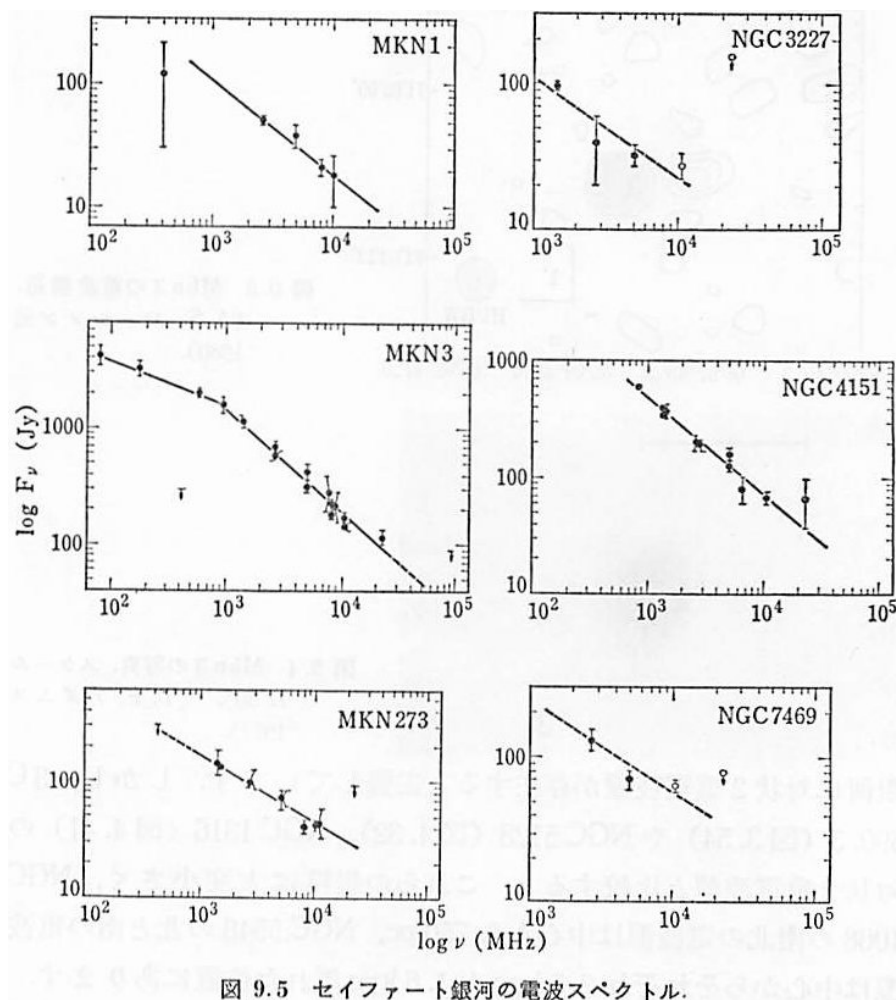


Figure 9.5 Radio spectra of Seyfert galaxies. Vertical axis $\log F_\nu$ (Jy), horizontal axis $\log \nu$ (MHz). Six panels: MKN1, NGC 3227, MKN3, NGC 4151, MKN273, NGC 7469. Horizontal scale 10^2 – 10^5 MHz, vertical scale 10–1000 Jy.

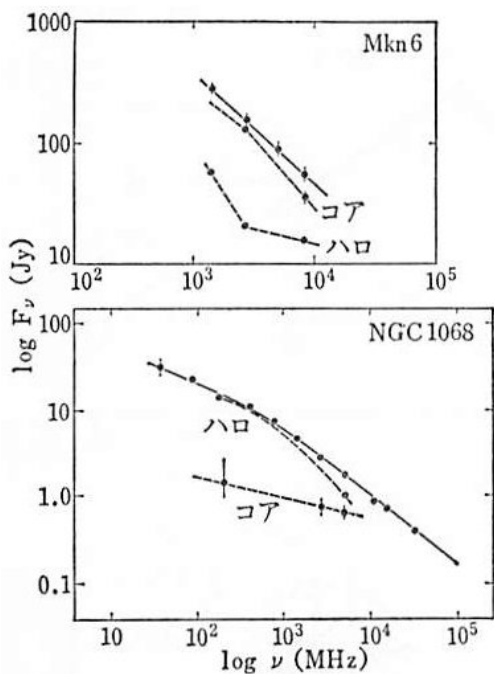


図 9.6 NGC 1068 と Mkn 6 の電波スペクトル.

Figure 9.6 Radio spectra of NGC 1068 and Mkn 6. Vertical axis $\log F_\nu$ (Jy), horizontal axis $\log \nu$ (MHz). Upper panel Mkn 6 (0.1–1000 Jy, 10^2 – 10^4 MHz), lower panel NGC 1068. Two curves labeled “core” (コア) and “halo” (ハロ) are shown in each panel.

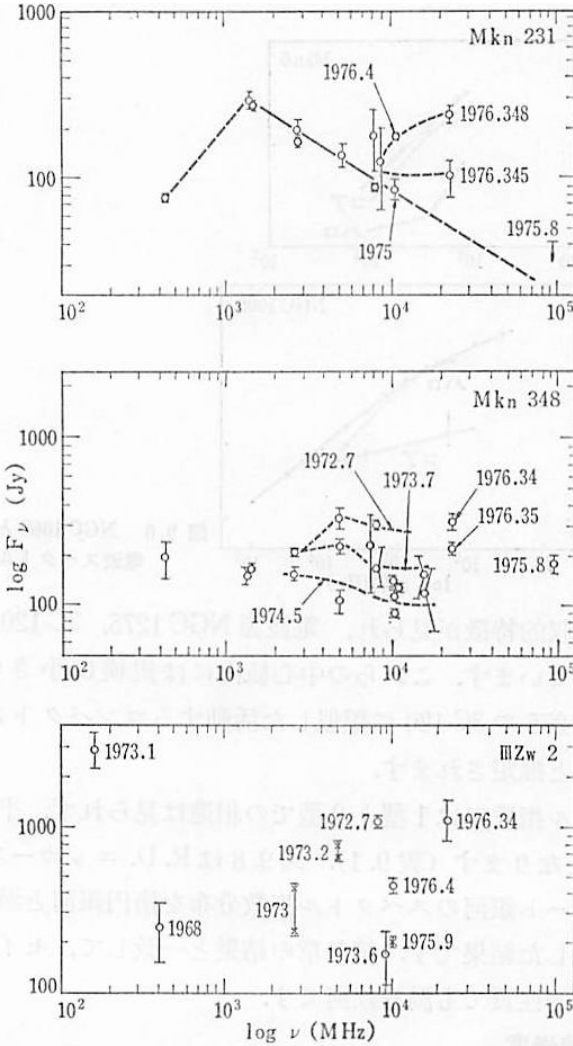


Figure 9.7 Mkn 231, Mkn 348, III Zw 2, in which variations of radio intensity are seen. Vertical axis $\log F_\nu$ (Jy), horizontal axis $\log \nu$ (MHz). Upper panel Mkn 231: epochs 1975, 1975.8, 1976.4, 1976.345, 1976.348 annotated. Middle panel Mkn 348: epochs 1972.7, 1973.7, 1974.5, 1975.8, 1976.34, 1976.35 annotated. Lower panel III Zw 2: epochs 1968, 1973, 1973.1, 1973.2, 1973.6, 1975.9, 1976.4, 1976.34, 1972.7 annotated.

No difference between types 1 and 2 is seen in the spectral index; on average $\langle\alpha\rangle \approx 0.8$ (Table 9.1). Figure 9.8 shows the result of R. D. Ekers' (1978) comparison of the spectral-index distribution of Seyfert galaxies with those of elliptical and spiral galaxies. In agreement with the results of Chapter V, Seyfert galaxies are spiral galaxies in their radio properties as well.

(3) Radio luminosity

Table 9.1 gives the radio intensity P_{1415} at 1,415 MHz. This is the absolute radiative flux F_ν divided by the total solid angle 4π ($F_\nu = 4\pi P_\nu$). If we exclude the radio Seyfert galaxies and examine the distributions of radio intensity for types 1 and 2, we find a tendency for type 2 Seyfert galaxies to be the stronger radio emitters (Figure 9.9). As Table 9.1 shows, more than half of the Seyfert galaxies with detected radio emission are of type 2, and for a considerable number of the type 1 objects only upper limits have been obtained.

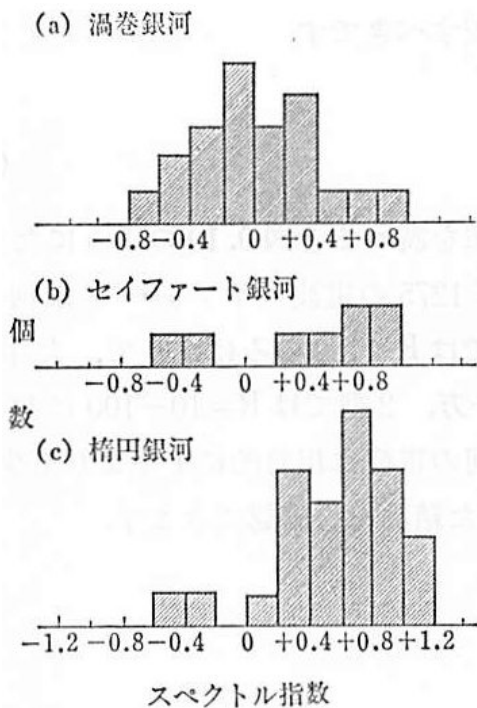


図 9.8 セイファート銀河のスペクトル指数と渦巻銀河、楕円銀河との比較. スペクトル指数は 1.4 と 5.0 GHz 間で定義. (R. D. エッカース 1978).

Figure 9.8 Comparison of the spectral indices of Seyfert galaxies with those of spiral and elliptical galaxies. The spectral index is defined between 1.4 and 5.0 GHz. (R. D. Ekers 1978). (a) spiral galaxies, (b) Seyfert galaxies, (c) elliptical galaxies. Vertical axis “number”, horizontal axis “spectral index”, scale $-1.2, -0.8, -0.4, 0, +0.4, +0.8, +1.2$.

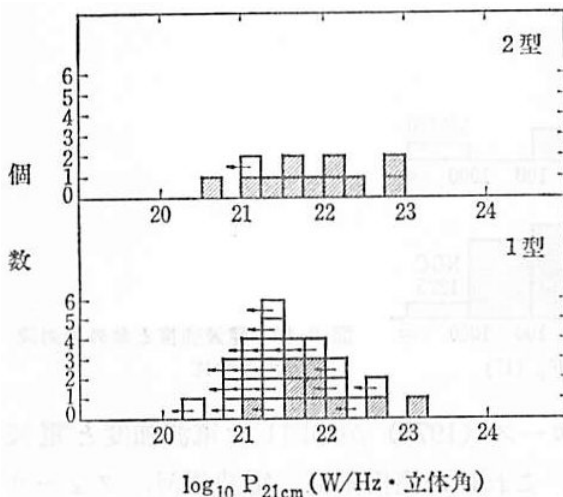


図 9.9 1型と2型セイファート銀河の電波強度。斜線は表 9.1 で電波が測定されたもの、矢印は上限値のみ。(A. G. ド・ブリヤンと A. S. ウィルソン 1978)。

Figure 9.9 Radio intensities of type 1 and type 2 Seyfert galaxies. The hatching denotes objects with measured radio emission in Table 9.1; the arrows denote upper limits only. (A. G. de Bruyn and A. S. Wilson 1978). Upper panel “type 2”, lower panel “type 1”. Vertical axis “number” (0–6), horizontal axis $\log_{10} P_{21\text{cm}}$ (W/Hz · sr), scale 20, 21, 22, 23, 24.

In general, objects are classified as strong radio sources or weak radio sources according to whether the radio luminosity lies above or below 10^{40} erg/s; but in order to investigate the properties of the nucleus over all wavelengths, it is better to compare the radio and the visible/ultraviolet intensities directly.

Defining this ratio as

$$R = \frac{4\pi P_{1415}}{F_{\nu}(U)}$$

and examining the distributions for types 1 and 2, we obtain Figure 9.10. Only the radio Seyfert galaxies 3 C 120 and NGC 1275 have $R \geq 1,000$. Type 1 Seyfert galaxies have only $R < 100$, and most are concentrated at $R \approx 1-10$. Type 2 objects, on the other hand, show a concentration at $R \approx 10-100$, reconfirming the conclusion obtained above that the radio emission of type 2 Seyfert galaxies is relatively at least 10 times stronger than that of type 1.

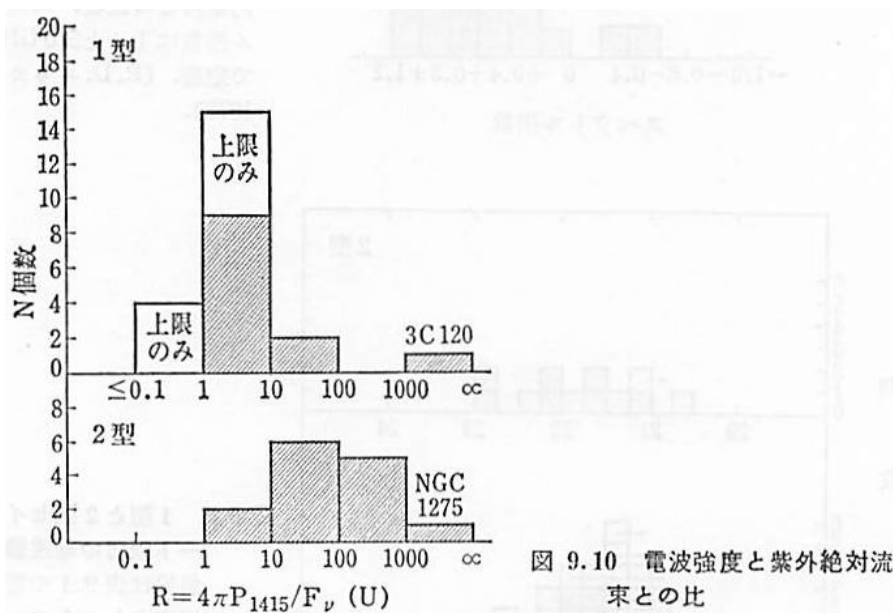


図 9.10 電波強度と紫外絶対流量との比

Figure 9.10 Ratio of radio intensity to absolute ultraviolet flux. Upper panel “type 1”, lower panel “type 2”. Vertical axis N (number), horizontal axis $R = 4\pi P_{1415}/F_v(U)$, scale $\leq 0.1, 1, 10, 100, 1000, \infty$. The upper panel has blocks marked “upper limits only”; 3C 120 is marked at its right end and NGC 1275 at the right end of the lower panel.

Figure 9.11 shows the correlation between radio intensity and radio-source size plotted by R. D. Ekers (1978). A clear separation is seen between the bright, compact group of elliptical galaxies, radio galaxies and quasars, and the group consisting of spiral galaxies and Seyfert galaxies. Here too, and not only in the

spectral index, the non-radio-source Seyfert galaxies belong to the spiral-galaxy group. Figure 9.11 also shows that within the spiral-galaxy group the Seyfert galaxies have the brightest radio luminosities. This is a property established by C. M. Wade (1968).

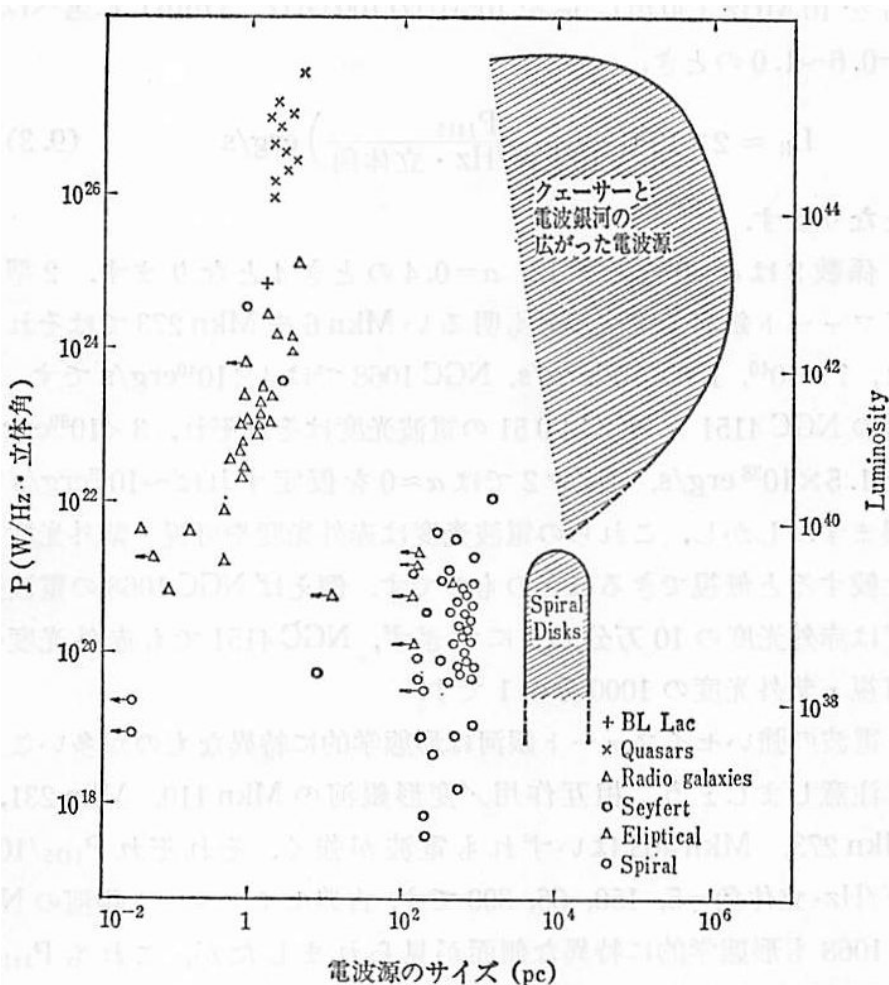


図 9.11 電波強度と電波源の大きさ. (R. D. エッカーズ 1978).

Figure 9.11 Radio intensity and radio-source size. (R. D. Ekers 1978). Vertical axis P (W/Hz $\cdot$ sr) 10^{18} – 10^{26} , right-hand vertical axis Luminosity 10^{38} – 10^{44} , horizontal axis “radio-source size (pc)” 10^{-2} – 10^6 . The hatched areas are labeled “extended radio sources of quasars and radio galaxies” and “Spiral Disks”. Legend: + BL Lac, $\times$ Quasars, $\triangle$ Radio galaxies, $\circ$ Seyfert, $\triangle$ Elliptical, $\circ$ Spiral.

The radio luminosity L_R is calculated from the intensity at 1,415 MHz by the following expression:

$$L_R = \int_{\nu_1}^{\nu_2} 4\pi P_{1415} \left(\frac{\nu}{1,415 \text{ MHz}} \right)^{-\alpha} d\nu$$

If ν_1 is chosen as 10 MHz (30 m) and ν_2 as 10^5 MHz (100 GHz; 3 mm), then for $\alpha = 0.6$ – 1.0 ,

$$L_R \approx 2 \times 10^{39} \left(\frac{P_{1415}}{10^{21} \text{ W Hz}^{-1} \text{ sr}^{-1}} \right) \text{ erg/s}$$

The coefficient 2 becomes 12 for $\alpha = 0$ and 4 for $\alpha = 0.4$. For Mkn 6 and Mkn 273, the brightest radio emitters among type 2 Seyfert galaxies, the values are 7×10^{40} and 1.6×10^{41} erg/s respectively, and for NGC 1068, 4×10^{40} erg/s. The radio luminosities of the type 1 galaxies NGC 4151 and NGC 4051 are 3×10^{39} erg/s and 1.5×10^{38} erg/s respectively, and for III Zw 2 we obtain $\sim 10^{43}$ erg/s if $\alpha \approx 0$ is assumed. These radio luminosities are, however, negligible compared with the infrared luminosity and the visible/ultraviolet luminosity. For example, the radio luminosity of NGC 1068 is only one hundred-thousandth of its infrared luminosity, and even for NGC 4151 it is one thousandth of the infrared or the visible/ultraviolet luminosity.

Let us note that many of the Seyfert galaxies with strong radio emission are morphologically peculiar. The interacting/deformed galaxies Mkn 110, Mkn 231, Mkn 273 and Mkn 463 are all strong radio emitters, with $P_{1415}/10^{21}\text{W/Hz} \cdot \text{sr} = 5, 150, 66$ and 300 respectively. The classical Seyfert galaxy NGC 1068 also showed morphologically peculiar aspects, and it too is powerful, with $P_{1415}/10^{21}\text{W/Hz} \cdot \text{sr} = 20$. NGC 4051 and NGC 3227 are both among the faintest Seyfert galaxies, but the double galaxy NGC 3227 is ten times brighter in the radio than NGC 4051. Likewise, the double galaxy NGC 7469 is also a powerful radio emitter, with $P_{1415}/10^{21}\text{W/Hz} \cdot \text{sr} = 19$.

(4) Correlations

As may be expected from Figure 9.10, the correlation between radio intensity and the absolute flux of the ultraviolet continuum $F\nu(U)$ is not clear-cut, but a tendency is seen for the brighter radio emitters also to have brighter emission-line luminosities. A. S. Wilson and A. G. Willis (1980) have found a correlation between radio intensity and the emission-line widths of type 2 Seyfert galaxies, in the sense that the stronger the radio emission the broader the emission lines (Figure 9.12).

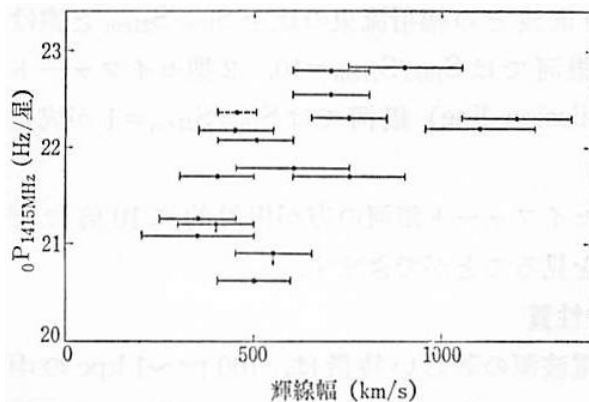


図 9.12 電波強度と2型セ
イファート銀河の輝
線幅. (A.S. ウィル
ソンと A.G. ウィリ
ス 1980).

Figure 9.12 Radio intensity and emission-line width of type 2 Seyfert galaxies. (A. S. Wilson and A. G. Willis 1980). Vertical axis $\log_{10} P_{1415} \text{ MHz (Hz/星)}$, scale 20, 21, 22, 23. Horizontal axis “emission-line width (km/s)”, scale 0, 500, 1000.

The correlation between radio and infrared was first found by P. C. van der Kruit (1971). Figure 9.13 shows the radio–infrared correlation for type 1 and type 2 Seyfert galaxies. Writing the ratio of the radiative fluxes at $\lambda = 10\mu$ in the infrared and at 1,415 MHz (21 cm) in the radio as $S_{10\mu}/S_{21\text{cm}}$, we have $S_{10\mu}/S_{21\text{cm}} \approx 10$ for type 1 Seyfert galaxies, and $S_{10\mu}/S_{21\text{cm}} \approx 1$ for type 2 Seyfert galaxies and SEL (sharp emission line) galaxies.

Here again we can see the property that type 2 Seyfert galaxies are relatively about ten times stronger in the radio.

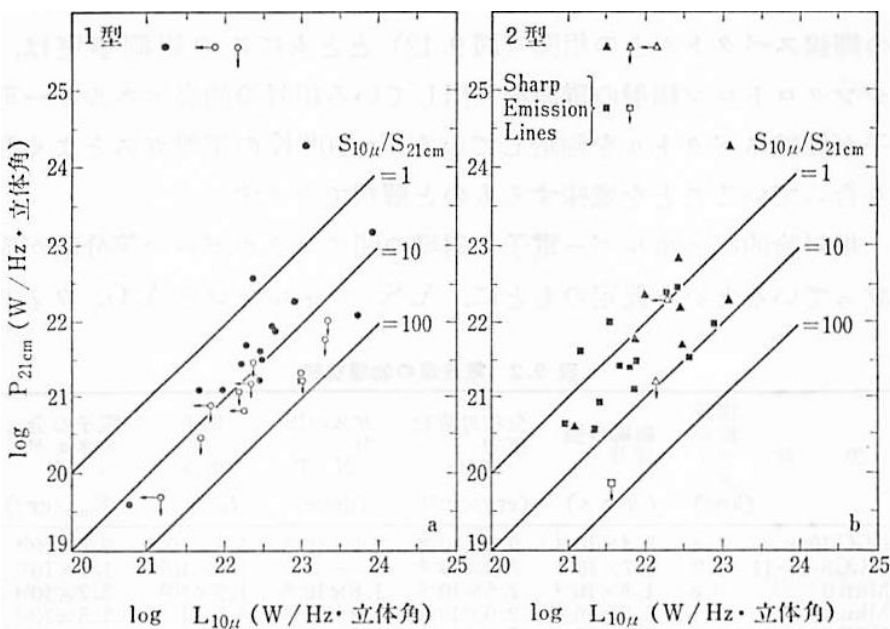


図 9.13 1型と2型セイファート銀河の電波と赤外強度. (A. G. ド・ブリヤンと A. S. ウィルソン 1978).

Figure 9.13 Radio and infrared intensities of type 1 and type 2 Seyfert galaxies. (A. G. de Bruyn and A. S. Wilson 1978). a: type 1, b: type 2. Vertical axis $\log P_{21}\text{cm}$ ($\text{W}/\text{Hz} \cdot \text{sr}$) 19–25, horizontal axis $\log L_{10\mu}$ ($\text{W}/\text{Hz} \cdot \text{sr}$) 20–25. The diagonal lines are $S_{10\mu}/S_{21\text{cm}} = 1, = 10, = 100$. Panel b carries the legend “Sharp Emission Lines”.

(5) Physical properties of the radio sources

The striking characteristic of the radio sources of Seyfert galaxies is that they coincide with the nuclear region of 100 pc–1 kpc. As noted earlier, such radio sources are observed in fewer than 20% of ordinary spiral galaxies. Together with the correlation of radio intensity with the emission-line spectrum (Figure 9.12), this observational fact can be interpreted as meaning that the relativistic high-energy electrons emitting the synchrotron radio emission are well mixed with the ionized gas at $T \sim 10^4\text{K}$ that radiates the emission-line spectrum.

Table 9.2 shows the physical properties of the radio sources of Seyfert galaxies calculated by A. S. Wilson and A. G. Willis (1980) on the assumption that equipartition of energy holds between the relativistic high-energy electrons and the magnetic field.

Table 9.2 Physical state of the radio sources

Galaxy	Radio-source size (kpc)	Magnetic field strength B (gauss)	Total relativistic pressure $B^2/4\pi$ (erg/cm ³)	Gas pressure N_{ekT} (dyne)	Electron lifetime t_R (yr)	Total electron energy E_{min} (erg)
NGC 1068	1.4	3.4×10^{-4}	9.5×10^{-9}	2.2×10^{-8}	5.1×10^4	2.5×10^{54}
MCG8-11-11	1.2	1.7×10^{-4}	2.2×10^{-9}	—	1.6×10^5	1.1×10^{55}
Mkn 6	0.8	1.8×10^{-4}	2.5×10^{-9}	1.8×10^{-9}	1.3×10^5	3.7×10^{54}
Mkn 78	4.1	5.7×10^{-5}	2.6×10^{-10}	2.2×10^{-9}	8.5×10^5	1.5×10^{55}
NGC 5548	4.8	3.0×10^{-5}	7.0×10^{-11}	5.0×10^{-8}	1.8×10^6	4.4×10^{54}
NGC 6764	2.2	6.0×10^{-5}	2.8×10^{-10}	3.5×10^{-9}	7.1×10^5	1.3×10^{55}
Mkn 315	5.7	3.4×10^{-5}	9.2×10^{-11}	7.0×10^{-9}	1.5×10^6	6.9×10^{55}

Here the total energy of the relativistic high-energy particles including protons is assumed to be twice that of the electrons. If this were taken to be 100 times, the magnetic field would be about three times stronger. The magnetic field lies in the range 3×10^{-5} – 3×10^{-4} gauss ($1 \text{ Tesla} = 1 \text{ Weber/m}^2 = 10^4 \text{ gauss}$), with an average of about $\sim 10^{-4}$ gauss. $B^2/4\pi$ is the total relativistic pressure.

t_R is the lifetime against the loss of energy by relativistic high-energy electrons through synchrotron radiation and inverse Compton scattering. E_{min} is the total energy carried by the relativistic high-energy particles; when equipartition of energy between relativistic electrons and the magnetic field is assumed, it is a minimum value. If we take the mass of the ionized gas radiating the forbidden lines as $M \sim 10^6 M_\odot$ and its velocity as $v \sim 500$ – $1,000 \text{ km/s}$, the kinetic energy becomes $E_{\text{kin}} \sim 10^{54}$ – 10^{55} erg , which we see is of the same order as the total energy carried by the relativistic high-energy particles.

Two possibilities may be considered for the origin of the relativistic high-energy particles. One is that they were ejected from the nucleus. If the paired double radio

sources of NGC 1068, NGC 5548 and Mkn 3 are not merely apparent but were produced by ejection from the nucleus, this interpretation is promising. The other is that shock waves generated within the ionized gas clouds accelerate the particles. The correlation seen between radio intensity and the emission-line spectrum is a fact convenient for this interpretation.

At present it is not clear which is correct, or whether still other interpretations are possible. Along with more detailed observations, theoretical studies of the particle-acceleration mechanism and of the interaction between high-energy particles and ordinary gas clouds will be needed.

2. Line Spectrum

(1) The 21 cm line of neutral hydrogen

The emission line at a wavelength of 21 cm (1420.406 MHz) radiated by neutral hydrogen atoms is invaluable for learning the amount, distribution and motion of low-temperature hydrogen gas, which cannot be observed by optical means. It is largely thanks to observations of this 21 cm line spectrum that we have been able to learn the spiral structure of the Milky Way galaxy.

The 21 cm observation of Seyfert galaxies was carried out from about 1970, in parallel with studies of neutral hydrogen in spiral galaxies. In the early observations, of course, it was limited to the classical Seyfert galaxies. Systematic 21 cm radio observations of Seyfert galaxies were carried out by T. M. Heckman, B. Balick and W. T. Sullivan (1978). They observed 58 Seyfert galaxies and similar galaxies within a distance of 200 Mpc with the 91 m and 305 m radio telescopes, and obtained the mass of neutral hydrogen gas for 25 galaxies. Table 9.3 gives Heckman et al.'s observational results. It lists the width of the 21 cm line (FWOI)

Δv , the optically determined velocity and the 21 cm line velocity v_{opt} and v_{HI} , the ratio $M_{\text{HI}}/L_{\text{pg}}$ of the neutral hydrogen mass M_{HI} to the luminosity L_{pg} derived from the photographic magnitude, and the morphological type T together with the profile of the 21 cm line. The morphological type is defined as $-5 = \text{E}$, $-1 = \text{SO}$, $1 = \text{Sa}$, $3 = \text{Sb}$, $5 = \text{Sc}$.

The representative Seyfert galaxies NGC 1068 and NGC 4151 possess $3\text{--}4 \times 10^9 M_{\odot}$ of neutral hydrogen. Even in NGC 3227 and NGC 4051, the smallest in scale, the neutral hydrogen mass is $\sim 2 \times 10^9 M_{\odot}$. In the comparatively bright NGC 5548 and NGC 7469, however, the values are $1 \times 10^9 M_{\odot}$ and $6 \times 10^9 M_{\odot}$ respectively. The mass of neutral hydrogen has no direct correspondence with the scale of the nuclear activity. In Mkn 10 (Figure 5.2) and Mkn 463 (Figure 5.9), which have the largest amounts of neutral hydrogen in Table 9.3, the mass reaches $\sim 1 \times 10^{11} M_{\odot}$, comparable to the total mass of an ordinary galaxy. In Mkn 348 (Figure 5.8), Mkn 358 and Mkn 541 (Figure 5.6) too, large amounts of neutral hydrogen of $\sim 3 \times 10^{10} M_{\odot}$ are observed. According to recent observations by M. Morris and P. Wannier (1980), the neutral hydrogen gas cloud of Mkn 348 is 300 kpc in diameter and has a mass of $5 \times 10^{10} M_{\odot}$. This galaxy is a peculiar type 2 Seyfert galaxy with a variable radio source (Figure 9.7), and morphologically it is a double galaxy.

Table 9.3 Neutral hydrogen in Seyfert galaxies

Galaxy	$\Delta\nu$	ν_{opt}	ν_{HI}	$M_{\text{HI}}/10^9 M_{\odot}$	$M_{\text{HI}}/L_{\text{pg}}$	T	21 cm line profile
III Zw 2		26930		<122	<.33	pec	
MK 348		4700	4534	34	3.3	0	1 ps
MK 352	400	4477	4448	3.2	0.20	−2	2 pa
MK 1	220	4793	4780	1.8	0.10	pec	1 ps
MK 358		13750		<53	<.5	4	
MK 590	1010	8100	7910	30	0.35	1	1 ps?
NGC 985		12950		<13	<.04	ring	
NGC 1068	670	1109	1140	3.5	0.02	3	2 ps
III Zw 55		7380		<7.7	<.13	−5	
3 C 120		9900		<22	<.11	−2	
MK 3	1450:	4054	3952	14.3	0.53	−2	cpx
MK 6		5660		<4.6	<.11	−1	abs.
MK 374		13200		<26	<.21	3	
MK 376		16800		<50	<.42	3	
MK 79		6598	6643	16.5	0.12	3	2 pa
MK 10	680	8685	8753	86	0.29	3	2 ps
MK 382		10200		<15	<0.25	4	
MK 391	505	3979	3992	4.0	0.40	1	2 ps?
NGC 2782	500	2537	2562	9.8	0.14	1	2 pa
MK 110		10800		<11	<.27	pec	
Zw 0934+01		15550		<39	<.26	3	
AKN 223	155	6600	6518	8.9	0.23	0	1 ps
MK 142		13500		<26	<.63	−2	
NGC 3227	800:	1152	1106	2.4	0.10	1	2 pa
MK 34		15300		<33	<.36	0	
AKN 253	910:	7800	7808	50	0.40	0	cpx
NGC 3516		2540		<1.0	<.02	−2	
MK 40		6150		<8	<.21	−2	

Galaxy	$\Delta\nu$	ν_{opt}	ν_{HI}	$M_{\text{HI}}/10^9 M_{\odot}$	$M_{\text{HI}}/L_{\text{pg}}$	T	21 cm line profile
MK 176	485	8080	8208	12.8	0.15	0	2 ps
MK 42		7200		<6	<.34	2	
NGC 4051	480	674	701	1.7	0.12	4	2 ps
MK 198		7220		<4	<.09	-2	
NGC 4151	295	970	994	4.4	0.16	2	2 ps
NGC 4235		2410		<1.3	<.02	1	
MK 50		6910		<6	<.26	-2	
NGC 4670	380	1159	1084	1.1	0.22	0	1 ps
MK 231		12430		<21	<.09	5	abs.
NGC 4939	605	3096	3109	41	0.33	4	2 ps
MK 270		2700		<.55	<.06	-2	
MK 273		11460		<100	<.55	pec	
MK 279		9220		<23	<.31	-2	
MK 463	210:	15140	14702	124	0.96	3	1 ps
NGC 5548	325	4981	5204	1.1	0.01	0	1 ps, abs.
MK 471	405	10132	10256	12.5	0.21	1	1 ps
MK 474		12300		<14	<.2	0	
MK 290		9240		<9	<.14	-5	
MK 291		10500		<27	<.28	1	
MK 298		10230		<8.4	<0.17	pec	
MK 501		10000		<40	<.13	pec	
MK 504		10800		<13	<.42	-1	
MK 506		12900		<25	<.22	-2	
MK 507		15900		<59	<.61	-2	

Table 9.3 Neutral hydrogen in Seyfert galaxies (continued)

Galaxy	$\Delta\nu$	ν_{opt}	ν_{HI}	$M_{\text{HI}}/10^9 M_{\odot}$	$M_{\text{HI}}/L_{\text{pg}}$	T	21 cm line profile
NGC 6764	365	2405	2412	8.2	0.19	3	2ps?
NGC 6814		1437	1560	7.8	0.16	4	2pa
II Zw 136		18510		<61	<.10	pec	
NGC 7469	1300:	4894	4754	6.3	0.04	1	cpx
NGC 7603		8800		<17	<.14	3	
MK 541	1495:	12300	11716	28	0.01	2	cpx

Compared with normal galaxies of the same morphological type, Seyfert galaxies show an abnormally large scatter in $M_{\text{HI}}/L_{\text{pg}}$ (Figure 9.14). The dashed line in the figure marks the region in which the normal galaxies observed by C. Balkowski (1973) are distributed. Within it, a tendency is seen for the ratio $M_{\text{HI}}/L_{\text{pg}}$ to become larger for later-type galaxies with larger T. Many Seyfert galaxies fall outside this region: Mkn 3, Mkn 348 and Mkn 463 (Table 9.4) deviate in the direction of large $M_{\text{HI}}/L_{\text{pg}}$, while NGC 1068, NGC 3516, NGC 5548 and NGC 7469 (Table 9.5) deviate in the direction of small ratios. It appears that the group with large $M_{\text{HI}}/L_{\text{pg}}$ contains many type 2 and deformed galaxies, while the group with small values contains many objects with a ring structure in their outermost parts.

The radial velocities of the 21 cm line agree well with those determined optically (Table 9.3). Figure 9.15 shows the distribution of the widths of the 21 cm line. Broad ones are comparatively numerous, and among the especially broad group (Table 9.6), NGC 3227, NGC 7469 and Mkn 590 are double galaxies.

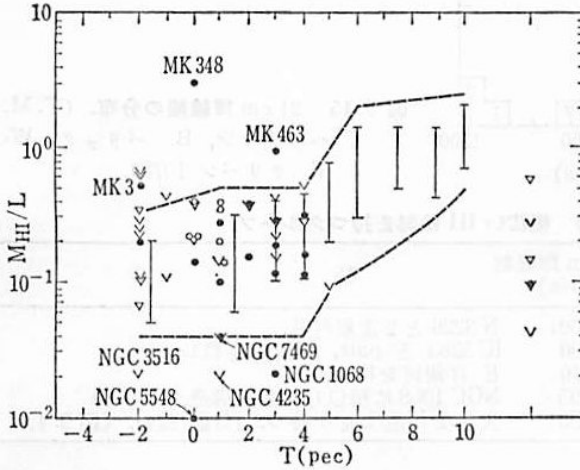


図 9.14 $M_{\text{HI}}/L_{\text{pg}}$ と形態学的タイプ T. (T. M. Heckman, B. Balick, W. T. Sullivan 1978).

Figure 9.14 $M_{\text{HI}}/L_{\text{pg}}$ and morphological type T. (T. M. Heckman, B. Balick, W. T. Sullivan 1978). Vertical axis M_{HI}/L 10^{-2} –10, horizontal axis T(pec) –4 to 10. MK 348, MK 463, MK 3, NGC 3516, NGC 5548, NGC 7469, NGC 1068 and NGC 4235 are marked in the figure. The dashed line marks the region occupied by normal galaxies.

If the neutral hydrogen gas is distributed throughout the whole spiral galaxy, the emission-line profile has a single peak (1 p); if it is distributed in a ring in the disk region, it has two peaks (2 p) corresponding to the rotational velocity. If we separate the objects into those with normal and those with anomalous $M_{\text{HI}}/L_{\text{pg}}$ ratios and examine their emission-line profiles, the former are all of the 1 p or 2 p type, whereas about half of the latter show complex profiles (cpx) that are neither 1 p nor 2 p (Table 9.7). Seyfert galaxies with anomalous $M_{\text{HI}}/L_{\text{pg}}$ largely have anomalous 21 cm emission-line profiles as well.

Table 9.4 Group with large $M_{\text{HI}}/L_{\text{pg}}$

Galaxy	Type	Characteristics
Mkn 3	2	SBO type resembling NGC 3516. [O III] strong, next after Mkn 6. (Figure 9.4)
Mkn 348	2	Low surface brightness, with thin arms. Enormous HI gas cloud. Variable galaxy (Figures 5.6, 9.7)
Mkn 463	1	Deformed galaxy with the largest amount of HI gas (Figure 5.9)

Table 9.5 Group with small $M_{\text{HI}}/L_{\text{pg}}$

Galaxy	Type	Characteristics
NGC 1068	2	Has a bright outer ring, D type, multiple-arm structure.
NGC 3516	1	Has a bright outer ring, D type, multiple-arm structure. Comparatively compact.
NGC 5548	1	Representative ring galaxy, N galaxy. (Figure 5.5)
NGC 7469	1	Has a bright outer ring, interacting galaxy

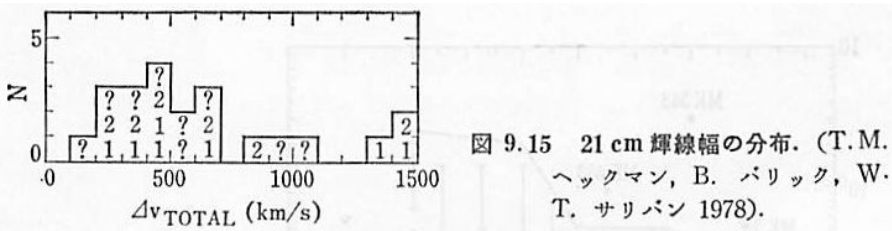


Figure 9.15 Distribution of 21 cm emission-line widths. (T. M. Heckman, B. Balick, W. T. Sullivan 1978). Vertical axis N (0–5), horizontal axis Δv_{TOTAL} (km/s), scale 0, 500, 1000, 1500. Symbols identifying the individual galaxies (? , 1, 2, etc.) are entered in each bar.

Table 9.6 Group with broad HI profiles

Galaxy	Type	21 cm line width (km/s)	Characteristics
NGC 3227	2/1	800:	Double galaxy system with N 3226.
NGC 7469	1	1300	Pair with IC 5283, low $M_{\text{HI}}/L_{\text{pg}}$
Mkn 590		1010	Has an E companion galaxy.
Mkn 541		1495	Multiple structure resembling NGC 1068 (Figure 5.6)
Mkn 3		1450:	Has large $M_{\text{HI}}/L_{\text{pg}}$. [O III] strong. (Figure 9.4)

In Mkn 6 and Mkn 231 a 21 cm absorption line is observed, and the absorption line of Mkn 6 in particular is abnormally broad, as much as 240 km/s. This is the largest yet observed. The radio sources of Mkn 6 and Mkn 231 are of the large halo–core type (Figure 9.1), and these are the Seyfert galaxies that also showed anomalies in the continuous spectrum (Table 9.8).

Table 9.7 Profile anomalies

Anomalous HI group	Normal HI group
4 objects.....cpx	4.....1 p
4 objects.....1 ps	7.....2 ps
1 object.....2 ps	5.....2 pa

cpx = complex, s = symmetric, a = asymmetric

Table 9.8 HI absorption

Galaxy	Type	Characteristics
Mkn 6	1/2	Large halo–core type, [O III] strong.
Mkn 231	1	Large halo–core type, strong reddening.

(2) The 2.6 mm molecular line of carbon monoxide

Besides neutral hydrogen H^0 and ionized hydrogen H^+ , hydrogen gas also exists as molecular hydrogen H_2 . Observation of the molecular line at a wavelength of 2.6 mm radiated by carbon monoxide CO is particularly important as a means of determining the mass of H_2 molecular gas.

The first to succeed in observing the CO molecular line from a Seyfert galaxy were L. J. Rickard et al. (1977). Using the 11 m telescope of the National Radio Astronomy Observatory in the United States, they detected the 2.6 mm CO molecular line in the inner region of NGC 1068, along with the peculiar infrared galaxies M 82, NGC 253 and others (Figure 9.16). Assuming a distance of 18 Mpc, the mass of H_2 molecules obtained is $(5.1-36) \times 10^9 M_\odot$. Considering that the neutral hydrogen gas of NGC 1068 is distributed over a region of several tens of kpc (Figure 3.2) and that its mass is $M_{HI} = 3.5 \times 10^9 M_\odot$, this mass is astonishing. It means that H_2 molecular gas with several times the mass of the neutral hydrogen is concentrated in a region of ~ 5 kpc. If the amount of H_2 molecules in NGC 1068 is taken as $15 \times 10^9 M_\odot$, the total mass of hydrogen gas becomes $M_H \sim 2 \times 10^{10} M_\odot$.

At present the only Seyfert galaxies in which the CO molecular line has been observed are the three NGC 1068, NGC 3227 and NGC 4051 (Table 9.9). These share the common morphological characteristic of possessing an amorphous disk region, or one containing numerous patches of ionized hydrogen regions. Observations have been attempted by L. J. Rickard et al. (1977), by M. Rowan-Robinson, T. G. Phillips and G. White (1980), and by J. H. Bieging et al. (1981), but none has succeeded in detecting the CO molecular line in NGC 4151, which has no clear spiral structure. Let us note too that these three Seyfert galaxies have strong Si absorption at $\lambda = 9.7\mu$ (Table 8.2). H_2 molecules are formed through contact reactions occurring on the surfaces of dust grains. Also, as is clear from the

comparison in Table 9.9, no proportional relation holds between the masses of molecular hydrogen and of neutral hydrogen.

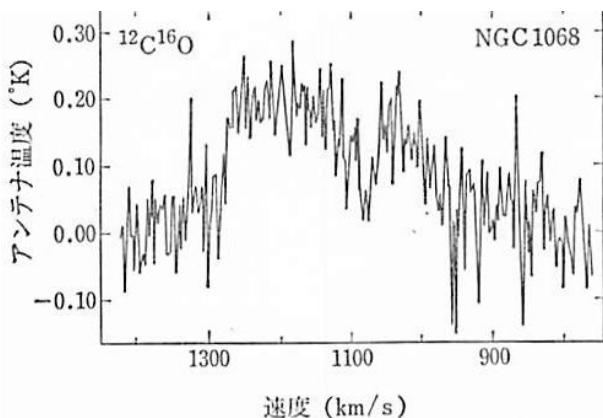


図 9.16 NGC 1068 の C
O 輝線. (L. J. リ
カード 達 1977)

Figure 9.16 CO emission line of NGC 1068. (L. J. Rickard et al. 1977) “ $^{12}\text{C}^{16}\text{O}$ ” at upper left of the panel, “NGC 1068” at upper right. Vertical axis “antenna temperature ($^{\circ}\text{K}$)” -0.10 to 0.30 , horizontal axis “velocity (km/s)” 900 , 1100 , 1300 .

Table 9.9 Seyfert galaxies in which CO molecules have been observed

Galaxy	$M_{\text{H}_2} (M_{\odot})$	$M_{\text{H}_2}/M_{\text{HI}}$	Surface density $M_{\odot}/\text{pc}^2$
NGC 1068	15×10^9	4.3	370
NGC 3227	1.1×10^9	0.47	12
NGC 4051	0.45×10^9	0.26	12

$H_0 = 50$ assumed.

The astonishing feature of Table 9.9 is the peculiarity of NGC 1068. The surface densities of H_2 molecular gas in NGC 3227 and NGC 4051 agree with that of the best-studied case, the Milky Way galaxy ($\sim 10 M_{\odot}/\text{pc}^2$), but in NGC 1068 the surface density is 30–40 times higher. The inner region of NGC 1068 is, as it were, a sea of H_2 molecular gas.

Chapter X. X-rays

1. Peculiar galaxies that emit X-rays

E. T. Byram, T. A. Chubb and H. Friedman succeeded in 1966 in the first observation of X-rays from the radio galaxy M 87. X-rays from the quasar 3C 273 and from the radio galaxy NGC 5128 were subsequently discovered in 1970 by C. S. Bowyer and his colleagues.

These early observations were made with rockets, so an all-sky survey for X-ray sources was quite out of the question. The X-ray satellite Uhuru (“freedom”), launched in December 1970 on Kenya’s Independence Day, opened the entirely new prospect of surveying the whole sky and came to lay the foundations of X-ray astronomy. This satellite carried two proportional counters working in the energy range 2–10 KeV ($1 \text{ KeV} = 2.42 \times 10^{17} \text{ Hz} = 12.4 \text{ \AA}$), with fields of view of $0^\circ.5 \times 5^\circ$ and $5^\circ \times 5^\circ$, arranged so that rotation of the satellite scanned the entire sky. The results of the all-sky survey were compiled into the 3U catalogue, published in 1974 by R. Giacconi and his colleagues. It registered 170 X-ray sources, more than 20 of which are identified with extragalactic objects. The 4U catalogue, comprising 339 X-ray sources, was also produced in 1978 by W. Forman and his colleagues. The results of the survey made with the Ariel V satellite ($0^\circ.75 \times 10^\circ.6$), launched in October 1974, have been compiled as the 2A catalogue by B. A. Cooke and his colleagues (1978). Of the 107 X-ray sources registered in it, 35 are identified with extragalactic objects.

Besides the two satellites Uhuru and Ariel V, X-ray satellites such as ANS, SAS-3, OSO-7, OSO-8, Copernicus, HEAO 1 and HEAO 2 have been launched. In particular the HEAO 2 satellite, launched in November 1978, was named the Einstein X-ray Observatory to commemorate the centenary of Einstein’s birth.

Unlike its predecessors this satellite has a genuine imaging system of 58 cm aperture and 3.4 m focal length using a rotational paraboloidal mirror as its lens, giving it performance comparable to the 5 m telescope of the Hale Observatory or the Soviet 6 m altazimuth telescope.

Apart from clusters of galaxies, extragalactic X-ray sources include the following kinds of peculiar galaxies.

- (1) SEL galaxies
- (2) Radio galaxies
- (3) N galaxies
- (4) Seyfert galaxies
- (5) Quasars
- (6) BL Lacertae (BL Lac) objects

The group of galaxies called SEL (sharp emission line) galaxies do not have emission-line profiles as broad as those of Seyfert galaxies, but they show strong, highly excited emission-line spectra. M 87 and NGC 5128 are good examples of X-ray radio galaxies. Complex structure is observed in these X-ray sources (M 87: Figure 4.16; NGC 5128: Figure 4.39). As shown in Table 10.1, some N galaxies belong to the radio galaxies or to the BL Lac objects. The radio Seyfert galaxies 3C 120 and 3C 390.3 are also classified as X-ray-emitting N galaxies. BL Lac objects have properties similar to those of quasars, but their emission-line spectra are very weak, and in some cases entirely absent.

Table 10.1 X-ray luminosities of peculiar galaxies

Galaxy	X-ray source name	L _x (2–10 KeV)(erg/s)	Characteristics
M 82	2A 0954+700 4U 0954+70	5×10^{40}	SEL galaxy, paired with M 81
NGC 526a	2A 0120–353	4×10^{43}	SEL galaxy, NGC 526/527 group
NGC 7582	2A 2315–428	$(\leq 3-7) \times 10^{42}$	SEL galaxy, Grus quartet
M 87	2A 1228+125 3U 1228+12	5×10^{42}	RG
NGC 5128	2A 1322–47	$(0.4-2.5) \times 10^{42}$	RG
3C 111	H0415+37	5.6×10^{44}	N
Pic A	H0519–45	8×10^{43}	N
3C 371	H0415+37	5.6×10^{44}	N, BL Lac
Mkn 421	2A 1102+384	2.2×10^{44}	BL Lac
Mkn 501	4U 1651+39	2.4×10^{44}	BL Lac
3C 273	2A 1225+022 4U 1226+02	1.7×10^{46}	Q ($z=0.158$)
4U 0241+61		2.4×10^{44}	Q ($z=0.044$)
2A 2251–179		3.6×10^{44}	Q ($z=0.068$)
Ton 256	1612+2612	3.4×10^{45}	Q ($z=0.131$)
PG 1351+640		1.2×10^{43}	Q ($z=0.088$)
3C 279		1.1×10^{46}	ovvQ ($z=0.536$)
3C 345		9.1×10^{45}	ovvQ ($z=0.595$)
3C 446		9.6×10^{46}	ovvQ ($z=1.404$)
3C 47		5.2×10^{45}	Q ($z=0.425$)
3C 9		8.7×10^{45}	Q ($z=2.012$)
OQ 172		1.2×10^{47}	Q ($z=3.53$)
OH 471		1.6×10^{47}	Q
CTA 102		2.1×10^{46}	Q

* For quasars, L_x (0.5–4.5 KeV)

Quasars and Seyfert galaxies make up the great majority of extragalactic X-ray sources. Before the Einstein satellite, only a few quasars had been detected in X-rays, but today the number exceeds 100. Their X-ray luminosities are also very high, $L_{\text{x}}(0.5\text{--}4.5 \text{ KeV}) \approx 10^{43} - 10^{47} \text{ erg/s}$. In the case of Seyfert galaxies, X-rays have been observed in about 60 objects, but we shall examine those in a separate section.

2. X-rays from Seyfert galaxies

(1) X-ray luminosity

The X-ray observational data for Seyfert galaxies are summarized in Table 10.2.

Table 10.2 X-ray luminosities of Seyfert galaxies

Galaxy	Type	L(0.5–4.5KeV)	L(2–10KeV)
Mkn 9	1	2.7×10^{43}	
Mkn 40	1	7.2×10^{42}	6.0×10^{43}
Mkn 78	2	7.6×10^{41}	
Mkn 79	1	4.8×10^{43}	$(5.9-6.3) \times 10^{43}$
Mkn 142	1	1.5×10^{44}	
Mkn 205	1/Q	2.8×10^{44}	
Mkn 290	1	6.3×10^{43}	
Mkn 291	1	2.1×10^{43}	
Mkn 304	1	2.2×10^{43}	6.4×10^{44}
Mkn 315	1	9.2×10^{42}	
Mkn 335	1		$(4-8) \times 10^{43}$
Mkn 348	2	4.2×10^{41}	
Mkn 352	1	3.1×10^{43}	
Mkn 372	1	7.1×10^{43}	
Mkn 376	1	3.1×10^{44}	$(3.8-4.1) \times 10^{44}$
Mkn 382	1	2.6×10^{43}	
Mkn 464	1		$(8-30) \times 10^{43}$
Mkn 474	1	2.6×10^{43}	
Mkn 504	1	1.9×10^{43}	
Mkn 506	1	6.1×10^{43}	
Mkn 507	2	8.1×10^{42}	
Mkn 509	1	1.9×10^{44}	2.5×10^{44}
Mkn 541	1		8.3×10^{43}
Mkn 590	1	8.0×10^{43}	
Mkn 618	1	4.5×10^{43}	
Mkn 766	1	2.2×10^{42}	
Mkn 876	1		9.8×10^{44}
NGC 931	1		1.6×10^{43}
NGC 1275	2?		5×10^{43} .
NGC 1365	1/SEL		2×10^{42}

Galaxy	Type	L(0.5–4.5KeV)	L(2–10KeV)
NGC 2110	1/SEL		1×10^{43}
NGC 2992	1/SEL		1.4×10^{43}
NGC 3227	1/2	1.1×10^{42}	$(1.4-3.6) \times 10^{44}$
NGC 3783	1	1.5×10^{43}	$(1.1-1.9) \times 10^{43}$
NGC 4151	1	5.7×10^{42}	$(3.6-7.1) \times 10^{42}$
NGC 4507	2	2.8×10^{41}	
NGC 4593	1		2.9×10^{42}
NGC 5033	1/SEL		1.5×10^{42}
NGC 5506	1/SEL		$(1-2) \times 10^{43}$
NGC 5548	1	3.6×10^{43}	$(2.5-7.3) \times 10^{43}$
NGC 6814	1		$(4.3-5.4) \times 10^{42}$
NGC 7213	1		2.9×10^{42}
NGC 7469	1	8.6×10^{43}	$(4.1-6.3) \times 10^{43}$
NGC 7582	1/SEL		$(\leq 3-7) \times 10^{42}$
IC 4329 A	1		$(3.3-7.1) \times 10^{43}$
I Zw 1	1	1.8×10^{44}	
II Zw 1	1	2.1×10^{43}	
III Zw 2	1	7.5×10^{44}	1.4×10^{45}
Ton 524a	1	8.5×10^{43}	
Akn 120	1	1.4×10^{44}	1×10^{44}
3C 120	1	3.7×10^{44}	$(1.1-2.7) \times 10^{44}$

Table 10.2 X-ray luminosities of Seyfert galaxies (continued)

Galaxy	Type	L(0.5–4.5KeV)	L(2–10KeV)
3C 382	1	2.5×10^{44}	4.6×10^{44}
3C 390.3	1	6.7×10^{44}	$(4.9-5.9) \times 10^{44}$
3C 445	1		$(4.5-7) \times 10^{44}$
MCG 2-58-22	1		$(3.3-6.9) \times 10^{44}$
MCG 8-11-11	1	6.9×10^{43}	
ESO 103-G 35	1		2.3×10^{43}
ESO 113-IG 45	1		$(2.2-2.9) \times 10^{44}$
ESO 140-G 43	1	2.2×10^{43}	
ESO 141-G 55	1	8.9×10^{43}	$(1.1-2.0) \times 10^{44}$

(X-ray luminosities are in erg/s)

For satellite observations such as Uhuru, Ariel V and HEAO-1, the standard measure of X-ray luminosity is $L(2-10 \text{ KeV})$, integrated over the 2–10 KeV energy range, whereas for the Einstein satellite the luminosity $L(0.5-4.5 \text{ KeV})$ in the 0.5–4.5 KeV range is used; the table therefore gives both luminosities. If we assume a spectral distribution $f_\nu \propto \nu^{-0.6}$, then $L(0.5-4.5 \text{ KeV}) \approx L(2-10 \text{ KeV})$.

Seyfert galaxies strong in X-rays are almost entirely restricted to type 1. Only four type 2 Seyfert galaxies have been detected in X-rays — Mkn 78, Mkn 348, Mkn 507 and NGC 4507 — and apart from Mkn 507, whose $L(0.5-4.5 \text{ KeV}) = 8.1 \times 10^{42} \text{ erg/s}$, the others are below 10^{42} erg/s . Mkn 348, whose radio intensity shows time variability, is a strong X-ray source for a type 2 Seyfert galaxy. Even NGC 1068, the apparently brightest and nearest type 2, is known only through the upper limit $L(2-10 \text{ KeV}) < 3 \times 10^{41} \text{ erg/s}$ on its X-ray luminosity. By contrast, the X-ray luminosities of type 1 Seyfert galaxies lie in the range $L(0.5-4.5 \text{ KeV}) \approx 10^{42} - 10^{45} \text{ erg/s}$, and the majority have luminosities of $10^{43} - 10^{44} \text{ erg/s}$. It is clear that the BL region which characterizes type 1 Seyfert galaxies is closely related to the X-ray source.

The correlation between X-ray luminosity and $F_v(U)$ is shown in Figure 10.1.

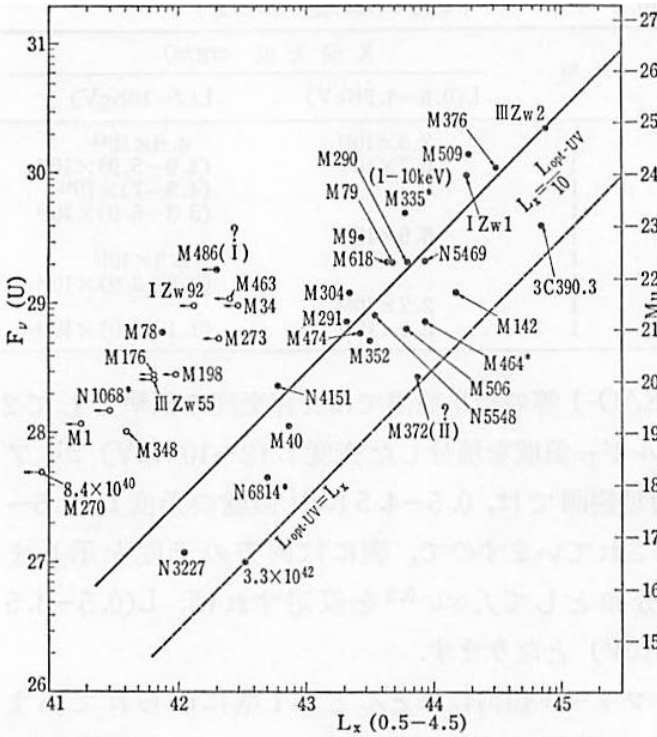


図 10.1 X線光度と $F_v(U)$ との相関。図中の2本の直線は $L_x = L(\text{opt-UV})$ と $L_x = \frac{1}{10} L(\text{opt-UV})$ 。

Figure 10.1 Correlation between X-ray luminosity and $F_v(U)$. The two straight lines in the figure are $L_x = L(\text{opt-UV})$ and $L_x = (1/10) L(\text{opt-UV})$. Left ordinate $F_v(U)$; right ordinate μ ; abscissa L_x (0.5–4.5). Symbols in the figure: M 376, III Zw 2, M 290, M 509, (1–10keV), M 79, M 335*, I Zw 1, M 9, M 618, N 5469, M 486(I) ?, I Zw 92, M 463, M 34, M 304, 3C 390.3, M 291, M 474, M 352, M 142, M 78, M 273, M 464*, M 506, M 176, M 198, N 5548, M 372(II) ?, N 1068*, III Zw 55, M 1, M 348, N 4151, M 40, M 270 (8.4×10^{40}), N 6814*, N 3227 (3.3×10^{42}). The two lines are labelled $L_{\text{opt}} - UV = L_x$ and $L_x = L_{\text{opt}} - UV/10$.

If we compare the visible-ultraviolet continuum luminosity $L(\text{opt-UV})$ calculated from equation (7.10) with the X-ray luminosity L_x , we find that $L_x \approx$

$(1/10)L(\text{opt-UV})$ holds for type 1 Seyfert galaxies. For type 2 Seyfert galaxies the X-ray luminosity is less than 1/100 of the visible–ultraviolet luminosity. Restricting ourselves to type 1 Seyfert galaxies, relatively good correlations are also seen with the H_α luminosity and the infrared luminosity. The correlation with radio intensity, however, is not good at all. Probably the radio and X-ray emission are independent phenomena.

(2) Spectral distribution

Because X-ray observations use counters as detectors, instead of the radiation flux f_ν (erg/s cm² Hz) one uses the number flux of X-ray photons N (*photons*/cm²s KeV), and instead of the frequency ν (Hz) one uses the energy E in units of KeV. Expressed as formulae:

$$\begin{aligned} f_\nu &= 6.6 \times 10^{-27} NE \text{ erg/scm}^2\text{Hz} \\ &= 6.6 \times 10^{-30} NE \text{ W/m}^2\text{Hz}. \end{aligned} \quad (10.1)$$

$$\nu = 2.42 \times 10^{17} E \text{ Hz},$$

$$\lambda = 12.4/E \text{ \AA}.$$

Only a few Seyfert galaxies have had their X-ray spectral distribution measured up to several tens of KeV. Figure 10.2 shows results obtained from the HEAO-1 satellite by R. F. Mushotzky and his colleagues (1980). Figure 10.3 is the X-ray spectral distribution of NGC 4151. This spectrum extends beyond ~ 100 KeV, out to the γ – ray region of 1–10 MeV (1 MeV = 1,000 KeV).

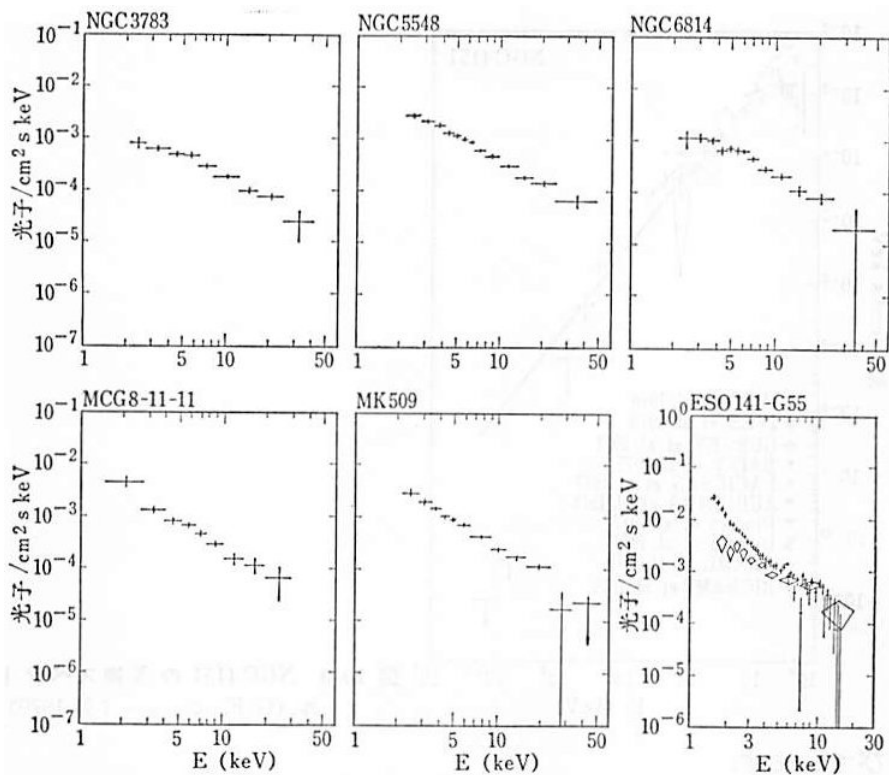


図 10.2 X線スペクトル. (R. F. ムショットキー達 1980).

Figure 10.2 X-ray spectra. (R. F. Mushotzky et al. 1980). Six panels: NGC 3783, NGC 5548, NGC 6814, MCG 8-11-11, MK 509, ESO 141-G 55. Ordinate “photons/cm²s keV” (10^{-7} – 10^{-1} ; for ESO 141-G 55, 10^{-6} – 10^0); abscissa E (keV) (1–50; for ESO 141-G 55, 1–30).

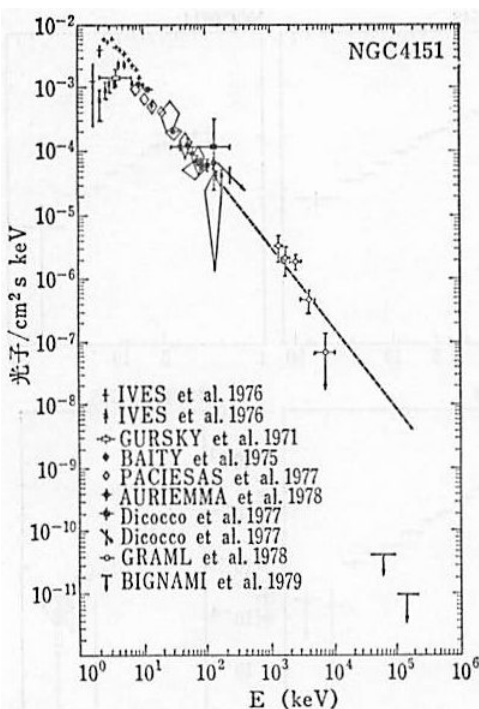


図 10.3 NGC 4151 の X 線スペクトル. (G. F. ビンヤーマー達 1979).

びています。

Figure 10.3 X-ray spectrum of NGC 4151. (G. F. Bignami et al. 1979). Ordinate “photons/cm²s keV” (10⁻¹¹–10⁻²); abscissa E (keV) (10⁰–10⁶). Legend: IVES et al. 1976 / IVES et al. 1976 / GURSKY et al. 1971 / BAITY et al. 1975 / PACIESAS et al. 1977 / AURIEMMA et al. 1978 / Dicocco et al. 1977 / Dicocco et al. 1977 / GRAML et al. 1978 / BIGNAMI et al. 1979.

If the X-ray spectral distribution is emitted by a non-thermal process such as inverse Compton scattering, it should be of the power-law form

$$dN/dE = AE^{-\gamma}$$

whereas if it is free–free thermal radiation from a high-temperature gas it should be expressed by the exponential form

$$dN/dE = B \exp(-E/kT) \cdot (1/E)$$

Here A and B are constants, k is Boltzmann's constant and T is the temperature. The photon spectral index γ is related to the spectral index α by $\gamma = \alpha + 1$.

In the case of NGC 4151, no difference between the two spectra is seen up to $E \approx 20$ KeV, but in the high-energy region $E \gtrsim 20$ KeV the departure from equation (10.4) becomes large, and the spectrum of equation (10.3) appears to reproduce the observations better (Figure 10.4).

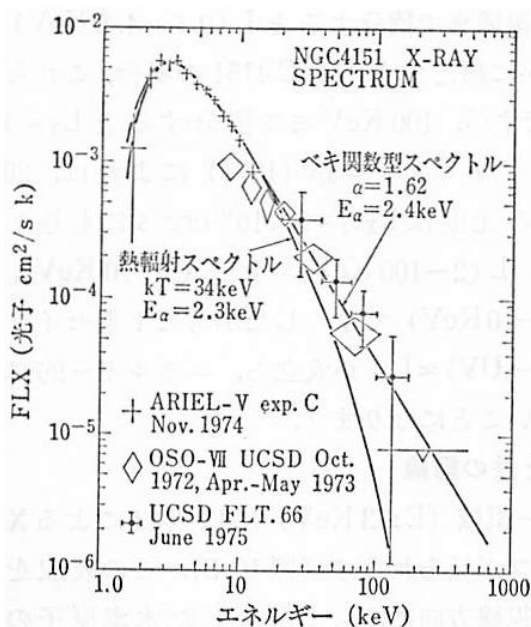


図 10.4 熱輻射スペクトル, べき関数型スペクトルと NGC 4151 の X 線スペクトル.
(W. S. Paciesas, R. F. Mushotzky, R. M. Pelling 1977).

Figure 10.4 Thermal radiation spectrum, power-law spectrum and the X-ray spectrum of NGC 4151. (W. S. Paciesas, R. F. Mushotzky, R. M. Pelling 1977). Labels in the figure: NGC4151 X-RAY SPECTRUM / power-law spectrum $\alpha = 1.62$, $E_\alpha = 2.4\text{keV}$ / thermal radiation spectrum $kT = 34\text{ keV}$, $E_\alpha = 2.3\text{keV}$ / ARIEL-V exp. C Nov. 1974 / OSO-VII UCSD Oct. 1972, Apr.-May 1973 / UCSD FLT. 66 June 1975. Ordinate FLX (photons $\text{cm}^2/\text{s k}$); abscissa Energy (keV) (1.0–1000).

Table 10.3 gives the photon spectral indices γ and temperatures T derived by R. F. Mushotzky and his colleagues (1980). On average $\gamma \approx 1.6$, $T \approx 3 \times 10^8$ K. Expressed as a spectral index this is $\alpha \approx 0.6$, so the X-ray spectral distribution is, like the visible–ultraviolet nuclear light, extremely flat.

Table 10.3 Photon spectral index and temperature

Galaxy	Power law: γ	Power law: $N_H(\times 10^{22})$	Power law: $T(\times 10^8 \text{ }^\circ\text{K})$	Exponential: $N_H(\times 10^{22}/\text{cm}^2)$
NGC 3783	1.74	2.0	3.8	<2.0
NGC 4151	1.43	10.0	>12	9.4
NGC 5548	1.56	<3.3	>2.3	<3.3
NGC 6814	1.75	≤ 5.4	>2.3	<5.0
Mkn 509	1.63	<0.65	3.7	<0.7
ESO 141-G 55	1.8	<7	2.2	<2.5
MCG 8-11-11	1.66	<2.5	3.2	<1.4

Integrated up to the high-energy region, the X-ray luminosity greatly exceeds L (0.5–4.5 KeV) or L (2–10 KeV). For NGC 4151 these luminosities are about 5×10^{42} erg/s, but integrating up to 100 KeV gives $L_x \approx 4 \times 10^{43}$ erg/s. According to G. Di Cocco and his colleagues (1977), the X- and γ – ray luminosity integrated up to 20 MeV reaches as much as $L_{X-\gamma} \approx 8 \times 10^{45}$ erg/s. If $\alpha = 0.6$ is assumed, L (2–100 KeV) = 4.2 L (2–10 KeV) and L (2–1,000 KeV) = 12 L (2–10 KeV). Hence for type 1 Seyfert galaxies $L_x \approx L(\text{opt-UV}) \approx L_{\text{IR}}$ holds, and there is no wavelength region that dominates energetically.

(3) Low-energy absorption and the iron emission line

In the low-energy region of NGC 4151 ($E \lesssim 3$ KeV) a cut-off of the X-ray spectrum due to absorption is seen (Figure 10.3). Expressed as the number of hydrogen atoms integrated along the line of sight — that is, as a column density —

the amount of gas producing this absorption is estimated at $N_H \approx 10^{23}$ atoms/cm² (Table 10.3).

The low-energy X-ray absorption is thought to be caused by gas clouds, or filaments, within the BL region. Taking the number density of the gas clouds/filaments to be $N_e \sim 10^9$ cm⁻³, we obtain a reasonable thickness for the absorber of $1 \sim 10^{14}$ cm. Figure 10.5 is the low-energy spectrum of NGC 4151 observed from the Einstein satellite. The absorption is not complete, and a marked excess is seen in the region $E \lesssim 2$ KeV.

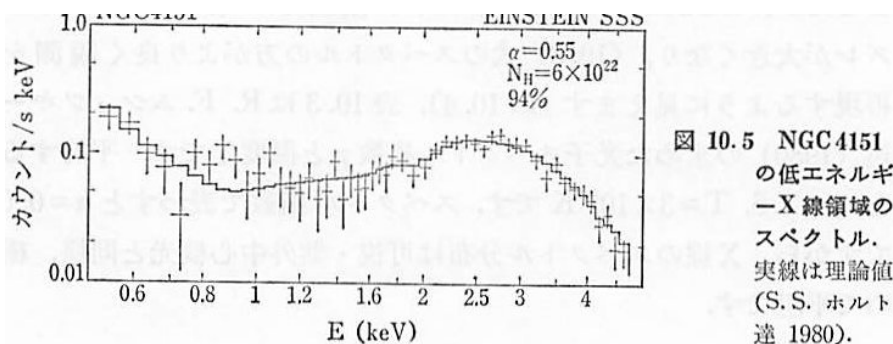


図 10.5 NGC 4151
の低エネルギー
X線領域の
スペクトル。
実線は理論値
(S. S. ホルト
達 1980)。

Figure 10.5 Spectrum of NGC 4151 in the low-energy X-ray region. The solid line is the theoretical curve (S. S. Holt et al. 1980). Labels in the figure: NGC4151 / EINSTEIN SSS / $\alpha = 0.55$, $N_H = 6 \times 10^{22}$, 94%. Ordinate counts/s keV (0.01–1.0); abscissa E (keV) (0.6–4).

S. S. Holt and his colleagues (1980) have shown that this low-energy spectrum can be explained if the X-ray source of NGC 4151 is covered to about ~94% by gas clouds — in other words, if about ~6% is left uncovered. Low-energy X-ray absorption similar to that of NGC 4151 is also observed in the type 1 Seyfert galaxy Mkn 464 (M. J. C. Hayes, J. L. Culhane, S. J. Bell Burnell 1980), but in most Seyfert galaxies it is not nearly so strong (Figure 10.2; Table 10.3). In this respect NGC 4151 is a peculiar case. As we have already seen, absorption is also

observed in the He I $\lambda 3889$ line and the Balmer lines of this galaxy (Figures 6.34 and 6.35), and in L_α and C IV $\lambda 1550$ (Figure 6.21).

Iron emission lines, or iron absorption, are observed in NGC 4151, NGC 5548 and NGC 5128. Figure 10.6 shows the iron emission line (~ 6.7 KeV) of NGC 5548 discovered by M. J. C. Hayes and his colleagues (1980) in Ariel V satellite observations in January 1977. It is not, however, recognizable in the X-ray spectrum observed a year and a half later with the HEAO-1 satellite (Figure 10.2). At that time the X-ray intensity had increased by about 50%. The iron absorption in NGC 4151 likewise appeared when the low-energy absorption strengthened and the X-ray intensity weakened (Figure 10.3).

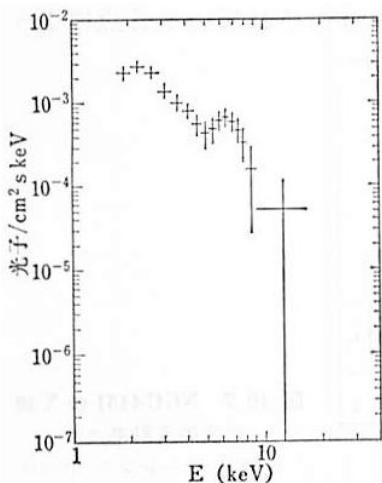


図 10.6 NGC 5548 の鉄の輝線. (M. J. C. ヘイズ達 1980).

Figure 10.6 The iron emission line of NGC 5548. (M. J. C. Hayes et al. 1980). Ordinate “photons/cm² s keV” (10^{-7} – 10^{-2}); abscissa E (keV) (1 to about 30).

The low-energy absorption in NGC 4151 and the iron emission line in NGC 5548 should be valuable sources of information about the structure inside the BL region, or around the X-ray source. Together with the X-ray intensity variations discussed

next, the accumulation of accurate observational data over still longer periods is to be hoped for.

3. Intensity variations

The first Seyfert galaxy in which variability of the X-ray intensity was discovered is 3C 390.3. Comparing observations from the Copernicus satellite and the Uhuru satellite, P. A. Charles, M. S. Longair and P. W. Sanford noticed in 1975 that this X-ray source had varied by about a factor of 4 over two years. Variations in the X-ray intensity of NGC 4151 were also discovered by J. C. Ives, P. W. Sanford and M. V. Penston (1976), and by M. Elvis (1976).

NGC 4151 is the best-observed Seyfert galaxy. Figure 10.7 shows the results of A. Lawrence (1980), who monitored NGC 4151 with the Ariel V satellite for four years. Each plotted point is a mean value integrated over 1–10 days. The source varies by about a factor of 2 about a mean of $L(2-10 \text{ KeV}) = 6 \times 10^{42} \text{ erg/s}$, but no regularity is discernible in the light curve.

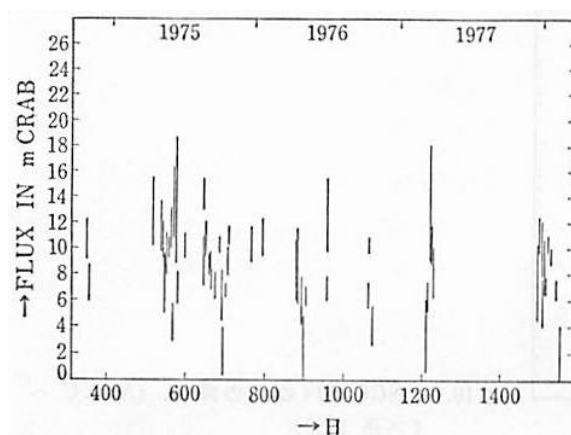


図 10.7 NGC 4151 の X 線
強度の変動モニター。
(A. ローレンス 1980)。

Figure 10.7 Monitoring of the X-ray intensity variations of NGC 4151. (A. Lawrence 1980). Ordinate $\rightarrow$ FLUX IN mCRAB (0–26); abscissa $\rightarrow$ days (about 350–1550); the years 1975, 1976, 1977 are marked along the top.

Figure 10.8 is the light curve of NGC 4151 at 2–6 KeV over 11 days, observed from the OSO-8 satellite by R. F. Mushotzky, S. S. Holt and P. J. Serlemitsos (1978). Flare-like variations on a time scale of 1–2 days are recorded in it. The X-ray spectral distribution remained constant throughout this observing period. Numerous similar flares have been confirmed in Lawrence's monitoring data. The X-rays of NGC 4151 are therefore thought to be emitted as flares on a time scale of a few days, occurring consecutively like the teeth of a saw.

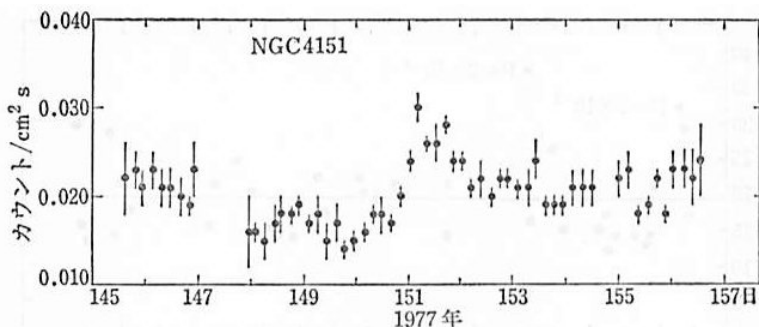


図 10.8 NGC 4151 の 11 日間の X 線変動. (R. ムショットキー, S. S. ホルト, P. J. セルレミツォス 1978).

Figure 10.8 The 11-day X-ray variability of NGC 4151. (R. Mushotzky, S. S. Holt, P. J. Serlemitsos 1978). Ordinate counts/cm²s (0.010–0.040); abscissa day of 1977 (145–157).

Properties similar to those of NGC 4151 are seen in common among other Seyfert galaxies, quasars and BL Lac objects. N. Marshall, R. S. Warwick and K. A. Pounds (1981) analysed five years of observational data obtained with the Ariel V satellite and showed that half of 28 active galaxies exhibit both variations by about a factor of 2 on time scales of ≤ 1 year and variations on time scales of 0.5–5 days.

The shortest time scale of intensity variation places a constraint on the size of the X-ray source. Taking it as $\Delta t \sim 1$ day (8.64×10^4 s), we get $l \lesssim 2.6 \times 10^{15}$ cm as a guideline length. H. Tananbaum and his colleagues (1978) report, from Uhuru satellite observations, a flare in which the X-ray intensity of NGC 4151 increased by more than a factor of 10 within the short time of ~ 730 s (Figure 10.9). This corresponds to $l \lesssim 2 \times 10^{13}$ cm. In the OSO-8 satellite observations of R. F. Mushotzky, S. S. Holt and P. J. Serlemitsos (1978), however, no fluctuation shorter than 4 hours and exceeding a factor of 3 was detected.

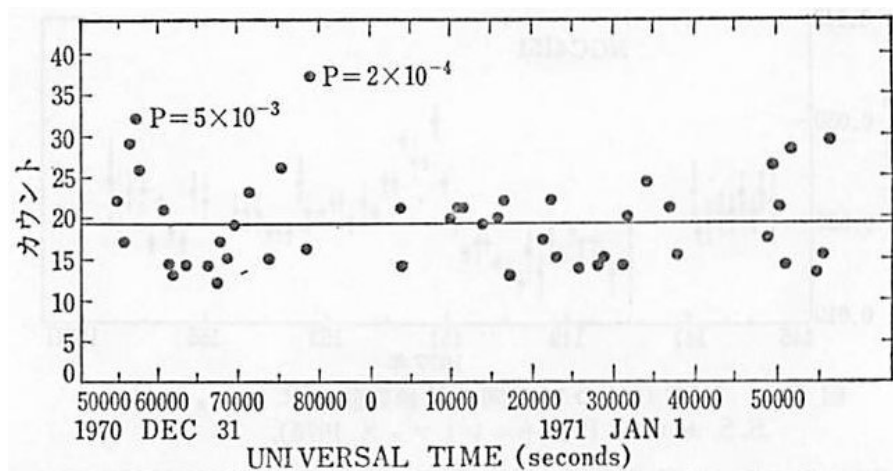


Figure 10.9 An X-ray flare of NGC 4151. (H. Tananbaum et al. 1978). Ordinate counts (0–40); abscissa UNIVERSAL TIME (seconds), from about 50000 s on 1970 DEC 31 to the 50000-s range on 1971 JAN 1. The figure is annotated $P = 5 \times 10^{-3}$ and $P = 2 \times 10^{-4}$.

Whether the X-ray intensity variations are correlated with other wavelength regions is an interesting question. Figure 10.10 is the comparison of the X-rays and ultraviolet light of NGC 4151 carried out by V. M. Lyutyi (1978). He argues that a correlation with the X-rays is seen both in the long-period first component (Figure 7.22) and in the short-period second component (Figure 7.23). J. H. Beall and his colleagues (1981) attempted a comparison of the radio, infrared, visible and X-ray

data obtained between 18 May and 12 June 1977, but here the radio and infrared showed no variation, and no correspondence was recognized among any of them.

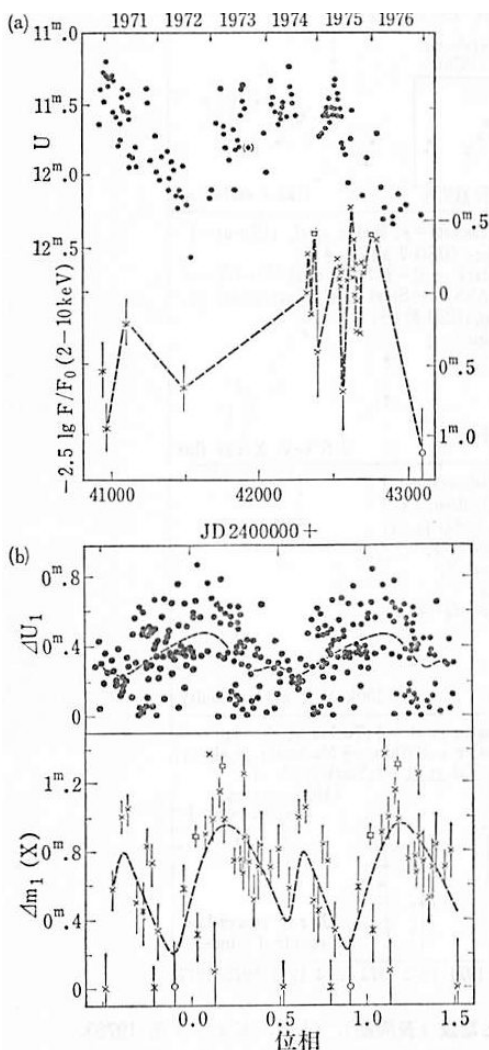


図 10.10 NGC 4151 に対する X 線と U 等級との比較.
(a) 長周期変動. (b) $P=127$ 日の変動 (1971-1976). (V.M. リュチュイ 1978).

Figure 10.10 Comparison of the X-rays and U magnitude for NGC 4151. (a) Long-period variation. (b) The $P = 127$ -day variation (1971–1976). (V. M. Lyutyi 1978). (a) Ordinate U ($11^m.0$ – $12^m.5$, left) and $-2.5 \lg F/F_0$ (2–10 keV) (right, $1^m.0$ to $-0^m.5$); abscissa JD 2400000+ (41000–43000), with the years 1971–1976 marked along the top. (b) Upper panel ordinate ΔU_1 (0 – $0^m.8$); lower panel ordinate Δm_1 (X) (0 – $1^m.2$); abscissa phase (0.0 – 1.5).

For the radio galaxy NGC 5128, simultaneous — though not perfect — variations have been reported between the X-rays and the radio. Figure 10.11 is a comparison including the simultaneous observations (1975–1976) carried out by J. H. Beall and his colleagues (1978). The 10.7 GHz radio emission strengthened by a factor of 1.5 between September 1973 and March 1974, passed through a minimum in July 1975, then increased again, and turned to decline in 1976. Similar variations are seen at 31.5, 89 and 90 GHz. The 2–6 KeV and 100 KeV X-rays likewise increased in 1972–1973 and then declined in 1975–1976. A change in the photon spectral index γ is also seen in 1972–1973.

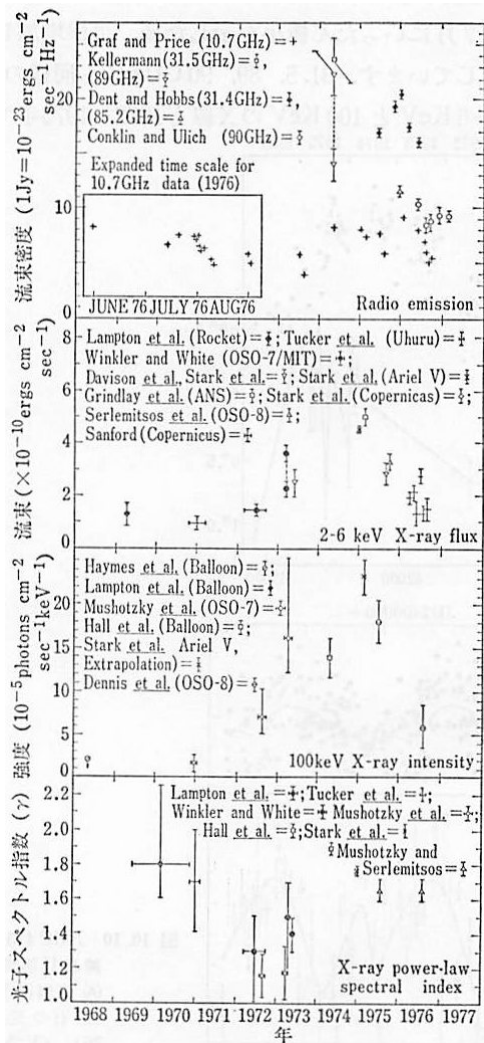


Figure 10.11 X-rays and radio emission of NGC 5128 (long period). (J. H. Beall et al. 1978). First panel: ordinate flux density ($1 \text{ Jy} = 10^{-23} \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ Hz}^{-1}$). Legend: Graf and Price (10.7GHz) = +; Kellermann (31.5GHz), (89GHz); Dent and Hobbs (31.4GHz), (85.2GHz); Conklin and Ulich (90GHz). Inset: “Expanded time scale for 10.7GHz data (1976)” (JUNE 76 / JULY 76 / AUG 76). Lower right: Radio emission. Second panel: ordinate flux ($\times 10^{-10} \text{ ergs cm}^{-2} \text{ sec}^{-1}$). Legend: Lampton et al. (Rocket); Tucker et al. (Uhuru); Winkler and White (OSO-7/MIT); Davison et al., Stark et al.; Stark et al. (Ariel V); Grindlay et al. (ANS); Stark et al. (Copernicus); Serlemitsos et al. (OSO-8); Sanford (Copernicus). Lower right: 2-6 keV X-ray flux. Third panel: ordinate intensity ($10^{-5} \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1}$). Legend: Haymes et al. (Balloon); Lampton et al. (Balloon); Mushotzky et al. (OSO-7); Hall et al. (Balloon); Stark et al. Ariel V, Extrapolation; Dennis et al. (OSO-8). Lower right: 100keV X-ray intensity. Fourth panel: ordinate photon spectral index (γ) (1.0–2.2). Legend: Lampton et al.; Tucker et al.; Winkler and White; Mushotzky et al.; Hall et al.; Stark et al.; Mushotzky and Serlemitsos. Lower right: X-ray power-law spectral index. Abscissa: year (1968–1977).

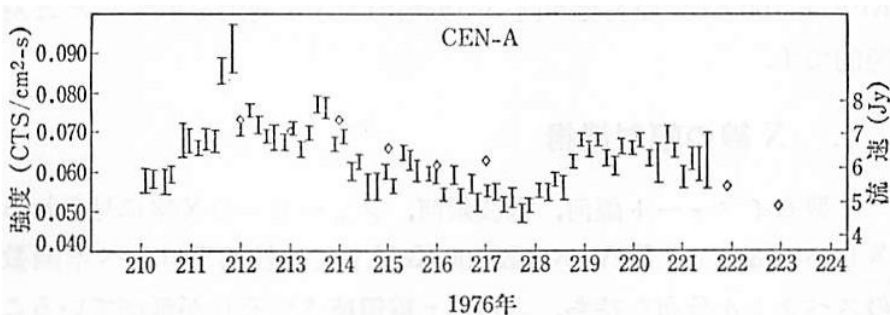


図 10.12 NGC 5128 の X 線と電波 (短周期). I が X 線, ◇が 10.7 GHz の電波. (R. F. ムショットキー達 1978).

Figure 10.12 X-rays and radio emission of NGC 5128 (short period). I denotes X-rays, ◇ denotes the 10.7 GHz radio emission. (R. F. Mushotzky et al. 1978). Label in the figure: CEN-A. Left ordinate intensity ($\text{CTS}/\text{cm}^2 \cdot \text{s}$) (0.040–0.090); right ordinate flux (Jy) (4–8); abscissa day of 1976 (210–224).

Figure 10.12 shows the results of R. F. Mushotzky and his colleagues (1978), comparing the 2–60 KeV X-ray intensity observed with the OSO-8 satellite and the 10.7 GHz radio intensity of Beall and his colleagues. Similar variations are seen

even on time scales of a few days. In the quasar 3C 273, however, which is a powerful radio source, no correlation exists among the variations of the radio, the B magnitude and the X-rays (H. V. Bradt et al. 1979).

The X-ray spectrum of NGC 5128 has strong low-energy absorption and closely resembles that of NGC 4151. Considering that NGC 4151 is a non-radio-source spiral Seyfert galaxy whereas NGC 5128 is an elliptical galaxy with a powerful double radio source, the similarity of the X-rays of the two galaxies is rather surprising. Recently, however, M. J. Coe and his colleagues (1981) have suggested that the variability of NGC 4151 in the 100 KeV region is not as marked as that of its 2–6 KeV X-rays (Figure 10.13). This contrasts with NGC 5128, whose 2–6 KeV and 100 KeV X-rays show large variations of the same amplitude.

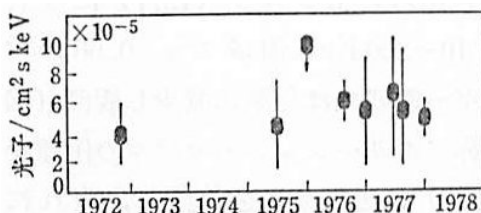


図 10.13 NGC 4151 の 100 KeV 変動. (M. J. コウ達 1981).

Figure 10.13 The 100 KeV variability of NGC 4151. (M. J. Coe et al. 1981). Ordinate “photons/cm² s keV” ($\times 10^{-5}$, 2–10); abscissa 1972–1978.

4. The radiation mechanism of the X-rays

The striking characteristic of the X-rays of type 1 Seyfert galaxies, radio galaxies and quasars is that they have a relatively flat power-law spectral distribution from ~ 1 KeV up to several hundred KeV, and that this extends further into the γ -ray region. To explain this, together with their enormous energy content,

- (1) thermal radiation from a high-temperature gas,
- (2) unsaturated Comptonized radiation,

- (3) synchrotron self-Compton radiation,

have been discussed in the context of various models of the nucleus.

Both (1) and (2) take as their energy source the gravitational energy released when gas falls onto the supermassive black hole (10^6 – $10^9 M_\odot$) that is expected to exist within the nucleus, and is accreted so as to increase its mass. As the origin of the gas, one may consider intergalactic gas, interstellar gas within the galaxy, or gas from stars broken up by collisions between stars in the nucleus or by the tidal force of the black hole.

If the accreting gas has small angular momentum and the gas is not opaque to radiation, the gas accretes spherically symmetrically and is heated to $\sim 10^9$ K by adiabatic compression and by dissipation of the energy of turbulence and magnetic fields. According to P. Mészáros and J. Silk (1977), who analysed the accretion of gas from stars broken up by the tidal force of a black hole, the spectral distribution of the thermal radiation is a power law with $\alpha = 0.66$ in the 10–200 KeV region, but it falls steeply in the high-energy region and does not agree with the observations (Figure 10.3). To avoid this difficulty of the spherically symmetric accretion model, L. Maraschi and his colleagues (1979) took magnetic turbulence into account and attempted Comptonization of the infrared synchrotron radiation produced by it.

If the photon energy is sufficiently small compared with the thermal energy of the electrons in the plasma, photons passing through the plasma are heated by scattering off the electrons, and in a single scattering gain the energy

$$\frac{\Delta(h\nu)}{h\nu} \sim \frac{kT_e}{m_0c^2}$$

Here $h\nu$ and $\Delta(h\nu)$ are the photon energy and its increment, and $\sim kT_e$ and m_0c^2 are the thermal energy and the rest energy of the electron. This process is called Comptonization; low-energy infrared and ultraviolet photons undergo multiple scattering and can reach the high-energy X-ray region.

The Comptonization model postulates a rotating disk (an accretion disk) formed when gas with large angular momentum accretes onto a black hole. The low-energy photons are radiated from this accretion disk ($T \sim 10^5$ K). Two models have been considered for producing the high-temperature plasma needed for the Comptonization. One is the idea of S. L. Shapiro, A. P. Lightman and D. M. Eardley (1976) that a hot, optically thin, puffed-up region is formed inside the accretion disk (Figure 10.14). Since the electrons and ions in this region are not in thermal equilibrium, and their temperatures become $T_e \sim 10^9$ K and $T_i \sim 10^{11}$ K respectively, this is called the two-temperature accretion disk model. The other is the corona model of E. P. T. Liang and R. H. Price (1977) and of G. S. Bisnovatyi-Kogan and S. I. Blinnikov (1977), in which a high-temperature corona is formed on the surface of the accretion disk.

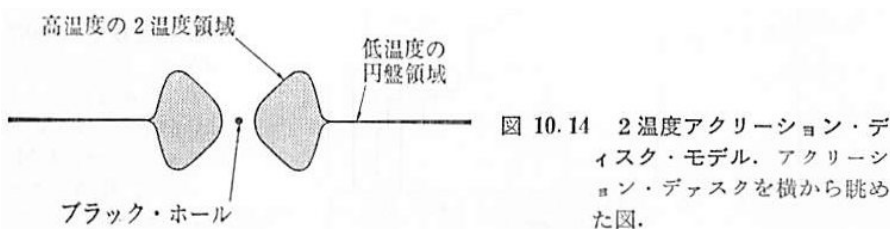


Figure 10.14 The two-temperature accretion disk model. An edge-on view of the accretion disk. Labels in the figure: high-temperature two-temperature region / low-temperature disk region / black hole.

In the two-temperature accretion disk model, the low-energy photons that undergo Comptonization enter from outside the high-temperature plasma and are scattered. In the corona model, on the other hand, the plasma contains them within itself. The

Comptonized spectrum corresponding to the former has been calculated by A. P. Lightman and G. B. Rybicki (1979), and that for the latter by L. A. Pozdnyakov, I. M. Sobol and R. A. Sunyaev (1979) and by Takahara, F. (1980); provided the optical depth τ for electron scattering in (6.22) is not too much greater than 1 (unsaturated Comptonization), both give a power-law spectrum over the range $h\nu_0 \lesssim h\nu \lesssim kT_e$. Here ν_0 is the frequency of the incident low-energy photons. As is clear from Figure 10.15, however, the slope of the Comptonized spectrum depends on the electron temperature T_e and the optical depth τ .

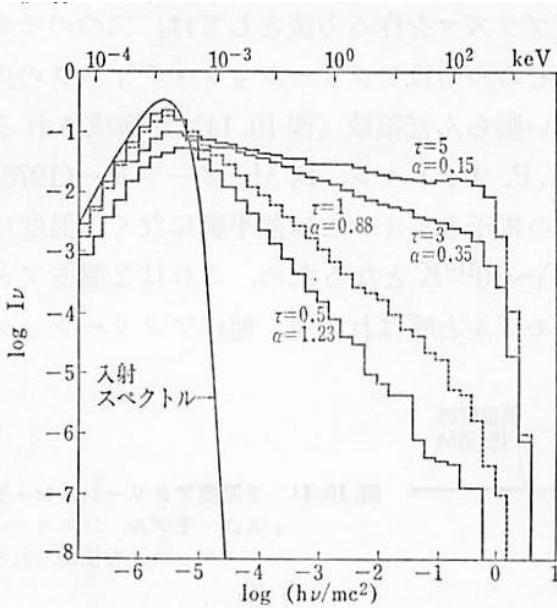


図 10.15 不飽和コンプトン化スペクトル. 電子温度 $kT_e=100\text{KeV}$, 輻射温度 $kT_r=0.5\text{eV}$ で, τ は光学的厚み, α はスペクトル指数. (L. A. ポズニャコフ, I. M. ソボル, R. A. スニャエフ 1979).

Figure 10.15 Unsaturated Comptonization spectra. For an electron temperature $kT_e = 100\text{KeV}$ and a radiation temperature $kT_r = 0.5\text{eV}$, where τ is the optical depth and α the spectral index. (L. A. Pozdnyakov, I. M. Sobol, R. A. Sunyaev 1979). Ordinate $\log I_\nu$ (-8 to 0); abscissa $\log (h\nu/mc^2)$ (-6 to 1), with a keV scale along the top ($10^{-4}, 10^{-3}, 10^0, 10^2$). Curve labels: $\tau = 5$, $\alpha = 0.15/\tau = 3$, $\alpha = 0.35/\tau = 1$, $\alpha = 0.88/\tau = 0.5$, $\alpha = 1.23/\text{incident spectrum}$.

Therefore, if unsaturated Comptonization is the X-ray radiation mechanism from faint Seyfert galaxies all the way up to bright quasars, fairly severe conditions must be required between the electron temperature T_e and the optical depth τ .

If a photon is scattered by a relativistic electron of energy E , its energy is multiplied by

$$\gamma^2 = (E/m_0c^2)^2 \approx (E/0.5\text{MeV})^2$$

where m_0c^2 is the rest energy of the electron. This is called inverse Compton scattering, and the case in which the radiation is inverse-Compton-scattered by the very relativistic high-energy electrons that emit it as synchrotron radiation is called, in particular, synchrotron self-Compton scattering.

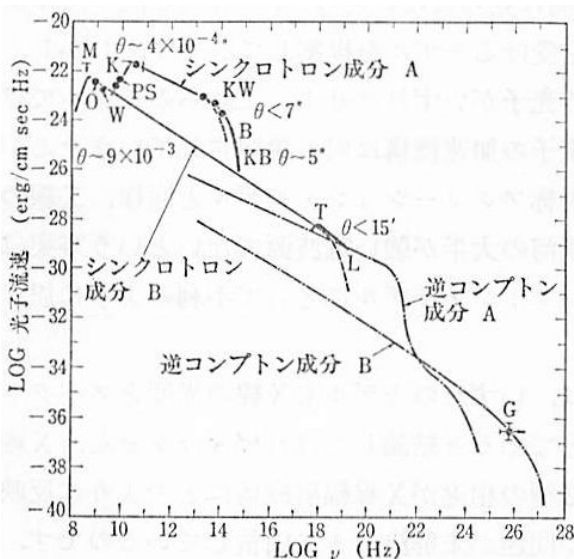


図 10.16 NGC 5128 に対するシンクロトロン自己コンプトン散乱モデル。電波源 A のサイズは 9.7×10^{-3} pc, 磁場は 2 gauss, B のサイズは 2×10^{-1} pc, 磁場は 0.01 gauss で, それぞれの逆コンプトン・スペクトルが一点波線で示されている。(J. E. グリンドリー 1975).

Figure 10.16 A synchrotron self-Compton scattering model for NGC 5128. The size of radio source A is 9.7×10^{-3} pc and its magnetic field 2 gauss; the size of B is 2×10^{-1} pc and its magnetic field 0.01 gauss; the inverse Compton spectrum of each is shown by a dot-dash curve. (J. E. Grindlay 1975). Ordinate LOG photon flux (erg/cm sec Hz) (-40 to -20); abscissa LOG ν (Hz) (8–28). Labels in the figure: synchrotron component A ($\theta \sim 4 \times 10^{-4}$)/synchrotron component B ($\theta \sim 9 \times 10^{-3}$)/inverse Compton component A / inverse Compton component B / M, K, O, W, PS, KW ($\theta < 7'$), KB ($\theta \sim 5'$), B, T ($\theta < 15'$), L, G.

Figure 10.16 is J. E. Grindlay's (1975) explanation of the X-rays of the radio galaxy NGC 5128 in terms of synchrotron self-Compton radiation. R. F. Mushotzky and his colleagues (1978) attach importance to the simultaneous X-ray and radio observations (Figure 10.12) and regard them as strong observational evidence for the synchrotron self-Compton model. J. H. Beall and his colleagues (1978), on the other hand, consider that no correlation is seen in Figure 10.12, and propose a model in which blackbody radiation within ≤ 10 pc undergoes inverse Compton scattering. Whatever the photons that are inverse-Compton-scattered may be, however, these models explain nothing about the acceleration mechanism of the relativistic high-energy electrons. Furthermore, as with the spherically symmetric accretion model of Maraschi and his colleagues, the fact that the majority of type 1 Seyfert galaxies strong in X-rays are not strong radio sources seems to count against the synchrotron self-Compton model.

From the above considerations we must conclude that none of the models is adequate to explain the luminosity and the spectrum of the X-rays. Many problems remain piled up and unsolved — such as how the X-ray intensity variations, and the difference between types 1 and 2, are reflected in the X-ray radiation mechanism.

Chapter XI. The Energy Source

1. Summary of the Observations

(1) Active galaxies

So far we have studied a great many active galaxies with differing properties. Putting them in order once more is useful for considering the energy source and the origin and evolution of Seyfert galaxies.

Table 11.1 gives a classification of active galaxies based on their optical and radio characteristics. In terms of optical characteristics they fall into four groups: BL Lacertae objects (BL Lacertae = BL Lac object), whose activity resides in a strong continuum spectrum; the broad-line (BL = broad line) group, represented by type 1 Seyfert galaxies and quasars; the narrow-line (NL = narrow line) group, represented by type 2 Seyfert galaxies and NL radio galaxies; and the sharp-emission-line (SEL = sharp emission line) group. In terms of radio characteristics, as discussed in Chapter IX, they divide into a radio-quiet (RQ = radio-quiet) group and a radio-loud (RL = radio-loud) group. It is most interesting that an RQ/RL pair exists corresponding to each of the four optical groups.

Table 11.1 Classification of active galaxies

Activity class (AC)	Optical characteristics	Radio characteristics: weak (RQ)	Radio characteristics: strong (RL)
0	Strong continuum spectrum, with no emission lines at all or very weak ones	RQ · BL Lac objects (I Zw 1727+50, Mkn 421)	(RL) BL Lac objects (BL Lac, OJ 287)
1	Strong continuum spectrum plus broad emission lines (several 1000 km/s or more)	RQ quasars = QSG (BSO 1, Ton 256)	OVV quasars (3C 345, 3C 446) ----- (RL) quasars = QSS (3C 48, 3C 273)
1	(same)	Type 1 Seyfert galaxies (NGC 4151, Mkn 79)	BL radio galaxies = RL Seyfert galaxies (3C 120, 3C 390.3)
2	Narrow emission lines (400–500 km/s or more)	Type 2 Seyfert galaxies (NGC 1068, Mkn 1)	NL radio galaxies (Cygnus A = 3C 405, 3C 33)
3	Sharp emission lines (a few 100 km/s or less)	SEL (spiral) galaxies (NGC 7582, M 82)	SEL (elliptical) galaxies (NGC 1052, NGC 4278)

Let us note that the classification of Table 11.1 corresponds well to the following properties.

- (1) Continuum light variation is observed only in BL Lac objects and the BL group.
- (2) Variation of the emission-line spectrum is observed only in the BL group.
- (3) Strong polarization of the continuum is observed mainly in BL Lac objects and OVV quasars.
- (4) Strong X-ray emission is observed mainly in the BL group and in BL Lac objects.

(5) The infrared emission of the RQ group has a thermal spectral distribution, while that of the RL group is of synchrotron character.

(6) Within the RQ group, type 1 Seyfert galaxies, type 2 Seyfert galaxies and SEL galaxies are for the most part spiral galaxies; in the RL group, BL radio galaxies are N-galaxy-like, NL radio galaxies are D/E-galaxy-like, and SEL galaxies are E-galaxy-like.

The four optical classes — BL Lac objects and the BL, NL and SEL groups — are thought to correspond to differences in the scale and kind of nuclear activity, or to different epochs in an evolutionary sequence, and matching the type 1 and type 2 of Seyfert galaxies one might also call them activity classes 0, 1, 2 and 3. No theoretical explanation can be given, but it is certain that the difference between the RQ and RL groups is closely related to the morphology of the galaxies.

The groups have in common that they are active, but they have clear differences. We therefore cannot discuss them all together. Among them, type 1 Seyfert galaxies have a particularly clear-cut character, and their similarity to quasars is obvious. In terms of numbers, too, they are the representative active galaxies. In this chapter, therefore, we shall consider mainly the radio-quiet type 1 Seyfert galaxies. When the radio-galaxy aspect is to be emphasized, there is a different way of approaching the problem.

(2) The nucleus

Let us collect the basic physical quantities the nucleus must possess, which we shall need in considering the energy source.

Luminosity and total radiated energy Table 11.2 gives the luminosity of NGC 4151 in each wavelength region, and Figure 11.1 its spectral distribution. The total luminosity is $L \approx 1.5 \times 10^{44}$ erg/s. The radio accounts for only 0.02% of this and

the emission lines for about 2%; most of it is emitted as continuum radiation in the infrared, the optical–ultraviolet and the X-ray regions. Moreover, these contributions are roughly equal, and there is no wavelength region that dominates energetically. If, however, the infrared light is thermal radiation from dust grains heated by ultraviolet light, then the optical–ultraviolet becomes dominant; and if wavelength regions above 100 KeV are taken into account, the X-ray luminosity becomes larger still. As we have often seen, the faintest, NGC 4051, is about one tenth of NGC 4151, and the brightest, III Zw 2, is about 100 times as energetic. We can therefore estimate the luminosity range of type 1 Seyfert galaxies as $L \approx 10^{43} - 10^{46}$ erg/s, with a typical luminosity of $L \approx 10^{45}$ erg/s. NGC 4151 has $L \approx 1.5 \times 10^{44}$ erg/s, which is somewhat small for a type 1 Seyfert galaxy.

Table 11.2 Luminosity of NGC 4151 in each wavelength region

Wavelength region	Luminosity (erg/s)
Radio	3×10^{39}
Infrared	4×10^{43}
Optical–ultraviolet	6×10^{43}
X-ray: 2–10 KeV	5×10^{42}
2–100 KeV	4×10^{43}
Emission lines: Balmer lines	1.8×10^{42}
forbidden lines	1.7×10^{42}
all emission lines	3.5×10^{42}

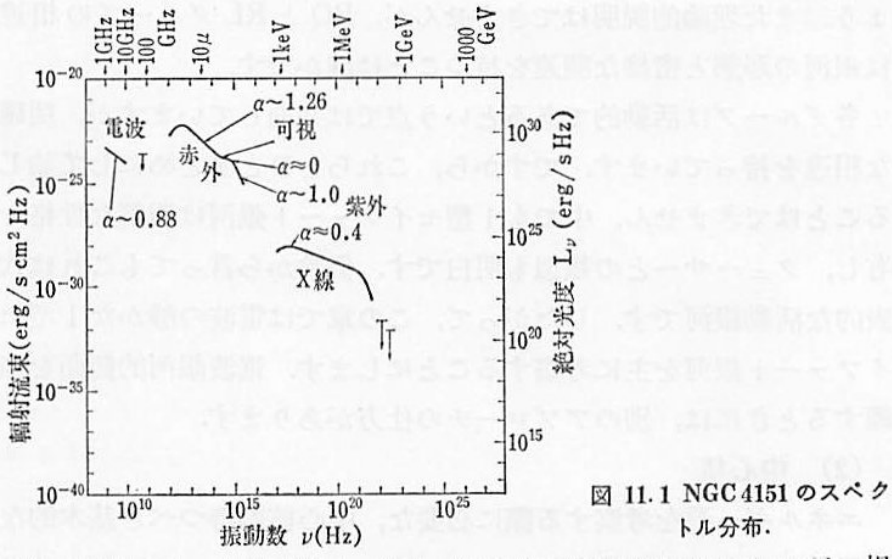


図 11.1 NGC 4151 のスペクトル分布.

Figure 11.1 Spectral distribution of NGC 4151. Abscissa: frequency ν (Hz), $10^{10} - 10^{25}$. Upper scale: 1 GHz, 10 GHz, 100 GHz, 10 μ , 1keV, 1 MeV, 1 GeV, 1000 GeV. Left ordinate: radiation flux ($\text{erg/s cm}^2 \text{Hz}$), $10^{-40} - 10^{-20}$. Right ordinate: absolute luminosity L_ν (erg/s Hz), $10^{30} - 10^{15}$. Labels within the figure: radio $\alpha \sim 0.88$; infrared $\alpha \sim 1.26$; optical $\alpha \approx 0$; ultraviolet $\alpha \sim 1.0$; X-ray $\alpha \approx 0.4$.

Following the argument of L. Woltjer (1959), the lifetime of a Seyfert galaxy is $t \approx 10^8 \text{yr}$. If it goes on shining during this time without changing its luminosity, the total radiated energy of NGC 4151 is calculated to be $E = Lt \approx 5 \times 10^{59} \text{erg}$. The total energy of type 1 Seyfert galaxies is therefore estimated as $E \approx 10^{59} - 10^{62} \text{erg}$, with a typical value of $E \approx 10^{61} \text{erg}$. Converting by way of the rest-mass energy $E = Mc^2$, the energy of NGC 4151 corresponds to $M \approx 2 \times 10^5 M_\odot$, and the above energies to $M \approx 10^4 - 10^7 M_\odot$ and $M \approx 10^6 M_\odot$ respectively.

Mass The quasi-stellar nucleus of the Andromeda galaxy has a mass of $1.6 \times 10^8 M_\odot$, and observations of the velocity field of NGC 1068 give $\leq 10^9 M_\odot$ for the nuclear region, so that we obtain $M \approx 10^8 - 10^9 M_\odot$ as an upper limit to the

mass of the energy source itself. The absolute lower limit is the rest mass obtained above, but that would demand an energy-conversion efficiency of 100%. If we assume 10%, the lower limit becomes $M \approx 10^5 - 10^8 M_\odot$. A reasonable mass is therefore thought to be $M \approx 10^6 - 10^8 M_\odot$.

This mass estimate should be compared with the Eddington luminosity

$$L_E \approx 1 \times 10^{45} \left(\frac{M}{10^7 M_\odot} \right) \text{ erg/s}$$

This is the expression giving the condition that the radiation pressure of the nuclear light balance gravity. If we set the typical luminosity $L \approx 10^{45} \text{ erg/s}$ equal to the Eddington luminosity, equation (11.1) gives a mass $M \approx 10^7 M_\odot$.

Size The structure and size of the nucleus can be inferred from the time scale of the light variations. For the optical–ultraviolet this is 10 days to 1 month, so the size of the radiating source is estimated as $l \approx (3 - 10) \times 10^{16} \text{ cm}$. Changes in X-ray intensity occur on the still shorter time scale of one to a few days, so $l \approx (3 - 10) \times 10^{15} \text{ cm}$ is a measure of the size of the X-ray source. On the other hand, the infrared variability at $\lambda = 2.2\mu$ observed in NGC 4151 and III Zw 2 is a phenomenon with a time scale of 1 month to 1 year, and for the infrared source we obtain $l \approx (1 - 10) \times 10^{17} \text{ cm}$, which is roughly equal to the size of the BL region that radiates the broad emission lines. The infrared light, however, is thought to be secondary thermal radiation from dust grains. We may therefore conclude that the energy source within the nucleus radiates optical–ultraviolet light and X-rays, and that its size is $l \approx 10^{15} - 10^{17} \text{ cm}$, corresponding to 10–100 times the diameter of the solar system.

2. Various Models of the Nucleus

The ultimate problem of Seyfert galaxies, radio galaxies and quasars lies in elucidating their energy source. The models that have been proposed are extremely varied, but they can be broadly divided into the following four kinds.

- (a) Models that assume the creation of matter, or antimatter.
- (b) Models that invoke supernova explosions occurring within a dense stellar system, collisions between stars, or a combination of these.
- (c) Models that postulate a single supermassive object.
- (d) Models that take the accretion of gas onto a supermassive black hole as the energy source.

Let us examine these and consider which of them does not conflict with the requirements of the previous section, or with the observational facts and physical reasoning.

The idea that the nucleus is an outlet from which matter wells up is not new: in 1928 Sir J. Jeans concluded Chapter 13 of *Astronomy and Cosmogony* by saying that “the centers of the nebulae are of the nature of ‘singular points’ at which matter is poured into our universe from some other, and entirely extraneous, spatial dimension, so that, to a denizen of our universe, they appear as points at which matter is being continually created.” In other words he suggested that matter flowing out of the nucleus forms the spiral arms. The delayed-core model, which regards quasars as the explosive expansion of superdense matter left behind by the expansion of the universe (V. A. Ambartsumyan 1958, 1966; I. D. Novikov 1965; Y. Ne’eman 1965), and the contention of the steady-state cosmologists, who look within the nucleus for the creation of matter that makes up for the dilution caused by the expansion of the universe (W. H. McCrea 1964; F. Hoyle and J. V. Narlikar

1966), are both basically the same as Jeans's idea. The irtron theory, which combines the antimatter hypothesis of H. Alfvén (1965) with Jeans's idea, was proposed by F. J. Low (1970). It maintains that in the infrared sources (irtrons) scattered through the nucleus matter and antimatter are continually being created, that the strong infrared light is synchrotron radiation from the electrons and positrons produced by annihilation, and that the matter flowing out of the nucleus formed the arms of the Seyfert galaxy. Quasars, it says, are at an early evolutionary stage, so that not enough matter to form arms has yet flowed out. As we have seen, the models belonging to class (a) assume a creation of matter commensurate with the energy involved, so they do not amount to an explanation of the energy source. Moreover, steady-state cosmology has been in disfavour ever since the discovery of the 3 °K background radiation.

A single supernova explosion releases an energy of $E \sim 10^{51}$ erg. If for some reason the frequency of supernova explosions within the nucleus were raised abnormally, and 1 to 100 explosions occurred per year, a luminosity of $L \sim 10^{43} - 10^{45}$ erg/s could be expected. This supernova hypothesis (I. S. Shklovsky 1961; G. R. Burbidge 1961; A. G. W. Cameron 1962; S. A. Colgate and A. G. W. Cameron 1963; K. Aizu et al. 1964) can account naturally for the emission-line widths, the light variations, and the acceleration mechanism for high-energy particles, but its explanation of the crucial mechanism that triggers a chain of explosions is inadequate. Among the suggestions made are: (i) the density of stars within the nucleus is high, so that one explosion triggers the explosion of another nearby star; (ii) stars are formed explosively within the nucleus, and the massive, rapidly evolving stars produce supernova explosions in succession; (iii) the large amount of gas within the nucleus speeds up stellar evolution, so that supernova explosions occur in succession. The same difficulty applies to the multiple-pulsar model of J. Arons, R. M. Kulsrud and J. P. Ostriker (1975), in which supernova explosions producing pulsars occur 1–100 times a year. Furthermore, in these models the

active region would seem to be far larger than the value obtained in the previous section.

As we saw in Chapter I, the quasi-stellar nucleus of the Andromeda galaxy has a mass of $M = 1.6 \times 10^8 M_\odot$ and a radius of $R = 5$ pc. In Seyfert galaxies and quasars the radius is smaller still, $R \sim 0.1$ pc or less, so we must suppose that collisions between stars play an important role (Table 11.3; Figure 11.2).

Table 11.3 Dynamical properties of galactic nuclei (L. Spitzer and W. C. Saslaw 1966)

Number of stars	Quantity	Nuclear radius 0.1 pc	1 pc	10 pc	100 pc
$N = 10^6$	stellar velocity v_s (km/s)	147	47	14.7	4.7
	relaxation time t_R (yr)	4.6×10^6	1.46×10^8	4.6×10^9	1.46×10^{11}
	collision time t_c (yr)	3.2×10^8	1.09×10^{11}	3.5×10^{13}	1.09×10^{16}
$N = 10^8$	stellar velocity v_s (km/s)	1470	470	147	47
	relaxation time t_R (yr)	3.4×10^7	1.08×10^9	3.4×10^{10}	1.08×10^{12}
	collision time t_c (yr)	2.8×10^6	5.2×10^9	3.1×10^{12}	1.09×10^{15}
$N = 10^{10}$	stellar velocity v_s (km/s)	14700	4700	1470	470
	relaxation time t_R (yr)	2.7×10^8	3.6×10^9	2.7×10^{11}	8.6×10^{12}
	collision time t_c (yr)	3.1×10^3	9.7×10^6	2.8×10^{10}	8.5×10^{13}

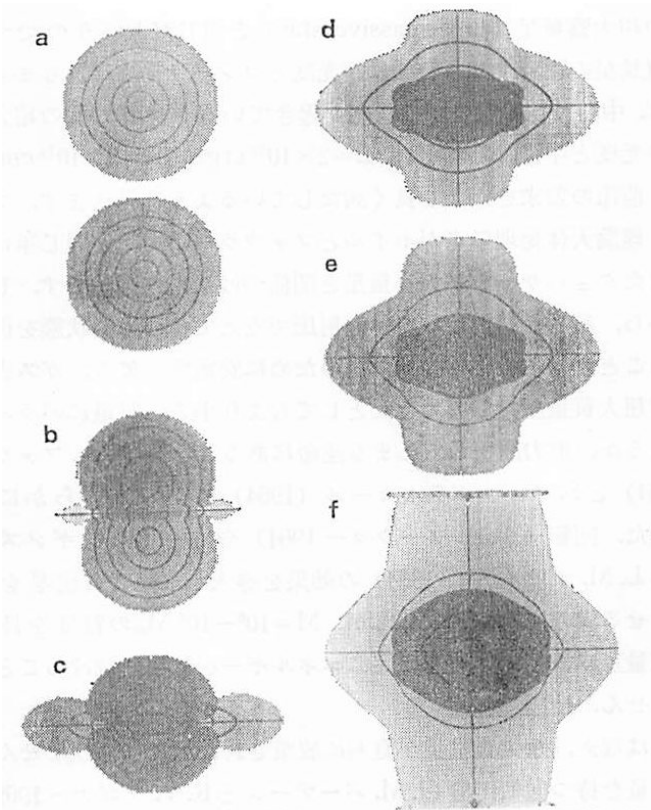


図 11.2 星と星との衝突：質量 $1 M_{\odot}$ の 2 個の星が相対初期速度 1000 km/s で衝突する。(a) $t=0$ ；中心間の距離は $2.2 R_{\odot}$ ，(b) $t=13$ 分；衝突面から横に物質の放出が起りはじめる，(c) $t=20$ 分；最も圧縮され，中心の密度と温度が初期値より上昇する，(d) $t=28$ 分；二つの反跳衝撃波が上下に伝播，(e) $t=30$ 分；横方向の物質の放出と二つの衝撃波によって作られた特徴的な外観，(f) $t=40$ 分；衝撃波によって生じた極方向の突出が成長，全質量の 18% が系からの脱出速度を超える。(F. G. P. サイドルと A. G. W. サムメロン 1972)。

Figure 11.2 Collision between two stars: two stars of mass $1M_{\odot}$ collide with a relative initial velocity of 1000 km/s. (a) $t = 0$; the separation of the centers is $2.2R_{\odot}$. (b) $t = 13$ min; ejection of matter sideways from the collision face begins. (c) $t = 20$ min; maximum compression, the central density and temperature rising above their initial values. (d) $t = 28$ min; two rebound shock waves propagate upward and downward. (e) $t = 30$ min: the characteristic appearance produced by the sideways ejection of matter and the two rebound waves. (f) $t = 40$ min: the polar protrusions produced by the shock waves grow, and 18% of the total mass exceeds the escape velocity of the system. (F. G. P. Seidl and A. G. W. Cameron 1972).

Since a collision releases a large amount of high-temperature gas within the nucleus, the collision hypothesis (L. Woltjer 1964; S. M. Ulam and W. E. Walden 1964; T. Gold, W. I. Axford and E. C. Ray 1965; S. van den Bergh 1965; L. Spitzer and W. C. Saslaw 1966) can, like the supernova hypothesis, explain the optical phenomena of Seyfert galaxies and quasars. S. A. Colgate (1967), on the other hand, put forward a theory combining the collision and supernova hypotheses, in which collisions between stars lead rather to the coalescence of stars, and a quasar is a system in which the massive stars of $M \sim 50M_{\odot}$ so produced explode as supernovae at the rate of five per year. These theories, which look like an inevitable final stage in the evolution of a stellar system, nevertheless run into the theoretical difficulty that realizing the conditions $M \gtrsim 10^8 M_{\odot}$ and $R \lesssim 0.1$ pc would take a time longer than the age of the universe. Supernova explosions and the collision and coalescence of stars must certainly be important processes occurring within the nucleus, but they cannot be regarded as explaining the ultimate energy source.

The bold idea that a Seyfert galaxy is the super-supernova explosion of a single object with a supermass of $M \sim 10^8 M_{\odot}$ was proposed by F. Hoyle and W. A. Fowler (1963). Their motivation was as follows. For one supernova explosion to induce others and set off a chain of supernova explosions, the nucleus must be compact enough for the stars to be in contact with one another; but this is essentially the same as a single supermassive star. The noteworthy features of a

supermassive star are its superluminosity and its compactness. For example, a supermassive star of $M = 10^8 M_\odot$ with hydrogen-burning nuclear reactions at its center has a luminosity and radius of $L = 2 \times 10^{46} \text{ erg/s}$ and $R = 8 \times 10^{14} \text{ cm}$ respectively, which appear to satisfy the requirements of the previous section fairly well. It was therefore only natural that theoretical astrophysicists should connect quasars — discovered in the same year as the Hoyle–Fowler paper — with supermassive stars. However, W. A. Fowler (1964) and S. Chandrasekhar (1964) showed that a supermassive star maintains its equilibrium by supporting gravity with radiation pressure, and that because of general-relativistic effects it lacks stability, so that even if one could be formed by the contraction of a gas cloud it is destined either to break up into smaller masses or to collapse gravitationally. Attempts were also made to stabilize supermassive stars by introducing the effects of rotation (W. A. Fowler 1964) or of a magnetic field (V. L. Ginzburg and L. M. Ozernoy 1964), but a supermassive star with a mass of $M \approx 10^6 - 10^8 M_\odot$ cannot go on stably releasing energy for longer than $t \sim 10^6 \text{ yr}$.

That said, supermassive stars were not immediately abandoned. Supermassive rotating disks were also examined (J. M. Bardeen and R. V. Wagoner 1969; E. Salpeter and R. V. Wagoner 1971), but the model that is interesting when set against the observations is a rotating supermassive star with a powerful magnetic field. These go under such names as the magnetoid model (L. M. Ozernoy 1966; L. M. Ozernoy and V. V. Usov 1973), the giant-pulsar model, or the spinar model (P. Morrison 1969; A. Cavaliere, F. Pacini and G. Setti 1969), the electrodynamic model (J. H. Piddington 1970), and the galactic-flare model (P. A. Sturrock 1965; P. A. Sturrock and C. Barnes 1972), but they have in common that the rotational energy of the supermassive star is converted, by way of magnetic field lines or magnetic dipole radiation, into acceleration energy of particles. Figure 11.3 shows the magnetoid model of Ozernoy and Usov. The strong low-frequency ($\nu \sim 10^{-7} \text{ Hz}$) magnetic dipole radiation emitted by a supermassive star ($M \sim 10^8 M_\odot$, $R \sim$

10^{16}cm) rotating with a period of about a year is absorbed by the plasma flowing out from the supermassive star, and the electrons accelerated there emit powerful synchrotron radiation of $L \sim 10^{48}\text{erg/s}$ in the submillimetre and infrared region. The supermassive star also emits thermal radiation of $L \sim 10^{46}\text{erg/s}$, so the magnetoid model appears to explain quasars well. A magnetoid formed as the final stage in the evolution of the nucleus as a stellar system, or as the result of the accumulation of gas lost by the stars in the nucleus during their evolution, gradually weakens its activity through magnetic dipole radiation and the ejection of plasma; but after $10^7 - 10^8\text{yr}$, Ozernoy and his colleagues maintain, it will accumulate gas again and enter a new active period. When one tries to interpret radio-quiet Seyfert galaxies with this model, however, one notices a decisive contradiction. As is clear from Chapter VIII, their infrared light is thermal radiation from dust grains, and the infrared source has an extent of $R \sim 1-100\text{ pc}$. We must conclude that although the magnetoid model may be applicable to radio-source quasars and BL Lac objects, it is incompatible with radio-quiet type 1 Seyfert galaxies.

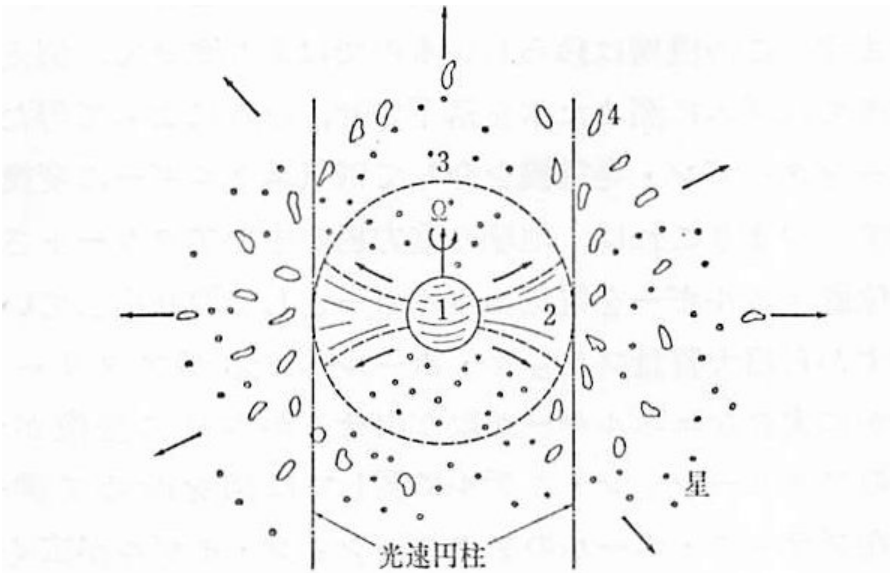


図 11.3 マグネトイド・モデル. 1—回転する超大質量天体; 2—回転不安定によって流出するプラズマ; 3—低周波電磁波によって占められる領域の境界; 4—1 から放出される輻射と粒子によって加速されたガス雲. (V. L. ギンズブルグと L. M. オゼルノイ 1977).

Figure 11.3 The magnetoid model. 1 — the rotating supermassive object; 2 — plasma flowing out because of rotational instability; 3 — the boundary of the region occupied by the low-frequency electromagnetic waves; 4 — gas clouds accelerated by the radiation and particles emitted from 1. (V. L. Ginzburg and L. M. Ozernoy 1977). Labels within the figure: an arrow marking the angular velocity Ω of the central object; “stars” outside; the two vertical lines marked “light cylinder”.

What is at present regarded as most promising is the accretion model of a supermassive black hole, proposed by E. E. Salpeter (1964), Ya. B. Zeldovich (1964), D. Lynden-Bell (1969) and others. Its basic idea is to extract efficiently the potential energy and rotational energy of gas accreting in the strong gravitational field of a supermassive black hole. This mechanism is nothing unusual. In a

hydroelectric power station, for instance, water stored behind a dam is allowed to fall, and the potential energy so obtained is converted into electrical energy by way of turbines and generators. That is, the potential energy of water made to accrete in the gravitational field of the Earth is extracted as electrical energy. It is therefore easy to imagine how much energy can be extracted if gas accretes onto a supermassive black hole. We shall examine this accretion model in a separate section, but besides the failure of the models belonging to the three categories examined above, the following reasons can be given for the wide acceptance the black-hole accretion model enjoys today.

(1) Black holes are extremely small.

From $r_g = 2GM_{\text{BH}}/c^2$, the radius of a non-rotating black hole (Schwarzschild black hole) is given by

$$r_g = 3 \times 10^{12} \left(\frac{M_{\text{BH}}}{10^7 M_{\odot}} \right) \text{ cm}$$

Here r_g stands for the gravitational radius, and $M_{\text{BH}}/10^7 M_{\odot}$ is the mass of the black hole in units of $10^7 M_{\odot}$. For $M_{\text{BH}}/M_{\odot} = 1$ we have $r_g = 3\text{km}$, and if we take the mass of the Earth ($6 \times 10^{27} \text{ g}$) for M_{BH} , then $r_g = 1\text{cm}$. For a supermassive black hole of $M = 10^6 - 10^8 M_{\odot}$ the radius is $r_g = 3 \times 10^{11} (4 R_{\odot}) - 3 \times 10^{13} (2 \text{ A.U.})$ cm. The extreme smallness of black holes is a very desirable property, both for interpreting a compact energy source and for producing a strong gravitational field.

(2) Energy conversion of high efficiency is possible.

It depends on the kind of black hole (a non-rotating Schwarzschild black hole or a rotating Kerr black hole), but 6–42% of the rest energy of the accreting gas can be released. This is an efficiency almost 10 times higher than that of nuclear reactions. Assuming 10% of the rest energy and writing $\dot{M}$ for the mass of gas accreting per year, the expected luminosity, from $L = 0.1\dot{M}c^2$, is given by

$$L = 6 \times 10^{45} \left(\frac{\dot{M}}{M_{\odot}} \right) \text{ erg/s}$$

To explain the total luminosity of NGC 4151, $L = 1.5 \times 10^{44} \text{ erg/s}$, requires $\dot{M} = 0.025 M_{\odot}/\text{yr}$, while the luminosity range of Seyfert galaxies, $L = 10^{43} - 10^{46} \text{ erg/s}$, requires accretion rates of $\dot{M} = 0.002 - 2 M_{\odot}/\text{yr}$.

(3) Supermassive black holes are thought to form inevitably within the nucleus.

Leaving its origin aside, if a gas cloud of $M \gtrsim 10^6 - 10^8 M_{\odot}$ contracts under its own gravity, three possibilities can be envisaged. One is a process of unlimited contraction (gravitational collapse) forming a supermassive black hole. The second process is the formation of a supermassive star, a magnetoid, and the like. But these too should ultimately break up to form a dense stellar system, or collapse gravitationally into a black hole. The remaining possibility is a process forming a dense stellar system directly out of the gas cloud. In a dense stellar system, collisions and mergers of stars and supernova explosions occur, a large amount of gas is released, and black holes of ordinary stellar mass are formed. The released gas contracts under its own gravity and enters a new cycle. Meanwhile the black holes of ordinary stellar mass swallow stars and gas, and are thought to grow to supermass in a period sufficiently short compared with the age of the universe. Both the dense stellar system of category (b) and the supermassive star of category (c) end up, finally, by forming a supermassive black hole.

3. The Accretion Model

(1) Spherically symmetric accretion

Let us consider the simplest case, in which gas accretes steadily onto a point mass M . If the angular momentum of the gas can be neglected, the accretion flow is

spherically symmetric. Far enough from the point mass the gas is at rest, but inside the region where the gravitational energy exceeds the thermal energy of the gas — that is, inside the accretion radius

$$r_a = \frac{GM}{a_\infty^2} \approx 1 \times 10^{14} \left(\frac{M}{M_\odot} \right) \left(\frac{10^4}{T_\infty} \right) \text{ cm}$$

the gas begins to fall, the flow is gradually accelerated by gravity, and at the critical point

$$r_c = \frac{GM}{2a^2}$$

it reaches the sound speed

$$a = \sqrt{\gamma \frac{p}{\rho}}$$

Here G is the gravitational constant, $a_\infty = \sqrt{(\gamma p_\infty / \rho_\infty)}$ is the sound speed far away, and T_∞ is the gas temperature far away. Also p and ρ are the pressure and density of the gas, and γ is the adiabatic index, which takes values $1 \leq \gamma \leq 5/3$. The accretion flow is subsonic (Mach number $M = v/a < 1$) outside the critical point and supersonic ($M > 1$) inside it, and if the point mass is a black hole the gas velocity v reaches the speed of light c at the gravitational radius r_g of (11.2). The accretion rate — that is, the mass of gas accreting per unit time, $\dot{M}$ — is obtained by multiplying the surface area $4\pi r^2$ of the sphere at radius r by the density ρ and the velocity v :

$$\dot{M} \approx 0.1 n_\infty \left(\frac{M}{10^7 M_\odot} \right)^2 \left(\frac{10^4}{T_\infty} \right)^{3/2} M_\odot / \text{yr}$$

Here n_∞ is the number density of the gas far away, and with a proton mass of $m_p = 1.67 \times 10^{-24} \text{ g}$ we have $\rho_\infty \approx m_p n_\infty$.

The gas accretes at very nearly the free-fall velocity

$$v \approx \left(\frac{2GM}{r} \right)^{1/2} \propto r^{-1/2}$$

Since the accretion rate is constant, independent of radius, the density therefore varies as

$$\rho = \frac{\dot{M}}{4\pi r^2 v} \propto r^{-3/2}$$

Using the Boyle–Charles law $p \propto \rho T$ and the equation of state $p \propto \rho^\gamma$, we find that the temperature rises according to

$$T \propto \rho^{\gamma-1} \propto r^{-\frac{3}{2}(\gamma-1)}$$

If we assume $T_\infty = 10^4$ K, then $a_\infty \approx 10$ km/s and

$$\frac{r_a}{r_g} \approx \left(\frac{c}{a_\infty} \right)^2 \approx 10^9$$

so that the temperature around the black hole is expected to reach

$$T \approx T_\infty \left(\frac{r_a}{r_g} \right)^{\frac{3}{2}(\gamma-1)} \sim 10^8 - 10^9 \text{ K} \quad (\gamma = 1.4)$$

This is a striking feature of spherically symmetric accretion. In the disk accretion to be discussed next, T only reaches $\sim 10^5 - 10^6$ K.

The high-temperature gas of spherically symmetric accretion radiates X-rays. However, if one calculates its thermal emission from the temperature and density distributions, one finds that it falls far short of 1% of the X-ray luminosity to be explained. If n_∞ is raised so as to increase the accretion rate, the accretion flow becomes optically thick, and the efficiency, on the contrary, drops further and further. This is only to be expected, because no mechanism has been taken into account for dissipating the kinetic energy the gas gains as it is accelerated.

As already stated in connection with the origin of the X-rays in the previous chapter, turbulence and magnetic fields work effectively as energy-dissipation mechanisms for spherically symmetric accretion. According to P. Mészáros and Silk (1977), energy dissipation by turbulence heats the gas to $T \gtrsim 10^9$ K, and, apart from the high-energy region, the X-ray luminosity and spectral distribution can be explained. Both the interstellar gas and the stars possess magnetic fields. Hence if gas originating in them accretes, the field lines are stretched, folded, or torn apart by the turbulence, and the energy density of the magnetic field is raised to the same order as the density of the kinetic and turbulent energy of the gas and as the gravitational energy density. Under such conditions synchrotron radiation becomes the principal radiation mechanism. According to the results of L. Maraschi and colleagues (1979), who discussed spherically symmetric turbulent accretion of magnetized gas, the gas temperature rises to $T \approx 10^9 - 10^{10}$ K and strong synchrotron radiation is emitted in the infrared region at $10^{13} - 10^{14}$ Hz. The X-rays can also be explained by its Comptonization.

However, the property of spherically symmetric accretion that the infrared light is synchrotron radiation contradicts, as we saw in Chapter VIII, the observations of radio-quiet Seyfert galaxies. This is because their infrared light is thought to be secondary thermal radiation from dust grains. Non-steady accretion, in which the accretion rate varies with time, and self-gravitating accretion, which takes the gravity of the gas into account, have not been studied sufficiently; but if spherically symmetric accretion does operate as an actual energy source, it would seem to be confined to radio sources.

(2) Disk accretion

The disk region of a spiral galaxy, the central bulge, and the quasi-stellar nucleus all rotate with velocities of ~ 100 km/s. If gas originating in them accretes onto a

supermassive black hole within the nucleus, then, because of its large angular momentum, a rotating disk called an accretion disk is thought to form around the black hole (D. Lynden-Bell 1969; J. E. Pringle and M. J. Rees 1972; N. I. Shakura and R. A. Sunyaev 1973).

Each point of the accretion disk has the rotational velocity determined by the balance between the centrifugal force of the rotation and the gravity of the black hole,

$$v_{\phi} = \sqrt{\frac{GM}{r}} \propto r^{-1/2}$$

so that the inner parts rotate faster. Expressed in terms of the angular velocity $\omega = v_{\phi}/r$, this becomes

$$\omega = \sqrt{\frac{GM}{r^3}} \propto r^{-3/2}$$

The angular momentum per unit mass, on the other hand, is

$$L = r^2 \omega \propto r^{1/2}$$

and takes larger values farther out. If we consider two annuli of slightly different radii r_1 and r_2 ($r_1 > r_2$), the viscosity arising from small-scale turbulence and magnetic fields acts as a frictional force between them, so that angular momentum is carried outward in such a way as to equalize the angular velocities ω_1 and ω_2 at r_1 and r_2 . This transport of angular momentum reduces the velocity of the inner annulus, so the annulus falls slightly inward. Writing the radial infall velocity as v_r and the surface density of the accretion disk as Σ , the accretion rate in the case of disk accretion is

$$\dot{M} = 2\pi r \Sigma v_r$$

Since the radial motion is sufficiently slow compared with the rotation ($v_r \ll v_{\phi}$), if we assume the same accretion rate as for spherically symmetric accretion, the

surface density of the accretion disk becomes high and the disk is thought to become optically opaque.

The gas within the accretion disk spirals slowly down onto the black hole. Part of the gravitational energy lost in this process increases the rotational energy, and the remainder is converted into thermal energy, which becomes the thermal radiation from the surface of the accretion disk. The frictional force that drives the transport of angular momentum also produces an outward flow of energy. Taking these into account and calculating the energy emitted per unit time from unit surface area of the accretion disk, we obtain

$$Q \approx \frac{3}{8\pi} \frac{GM_{\text{BH}}\dot{M}}{r^3}$$

If this energy flux is radiated as blackbody radiation, then from the Stefan–Boltzmann law ($Q=\sigma T^4$) the temperature of the annulus at radius r is

$$T \approx 1 \times 10^6 \left(\frac{10^7 M_{\odot}}{M_{\text{BH}}} \right)^{1/2} \left(\frac{\dot{M}}{M_{\odot}} \right)^{1/4} \left(\frac{3r_g}{r} \right)^{3/4} \text{ } ^{\circ}\text{K}$$

Here $\dot{M}/M_{\odot}$ is the mass of gas accreted in one year in units of the solar mass. Also, $r = 3r_g$ is the smallest radius at which circular motion around a Schwarzschild black hole is possible, and it gives the innermost radius of the accretion disk. Although it depends somewhat on the mass of the black hole and on the accretion rate, equation (11.18) shows that the temperature of the accretion disk is $T \approx 10^5 - 10^6$ K. This is the temperature range that radiates ultraviolet light. The suggestion by V. M. Lyutiyi (1977) and G. A. Shields (1978) that the accretion disk is the visible and ultraviolet continuum source of Seyfert galaxies and quasars is based on this property.

As can be seen from equation (11.3), if the accretion rate $\dot{M}$ is increased, the luminosity L increases in proportion to it. However, once the luminosity exceeds

the Eddington limit L_E of (11.1), the outward radiation pressure becomes stronger than the inward gravity, and the gas is pushed back and turns into an outflow. If accretion is halted, the luminosity falls below the Eddington limit and accretion again becomes vigorous. If in this way the luminosity of disk accretion is regulated at the Eddington limit (supercritical accretion), the accretion rate is given by

$$\dot{M} \approx 0.2 \left(\frac{M_{\text{BH}}}{10^7 M_{\odot}} \right) M_{\odot}/\text{yr}$$

and part of the accreted gas is thought to be ejected in the polar directions by radiation pressure (Figure 11.4). A leading explanation for the broadening mechanism of the emission lines was the Doppler effect due to gas outflow from the nucleus, and one could identify the gas outflow accompanying supercritical accretion with this. S. Tsuruta (1977) has also proposed a fountain model in which the collision of the outflowing gas of supercritical accretion with gas clouds inside the nucleus produces an enormous number of low-energy photons from the microwave to the infrared region, and these undergo inverse Compton scattering to become a powerful infrared and ultraviolet source.

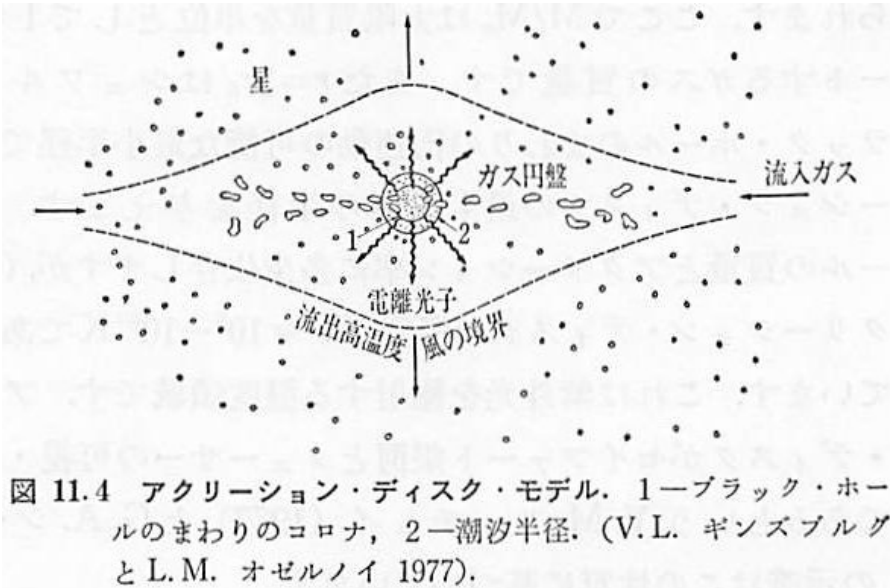


図 11.4 アクリーション・ディスク・モデル. 1—ブラック・ホールのまわりのコロナ, 2—潮汐半径. (V. L. ギンズブルグと L. M. オゼルノイ 1977).

Figure 11.4 Accretion-disk model. 1 — corona around the black hole; 2 — tidal radius. (V. L. Ginzburg and L. M. Ozernoy 1977). Labels in the figure: stars / gas disk / inflowing gas / ionizing photons / boundary of the outflowing high-temperature wind / 1 / 2

Disc accretion contains several other interesting possibilities besides these. As we have already seen in the previous chapter, if inside the accretion disk, around the black hole, there forms an optically thin, puffed-up high-temperature region called the two-temperature region — or above it a high-temperature region resembling the solar corona — then the unsaturated Comptonization occurring there can raise the energy of the low-energy photons radiated by the accretion disk up to the X-ray region. The various radii of the accretion disk rotate with different angular velocities (differential rotation). The magnetic field of the accreting gas is amplified by this differential rotation, and the energy stored in the magnetic field is released, through explosive phenomena resembling solar flares, as ejection of plasma clouds and as synchrotron radiation and inverse Compton radiation (D. Lynden-Bell 1969; G. A. Shields and J. C. Wheeler 1976; F. Takahara 1979). This

energy release by flares is an important mechanism that cannot be ignored, both for the time variation of the radiation intensity seen in every wavelength region from the radio to X-rays and for the formation of the coronal region. Furthermore, if magnetic lines of force pierce the accretion disk vertically and regularly, double radio sources can also be explained (R. V. E. Lovelace 1976; R. D. Blandford 1976; R. D. Blandford and R. L. Znajek 1977). Such field lines are dragged inward by the accreting gas and at the same time are made to rotate at high velocity. Since this acts as a kind of gigantic dynamo, an electric field is induced, and the accelerated high-energy particles are ejected in beams along the field lines in both polar directions (Figure 11.5).

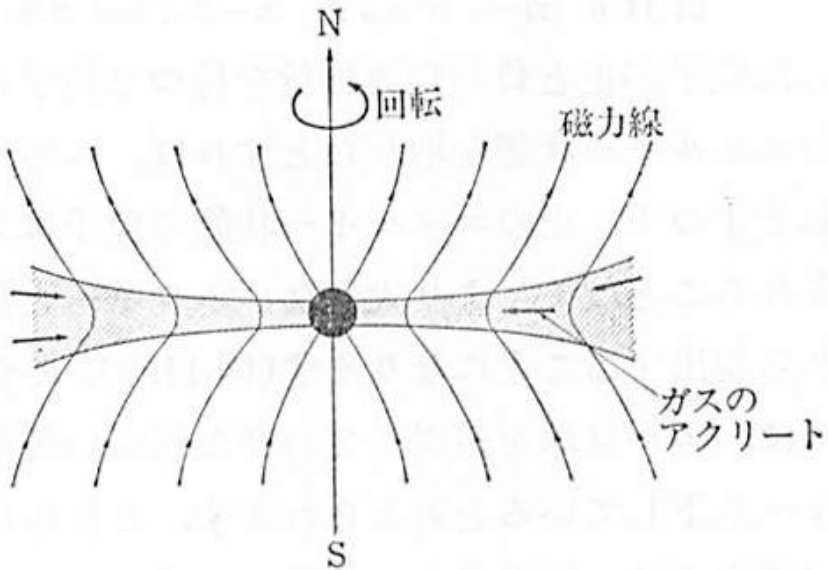


図 11.5 磁場を持ったアクリーション・ディスク.

Figure 11.5 Accretion disk with a magnetic field. Labels in the figure: N / S / rotation / magnetic lines of force / gas accretion

If the black hole itself is rotating (a Kerr black hole), the Penrose mechanism (R. Penrose 1969) can be expected as a way of extracting energy. In this case a region in which the inertial frame is dragged by the rotation of the black hole — that is, the ergosphere — is formed outside the black hole (Figure 11.6). At the surface of the ergosphere the inertial frame rotates at the speed of light, and inside it a particle moving with sufficiently large angular momentum in the direction opposite to the black hole's rotation can take a negative-energy state. Suppose now that a particle that has entered the ergosphere with positive angular momentum splits into two particles with positive and negative angular momentum, and that each is able to take a positive and a negative energy state respectively; then, since energy and angular momentum are conserved, the particle in the positive-energy state is not swallowed by the black hole but escapes from the ergosphere with greater energy and angular momentum (Figure 11.7). In the nuclei of Seyfert galaxies, an enormous number of X-ray photons are thought to pass through the ergosphere and fall onto the black hole. Because of the blueshift, these appear inside the ergosphere as γ - ray photons. If they are Compton-scattered by electrons within the ergosphere and the electron after scattering takes a negative-energy state, these photons can escape from the ergosphere and are observed as γ - rays of 300 KeV–3 MeV, of the order of the rest energy of the electron (T. Piran and J. Shaham 1977).

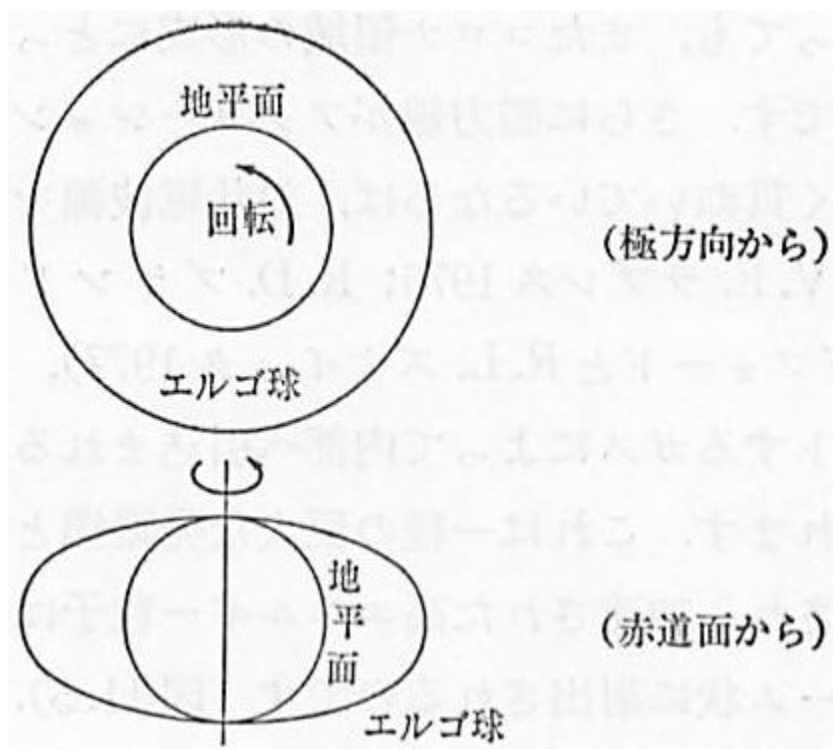


Figure 11.6 The ergosphere of a Kerr black hole. Labels in the figure: horizon / rotation / ergosphere / (viewed from the polar direction) / (viewed from the equatorial plane)

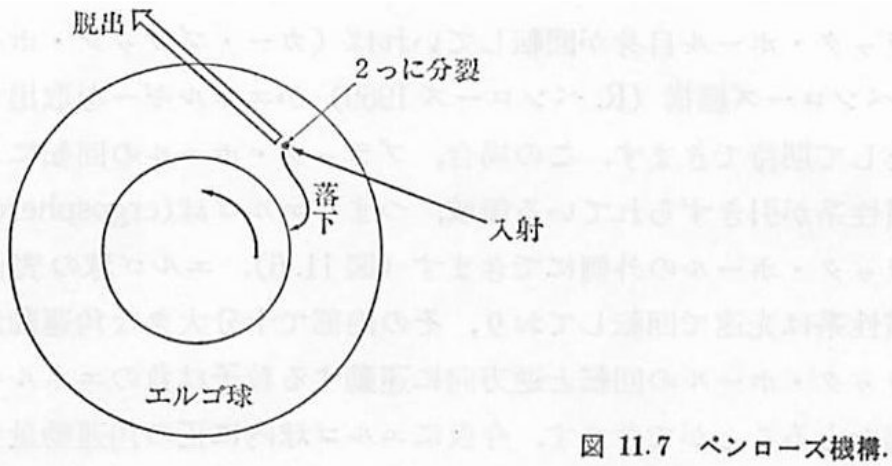


Figure 11.7 The Penrose mechanism. Labels in the figure: escape / splits into two / infall / incidence / ergosphere

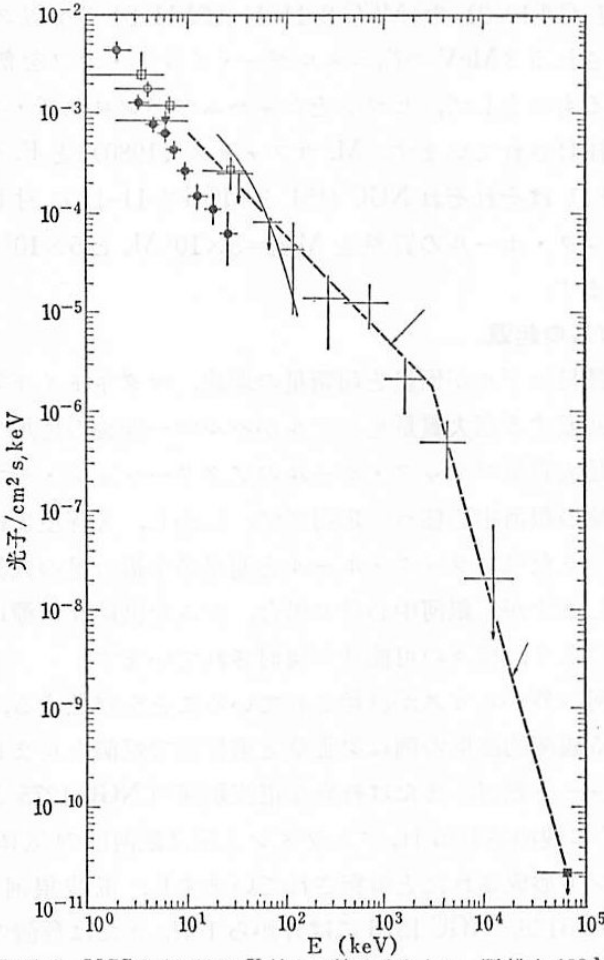


図 11.8 MCG 8-11-11 の X 線と γ 線スペクトル。距離を 123 Mpc ととれば, $L(0.09-3 \text{ MeV})=7 \times 10^{46} \text{ erg/s}$. (F. ペロッチ 達 1981).

Figure 11.8 X-ray and γ -ray spectrum of MCG 8-11-11. If the distance is taken to be 123 Mpc, $L(0.09-3 \text{ MeV})=7 \times 10^{46} \text{ erg/s}$. (F. Perotti et al. 1981). Ordinate: photons/cm²s, keV (10^{-11} to 10^{-2})/Abscissa: E (keV) (10^0 to 10^5)

Besides the above, the Penrose pair-production process involving scattering off protons within the ergosphere (D. Leiter and M. Kafatos 1978), the decay of pions produced in proton–proton collisions within the two-temperature region (J. A. Eilek 1980), and inverse Compton scattering of X-ray photons (R. Schlickeiser 1980) have been proposed as γ – ray radiation mechanisms; but the Penrose–Compton process of Piran and Shaham is attracting attention as one that can naturally explain the 3 MeV high-energy cut-off observed in the γ – ray spectra of NGC 4151 (Figure 10.3) and MCG 8-11-11 (Figure 11.8). M. Kafatos (1980) and F. Perotti et al. (1981) estimate the mass of the Kerr black hole as $M_{\text{BH}} = 5 \times 10^7 M_{\odot}$ and $5 \times 10^9 M_{\odot}$ for NGC 4151 and MCG 8-11-11 respectively.

(3) The origin of the gas

Just as the supermassive-star model was an application of the theory of stars and supernovae, and the model of a supermassive star rotating with a magnetic field (a magnetoid and the like) was an application of pulsar theory, the accretion model of a supermassive black hole is an application of the theory of X-ray stars to galactic nuclei. However, whereas in X-ray stars the gas accretes from the atmosphere of a star forming a binary system with a neutron star or a black hole, in the case of a galactic nucleus the source that supplies the gas is not so obvious, and various possibilities have been examined.

We saw a number of examples in Chapters III and IV of observational evidence that proves, or hints at, gas being supplied from outside the active galaxy. The H_{α} filament systems observed in NGC 1275 — a radio Seyfert galaxy, or peculiar radio galaxy — and in the radio galaxy M 87 are interpreted as having been formed by accretion of intracluster gas; and in the radio galaxies NGC 1275, NGC 5128 and NGC 1316 one can recognize clear traces showing that one, or several, galaxies have each fallen in from outside. The H_{α} filaments of M 82, once regarded

as the representative exploding galaxy, probably originate in gas stripped from one or other of the galaxies by the gravitational interaction with M 81. When a galaxy possesses a huge neutral-hydrogen halo, as does Mkn 348 — a peculiar type 2 Seyfert galaxy with a variable radio source — accretion of gas from the halo is also conceivable. Furthermore, although it was not mentioned in this book, there is also the possibility of collision with intergalactic gas clouds, as has been suggested for NGC 1052 and NGC 4278. That there exist active galaxies with a gas supply source outside the galaxy is clear from the above examples, but one should also note that examples among typical Seyfert galaxies, particularly of type 1, are few. As a tendency, these appear to have a strong radio character.

Stars within a galaxy release gas in the course of their evolution. Through supernova and nova explosions, the formation of planetary nebulae, mass loss from the atmospheres of pulsating stars and red giants, or the stellar winds of ordinary stars, gas is continually supplied within a galaxy, and the rate is estimated to reach $0.1\text{--}1.0\ M_{\odot}$ per year for one galaxy ($M \sim 10^{11}\ M_{\odot}$). If gas were released at this rate over the $\sim 10^{10}$ years corresponding to the age of the universe, a total of $10^9\text{--}10^{10}M_{\odot}$ of gas would be obtained, and unless it is stripped away by supernova explosions, collisions with galaxies, or intracluster/intergalactic gas, this gas can become one of the supply sources for accretion. Concrete observational evidence for this has not been found at present, but it is thought to be a process that cannot be neglected in elliptical galaxies, in which radio sources are often found. The reason is that, although gas ought certainly to be released within the galaxy at a rate of $0.1\text{--}1.0\ M_{\odot}/\text{year}$, elliptical galaxies generally possess no neutral hydrogen gas in amounts detectable by 21 cm radio observations, nor do they contain ionized hydrogen regions where new stars are being born. In an elliptical galaxy where no gas stripping has occurred, the gas has no choice but to accrete toward the center. In the case of a spiral galaxy the gas has large angular momentum and, moreover, star formation is occurring vigorously, so such a supply

source does not seem so important; but gas that has been lifted up into the halo region and then accretes again onto the nucleus may be considered as one possibility.

If stars within the nucleus can be efficiently destroyed, or their atmospheres stripped away, the nucleus itself becomes a supply source of gas for the black hole. The chain supernova explosions and stellar collisions discussed earlier as energy sources also release large amounts of gas, but if a supermassive black hole exists within the nucleus, an even more promising mechanism for destroying stars can be expected. This is the destruction of stars by the tidal force of a black hole, proposed by J. G. Hills (1975). The gravity of a black hole varies inversely as the square of the distance from it, becoming stronger the closer one approaches. For this reason, a body of finite size experiences a force stretching it in the direction of the black hole (a tidal force). If it is sufficiently far from the black hole a star suffers only slight deformation, but once it approaches closer than a certain distance (the tidal radius), the star is torn to pieces by the tidal force of the black hole. For a star like the Sun, the tidal radius is given by

$$R_T \sim 4 \times 10^{13} \left(\frac{M_{\text{BH}}}{10^7 M_\odot} \right)^{1/3} \text{ cm}$$

Here $M_{\text{BH}}/10^7 M_\odot$ is the mass of the black hole in units of $10^7 M_\odot$. If this tidal radius is larger than the gravitational radius of (11.2) — that is, if the mass of the black hole is

$$M_{\text{BH}} \lesssim 3 \times 10^8 M_\odot$$

then the gas is scattered outside the black hole. Since the destruction of the star occurs at the expense of the energy of its orbital motion, most of the gas is gravitationally bound to the black hole and accretes onto it. However, if the mass of the black hole exceeds $3 \times 10^8 M_\odot$, the star is swallowed by the black hole before it

is broken up by the tidal force, and energy cannot be extracted from accretion. As Hills suggested, the upper limit $M_{\text{BH}} \sim 3 \times 10^8 M_{\odot}$ on the black-hole mass from which energy can be extracted corresponds to an Eddington luminosity $L_E \sim 3 \times 10^{46} \text{ erg/s}$, roughly equal to the luminosity of the brightest quasars. The tidal-disruption hypothesis appears to be able to explain the maximum luminosity of quasars as well without strain.

A black hole destroys by its tidal force only those stars whose orbits pass within the tidal radius. Stars moving within the nucleus tend to refill the orbits that have been lost, through gravitational interaction (two-body encounters) when they approach one another, so the tidal disruption rate is determined by the rate at which stars diffuse into such particular orbits. Since Hills's paper, many theoretical studies attempting to derive a more realistic tidal disruption rate have appeared one after another (J. Frank and M. J. Rees 1976; J. N. Bahcall and R. A. Wolf 1976; A. P. Lightman and S. L. Shapiro 1977; P. J. Young, G. A. Shields and J. C. Wheeler 1977; P. J. Young 1977; W. A. Hiscock 1977; J. G. Hills 1978; J. Frank 1978; G. A. Shields and J. C. Wheeler 1978; L. M. Ozernoy and M. Reinhardt 1978). According to them it is easy to account for accretion rates of the order required by Seyfert galaxies, but in order to explain an accretion rate $\dot{M} \gtrsim 1 M_{\odot}/\text{year}$ commensurate with the luminosity of quasars, the nucleus must be unrealistically dense. However, this is a result that should encourage us rather than dishearten us. If there is a huge gas cloud within the nucleus, the gravitational interaction with it raises the diffusion rate of stars into disruptive orbits; and in the region made dense by the gravity of the black hole, collisions and mergers between stars become important, so that a still higher rate of gas release can also be expected. Furthermore, if the black hole is a rotating Kerr black hole, the upper limit of the mass rises by one order of magnitude. Also, if there is a mechanism that stores gas temporarily, a high accretion rate can easily be explained. In this case nuclear activity becomes essentially intermittent.

The tidal-disruption hypothesis is also advantageous for the formation of a supermassive black hole. From the standpoint of accretion of gas from outside the galaxy or from the galaxy as a whole, one must suppose that the black hole was produced by the gravitational collapse of a supermassive star or of a compact stellar system, or else that it was incorporated at the time the galaxy formed. But if the process of tidal disruption exists, then even a black hole of $\sim 10M_{\odot}$ formed by a supernova explosion can grow in $\sim 10^9$ years to a supermass of $\gtrsim 10^6M_{\odot}$. Moreover, once a black hole becomes larger than $M_{\text{BH}} \sim 3 \times 10^8M_{\odot}$ it must cease its activity; and it is not unnatural to regard the radio galaxies NGC 5128 and NGC 1316 — which possess gigantic double radio sources yet have relatively weak nuclear activity — as such dead quasars.

4. The origin of nuclear activity

If the essence of nuclear activity lies in the accretion of gas onto a supermassive black hole, then a galaxy is thought to display Seyfert-like or quasar-like activity only when both the formation of a supermassive black hole and the supply of gas are realized together. Even if a supermassive black hole has formed within the nucleus, nuclear activity will not occur if there is no gas to accrete; and even if a large amount of gas is supplied to the nuclear region, if no supermassive black hole is present the object will merely become a galaxy with a huge ionized hydrogen region at its center, like an emission-line galaxy or a hot-spot galaxy, and no broad emission-line spectrum or strong ultraviolet and X-ray radiation would be observed.

The ways of forming a supermassive black hole within the nucleus can be broadly divided into the following three. The first is the possibility that the galaxy already possessed a supermassive black hole in its nucleus when it was born. If the galaxy was born from the gravitational contraction of a huge gas cloud, one cannot deny

the possibility that a supermassive black hole formed in the nucleus as a singularity; and one could also suppose that the galaxy formed around a black hole created in the early universe as a nucleus. The second is the method of forming a supermassive black hole by the gravitational collapse of a supermassive star or of a superdense stellar system at some period in the galaxy's evolution. For instance, if a galaxy collides with a huge gas cloud, it is conceivable that the accretion of that gas temporarily forms a supermassive star within the nucleus. The remaining method is the tidal-disruption hypothesis of J. G. Hills (1975). This asserts that a black hole of $\sim 10M_{\odot}$ born in a supernova explosion can grow within $\sim 10^9$ years to a mass of $\sim 10^6M_{\odot}$ or more.

The supply sources of the gas have already been discussed in detail. Three are conceivable: gas clouds and galaxies falling in from outside the galaxy; gas released by the mass loss of the stars within the galaxy; and tidal disruption and stellar collisions occurring within the nucleus. Accordingly, if we organize the possibilities for the origin of nuclear activity, there are nine combinations, as shown in Table 11.4. The tidal-disruption hypothesis advocated by Hills corresponds to G_3H_3 .

Table 11.4 The origin of nuclear activity

Gas supply source \ Black-hole formation	H_1 Already possessed when the galaxy was born	H_2 Formed at some period in the galaxy's evolution	H_3 Grown over a long time from a small black hole
G_1 Gas clouds or galaxies falling in from outside the galaxy	G_1H_1	G_1H_2	G_1H_3
G_2 Gas released by mass loss etc. of the stars making up the galaxy	G_2H_1	G_2H_2	G_2H_3
G_3 Gas produced by tidal disruption and stellar collisions occurring within the nucleus	G_3H_1	G_3H_2	G_3H_3

The rows and columns of Table 11.4 each have distinct characteristics. If the formation of the supermassive black hole is H_1 , nuclear activity must have occurred every time gas was supplied since the birth of the galaxy, and in the early universe it is thought to have had a considerable influence on the physical state of the intergalactic gas. The quasar with the largest redshift known at present is OQ 172 (Q 1442 + 101) at $z=3.53$, but the discovery of quasars with still larger redshifts can be expected. One can also take the view that H_1 was possible only in a certain limited class of galaxies. In this case some correspondence is expected to exist between the morphology of galaxies and nuclear activity. If the formation of the supermassive black hole is H_2 , then if it occurred relatively early in the universe there ought, as with H_1 , to be quasars beyond $z \sim 4$; whereas if it has been occurring continuously up to the present, then both early and late stages of nuclear activity should be observed irrespective of redshift, and active galaxies would be expected to show great variety. Whether the factor causing supermassive black-hole formation lies inside or outside the galaxy, not all galaxies can necessarily form one, so a correspondence with morphology can still be expected in the case of

H_2 as well. In the case of H_3 , a long time ($t \geq 10^9$ years) is required for the black hole to grow. Accordingly, $z=3.53$ of OQ 172 is close to the upper limit of the redshift of active galaxies, and quasars beyond $z \sim 4$ are predicted to be extremely few. Also, if every kind of galaxy has a similar nucleus, then supermassive black holes would form in all galaxies.

Differences in the gas supply source are also strongly reflected in morphology. For the gas supply G_1 to work effectively, giant spiral galaxies and giant elliptical galaxies — or still larger D galaxies and cD galaxies — are far more favorable than small, light dwarf galaxies; and those belonging to large groups or clusters of galaxies find it easier to accrete the gas within them than isolated galaxies do, and their frequency of collision with gas clouds or other galaxies is also higher. Moreover, since the mean density of the universe must have been higher at earlier epochs, galaxies with larger redshift z are thought to have been more prone to nuclear activity. If the gas supply is G_2 , elliptical galaxies, with their smaller angular momentum, are more likely to display nuclear activity than spiral galaxies; and, contrary to G_1 , because of the removal of gas by intergalactic gas (G. R. Gisler 1976; S. M. Lee and D. S. De Young 1976; K. Toyama and S. Ikeuchi 1980), isolated galaxies ought to be more prone to nuclear activity than those within clusters. Also, if the properties of the nucleus have no direct relation to the exterior, then in the case of G_3 no definite correspondence between nuclear activity and morphology would exist.

Now, we have already studied the morphological characteristics of Seyfert galaxies in detail in Chapter V. Summarizing them once more:

1. The majority of Seyfert galaxies belong to the spiral galaxies, and those that are elliptical galaxies are extremely few.

2. Seyfert galaxies are found among SA, SAB, SB as well as among SO, Sa, Sb and Sc, but many possess inner and outer ring structures (R)S (r) and show multiple structure.
3. N galaxies, distorted galaxies and interacting galaxies are frequently seen.
4. Many possess jets, filament systems, gas clouds, huge neutral hydrogen (HI) halos, and the like.
5. Their tendency to belong to clusters of galaxies is weak; the majority of Seyfert galaxies are isolated galaxies or members of small groups.

It must be said that to try to discuss the origin of nuclear activity from these limited morphological characteristics alone is a reckless undertaking; but let us, in full knowledge of that, compare them with Table 11.4.

The fifth property — the weak tendency to belong to clusters of galaxies — leaves open the possibility that the G_2 gas is being removed by intracluster gas, but it seems to suggest that G_1 is not essential as a method of supplying gas to Seyfert galaxies. As examples of G_1 one can cite NGC 1275, NGC 5128, NGC 1316 and so on, but these are all peculiar radio galaxies of elliptical type and are not typical type 1 Seyfert galaxies. From the third property — that interacting galaxies are numerous — one may also suppose that G_1 gas stripped from the other galaxy accretes onto the nucleus, just as in the case of M 82; but not all Seyfert galaxies are interacting galaxies, and viewed as a whole they are only a fraction.

Spiral galaxies are classified as SO, Sa, Sb, Sc according to the morphology of their spiral arms, but this at the same time forms a sequence in which the central bulge becomes relatively smaller with respect to the disk. Seyfert galaxies tend to be found somewhat more often among the early types SO-Sa, but they are found among all types from SO to Sc, and no direct correspondence exists between the

presence or absence of nuclear activity and the size of the central bulge. This can be interpreted to mean both that the size of the central bulge is unrelated to the formation of a supermassive black hole, and that the G_2 gas lost by stars within the central bulge is not the principal supply source. Noting the property that SO-Sa Seyfert galaxies are numerous, T. M. Heckman, B. Balick and W. T. Sullivan III (1978) suggested that evolved stars within the central bulge supply the accreting gas; but if this G_2 is important as a supply source, then many more Seyfert galaxies ought to have been discovered among elliptical galaxies, which have still larger elliptical structures.

In the case of spiral galaxies, the region rich in gas is not the central bulge but the disk region where the spiral arms are observed. S. M. Simkin, H. J. Su and M. P. Schwarz (1980) showed that if a rotating disk system possesses a bar structure, an inward gas flow arises and patterns very similar to those of Seyfert galaxies are reproduced, and they argue that nuclear activity is caused by the accretion of the abundant gas (G_2) in the disk region. This claim also appears compatible with the second morphological characteristic that they found (see also Table 5.2); but not all Seyfert galaxies possess the bar region that generates the inward gas flow, and it is not clear whether that flow, which creates the ring structures inside and outside the galaxy, accretes all the way into the nucleus. There is also an explosion hypothesis of the nucleus as an interpretation of ring structure (P. W. Hodge 1968; M. Nishimura 1979). Furthermore, T. M. Heckman, B. Balick and W. T. Sullivan III (1978), relating it to the $M_{\text{HI}}/L_{\text{pg}}$ anomaly they discovered in the ratio of neutral hydrogen gas mass to luminosity (Figure 9.16), suggest an evolutionary sequence in which early Seyfert galaxies begin as systems rich in neutral hydrogen gas like Mkn 348. If neutral hydrogen gas plays an important role in nuclear activity, anomalies in the distribution or motion of neutral hydrogen gas ought to be observed in Seyfert galaxies. Yet even in NGC 4151, the most thoroughly observed of all, no such anomaly whatever has been found.

If we judge that both G_1 and G_2 are unlikely as gas supply sources for Seyfert galaxies, then G_3 — in which stars within the nucleus are destroyed by the tidal force of the black hole or by stellar collisions — remains as the important process. However, if we take the formation of the supermassive black hole to be H_3 of Hills's theory, the explanation of the first characteristic becomes difficult. For supernova explosions that leave behind black holes of $\sim 10M_\odot$ must naturally also occur within the nuclei of elliptical galaxies, and once such a hole is born it is expected to grow gradually into a black hole of large mass, provided only that suitable conditions are met, regardless of whether the galaxy is a cluster member or an isolated galaxy. At present, when the problem of the formation of elliptical and spiral galaxies has not been sufficiently elucidated, nothing conclusive can be said; but from the above considerations it does not seem entirely mistaken to conjecture that there was some hidden relation between the formation of the disk regions of spiral galaxies and N galaxies and the origin of black holes. Would it be too bold a conjecture to suppose that galaxies possessing disk systems easily produce massive black holes ($1-10 M_\odot \ll M_{\text{BH}} \ll 10^6 - 10^8 M_\odot$) at the time of their formation, that these probably grow to supermasses in a comparatively short period through tidal disruption, and that they have given rise to nuclear activity every time gas has been supplied?

As summarized in Table 11.1, active galaxies are extremely diverse, and there is no need for all of them to be explained by accretion onto a supermassive black hole and by tidal disruption. Taking as just one example the $\sim 10^{10}M_\odot$ of molecular hydrogen gas observed within the inner region of NGC 1068, the representative type 2 Seyfert galaxy, it is obvious that this gas cannot be attributed to tidal disruption occurring within a nucleus having a mass of only $10^8 - 10^9 M_\odot$. If so, then type 2 Seyfert galaxies do not require a supermassive black hole to cause tidal disruption, and they become a phenomenon essentially different from the nuclear

activity of type 1 Seyfert galaxies. Of course, it is also possible to regard the two as phenomena belonging to different evolutionary epochs of Seyfert galaxies.

The great variety of phenomena seen in active galaxies is thought to reflect (i) the presence or absence of a supermassive black hole and the manner of its formation, (ii) the origin of the gas involved in the activity, (iii) the morphology of the galaxy, (iv) the evolutionary epoch of the activity, and (v) the interaction with the environment in which the galaxy is placed; but the present situation is that not even a clue to elucidating them has been found. This, however, is not something for us to be pessimistic about. For the astronomy of active galaxies is a world full of a fascination that cannot fail to excite us, and their elucidation rests upon our own efforts. The “phantom” paper that Seyfert foretold is a problem left to us.

References

The references are collected by chapter; items already listed in an earlier chapter are omitted.

Chapter I

1. Ambartsumyan, V. A. 1958, 11th Solvay Conference (Brussels: *Inst. internat. phys. Solvay*), p. 241; 1960, *Q. J. R. A. S.*, **1**, 152; 1966, 13th Solvay Conference: The Structure and Evolution of Galaxies (Interscience Publishers), p. 1.
2. Baade, W. 1956, *Astrophys. J.*, **123**, 550.
3. Baade, W. & Minkowski, R. 1954, *Astrophys. J.*, **119**, 206.
4. Bolton, J. G., Stanley, G. J. & Slee, O. B. 1949, *Nature*, **164**, 101.
5. Burbidge, E. M. & Burbidge, G. R. 1965, *Astrophys. J.*, **142**, 1351.
6. Burbidge, E. M., Burbidge, G. R., & Prendergast, K. H. 1959, *Astrophys. J.*, **130**, 26; 1963, *Astrophys. J.*, **137**, 1022.
7. Burbidge, G. R. 1956, *Phys. Rev.*, **103**, 264.
8. Burbidge, G. R. 1961, *Nature*, **190**, 1053.
9. Burbidge, G. R., Burbidge, E. M. & Sandage, A. R. 1963, *Rev. Mod. Phys.*, **35**, 947.
10. Conway, R. G., Davis, R. J., Foley, A. R. & Ray, T. P. 1981, *Nature*, **294**, 540.

11. Dent, W. A. & Haddock, F. T. 1966, *Astrophys. J.*, **144**, 568.
12. Dibay, E. A. & Pronik, U. I. 1965, *Astrofizika*, **1**, 78.
13. Fitch, W. S., Pacholczyk, A. G. & Weymann, R. J. 1967, *Astrophys. J.*, **150**, L67.
14. Greenstein, J. L. & Matthews, T. A. 1963, *Nature*, **197**, 1041.
15. Greenstein, J. L. & Schmidt, M. 1964, *Astrophys. J.*, **140**, 1.
16. Hazard, C., Mackey, M. B. & Shimmins, A. J. 1963, *Nature*, **197**, 1037.
17. Hoyle, F. & Fowler, W. A. 1963, *M. N. R. A. S.*, **125**, 169.
18. Khachikian, E. Ye. & Weedman, D. M. 1971, *Astrofizika*, **7**, 389; 1974, *Astrophys. J.*, **192**, 581.
19. Light, E. S., Danielson, R. E. & Schwarzschild, M. 1974, *Astrophys. J.*, **194**, 257.
20. Lynds, C. R. & Sandage, A. R. 1963, *Astrophys. J.*, **137**, 1005.
21. Matthews, T. A. & Sandage, A. R. 1963, *Astrophys. J.*, **138**, 30.
22. Minkowski, R. 1957, I. A. U. Symposium No. 4; Radio Astronomy (Cambridge University Press), ed. H. C. van de Hulst, p. 107.
23. Moffet, A. T. 1975, Galaxies and the Universe (The University of Chicago Press), ed. A. Sandage, M. Sandage, and J. Kristian, p. 212.
24. Morton, D. C. & Thuan, T. X. 1973, *Astrophys. J.*, **180**, 705.
25. Osterbrock, D. E. & Parker, R. A. R. 1965, *Astrophys. J.*, **141**, 892.
26. Pacholczyk, A. G. & Weymann, R. J. 1968, *Astron. J.*, **73**, 836: Proceedings of the Conference on Seyfert Galaxies and Related Objects, Held at

- Steward Observatory, University of Arizona 14–16 February 1968.
27. Pacholczyk, A. G. & Wisniewski, W. Z. 1967, *Astrophys. J.*, **147**, 394.
 28. Sandage, A. R. 1965, *Astrophys. J.*, **141**, 1560.
 29. Schmidt, M. 1963, *Nature*, **197**, 1040.
 30. Seyfert, C. K. 1943, *Astrophys. J.*, **97**, 28.
 31. Shklovsky, I. 1953, *Astron. Zh.*, **30**, 15.
 32. Shklovsky, I. 1960, *Soviet Astron.*, **4**, 885.
 33. Shklovsky, I. 1966, *Soviet Astron.*, **9**, 683.
 34. Smith, F. G. 1951, *Nature*, **168**, 555.
 35. Smith, H. J. & Hoffleit, D. 1963, *Nature*, **198**, 650.
 36. Walker, M. F. 1974, *Publ. A. S. P.*, **80**, 861.
 37. Weedman, D. W. 1973, *Astrophys. J.*, **183**, 29.
 38. Woltjer, L. 1959, *Astrophys. J.*, **130**, 38.

Chapter II

1. Arp, H. 1966, *Astrophys. J. Suppl.*, **14**, 1; Atlas of Peculiar Galaxies (California Institute of Technology).
2. Huchra, J. & Sargent, W. L. W. 1973, *Astrophys. J.*, **186**, 433.
3. Markarian, B. E.;
 - I. Markarian, B. E. 1967, *Astrofizika*, **3**, 55.
 - II. Markarian, B. E. 1969, *Astrofizika*, **5**, 443.
 - III. Markarian, B. E. 1969, *Astrofizika*, **5**, 581.

- IV. Markarian, B. E. & Lipovetsky, V. A. 1971, *Astrofizika*, **7**, 511.
 - V. Markarian, B. E. & Lipovetsky, V. A. 1972, *Astrofizika*, **8**, 155.
 - VI. Markarian, B. E. & Lipovetsky, V. A. 1973, *Astrofizika*, **9**, 487.
 - VII. Markarian, B. E. & Lipovetsky, V. A. 1974, *Astrofizika*, **10**, 307.
 - VIII. Markarian, B. E. & Lipovetsky, V. A. 1976, *Astrofizika*, **12**, 389.
 - IX. Markarian, B. E. & Lipovetsky, V. A. 1976, *Astrofizika*, **12**, 657.
 - X. Markarian, B. E., Lipovetsky, V. A. & Stepanian, J. A. 1977, *Astrofizika*, **13**, 227.
 - XI. Markarian, B. E., Lipovetsky, V. A. & Stepanian, J. A. 1977, *Astrofizika*, **13**, 397.
 - XII. Markarian, B. E., Lipovetsky, V. A. & Stepanian, J. A. 1979, *Astrofizika*, **15**, 201.
 - XIII. Markarian, B. E., Lipovetsky, V. A. & Stepanian, J. A. 1979, *Astrofizika*, **15**, 363.
 - XIV. Markarian, B. E., Lipovetsky, V. A. & Stepanian, J. A. 1979, *Astrofizika*, **15**, 549.
4. Matthews, T. A., Morgan, W. W. & Schmidt, M. 1964, *Astrophys. J.*, **140**, 35.
 5. Morgan, W. W. 1958, *Publ. A. S. P.*, **70**, 364.
 6. Morgan, W. W. & Lesh, J. R. 1965, *Astrophys. J.*, **142**, 1364.
 7. Osterbrock, D. E. 1978, *Physica Scripta*, **17**, 137.
 8. Sargent, W. L. W. 1970, *Astrophys. J.*, **160**, 405.
 9. Shuder, J. M. 1980, *Astrophys. J.*, **240**, 32.
 10. Shuder, J. M. & Osterbrock, D. E. 1981, *Astrophys. J.*, **250**, 55.
 11. Simkin, S. M., Su, H. J. & Schwartz, M. P. 1980, *Astrophys. J.*, **237**, 404.

12. Smith, M. G. 1975, *Astrophys. J.*, **202**, 591; 1976, *Astrophys. J. (Letters)* **206**, L125.
13. Smith, M. G., Aquirre, C. & Zemelman, M. 1976, *Astrophys. J. Suppl.*, **32**, 217.
14. Terebizh, V. Yu. 1980, *Astrofizika*, **16**, 45.
15. Ulrich, M.-H. 1971, *Astrophys. J. (Letters)* **165**, L61.
16. Vorontsov-Velyaminov, B. A. 1960, Atlas and Catalogue of Interacting Galaxies (Sternberg Institute, Moscow State University, Moscow).
17. Weedman, D. W. 1970, *Astrophys. J.*, **159**, 405.
18. Weedman, D. W. 1977, *Ann. Rev. Astron. Astrophys.*, **15**, 69; 1979, *M. N. R. A. S.*, **184**, 11P.
19. Zwicky, F. 1971, Catalogue of Selected Compact Galaxies and of Post-Eruptive Galaxies (Offsetdruck L. Speich Zuerich, Switzerland).

Chapter III

1. Abell, G. O. 1958, *Astrophys. J. Suppl.*, **3**, 211.
2. Anderson, K. S. 1973, *Astrophys. J.*, **182**, 369.
3. Anderson, K. S. 1974, *Astrophys. J.*, **187**, 445.
4. Arp, H. 1971a, *Astrophys. Letters*, **9**, 1.
5. Arp, H. 1971b, *Astrophys. Letters*, **7**, 221.
6. Arp, H. 1975, *Publ. A. S. P.*, **87**, 545.
7. Arp, H. 1977, *Astrophys. J.*, **218**, 70.
8. Arp, H. & Bertola, F. 1971, *Astrophys. J.*, **163**, 195.
9. Bahcall, N. A. 1974, *Astrophys. J.*, **187**, 439.

10. Baldwin, J. A., Carswell, R. F., Wampler, E. J., Smith, H. E., Burbidge, E. M., & Boksenberg, A. 1980, *Astrophys J.*, **236**, 388.
11. Barbieri, C., di Serego Alighieri, S. & Zambon, M. 1977, *Astron. Astrophys.*, **57**, 353.
12. Bautz, L. P. & Morgan, W. W. 1970, *Astrophys. J. (Letters)*, **162**, L149.
13. Becklin, E. E., Matthews, K., Neugebauer, G. & Williams, C. G. 1973, *Astrophys. J. (Letters)*, **186**, L69.
14. Birkinshaw, M. 1980, *M. N. R. A. S.*, **190**, 793.
15. Bosma, A., Ekers, R. D. & Lequeux, J. 1977, *Astron. Astrophys.*, **57**, 97.
16. Branduardi-Raymont, G., Fabricant, D., Feigelson, E., Gorenstein, P., Grindlay, J., Soltan, A. & Zamorani, G. 1981, *Astrophys. J.*, **248**, 55.
17. Burbidge, E. M., Smith, H. E. & Burbidge, G. R. 1978, *Astrophys. J.*, **219**, 400.
18. Chincarini, G. & Rood, H. J. 1971, *Astrophys. J.*, **168**, 321.
19. Clark, M., Bolton, J. & Shimmins, A. 1966, *Aust. J. Phys.*, **19**, 375.
20. Condon, J. J. 1980, *Astrophys. J.*, **242**, 894.
21. Cowie, L. L., Fabian, A. C. & Nulsen, P. E. J. 1980, *M. N. R. A. S.*, **191**, 399.
22. Crane, P. C. 1979, *Astron. J.*, **84**, 281.
23. Davies, R. D. 1973, *M. N. R. A. S.*, **161**, 25P.
24. de Bruyn, A. G. & Willis, A. G. 1974, *Astron. Astrophys.*, **33**, 351.

25. de Vaucouleurs, 1952, *Handbuch der Physik* **53** (Springer-Verlag), ed. S. Flügge, p. 275; 1962, IAU Symposium No. 15: Problems of Extragalactic Research (The MacMillan Company), ed. G. C. McVittie, p. 3.
26. de Young, D., Roberts, M. & Saslaw, W. 1973, *Astrophys. J.*, **185**, 809.
27. Einasto, J., Jõeveer, M. & Saar, E. 1980, *Nature*, **283**, 47.
28. Ekers, R. D., van de Hulst, J. M. & Miley, G. K. 1976, *Nature*, **262**, 369.
29. Elvius, A. 1978, *Astron. Astrophys.*, **65**, 233.
30. Fabian, A. C., Hu, E. M., Cowie, L. L. & Grindlay, J. 1981, *Astrophys. J.*, **248**, 47.
31. Fabian, A. C. & Nulsen, P. E. J. 1977, *M. N. R. A. S.*, **180**, 479.
32. Fricke, K. J. & Reinhardt, M. 1974, *Astron. Astrophys.*, **37**, 349.
33. Gisler, G. R. & Miley, G. K. 1979, *Astron. Astrophys.*, **76**, 109.
34. Heckman, T. M. & Balick, B. 1979, *Astron. Astrophys.*, **76**, L7.
35. Heckman, T., Balick, B. & Sullivan III, W. T. 1978, *Astrophys. J.*, **224**, 745.
36. Hildebrand, R. H., Whitcomb, S. E., Winston, R., Stiening, R. F., Harper, D. A. & Moseley, S. H. 1977, *Astrophys. J.*, **216**, 698.
37. Hodge, P. W. 1968, *Astron. J.*, **73**, 846.
38. Hoyle, F. & Burbidge, G. R. 1966, *Astrophys. J.*, **144**, 534.
39. Jõeveer, M., Einasto, J. & Tago, E. 1978, *M. N. R. A. S.*, **185**, 357.
40. Jones, T. W., Leung, C. M., Gould, R. J. & Stein, W. A. 1977, *Astrophys. J.*, **212**, 52.

41. Kaneko, N. 1980, *Publ. A. S. J.*, **32**, 185.
42. Kellermann, K. I. 1978, *Physica Scripta*, **17**, 257.
43. Kellermann, K. I., Clark, B. G., Jauncey, D. L., Cohen, M. H., Shaffer, D. B., Moffet, A. T. & Gulkis, S. 1970, *Astrophys. J.*, **161**, 803.
44. Kent, S. M. & Sargent, W. L. W. 1979, *Astrophys. J.*, **230**, 667.
45. Knapp, G. R., Kerr, F. J. & Williams, B. A. 1978, *Astrophys. J.*, **222**, 800.
46. Kormendy, J. & Bahcall, J. N. 1974, *Astron. J.*, **79**, 671.
47. Lynds, R. 1970, *Astrophys. J. (Letters)*, **159**, L151.
48. Martin, W. L. 1974, *M. N. R. A. S.*, **168**, 109.
49. Mathews, W. G. & Bregman, J. N. 1978, *Astrophys. J.*, **224**, 308.
50. Mitchell, R. J., Culhane, J. C., Davison, P. J. N. & Ives, J. C. 1976, *M. N. R. A. S.*, **175**, 29P.
51. Oemler, A. 1976, *Astrophys. J.*, **209**, 693.
52. Pauliny-Toth, I. I. K., Preuss, E., Witzel, A., Kellermann, K. I., Shaffer, D. B., Purcell, G. H., Grove, G. W., Jones, D. L., Cohen, M. H., Moffet, A. T., Romney, J., Schilizzi, R. T. & Rinehart, R. 1976, *Nature*, **259**, 17.
53. Penston, M. V. 1968, I. A. U. Inform. Bull. of Var. Stars No. 255.
54. Penston, M. V. & Penston, M. J. 1973, *M. N. R. A. S.*, **162**, 109.
55. Preuss, E., Kellermann, K. I., Pauliny-Toth, I. I. K., Witzel, A. & Shaffer, D. B. 1979, *Astron. Astrophys.*, **79**, 268.
56. Preuss, E., Kellermann, K. I., Pauliny-Toth, I. I. K. & Shaffer, D. B. 1980, *Astrophys. J. (Letters)*, **240**, L7.

57. Readhead, A. C. S., Pearson, T. J., Cohen, M. H., Ewing, M. S. & Moffet, A. T. 1979, *Astrophys. J.*, **231**, 299.
58. Richstone, D. O. & Morton, D. C. 1975, *Astrophys. J.*, **201**, 289.
59. Rickard, L. J., Palmer, P., Morris, M., Turner, B. E. & Zuckerman, B. 1977, *Astrophys. J.*, **213**, 673.
60. Rood, H. J. & Sastry, G. N. 1971, *Publ. A. S. P.*, **83**, 313.
61. Rubin, V. C. & Ford, W. K. 1968, *Astrophys. J.*, **154**, 431.
62. Rubin, V. C., Ford, W. K., Peterson, C. J. & Oort, J. H. 1977, *Astrophys. J.*, **211**, 693.
63. Ryle, M. & Windram, M. D. 1968, *M. N. R. A. S.*, **138**, 1.
64. Sandage, A. 1973, *Astrophys. J.*, **180**, 687.
65. Sargent, W. L. W. 1967, *Publ. A. S. P.*, **79**, 369.
66. Schild, R. E. 1972, *Astrophys. J.*, **178**, 617.
67. Schwarzschild, M. 1973, *Astrophys. J.*, **182**, 357.
68. Seielstad, G. A., Cohen, M. H., Linfield, R. P., Moffet, A. T., Romney, J. D., Schilizzi, R. T. & Shaffer, D. B. 1979, *Astrophys. J.*, **229**, 53.
69. Simkin, S. M. 1975, *Astrophys. J.*, **200**, 567.
70. Smith, M. G., Weedman, D. W. & Spinrad, H. 1972, *Astrophys. Letters*, **11**, 21.
71. Strom, S. E. & Strom, K. M. 1978, *Astron. J.*, **83**, 73.
72. Terrell, J. 1964, *Science*, **145**, 918.

73. Toomre, A. & Toomre, J. 1972, *Astrophys. J.*, **178**, 623.
74. Ulmer, M. P., Cruddace, R. G., Wood, K., Meekins, J., Yentis, D., Evans, W. D., Smathers, H. W., Byram, E. T., Chubb, T. A. & Friedman, H. 1980, *Astrophys. J.*, **236**, 58.
75. Ulrich, M.-H. 1973, *Astrophys. J.*, **181**, 51.
76. Ulrich, M.-H. & Pequignot, D. 1980, *Astrophys. J.*, **238**, 45.
77. van den Bergh, S. 1969, *Astrophys. Letters*, **4**, 117.
78. van der Kruit, P. C. 1971, *Astron. Astrophys.*, **15**, 110.
79. Walker, M. F. 1968, *Astrophys. J.*, **151**, 71.
80. Walker, M. F., Pike, C. D. & McGee, J. D. 1974, *Publ. A. S. P.*, **86**, 870.
81. Willis, A. G. 1979, *Astron. Astrophys.*, **73**, 354.
82. Wilson, A. S. & Willis, A. G. 1980, *Astrophys. J.*, **240**, 429.
83. Wyckoff, S., Wehinger, P. A., Spinrad, H. & Boksenberg, A. 1980, *Astrophys. J.*, **240**, 25.

Chapter IV

1. Andernach, H., Baker, J. R., von Kapherr, A. & Wielebinski, R. 1979, *Astron. Astrophys.*, **74**, 93.
2. Appleton, P. N., Davies, R. D. & Stephenson, R. J. 1981, *M. N. R. A. S.*, **195**, 327.
3. Arp, H. 1965, *Science*, **148**, 363; *Sky and Tel.*, **30**, 141.
4. Arp, H. 1967, *Astrophys. Letters*, **1**, 1.

5. Arp, H. 1968, *Publ. A. S. P.*, **80**, 129.
6. Arp, H. & Bertola, F. 1969, *Astrophys. Letters*, **4**, 23.
7. Arp, H. & Lorre, J. 1976, *Astrophys. J.*, **210**, 58.
8. Baade, W. 1956, *Astrophys. J.*, **123**, 550.
9. Bingham, R. G., McMullan, D., Pallister, W. S., White, C., Axon, D. J. & Scarrott, S. M. 1976, *Nature*, **259**, 463.
10. Blanco, V. M., Graham, J. A., Lasker, B. M. & Osmer, P. S. 1975, *Astrophys. J. (Letters)* **198**, L63; *Sky and Tel.*, **50**, 85.
11. Burbidge, E. M. & Burbidge, G. R. 1959, *Astrophys. J.*, **129**, 271.
12. Burbidge, E. M., Burbidge, G. R. & Rubin, V. C. 1964, *Astrophys. J.*, **140**, 942.
13. Burbidge, G. R., Crowne, A. H. & Smith, H. E. 1977, *Astrophys. J. Suppl.*, **33**, 113.
14. Byram, E. T., Chubb, R. A. & Friedman, H. 1966, *Science*, **152**, 66.
15. Cooper, B. F. C., Price, R. M. & Cole, D. J. 1965, *Aust. J. Phys.*, **18**, 589.
16. Curtis, H. D. 1918, *Publ. Lick. Obs.*, **13**, 11.
17. Davies, J. D., Anderson, B. & Morison, I. 1980, *Nature*, **288**, 65.
18. Deharveng, J. M. & Pellet, A. 1970, *Astron. Astrophys.*, **9**, 181.
19. de Vaucouleurs, G. & Nieto, J. N. 1978, *Astrophys. J.*, **220**, 449.
20. de Vaucouleurs, G. & Nieto, J. N. 1979, *Astrophys. J.*, **231**, 364.
21. Dressler, A. 1980, *Astrophys. J. (Letters)*, **240**, L11.

22. Dufour, R. J., van den Bergh, S., Harvel, C. A., Martins, D. H., Schiffer III, F. H., Talbot Jr., R. J., Talent, D. L. & Wells, D. C. 1979, *Astron. J.*, **84**, 284.
23. Dufour, R. J. & van den Bergh, S. 1978, *Astrophys. J. (Letters)*, **226**, L73; *Sky and Tel.*, **56**, 389.
24. Duncan, M. J. & Wheeler, J. C. 1980, *Astrophys. J. (Letters)*, **237**, L27.
25. Ekers, R. D. 1974, I. A. U. Symposium No. 58: The Formation and Dynamics of Galaxies (D. Reidel Publishing Co.), ed. J. B. Shakeshaft, p. 257.
26. Elvius, A. 1972, *Astron. Astrophys.*, **19**, 193.
27. Evans, D. S. 1949, *M. N. R. A. S.*, **109**, 94.
28. Fabricant, D., Lecar, M. & Gorenstein, P. 1980, *Astrophys. J.*, **241**, 552.
29. Ford, H. C. & Butcher, H. 1979, *Astrophys. J. Suppl.*, **41**, 147.
30. Geldzahler, B., Kellermann, K. I., Shaffer, D. B. & Clark, B. G. 1977, *Astrophys. J. (Letters)*, **215**, L5.
31. Graham, J. A. 1979, *Astrophys. J.*, **233**, 60.
32. Hargrave, P. J. 1974, *M. N. R. A. S.*, **168**, 491.
33. Harris, W. E. & Smith, M. G. 1976, *Astrophys. J.*, **207**, 1036.
34. Heckathorn, H. M. 1972, *Astrophys. J.*, **173**, 501.
35. Hewitt, A. & Burbidge, G. 1980, *Astrophys. J. Suppl.*, **43**, 57.
36. Hiltner, W. A. 1959, *Astrophys. J.*, **130**, 340.
37. Kaneko, N., Nishimura, M. & Toyama, K. 1973, *Publ. A. S. J.*, **25**, 175.

38. Kellermann, K. I., Shaffer, D. B., Purcell, G. H., Pauliny-Toth, I. I. K., Preuss, E., Witzel, A., Graham, D., Schilizzi, R. T., Cohen, M. H., Moffet, A. T. & Romney, J. D. 1977, *Astrophys. J.*, **211**, 658.
39. Kinman, T. D., Grasdalen, G. L. & Rieke, G. H. 1974, *Astrophys. J.* (Letters), **194**, L1.
40. Kronberg, P. P. & Wilkinson, P. N. 1975, *Astrophys. J.*, **200**, 430.
41. Kunkel, W. E. & Bradt, H. V. 1971, *Astrophys. J.* (Letters), **170**, L7.
42. Larson, R. B. 1972, *Nature*, **236**, 21.
43. Lawrence, A. 1978, *M. N. R. A. S.*, **185**, 423.
44. Lynds, C. R. & Sandage, A. R. 1963, *Astrophys. J.*, **137**, 1005.
45. O'Connell, R. W. & Mangano, J. J. 1978, *Astrophys. J.*, **221**, 62.
46. Owen, F. N., Hardee, P. E. & Bignell, R. C. 1980, *Astrophys. J.* (Letters), **239**, L11.
47. Perola, G. C. & Tarenghi, M. 1980, *Astrophys. J.*, **240**, 447.
48. Rieke, G. H., Lebofsky, M. J., Thompson, R. I., Low, F. J. & Tokunaga, A. T. 1980, *Astrophys. J.*, **238**, 24.
49. Sandage, A. 1961, *The Hubble Atlas of Galaxies* (Carnegie Institution of Washington).
50. Sandage, A. & Miller, W. C. 1966, *Astrophys. J.*, **144**, 1238.
51. Sandage, A. R. & Visvanathan, N. 1969, *Astrophys. J.*, **157**, 1065.
52. Sargent, W. L. W., Young, P. J., Boksenberg, A., Shortridge, K., Lynds, C. R. & Hartwick, F. D. A. 1978, *Astrophys. J.*, **221**, 731.

53. Schmidt, G. D., Peterson, B. M. & Beaver, E. A. 1978, *Astrophys. J. (Letters)*, **220**, L31.
54. Schreier, E. J., Feigelson, E., Delvaille, J., Giacconi, R., Grindlay, J. & Schwartz, D. A. 1979, *Astrophys. J. (Letters)*, **234**, L39.
55. Schweizer, F. 1980, *Astrophys. J.*, **237**, 303.
56. Solinger, A. B. 1969, *Astrophys. J.*, **155**, 403.
57. Solinger, A., Morrison, P., & Markert, T. 1977, *Astrophys. J.*, **211**, 707.
58. Stockton, A. 1978, *Astrophys. J.*, **223**, 747.
59. Sulentic, J. W., Arp, H. & Lorre, J. 1979, *Astrophys. J.*, **233**, 44.
60. Toomre, A. 1977, *The Evolution of Galaxies and Stellar Populations* (New Haven: Yale University Observatory), ed. B. M. Tinsley and R. B. Larson, p. 418.
61. Turland, B. D. 1975, *M. N. R. A. S.*, **170**, 281.
62. van den Bergh, S. 1971, *Astron. Astrophys.*, **12**, 474.
63. van den Bergh, S. 1976, *Astrophys. J.*, **208**, 673.
64. Visvanathan, N. & Sandage, A. 1972, *Astrophys. J.*, **176**, 57.
65. Walker, M. F. 1968, *Astrophys. Letters*, **2**, 65.
66. Wyckoff, S., Wehinger, P. A., Gehren, T., Morton, D. C., Boksenberg, A. & Albrecht, R. 1980, *Astrophys. J. (Letters)*, **242**, L59.
67. Young, P. J., Westphal, J. A., Kristian, J., Wilson, C. P. & Landauer, F. P. 1978, *Astrophys. J.*, **221**, 721.

Chapter V

1. Adams, T. F. 1977, *Astrophys. J., Suppl.*, **33**, 19.
2. Arp, H. 1970, *Astrophys. J.*, **162**, 811.
3. de Vaucouleurs, G. 1975, *Galaxies and the Universe* (The University of Chicago Press), ed. A. Sandage, M. Sandage and J. Kristian, p. 557.
4. de Vaucouleurs, G., de Vaucouleurs, A. & Corwin, H. G. 1976, *Second Reference Catalogue of Bright Galaxies* (University of Texas).
5. Heckman, T. 1978, *Publ. A. S. P.*, **90**, 241.
6. Longair, M. S. & Seldner, M. 1979, *M. N. R. A. S.*, **189**, 433.
7. Morgan, W. W. 1972, I. A. U. Symposium No. 44: External Galaxies and Quasi-Stellar Objects (D. Reidel Publishing Company, Inc.), ed. D. S. Evans, p. 97.
8. Schmidt, K.-H. 1977, I. A. U. Symposium No. 79: The Large Scale Structure of the Universe (D. Reidel Publishing Company, Inc.), ed. M. S. Longair and J. Einasto, p. 101.
9. Sersic, J. L. 1973, *Publ. A. S. P.*, **85**, 103.
10. Simkin, S. M., Su, H. J. & Schwarz, M. P. 1980, *Astrophys. J.*, **237**, 404.
11. Theys, J. C. & Spiegel, E. A. 1976, *Astrophys. J.*, **208**, 650.
12. van den Bergh, S. 1975, *Astrophys. J. (Letters)*, **198**, L1.
13. Wyckoff, S., Wehinger, P. A., Spinrad, H. & Boksenberg, A. 1980, *Astrophys. J.*, **240**, 25.

Chapter VI

1. Adams, T. F. & Weedman, D. W. 1975, *Astrophys. J.*, **199**, 19.
2. Anderson, K. S. 1970, *Astrophys. J.*, **162**, 743.
3. Anderson, K. S. 1971, *Astrophys. J.*, **169**, 449.
4. Anderson, K. S. 1974, *Astrophys. J.*, **189**, 195.
5. Anderson, K. S. & Kraft, R. P. 1969, *Astrophys. J.*, **158**, 859.
6. Andrillat, Y. & Souffrin, S. 1968, *Astrophys. Letters*, **1**, 111.
7. Baldwin, J. A. 1977, *M. N. R. A. S.*, **178**, 67P.
8. Blumenthal, G. R. & Mathews, W. G. 1975, *Astrophys. J.*, **198**, 517.
9. Boksenberg, A. & Netzer, H. 1977, *Astrophys. J.*, **212**, 37.
10. Boksenberg, A., Shortridge, K., Allen, D. A., Fosbury, R. A. E., Penston, M. V. & Savage, A. 1975, *M. N. R. A. S.*, **173**, 381.
11. Burbidge, G. R., Burbidge, E. M., Hoyle, F. & Lynds, C. R. 1966, *Nature*, **210**, 774.
12. Capriotti, E., Foltz, C. & Byard, P. 1979, *Astrophys. J.*, **230**, 681.
13. Capriotti, E., Foltz, C. & Byard, P. 1980, *Astrophys. J.*, **241**, 930.
14. Cherepashchuk, A. M. & Lyutyi, V. M. 1973, *Astrophys. Letters*, **13**, 165.
15. Code, A. D., Davis, J., Bless, B. C. & Brown, R. H. 1976, *Astrophys. J.*, **203**, 417.
16. Cromwell, R. & Weymann, R. E. 1970, *Astrophys. J. (Letters)*, **159**, L147.

17. de Bruyn, A. G. 1980, Highlights of Astronomy (D. Reidel Publishing Company Inc.), ed. P. A. Wayman, vol. 5, p. 631.
18. Dibay, E. A. & Pronik, V. I. 1967, *Soviet Astron.*, **11**, 553.
19. Disney, M. J. 1973, *Astrophys. J.* (Letters), **181**, L55.
20. Field, G. B. 1958, Abstracts of papers presented at Gainesville meeting of A. A. S.
21. Kaneko, N. & Ohtani, H. 1968, *Astron. J.*, **73**, 899.
22. Koski, A. T. 1978, *Astrophys. J.*, **223**, 56.
23. Miller, J. S. 1968, *Astrophys. J.* (Letters), **154**, L57.
24. Neugebauer, G., Morton, D., Oke, J. B., Becklin, E. E., Daltabuit, E., Matthews, K., Persson, S. E., Smith, A. M., Soifer, B. T., Torres-Peimbert, S. & Wynn-Williams, C. G. 1980, *Astrophys. J.*, **238**, 502.
25. Oke, J. B. & Sargent, W. L. W. 1968, *Astrophys. J.*, **151**, 807.
26. Oke, J. B. & Zimmerman, B. 1979, *Astrophys. J.* (Letters), **231**, L13.
27. Osterbrock, D. E. 1970, Nuclei of Galaxies (American Elsevier), ed. D. J. K. O'Connell, p. 151.
28. Osterbrock, D. E. 1974, Astrophysics of Gaseous Nebulae (W. H. Freeman).
29. Osterbrock, D. E. 1976, *Astrophys. J.*, **203**, 329.
30. Osterbrock, D. E. 1977, *Astrophys. J.*, **215**, 733.
31. Osterbrock, D. E. 1978, *Physica Scripta*, **17**, 285.
32. Osterbrock, D. E. 1979, *Astron. J.*, **84**, 901.

33. Osterbrock, D. E. & Koski, A. T. 1976, *M. N. R. A. S.*, **176**, 61P.
34. Osterbrock, D. E., Koski, A. T. & Phillips, M. M. 1976, *Astrophys. J.*, **206**, 898.
35. Osterbrock, D. E. & Miller, J. S. 1975, *Astrophys. J.*, **197**, 535.
36. Pelat, D. & Alloin, D. 1980, *Astron. Astrophys.*, **81**, 172.
37. Penston, M. V., Clavel, J., Snijders, M. A. J., Boksenberg, A. & Fosbury, R. A. E. 1979, *M. N. R. A. S.*, **189**, 45P.
38. Péquignot, D. 1980, *Astron. Astrophys.*, **81**, 356.
39. Phillips, M. M. & Osterbrock, D. E. 1979, *Publ. A. S. P.*, **87**, 949.
40. Ptak, R. & Stoner, R. E. 1973, *Astrophys. J.*, **185**, 121; 1975, *Astrophys. J.*, **200**, 558.
41. Schmidt, G. D. & Miller, J. S. 1980, *Astrophys. J.*, **240**, 759.
42. Shields, G. A. & Oke, J. B. 1975, *Astrophys. J.*, **197**, 5.
43. Stoner, R. E. & Ptak, R. 1974, *Astrophys. J.*, **191**, 291; 1977, *Astrophys. J.*, **214**, 653.
44. Su, H. J. & Simkin, S. M. 1980, *Astrophys. J. (Letters)*, **238**, L1.
45. Tohline, J. E. & Osterbrock, D. E. 1976, *Astrophys. J. (Letters)*, **210**, L117.
46. Wampler, E. J. 1968, *Astrophys. J. (Letters)*, **154**, L53; 1971, *Astrophys. J.*, **164**, 1.
47. Weymann, R. J. 1970, *Astrophys. J.*, **160**, 31.
48. Weymann, R. J. & Cromwell, R. 1972, I. A. U. Symposium No. 44: External Galaxies and Quasi Stellar Objects (D. Reidel Publishing

- Company, Inc.), ed. D. S. Evans. p. 155.
49. Wilson, A. S. & Penston, M. V. 1979, *Astrophys. J.*, **232**, 389.
50. Wu, C. C., Boggess, A. & Gull, T. R. 1980a, *Astrophys. J.*, **242**, 14.
51. Wu, C. C., Boggess, A. & Gull, T. R. 1980b, *Astrophys. J.*, **247**, 449.

Chapter VII

1. Adams, T. F. 1974, *Astrophys. J.*, **188**, 463.
2. Angel, J. R. P., Stockman, H. S., Woolf, N. J., Beaver, E. A. & Martin, P. G. 1976, *Astrophys. J. (Letters)*, **206**, L5.
3. Barnes, T. G. 1968, *Astrophys. Letters*, **1**, 171.
4. Belokon, E. T., Babazhanyants, M. K. & Lyutyi, V. M. 1978, *Astron. Astrophys. Suppl.*, **31**, 383.
5. Boksenberg, A., Snijders, M. A., Wilson, R., Benvenuti, P., Clavell, J., Macchetto, F., Penston, M., Boggess, A., Gull, T. R., Gondhalekar, P., Lane, A. L., Turnrose, B., Wu, C. C., Burton, W. M., Smith, A., Bertola, F., Capaccioli, M., Elvius, A. M., Fosbury, R., Tarengi, M., Ulrich, M.-H., Hackney, R. L., Jordan, C., Perola, C. G., Roeder, R. C. & Schmidt, M. 1978, *Nature*, **275**, 404.
6. de Bruyn, A. G. & Sargent, W. L. W. 1978, *Astron. J.*, **83**, 1257.
7. Dibay, E. A. & Shakhovskoy, N. M. 1966, *Astron. Tsirk.* No. 375.
8. Epstein, E. E., Fogarty, W. G., Hackney, K. R., Hackney, R. L., Leacock, R. J., Pomphrey, R. B., Scott, R. L., Smith, A. G., Hawkins, R. W., Roeder, R. C., Gary, B. L., Penston, M. V., Tritton, K. P., Bertaud, C., Véron, M. P.,

- Wlérick, G., Bernard, A., Bigay, J. H., Merlin, P., Durand, A., Sausse, G., Becklin, E. E., Neugebauer, G. & Wynn-Williams, C. G. 1972, *Astrophys. J. (Letters)*, **178**, L51.
9. Geller, M. J., Turner, E. L. & Bruno, M. S. 1979, *Astrophys. J. (Letters)*, **230**, L141.
10. Green, R. F., Pier, J. R., Schmidt, M., Estabrook, F. B., Lane, A. L. & Wahlguist, H. D. 1980, *Astrophys. J.*, **239**, 483.
11. Guskell, C. M. 1980, *Observatory*, **100**, 148.
12. Jurkevich, I., Usher, P. D. & Shen, B. S. P. 1971, *Astrophys. Space Sci.*, **10**, 402.
13. Kaneko, N. 1980, *Publ. A. S. J.*, **32**, 185.
14. Kellermann, K. 1964, *Astrophys. J.*, **140**, 969.
15. Kinman, T. D. 1967, *Astrophys. J.*, **148**, L53.
16. Kraus, J. D. 1966, *Radio Astronomy* (McGraw-Hill Book Company).
17. Kruszewski, A. 1977, *Acta Astron.*, **27**, 319.
18. Lyutyi, V. M. 1973, *Soviet Astron.*, **16**, 763.
19. Lyutyi, V. M. 1977, *Soviet Astron.*, **21**, 655.
20. Martin, P. G., Angel, J. R. P. & Maza, J. 1976, *Astrophys. J. (Letters)*, **209**, L21.
21. Neugebauer, G., Becklin, E., Oke, J. B. & Searle, L. 1976, *Astrophys. J.*, **205**, 29.

22. Neugebauer, G., Morton, D., Oke, J. B., Becklin, E. E., Daltabuit, E., Matthews, K., Persson, S. E., Smith, A. M., Soifer, B. T., Torres-Peimbert, S. & Wynn-Williams, C. G. 1980, *Astrophys. J.*, **238**, 502.
23. Oke, J. B. 1965, *Astrophys. J.*, **141**, 6.
24. Oke, J. B. 1972, External Galaxies and Quasi Stellar Objects (D. Reidel Publishing Company Inc.), ed. D. S. Evans, p. 139.
25. Oke, J. B. & Goodrich, R. W. 1981, *Astrophys. J.*, **243**, 445.
26. Pacholczyk, A. G. 1971, *Astrophys. J.*, **163**, 449.
27. Penston, M. V., Penston, M. J., Neugebauer, G., Tritton, K. P., Becklin, E. E. & Visvanathan, N. 1971, *M. N. R. A. S.*, **153**, 29.
28. Penston, M. V., Penston, M. J., R. A., Selmes, Becklin, E. E. & Neugebauer, G. 1974, *M. N. R. A. S.*, **169**, 357.
29. Peterson, B. A. 1969, *Astrophys. Letters*, **3**, 103.
30. Richstone, D. O. & Schmidt, M. 1980, *Astrophys. J.*, **235**, 377.
31. Rieke, G. H. & Lebofsky, M. J. 1981, *Astrophys. J.*, **250**, 87.
32. Sandage, A. 1973, *Astrophys. J.*, **180**, 687.
33. Selove, D. M. 1969, *Astrophys. J. (Letters)*, **158**, L19.
34. Serkowski, K., Mathewson, D. S. & Ford, V. L. 1975, *Astrophys. J.*, **196**, 261.
35. Shields, G. A. 1978, *Nature*, **272**, 706.
36. Stein, W. A. & Weedman, D. W. 1976, *Astrophys. J.*, **205**, 44.
37. Stockman, H. S. & Angel, J. R. P. 1978, *Astrophys. J. (Letters)*, **220**, L67.

38. Takarada, K. 1968, *Prog. Theor. Phys.*, **40**, 770; 1970, *Prog. Theor. Phys.*, **43**, 303.
39. Takayanagi, K. 1968, *Astrophys. Letters*, **2**, 77.
40. Thompson, I., Landstreet, J. D., Stockman, H. S., Angel, J. R. P. & Beaver, E. A. 1980, *M. N. R. A. S.*, **192**, 53.
41. Visvanathan, N. & Oke, J. B. 1968, *Astrophys. J. (Letters)*, **152**, L165.
42. Walker, M. F. 1966, *Astron. J.*, **71**, 184.
43. Webbing, R. F. & Jeffers, W. Q. 1969, *Space Science Review*, **10**, 191.
44. Wilson, R., Carnochan, D. J. & Gondhalekar, P. M. 1979, *Nature*, **277**, 457.
45. Yee, H. K. C. & Oke, J. B. 1978, *Astrophys. J.*, **226**, 753.
46. Zaitseva, G. V. & Lyutyi, V. M. 1968, *Soviet Astron.*, **13**, 184.

Chapter VIII

1. Colgate, S. A. 1967, *Astrophys. J.*, **150**, 163.
2. Cultri, R. M. & Rudy, R. J. 1980, *Astrophys. J. (Letters)*, **241**, L141.
3. Epstein, E. E., Pomphrey, R. B. & Fogarty, W. G. 1979, *Publ. A. S. P.*, **91**, 163.
4. Hildebrand, R. H., Whitcomb, S. E., Winston, R., Stiening, R. F., Harper, D. A. & Moseley, S. H. 1977, *Astrophys. J.*, **216**, 698.
5. Hobbs, R. W. & Dent, W. A. 1977, *Astron. J.*, **82**, 257.
6. Jones, T. W., Leung, C. M., Gould, R. J. & Stein, W. A. 1977, *Astrophys. J.*, **212**, 52.

7. Kaneko, N., Toyama, K. & Nishimura, M. 1972, *Astrophys. Space Sci.*, **18**, 121.
8. Kemp, J. C., Rieke, G. H., Lebofsky, M. J. & Coyne, G. V. 1977, *Astrophys. J. (Letters)*, **215**, L107.
9. Kleinmann, D. E., Gillett, F. G. & Wright, E. 1976, *Astrophys. J.*, **208**, 42.
10. Lebofsky, M. J. & Rieke, G. H. 1979, *Astrophys. J.*, **229**, 111.
11. Lebofsky, M. J. & Rieke, G. H. 1980, *Nature*, **285**, 410.
12. Lebofsky, M. J., Rieke, G. H. & Kemp, J. C. 1978, *Astrophys. J.*, **222**, 95.
13. Low, F. J. 1970, *Astrophys. J. (Letters)*, **159**, L173.
14. Oke, J. B., Readhead, A. C. S. & Sargent, W. L. W. 1980, *Publ. A. S. P.*, **92**, 758.
15. Rees, M. J., Silk, J. I., Werner, M. W. & Wickramasinghe, N. C. 1969, *Nature*, **223**, 788.
16. Rieke, G. H. 1978, *Astrophys. J.*, **226**, 550.
17. Rieke, G. H. & Low, E. J. 1972, *Astrophys. J. (Letters)*, **177**, L115.
18. Rieke, G. H. & Low, E. J. 1975, *Astrophys. J. (Letters)*, **199**, L13.
19. Stein, W. A., Gillett, F. C. & Merrill, K. M. 1974, *Astrophys. J.*, **187**, 213.
20. Telesco, C. M. & Harper, D. A. 1980, *Astrophys. J.*, **235**, 392.
21. Thompson, R. I., Lebofsky, M. J. & Rieke, G. H. 1978, *Astrophys. J. (Letters)*, **222**, L49.

Chapter IX

1. Balkowski, C. 1973, *Astron. Astrophys.*, **29**, 43.
2. Bieging, J. H., Blitz, L., Lada, C. J. & Stark, A. A. 1981, *Astrophys. J.*, **247**, 443.
3. Crane, P. C. 1979, *Astron. J.*, **84**, 281.
4. de Bruyn, A. G. & Wilson, A. S. 1976, *Astron. Astrophys.*, **53**, 93.
5. de Bruyn, A. G. & Wilson, A. S. 1978, *Astron. Astrophys.*, **64**, 433.
6. Ekers, R. D. 1978, *Physica Scripta*, **17**, 171.
7. Heckman, T. M., Balick, B. & Sullivan III, W. T. 1978, *Astrophys. J.*, **224**, 745.
8. Morris, M. & Wannier, P. 1980, *Astrophys. J. (Letters)*, **238**, L7.
9. Rickard, L. J., Palmer, P., Morris, M., Turner, B. E. & Zuckerman, B. 1977, *Astrophys. J.*, **213**, 673.
10. Rowan-Robinson, M., Phillips, T. G. & White, G. 1980, *Astron. Astrophys.*, **82**, 381.
11. van der Kruit, P. C. 1971, *Astron. Astrophys.*, **15**, 110.
12. van der Kruit, P. C. 1973, *Astron. Astrophys.*, **29**, 263.
13. Wade, C. M. 1968, *Astron. J.*, **73**, 876.
14. Wilson, A. S. & Willis, A. G. 1980, *Astrophys. J.*, **240**, 429.
15. Wilson, A. S., Pooley, G. G., Willis, A. G. & Clements, E. D. 1980, *Astrophys. J. (Letters)*, **237**, L61.

Chapter X

1. Beall, J. H., Rose, W. K., Graf, W., Price, K. M., Dent, W. A., Hobbs, R. W., Conklin, E. K., Ulich, B. L., Dennis, B. R., Crannell, C. J., Dolan, J. F., Frost, K. J. & Orwig, L. E. 1978, *Astrophys. J.*, **219**, 836.

2. Beall, J. H., Rose, W. K., Dennis, B. R., Crannell, C. J., Dolan, J. F., Frost, K. J. & Orwig, L. E. 1981, *Astrophys. J.*, **247**, 458.
3. Bignami, G. F., Fichtel, C. E., Hartman, R. C. & Thompson, D. J. 1979, *Astrophys. J.*, **232**, 649.
4. Bisnovatyi-Kogan, G. S. & Blinnikov, S. I. 1977, *Astron. Astrophys.*, **59**, 111.
5. Blatt, H. V., Doxsey, R. E., Johnson, M. D., Schwartz, D. A., Burkhead, M. S., Dent, W. A., Liller, W. & Smith, A. G. 1979, *Astrophys. J. (Letters)*, **230**, L5.
6. Bowyer, C. S., Lampton, M., Mack, J. & de Mendonca, F. 1970, *Astrophys. J. (Letters)*, **161**, L1.
7. Byram, E. T., Chubb, T. A. & Friedman, H. 1966, *Science*, **152**, 66.
8. Charles, P. A., Longair, M. S. & Sanford, P. W. 1975, *M. N. R. A. S.*, **170**, 175.
9. Coe, M. J., Bassani, L., Engel, A. R. & Quenby, J. J. 1981, *M. N. R. A. S.*, **195**, 241.
10. Cooke, B. A., Ricketts, M. J., Maccacaro, T., Pye, J. P., Elvis, M., Watson, M. G., Griffiths, R. E., Pounds, K. A., McHardy, J., Maccagni, D., Seward, F. D., Page, C. G. & Turner, M. J. L. 1978, *M. N. R. A. S.*, **182**, 489.
11. di Cocco, G., Boella, G., Perotti, F., Sliglitz, R., Villa, G., Baker, R. E., Butler, R. C., Dean, A. J., Martin, S. J. & Ramsden, D. 1977, *Nature*, **270**, 319.
12. Elvius, M. 1976, *M. N. R. A. S.*, **177**, 7P.

13. Giacconi, R., Murray, S., Gursky, H., Kellogg, E., Schreier, E., Matilsky, T., Kock, D. & Tananbaum, H. 1974, *Astrophys. J. Suppl.*, **27**, 37.
14. Grindlay, J. E. 1975, *Astrophys. J.*, **199**, 49.
15. Hayes, M. J. C., Culhane, J. L. & Bell Burnell, S. J. 1980, *M. N. R. A. S.*, **192**, 1P.
16. Hayes, M. J. C., Culhane, J. L., Blissett, R. J., Barr, P. & Bell Burnell, S. J. 1980, *M. N. R. A. S.*, **193**, 15P.
17. Holt, S. S., Mushotzky, R. F., Becker, R. H., Boldt, E. A., Serlemitsos, P. J., Szymkowiak, A. E. & White, N. E. 1980, *Astrophys. J. (Letters)*, **241**, L13.
18. Ives, J. C., Sanford, P. W. & Penston, M. V. 1976, *Astrophys. J. (Letters)*, **207**, L159.
19. Kriss, G. A., Canizares, C. R. & Ricker, G. R. 1980, *Astrophys. J.*, **242**, 492.
20. Lawrence, A. 1980, *M. N. R. A. S.*, **192**, 83.
21. Liang, E. P. T. & Price, R. H. 1977, *Astrophys. J.*, **218**, 247.
22. Lightman, A. P. & Rybicki, G. B. 1979, *Astrophys. J.*, **232**, 882.
23. Lyutyi, V. M. 1978, *Pis'ma Astron. Zh.*, **4**, 496.
24. Maraschi, L., Perola, G. C., Reina, C. & Treves, A. 1979, *Astrophys. J.*, **230**, 243.
25. Marshall, N., Warwick, R. S. & Pounds, K. A. 1981, *M. N. R. A. S.*, **194**, 987.
26. Mészáros, P. & Silk, J. 1977, *Astron. Astrophys.*, **55**, 289.

27. Mushotzky, R. F., Holt, S. S. & Serlemitsos, P. J. 1978, *Astrophys. J. (Letters)*, **225**, L115.
28. Mushotzky, R. F., Serlemitsos, P. J., Becker, R. H., Boldt, E. A. & Holt, S. S. 1978, *Astrophys. J.*, **220**, 790.
29. Mushotzky, R. F., Marshall, F. E., Boldt, E. A., Holt, S. S. & Serlemitsos, P. J. 1980, *Astrophys. J.*, **235**, 377.
30. Paciesas, W. S., Mushotzky, R. F. & Pelling, R. M. 1977, *M. N. R. A. S.*, **178**, 23P.
31. Pozdnyakov, L. A., Sobol, J. M. & Sunyaev, R. A. 1979, *Soviet Astron. Letters*, **5**, 149.
32. Shapiro, S. L., Lightman, A. P. & Eardley, D. M. 1976, *Astrophys. J.*, **204**, 187.
33. Takahara, F. 1980, *Prog. Theor. Phys.*, **63**, 1551.
34. Tananbaum, H., Peters, G., Forman, W., Giacconi, R., Jones, C. & Avni, Y. 1978, *Astrophys. J. (Letters)*, **218**, 1.

Chapter XI

1. Aizu, K., Fujimoto, Y., Hasegawa, H., Kawabata, K. & Taketani, M. 1964, *Prog. Theor. Phys. Suppl.*, **31**, 35.
2. Alfvén, H. 1965, *Rev. Mod. Phys.*, **37**, 652.
3. Arons, J., Kuksrud, R. M. & Ostriker, J. P. 1975, *Astrophys. J.*, **198**, 683.
4. Bahcall, J. N. & Wolf, R. A. 1976, *Astrophys. J.*, **209**, 214.

5. Bardeen, J. M. & Wagoner, R. W. 1969, *Astrophys. J. (Letters)*, **158**, L65.
6. Blandford, R. D. 1976, *M. N. R. A. S.*, **176**, 465.
7. Blandford, R. D. & Znajek, R. L. 1977, *M. N. R. A. S.*, **179**, 433.
8. Cameron, A. G. W. 1962, *Nature*, **194**, 963.
9. Cavaliere, A., Pacini, F. & Setti, G. 1969, *Astrophys. Letters*, **4**, 103.
10. Chandrasekhar, S. 1964, *Phys. Rev. Letters*, **12**, 114, 437E.
11. Colgate. S. A. & Cameron, A. G. W. 1963, *Nature*, **200**, 870.
12. Eilek, J. A. 1980, *Astrophys. J.*, **236**, 664.
13. Fowler, W. A. 1964, *Rev. Mod. Phys.*, **36**, 545, 1104E.
14. Frank, J. 1978, *M. N. R. A. S.*, **184**, 87.
15. Frank, J. & Rees, M. J. 1976, *M. N. R. A. S.*, **176**, 633.
16. Ginzburg, V. L. & Ozernoi, L. M. 1964, *Zh. Exp. Theor. Fiz.*, **47**, 1030.
17. Ginzburg, V. L. & Ozernoi, L. M. 1977, *Astrophys. Space Sci.*, **50**, 23.
18. Gisler, G. R. 1976, *Astron. Astrophys.*, **51**, 137.
19. Gold, T., Axford, W. I. & Ray, E. C. 1965, *Quasi-Stellar Sources and Gravitational Collapse* (University of Chicago Press), ed. I. Robinson, A. Schild, and E. L. Schucking, p. 93.
20. Hills, J. G. 1975, *Nature*, **254**, 295.
21. Hills, J. G. 1978, *M. N. R. A. S.*, **182**, 517.
22. Hiscock, W. A. 1977, *Astrophys. J.*, **216**, 908.

23. Hoyle, F. & Narlikar, J. V. 1966, *Proc. Roy. Soc.*, **290**, 143, 162.
24. Jeans, J. 1928, *Astronomy and Cosmogony* (Dover Publications).
25. Kafatos, M. 1980, *Astrophys. J.*, **236**, 99.
26. Lea, S. M. & De Young, D. S. 1976, *Astrophys. J.*, **210**, 647.
27. Leiter, D. & Kafatos, M. 1978, *Astrophys. J.*, **226**, 32.
28. Lightman, A. P. & Shapiro, S. 1977, *Astrophys. J.*, **216**, 865.
29. Lovelace, R. V. E. 1976, *Nature*, **262**, 649.
30. Lynden-Bell, D. 1969, *Nature*, **223**, 690.
31. McCrea, W. H. 1964, *M. N. R. A. S.*, **128**, 336.
32. Morrison, P. 1969, *Astrophys. J.* (Letters), **157**, L73.
33. Ne'eman, Y. 1965, *Astrophys. J.*, **141**, 1303.
34. Nishimura, M. 1979, *Prog. Theor. Phys.*, **62**, 1584.
35. Novikov, I. D. 1965, *Soviet Astron.*, **8**, 857.
36. Ozernoy, L. M. 1966, *Soviet Astron.*, **10**, 241.
37. Ozernoy, L. M. & Reinhardt, M. 1978, *Astrophys. Space Sci.*, **59**, 171.
38. Ozernoy, L. M. & Usov, V. U. 1973, *Astrophys. Space Sci.*, **25**, 149.
39. Penrose, R. 1969, *Rev. Nuovo Cimento*, **1**, 252.
40. Perotti, F., Della Ventura, A., Villa, G., Di Cocco, G., Butler, R. C., Carter, J. N. & Dean, A. J. 1981, *Nature*, **292**, 133.
41. Piddington, J. H. 1970, *M. N. R. A. S.*, **148**, 131.

42. Piran, T. & Shaham, J. 1977, *Astrophys. J.*, **214**, 268.
43. Pringle, J. E. & Rees, M. J. 1972, *Astron. Astrophys.*, **21**, 1.
44. Salpeter, E. E. 1964, *Astrophys. J.*, **140**, 1796.
45. Salpeter, E. E. & Wagoner, R. V. 1971, *Astrophys. J.*, **167**, 359.
46. Schlickeiser, R. 1980, *Astrophys. J.*, **240**, 636.
47. Seidl, F. G. P. & Cameron, A. G. W. 1972, *Astrophys. Space Sci.*, **15**, 44.
48. Shakura, N. I. & Sunyaev, R. A. 1973, *Astron. Astrophys.*, **24**, 337.
49. Shields, G. A. & Wheeler, J. C. 1976, *Astrophys. Letters*, **17**, 69.
50. Shields, G. A. & Wheeler, J. C. 1978, *Astrophys. J.*, **222**, 667.
51. Shklovsky, I. S. 1961, *Soviet Astron.*, **4**, 885.
52. Spitzer, L. & Saslaw, W. C. 1966, *Astrophys. J.*, **143**, 400.
53. Sturrock, P. A. 1965, *Nature*, **208**, 861.
54. Sturrock, P. A. & Barnes, C. 1972, *Astrophys. J.*, **176**, 31.
55. Takahara, F. 1979, *Prog. Theor. Phys.*, **62**, 629.
56. Toyama, K. & Ikeuchi, S. 1980, *Prog. Theor. Phys.*, **64**, 831.
57. Tsuruta, S. 1977, *Astron. Astrophys.*, **61**, 647.
58. Ulam, S. M. & Walden, W. E. 1964, *Nature*, **201**, 1202.
59. van den Bergh, S. 1965, *Astron. J.*, **70**, 124.
60. Woltjer, L. 1964, *Nature*, **201**, 807.
61. Young, P. J. 1977, *Astrophys. J.*, **212**, 227.

62. Young, P. J., Shields, G. A. & Wheeler, J. C. 1978, *Astrophys. J.*, **212**, 367.
63. Zeldovich, Ya. B. 1964, *Soviet Physics-Doklady*, **9**, 195.

Appendix — Table A.1 Catalogs of Seyfert

Galaxies

Table A·1 Catalogs of Seyfert Galaxies (book p. 347)

Object	Alternative name(s)	$\alpha(1950)$ h m s	$\delta(1950)$ ° ' "	Sy type	cz (km/s)	θ (")	m
UM 16	Tol 0000-044	00 00.6	+04 29	2		7×6	17
Mkn 335		00 03 45	+19 55 28	1	7500	16	14
III Zw 2		00 07 57	+10 41 48	1	26900	12	
Mkn 938		00 08 34	−12 23 08	2	5800	27×20	14
Mkn 945	MCG 1-2-12	00 23 22	−03 41 50	2	4500	13	15
UM 246	Tol 0027-001	00 27 10	−00 06.0	2	5100	12×8	16
Zw 0033+45		00 33.7	+45 24	1	14500		15.3
Mkn 955	MCG 0-2-94	00 35 02	+00 00 21	2	10600	12	15
S 10721		00 35 49	+41 12 21	1	21700		16.9
IV Zw 29	Zw 0039+40	00 39.5	+40 03	1	30800	8	
Mkn 1146	MCG 02-3-1	00 44 42	+14 25 50	1	11800	20×12	15.2
Mkn 348	NGC 262	00 46 05	+31 41 04	2	4200	77	15.0
I Zw 1		00 50 58	+12 25 20	1	18300	22	14.0
Mkn 352		00 57 09	+31 33 27	1	4500	15×12	14.8
Tol 109-383		01 09	−38.3	2	3300	135	
Mkn 975	MCG 2-4-14	01 11 13	+13 00 27	1	14900	12×9	15.5
Mkn 1152		01 11 22	−15 06 39	2	15700	15×13	15
Mkn 1	NGC 449	01 13 20	+32 49 33	2	4800	16×27	15.5

Object	Alternative name(s)	$\alpha(1950)$ h m s	$\delta(1950)$ ° ' "	Sy type	cz (km/s)	θ (")	m
Fairall 294	ESO 195-G 35	01 13 45	−50 27 00	2	5100		
Mkn 984	MCG 2-4-21	01 16 45	+12 11 03	2	14400	15	15.5
II Zw 1		01 19 27	−01 18 05	1	16200	15	
Fairall 9	ESO 113-IG 45	01 21 51	−59 03 58	1	13800		13
Mkn 993	MCG 5-4-58	01 22 43	+31 52 35	2	5100	18×48	14.5
Mkn 358		01 23 45	+31 21 25	1	13800	12	16
Mkn 1157	NGC 591 / UGC 1111	01 30 39	+35 24 45	2	4500	40×20	14.0
Mkn 573	MCG 0-5-33	01 41 23	+02 05 56	2	5200	25×22	14
Mkn 577	MCG 2-5-46	01 46 50	+12 15 40		12600	9	14.2
Mkn 1014	Mich 385	01 57 16	+00 09 10	1	49000	6	16
Mkn 584		01 57 51	+02 25 40	1	23400	11	16
Mkn 1018	MCG 0-6-30 / Mich 393	02 03 43	−00 31 47	2	12700	23×17	14.6
4C 29.6		02 04 09	+29 16 40	1	32700		
Mkn 590	NGC 863	02 12 00	−00 59 58	1	8100	18	14.5
Akn 79	UGC 1757	02 14 20	+38 10 59	1	6000	60	
Fairall 296		02 23 49	−63 26 50	1	17200		
Mkn 1040	NGC 931 / UGC 1935	02 25 14	+31 05 23	1	5200	7	13.9
Mkn 1044	MCG 2-7-24	02 27 38	−09 13 11	1	4800	18×12	14.5
Mkn 1179		02 30 27	+27 43 04		11100	15×12	16
NGC 985	Mkn 1048 / VV 285	02 32 10	−09 00 22	1	12900	13 × 10	14.5
Mkn 595		02 38 56	+06 58 27	2	8400	15×11	16

Object	Alternative name(s)	$\alpha(1950)$ h m s	$\delta(1950)$ ° ' " "	Sy type	cz (km/s)	θ (")	m
NGC 1068	M 77 / Arp 37 / 3C 71	02 40 07	−00 13 31	2	1100	380	9.7
UKS 242- 724		02 42 54	−72 29 30	1	30500		
Mkn 1187		02 45 37	+13 43 39	1	13400	8	15.5
Mkn 372	IC 1854	02 46 31	+19 05 49	2	9300	20×14	15.5
Mkn 1058		02 46 47	+34 46 54	2	5300	25×13	15.5
Mkn 1066	MCG 6-7- 27	02 56 49	+36 37 18	2	3700	30×17	13.8

(45 rows on this page)

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Object	Alternative name(s)	$\alpha(1950)$ h m s	$\delta(1950)$ ° ' " "	Sy type	cz (km/s)	θ (")	m
Mkn 1073	MCG 7-7-37	03 11 43	+41 51 03	2	7100	33×13	14.0
NGC 1275	3C 84	03 16 29	+41 19 52	2p	5300	68	13.0
Mkn 609		03 22 57	−06 19 09	1	10000	13	14.5
Mkn 612		03 28 10	−03 18 35	2	6000	10	15.5
NGC 1365		03 31 42	−36 18 27	1	1500		10.2
III Zw 55	NGC 1410	03 38 38	−01 27 44	2	7400	13	14.7
3C 109		04 10 55	+11 04 32	1	91700		
NGC 1566		04 18.9	−55 04	1	1200	420	10.4
ESO 202-G 23	Carafe	04 26 34	−48 01 23	2	4900	80	
Fairall 303		04 29 33	−53 43 00	1	11500		15
3C 120	PKS 0430+05 / II Zw 0430+05	04 30 32	+05 15 00	1	9900	42	14.2
Mkn 618	MCG-2-12-15	04 34 00	−10 28 36	1	10200	10	14.5
Akn 120	Mkn 1095	05 13 38	−00 12 15	1	9800	18×15	14.5
NGC 2110		05 51.0	−07 18	1	2300		14
MCG 8-11-11	UGC 3374	05 51 10	+46 25 51	1	6100		14
Mkn 3		06 09 48	+71 03 11	2	4100	25×35	15
Mkn 6	IC 450	06 45 44	+74 29 10	1	5300	20	14.8
Mkn 374		06 55 35	+54 15 57	1	13200	7×7	15.5 +16.5
VII Zw 118		07 02.3	+64 42	1	23700		14.5
Mkn 376		07 10 36	+45 47 02	1	16800	12×10	16
Mkn 378		07 13 19	+49 46 57	2		7	17
Mkn 9		07 32 42	+58 52 56	1	12000	25	15.2
Mkn 78		07 37 56	+65 17 42	2	11300	10×15	15

Object	Alternative name(s)	$\alpha(1950)$ h m s	$\delta(1950)$ ° ' "	Sy type	cz (km/s)	θ (")	m
Mkn 79		07 38 47	+49 55 41	1	6600	20×40	13.5
Mkn 10		07 43 07	+61 03 25	1	8800	20	14.0
Mkn 382		07 52 03	+39 19 07	1	10200	12×7	15.5
Mkn 622		08 04 21	+39 09 01	2	7000	14×12	15
Mkn 1218	NGC 2622	08 35 13	+25 04 17	1	9300	20×15	14.8
VII Zw 244		08 38.6	+77 05	1	39100		16.0
Mkn 391	NGC 2691	08 51 32	+39 43 40	1	3900	24×18	14.5
Mkn 704		09 15 39	+16 30 59	1	8800	20×12	15
Mkn 106		09 16 18	+55 34 21	1	37200	5	16
Mkn 110		09 21 44	+52 30 08	1	10800	7×10	16
Mkn 705	Akn 202 / UGC 5025	09 23 20	+12 57 04	1	8400	11	13.9
Zw 0934+01	Mkn 707	09 34 26	+01 19 14	1	15200	10×8	15.4
Mkn 403		09 37 56	+21 27 26	2	7100	14×12	16.5
NGC 2992	Arp 245	09 43.3	−14 05.8	1	1900		12.6
3C 227		09 45 06	+07 39 17	1	25600	8	17.3
Mkn 124		09 45 24	+50 43 29		17000	7	16
Mkn 1239		09 49 46	−01 22 35	1	5800	14	14.5
NGC 3081		09 57.9	−22 40	2	2400		12.5
Mkn 1243	NGC 3080 / UGC 5372	09 57 14	+13 17 02	1	10900	12×18	15
3C 234		09 58 58	+29 01 30	1	55400		
Mkn 715		10 02.0	+15 01	2	25200	7	16
Mkn 716		10 07.4	+23 20		17400	7	16.5
Mkn 720	MCG 1-26-32	10 15.0	+07 13		13500	15×12	15.5
Mkn 141		10 15 39	+64 13 06	1	11700	11×14	15.2
NGC 3227	VV 209	10 20 47	+20 07 06	1	1000	330	12.2

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Table A·1 Catalogs of Seyfert Galaxies (book p. 349)

Object	Alternative name(s)	$\alpha(1950)$ h m s	$\delta(1950)$ ° ' " "	Sy type	cz (km/s)	θ (")	m
NGC 3227 (continued from previous page)	Arp 94						
Mkn 142		10 22 23	+51 55 50	1	13500	7×9	16.5
Ton 524 a		10 28 46	+29 02 27	1	18000	10	
Mkn 34		10 30 51	+60 17 22	2	15300	12×25	16
Mkn 634		10 55 21	+20 45 03	1	19700	13×10	16
ESO 215- G 14		10 57 07	−51 10.4	2	5300	90	
Mkn 728		10 58.4	+11 19	2	10200	13×11	16
Tol 1059+105		10 59 21	+10 33 47	1	10200		
NGC 3516		11 03 23	+72 50 20	1	2800	80	12.3
Mkn 734		11 19 11	+12 00 45	1	14900	11	15
VV 144	Mkn 40 / Arp 151 / I Zw 25	11 22 48	+54 39 27	1	2800	10	16
Mkn 423	MCG 6-25- 72	11 24 08	+35 31 17	2	9600	20	15.5
Mkn 1298		11 26 44	−04 07 34	1	17900	14×9	15
VV 150	Mkn 176 / I Zw 27 / Arp 322	11 29 55	+53 13 35	2	8100	8×60	16
Mkn 739	NGC 3758	11 33 53	+21 52 22	2	9000	10	14.8
NGC 3783		11 36.5	−37 28	1	2700	72	
Mkn 744	NGC 3786	11 37 04	+32 11.2	1	2900	7	15.5
Mkn 42		11 51 06	+46 29 24	1	7200	12	15.2
Mkn 1310		11 58.7	−03 23		5700	13×11	16.5
NGC 4051		12 00 36	+44 48 35	1	700	280	11.5
Akn 347	NGC 4074	12 01 56	+20 35 40	2	6600		15.4

Object	Alternative name(s)	$\alpha(1950)$ h m s	$\delta(1950)$ ° ' " "	Sy type	cz (km/s)	θ (")	m
Mkn 198	MCG 8-22-73	12 06 43	+47 20 07	2	7200	12	15.0
NGC 4151		12 08 01	+39 41 02	1	1000	450	11.2
NGC 4235		12 14 37	+07 28 09	1	2300		
Mkn 766	NGC 4253	12 15 56	+30 05 26	1	3800	25×13	13.7
Mkn 1320		12 16.7	−01 33	1	30800	7	15
Mkn 205		12 19 32	+75 35 10	1/QSO	21000	6	14.5
Mkn 50		12 20 51	+02 57 22	1	6900	12	15.5
1222+04		12 22 48	+04 37 52		22900		17
Ton 1542	Mkn 771 / Akn 374	12 29 33	+20 26 02	1	19200	10×7	15.1
NGC 4507		12 32.9	−39 38	1	3300	68	
NGC 4593		12 37.0	−05 04	1	2600		11.7
Mkn 231		12 54 05	+57 08 38	1	12300	12	14.1
X Comae		12 57 58	+28 40.2	1	27600	10	
Mkn 236		12 58 18	+61 55 26	1	15600	7×11	17
Mkn 783		13 00 30	+16 40 33	2	20400	7	16
NGC 4939		13 01.7	−10 05	?	3100		12.2
Mkn 64	B 340	13 04 48	+34 40 22	1	55200	7	17
NGC 5033		13 11 08	+36 51.8	1	1000		10.6
Mkn 1347		13 20.4	+08 25	2	15200	15×10	15.5
Mkn 789		13 29 54	+11 22	2	9300	13×11	14.5
3C 287.1		13 30 21	+02 16 11	1	64700	8	
MCG-6-30-15		13 33 02	−34 02 44	1	2400		
Mkn 266	NGC 5256	13 36 15	+48 31 53	2	8400	20×25	14 +15
Mkn 268		13 38 54	+30 37 49	2	12300	12	15.3
Mkn 270	NGC 5283	13 39 41	+67 55 27	2	2700	15	14.5

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Table A·1 Catalogs of Seyfert Galaxies (book p. 350)

Object	Alternative name(s)	$\alpha(1950)$ h m s	$\delta(1950)$ ° ' " "	Sy type	cz (km/s)	θ (")	m
Mkn 273		13 42 51	+56 08 20	2	10200	12×20	14.5
Mkn 69		13 43 51	+29 53 09	1	22900	8	16.5
IC 4329 A		13 46.2	−30 03	1	4100	70	
Tol 1351- 375		13 51.3	−37 32	1	15500		
Mkn 662		13 51 46	+23 40 29	2	16600	9	15.5
Mkn 279		13 51 53	+69 33 13	1	9200	15	14.5
Mkn 463	MCG 3-36- 5	13 53 40	+18 36 58	2	15100	25×15	14.8
Mkn 464		13 53 45	+38 49 07	1	15300	6	16.5
Mkn 668	OQ 208	14 04 46	+28 41 35	1	23700	11	16
I Zw 81		14 06.4	+49 05	2	15600		
NGC 5506		14 10 39	−02 58 26	1	1700		13.5
Mkn 673	NGC 4397	14 15 06	+27 05 15	2	10900	26×20	15
NGC 5548		14 15 43	+25 22 01	1	5000		13.5
Mkn 1383		14 26.5	+01 31	1	26500	10	15
Mkn 474	NGC 5683	14 33 06	+48 52 47	1	12300	12 × 10	16.5
Mkn 817		14 34 58	+59 00 39	1	9400	12 × 10	14
Mkn 686	NGC 5695	14 35 21	+36 47 13	2	4200	45×30	13.9
I Zw 92	Mkn 477	14 39 03	+53 43 04	2	11200	20×12	15.2
NGC 5728		14 39 37	−17 02.4	2	2900		12.4
Mkn 478		14 40 04	+35 39 07	1	23700	50×15	16
Mkn 841		15 01 36	+10 37 56	1	10900	11	14
Mkn 845	MCG 9-25- 22	15 06 12	+51 38 41	1	13900	20×9	15.6
Mkn 849		15 17 51	+28 45 26	1	24700	6	17
Mkn 854		15 24 37	+43 34 15	1	46800	6	17.5
Mkn 1098	MCG 5-37- 2	15 27 38	+30 39 23	2	10600	13	15.1
4C 35.37		15 31 44	+35 54 18	1	47000	8	

Object	Alternative name(s)	$\alpha(1950)$ h m s	$\delta(1950)$ ° ' "	Sy type	cz (km/s)	θ (")	m
Mkn 290		15 34 44	+58 04 01	1	9200	10	15
Mkn 486		15 35 21	+54 43 22	1	11700	8	15.2
Mkn 291		15 52 54	+19 20 16	1	10500	10×13	15
Mkn 493	MCG 6-35-17	15 57 17	+35 10 13	1	9400	10	14.9
Mkn 298	IC 1182	16 03 22	+17 56 11	2	10300	16×20	15
Mkn 871	IC 1198	16 06 15	+12 27 44	1	10000	20×15	14.9
Mkn 876		16 13 36	+65 50 37	1	38700	9	15.5
ESO 1615+061		16 15 18	+06 11 12	1	11400		16
Mkn 877		16 17 57	+17 31 35	1	33900	7	15.5
III Zw 77	Mkn 699	16 22 05	+41 11 48	1	10100	8	15.4
Mkn 883	MCG 4-39-8	16 27 47	+24 33 06	2	11600	10	15.2
Mkn 885	MCG 11-20-16	16 29 43	+67 29 06	1	7900	13	15.4
NGC 6251		16 38	+83 39	2			14
Mkn 504		16 59 10	+29 28 43	1	10800	18×12	17
Mkn 700	MCG 5-40-34	17 01 22	+31 31 39	1	10300	8	15.4
UGC 10683 B		17 02 24	−01 28 23	1	9200		17.6
Mkn 506		17 20 45	+30 55 39	1	12900	24×18	15.3
Mkn 507		17 48 55	+68 42 50	2		10×8	16
KK H 21		18 06 20	+67 38	1	40800		
Akn 539		18 27 34	+50 20 19	2	5100		
3C 382		18 33 12	+32 39 18	1	17600	15	
ESO 103-G 35		18 33 22	−65 28.3	1	4000		15
ESO 140-G 43	Fairall 51	18 40 15	−62 24 58	1	4100		15

Object	Alternative name(s)	$\alpha(1950)$ h m s	$\delta(1950)$ ° ' " "	Sy type	cz (km/s)	θ (")	m
Fairall 334	IC 4777 / ESO 183-G 13	18 44 11	−53 12 30	2	5500		
3C 390.3		18 45 38	+79 43 06	1	17100	12	16
NGC 6764		19 07 01	+50 51 08	2	2400	120×60	13.2

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Table A·1 Catalogs of Seyfert Galaxies (book p. 351)

Object	Alternative name(s)	$\alpha(1950)$ h m s	$\delta(1950)$ ° ' " "	Sy type	cz (km/s)	θ (")	m
ESO 141-G 55		19 16 57	−58 45 52	1	11000		14
IC 4870		19 32 48	−65 55.5	2	760		
NGC 6814		19 39 56	−10 26 33	1	1600	136	12
ESO 185-IG 13		19 41 03	−54 22.3	2	5500		
Fairall 339		20 07 59	−57 14 00	1	16300		
NGC 6890		20 14 17	−71 01.0	2	2400		13
Fairall 348	ESO 234-IG 56	20 33 24	−50 15 50	2	2300		
Mkn 509		20 41 26	−10 54 18	1	10600	10	13
Mkn 896	MCG-1-53-38	20 43 44	−02 59 47	1	8000	22×15	16
IC 5063		20 48.2	−57 16	2	3400		13
II Zw 136		21 30 01	+09 55 01	1	18500	30	14.3
NGC 7212		22 05.8	+10 07	2	7800		15
NGC 7213		22 06 12	−47 25.0	1	1700		12
II Zw 175	Mkn 304	22 14 46	+13 59 20	1	19900	9	15.5
3C 445		22 21 14	−02 20 58	1	17100		
Fairall 357		22 23 39	−70 39 00	2	8500		
Mkn 915	MCG-2-57-23	22 34 07	−12 48 15	1	7800	27×14	15
Mkn 917	MCG 5-53-9	22 38 48	+31 54 30	2	7500	20×13	14.5
Akn 564		22 40 18	+29 27 47	1	7500		14.4
Mkn 309		22 50 10	+24 27 54	2	12900	8	15.3
Mkn 1126	NGC 7450	22 58 10	−13 11 14	2	3100	33×20	14.5
Mkn 1127	NGC 7466 / UGC 12319	22 59 38	+26 46 59	2	7400	24×17	14.4
NGC 7469	VV 254 / Arp 298	23 00 44	+08 36 16	1	5000	89	13

Object	Alternative name(s)	$\alpha(1950)$ h m s	$\delta(1950)$ ° ' "	Sy type	cz (km/s)	θ (")	m
Mkn 315	II Zw 187	23 01 36	+22 21 16	1	11800	15	14.8
MCG-2-58-22	Mkn 926	23 02 07	−08 57 19	1	14400	10	14.5
3C 459		23 14 03	+03 48 52	1	66000		
NGC 7582		23 15 38	−42 38 42	2	1500		11.8
NGC 7603	Mkn 530 / Arp 92	23 16 23	−00 01 47	1	8800	55	14.4
Mkn 533	NGC 7674	23 25 24	+08 30 17	2	8800	10	13.6
Tol 2327-027		23 27 58	−02 44.3	1			
Mkn 1133		23 41 30	+27 26 16	2	7300	20×13	15.5
PKS 2349-01		23 49 22	−01 25 54	1	52200	12	
Mkn 541		23 53 28	+07 14 42	1	12300	10	15.5
Mkn 543	NGC 7811	23 59 52	+03 04 30	1	7800	18	15.5

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Colophon

Nebulae and Star Clusters Series (星雲星団シリーズ)

Seyfert Galaxies (セイファート銀河) <Inspection seal omitted>

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