THE NATURE AND STRUCTURE OF ACTIVE GALACTIC NUCLEI

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Received 1992 July 7; accepted 1992 August 25

ABSTRACT

Current knowledge of the structure of AGNs and the physical principles that govern them are reviewed, along with clues as to their formation and evolution. Evidence from optical observational data is stressed, but the importance of radio, millimeter, infrared, ultraviolet, and X-ray results is also emphasized. Overall, AGNs form one family, but there are many differences in detail among them. Spectral classification of AGNs is reviewed. Diagnostic diagrams involving optical and near-infrared emission-line ratios to separate AGNs from H II regions or starburst galaxies are briefly discussed.

Observed jets indicate that many, if not all, AGNs have an axis, and that cylindrical rather than spherical symmetry governs them. The central source is very probably an accretion disk around a massive black hole, and photoionization by high-energy photons is an important energy-input mechanism to the observed gas. The photoionizing spectrum is a hard one, generally more complicated than a simple power law. There is considerable evidence, especially from spectropolarimetry, that many Seyfert 2 galaxies contain a broad-line region, hidden within an obscuring torus, and would be observed as Seyfert 1 galaxies from a different orientation. At high luminosities there are essentially no Seyfert 2 galaxies, indicating that the obscuring torus is very thin or cannot exist under these conditions, or that the nuclear radiation is highly anisotropic.

The velocity field in AGNs includes rotation and "turbulence" (disordered motion) in the broad-line region. There may also be inflow and outflow (or both, in different parts of the BLR), but if so its net amount is small. In both the BLR and the NLR axial symmetry is a better approximation than spherical symmetry, but the structure no doubt is warped in many objects, with the axis shifting from the direction of the jet in the inner BLR to the direction of the normal to the galaxy in the outer NLR. High-resolution long-slit spectral observation suggests the flow in the NLR tends to be outward along the axis, perhaps with a conical distribution, but rotational in the equatorial region, perhaps with an inward component.

Star formation occurs near many but not all AGNs. Dust is certainly present in many if not all AGNs, and heated by radiation it is an important source of infrared emission. Black holes appear to exist in several nearby inactive galactic nuclei. Statistical studies and recent imaging studies have suggested that many if not all AGNs form or are reactivated in galaxy-galaxy interactions, including both mergers and close passages. Theoretical calculations are beginning to show how some of the gas in a galaxy can lose sufficient angular momentum to fall nearly to a nucleus as a consequence of such interactions, and thus become available as fuel. In general the evolution is expected to occur in bursts of activity, each decreasing to zero as the available fuel is exhausted and then restarting after the next interaction at a higher luminosity, made possible by the now higher black hole mass.

Subject headings: galaxies: active — galaxies: jets — galaxies: kinematics and dynamics — galaxies: nuclei — galaxies: Seyfert

1. INTRODUCTION

Active galactic nuclei are the most luminous objects we know in the universe, and thus the most distant markers we can observe. They are the most powerful energy sources we have identified. For all these reasons we must understand them physically.

Active galactic nuclei emit energy in all wavelength or energy regions. This lecture is concerned mostly with results from optical spectroscopy, the special field which I know best, but I have striven to bring in results from other spectral regions as best I can. All of them are quite important for our understanding of AGNs.

Active galactic nuclei, from Seyfert galaxy nuclei to quasi-stellar objects (QSOs), and from radio galaxies to quasi-stellar radio sources (quasars), appear to form one family. This is very well illustrated in a diagram by Morgan & Dreiser (1983), which includes a progression from the Seyfert galaxy NGC 4151, through II ZW 1 and I ZW 1 (which have appeared in both Seyfert galaxy and QSO catalogs, and which these authors classify as N galaxies) to the quasar 3C 48. Out to redshift $z \approx 0.5$, many objects originally called quasi-stellar on the basis of their appearance on Palomar Observatory Sky Survey plates or even larger-scale direct photographs have turned out, on the basis of more recent, better, processed images, obtained with digital detectors on large telescopes at excellent-seeing sites, to show extended features which can be understood as galaxies, often involved in interactions, (e.g., Hutchings & Neff 1991a; Block & Stockton 1991 and references therein). These observations strongly suggest that most if not all QSOs are AGNs. That QSOs and Seyfert galaxy nuclei, quasars, and radio galaxy nuclei all belong to one family does not mean that they are all identical, scaled versions of one
single object, any more than that all stars, such as O main-sequence stars, M2 Ia supergiants, and M8 V dwarfs are all scaled versions of the Sun. Rather it implies that they are similar in physical nature, as well as we understand AGNs at present.

Of course such arguments cannot eliminate the possibility that some QSOs (on the basis of their appearance and spectra) are in fact very different physically, but to most workers in the field the best current working hypothesis is that they all form one family. The contrary view, that many QSOs are not at cosmological distances, has been expressed by Arp (1987), Burbidge et al. (1990), and in other references listed in them.

Seyfert galaxy nuclei are the most abundant AGNs "here and now" in the universe; according to, for instance, Table 11.1 of Osterbrock (1989) they comprise approximately 1% of the nuclei of luminous spiral galaxies. Luminous radio galaxies, which are mostly N, cD, D, and E galaxies rather than spirals, are still less abundant by another factor $10^{-2}$. QSOs and quasars, the most luminous analogues of Seyfert galaxies and radio galaxies, respectively, are both down by factors $10^{-3}$ with respect to these two classes of active galaxies. These numbers are based on the definition (Schmidt & Green 1983) that the dividing line between Seyfert galaxies and QSOs is at absolute magnitude $M_B = -23$. Note that there may be many more AGNs at lower luminosity levels; they would be very difficult to detect if they exist. This is one of the most interesting current problems in AGN research, to which we will return in § 5. Most of the remainder of this paper will be devoted chiefly to Seyfert galaxy nuclei, the most abundant and hence nearest and most thoroughly studied type of AGN.

There are three questions we should like to be able to answer about any class of astronomical objects, such as AGNs:

1. What is it? Describe it.
2. How does it work? What are the physical principles which make it the way it is?
3. How did it form? How does it evolve? How long will it live? How will it die?

Clearly the last question is very difficult to answer until the answers to the first two are well understood. Nevertheless it is the most interesting and challenging question, and like other authors, I will not hesitate to discuss it in this paper.

For stars the answers to the three questions are understood in rough outline, although many interesting details, particularly the evolution of various types, remain to be worked out. For AGNs our understanding is much less complete. Some astronomers are very disappointed by this, and a few have even suggested that we ought to give up! Personally, I wish that we understood AGNs better than we do, but we must remember that Seyfert galaxies were only isolated as a class as recently as 1943, and that quasars were not recognized as such until 1963. Stars have been known since antiquity and have been studied spectroscopically with multiplexing, integrating detectors since the 1880s. We might compare our present understanding of AGNs with the understanding of stars in the mid-1930s. It then seemed clear to most advanced thinking astronomers that nuclear energy powers stars, and many empirical and quasi-theoretical ideas about how it worked were current, but all the quantitative data on nuclear cross sections and opacities were still a decade or more in the future, along with quantitative understanding of stellar structure and evolution.

This paper is a review of our current level of understanding of AGNs, emphasizing the observational results, the diagnostic information, and the interpretations relatively close to them. To review AGNs is a daunting task; currently about 20 or 30 new papers are published every month on this subject in the Astrophysical Journal, the Astronomical Journal, Monthly Notices of the Royal Astronomical Society, and Astronomy and Astrophysics alone. It is impossible to be up to date, and I apologize to all the research workers I have overlooked, or simply failed to mention because I was more familiar with other papers, naturally mostly by my collaborators and students. I can only say I tried to bring in as much as I could.

2. SPECTROSCOPY AND DIAGNOSTICS

The primary spectral classification types of Seyfert galaxies are Seyfert 1, with strong broad permitted emission lines and narrow forbidden emission lines, and Seyfert 2, with strong narrow permitted and forbidden emission lines. The intermediate types, defined somewhat later, are Seyfert 1.5, with strong broad and narrow components of their permitted emission lines, Seyfert 1.8, with strong narrow and weak broad components of permitted Hα and Hβ, and Seyfert 1.9, with still a weaker broad component of Hα, and the broad component of Hβ too faint to be easily visible. They have been thoroughly described, for example, by Osterbrock (1989, 1991), and appear to form a continuous sequence.

The interpretation must be that the broad lines are emitted in a region with relatively high electron density, comparable to the chromosphere, in which all the forbidden lines which would otherwise be emitted are so weakened by collisional de-excitation as to be unobservable. In this broad-line region (BLR) the gas must have a large range of internal velocity, presumably resulting from rotation plus "turbulence" (in its astronomical sense of a somewhat "random" velocity field of unknown origin). The narrow lines must be emitted in a region of lower electron density, comparable to gaseous nebulae, in which the ordinary forbidden lines are not appreciably collisionally de-excited. In this narrow-line region, the range in internal velocity must be much smaller. Wolter (1959) recognized that the forbidden lines must be greatly weakened in the BLR, and the picture sketched above was proposed by Oke & Sargent (1968), Wolter (1968), and Souffrin (1969). A highly schematic model, not to scale, is shown in Figure 1 (Osterbrock 1978). Note that the BLR is drawn with cylindrical symmetry, rather than spherical, for observational reasons that will be discussed below. Studies of the narrow line profiles as functions of ionization potential and critical density for collisional de-excitation suggest that in the NLR the velocity range decreases outward, the mean density decreases outward, and the mean ionization decreases outward or remains constant (De Robertis & Osterbrock 1984, 1986; Whittle 1985b; Appenzeller & Östreich 1988; Wilson & Nath 1990). In the BLR the velocity range also appears to decrease outward, and the mean level of ionization remains constant (Shuder 1982, 1984).

Undoubtedly the gas is clumped into condensations, as in all resolved nebulae, so that the density distribution is not in the least smooth or nearly homogeneous.

Well-known nebular spectroscopic diagnostic techniques give order-of-magnitude mean values $T \approx 10^4$ K, $N_e \approx 10^4$ cm$^{-3}$ for the temperature and electron density in NLRs. The observed luminosities in H I narrow lines (such as Hβ) then give order-of-magnitude estimates of their mean size and mass, $r \approx 10^4$ pc, $M \approx 10^8$ $M_\odot$. In a few of the nearest Seyfert 2 galaxies, the NLRs have been resolved and are of this order of size. For the BLRs the spectroscopic diagnostics are not very
Fig. 1.—Model, not to scale, showing dense (BLG) and low-density (NLG) gas components, with cylindrical symmetry about central photoionizing source. Ionized regions are indicated by shading; highly ionized regions by crosshatching.

sharp for the temperature, but again probably \( T \approx 10^4 \) K. The representative mean electron density in the BLR, \( N_e \approx 10^{6.5} \) cm\(^{-3}\), is better determined, chiefly by the observed presence of C iii \( \lambda 1909 \). More observational comparisons of the strength of this emission line with C iii \( \lambda 4267 \), which should be possible with the Hubble Space Telescope for redshifts as small as \( z \approx 0.25 \), will be especially useful in defining both \( T \) and \( N_e \) in the BLR (Kinney et al. 1991). The size and mass of the ionized gas in the BLR, with the parameters stated, are typically \( r \approx 3 \times 10^{-2} \) pc, \( M \approx 10 \, M_\odot \), both very small on the scale of the galaxy.

The low temperature, together with the observed ionization, clearly indicates that the energy input to the NLR gas at least is mostly by photoionization. The great range of ionization, from observed [O i], [N i], and [S ii] lines to [Ne v] and [Fe vii], shows that the photoionizing spectrum extends to high energies. Models based on power-law input spectra of the general form \( F \propto \nu^{-s} \), with \( s \approx 1 \) provide a fair first approximation. Direct X-ray measurements of many AGNs show that a “broken” power law, with index decreasing to \( n \approx 0.7 \) around 2 keV, is often a better approximation, and such photoionization models do fit somewhat better (Krupper, Urry, & Canizares 1990; see also § 8). Quite sophisticated models, including assumed density distributions decreasing outward, can give even better fits to the observed NLR emission spectra (Binette & Raga 1990). Direct abundance determinations and fitting the models to the observed emission-line spectra both agree that the abundances of the elements are roughly solar, except that there are many indications that N may be overabundant by as much as a factor of 3 (Veilleux & Osterbrock 1987; Storchi-Bergmann 1991). However, there is still enough freedom in the models or assumed structure so that this result is not certain. Abundance determinations in H ii regions in several Seyfert galaxies, outside their nuclei, show no evidence for an enhancement of N in them (Evans & Dopita 1987). One of the objects included in that study is the nearby Seyfert 2 galaxy NGC 1068, in which the H ii regions observed range in distance from the nucleus from 1.5 to 4.5 kpc.

For the BLR it is not as certain that the energy input is by photoionization, but it seems most likely that it is, as discussed in more detail, for example, by Osterbrock (1989, 1991). The highest-ionization, “coronal” lines observed in the optical and near-IR spectral regions in a reasonable fraction of Seyfert galaxies, [Fe x] \( \lambda 6375 \) and [Fe xii] \( \lambda 7892 \), tend to have widths somewhat greater than most of the narrow lines, but well below the widths of the broad lines. Again, it is not certain that they arise in photoionized regions, but this currently appears to be the most likely interpretation (Korista & Ferland 1989).

In many Seyfert 1 galaxies and some QSOs, the continuum varies, apparently in overall intensity but without large changes in form. The broad emission lines vary, and in the photoionization picture, the time delay provides information on the size of the BLR. For a simple spherical model the light delay time \( \tau = r/c \). The results of early observing programs along these lines mostly showed that closer time monitoring was necessary (e.g., Peterson 1988). Several recent results from large collaborations (Clavel et al. 1991; Peterson et al. 1991), intermediate (Netzer et al. 1990), and smaller groups (Koratkar & Gaskell 1991; Stirpe & de Bruyn 1991) tend to give somewhat smaller dimensions, and correspondingly higher electron densities in the BLRs than the results from diagnostics quoted above. The discrepancies are not large and probably mean that more sophisticated models are needed, rather than indicating a fundamental problem.

These “time-delay mapping” results tend to show that the higher ionization lines, such as C iv, are emitted closer to the nucleus, while the collisionally de-excitation line C iii \( \lambda 1909 \) is emitted further out, consistent with the idea that the ionization and electron density both decrease outward. Much research is going on in this area. It is very important and no doubt will refine the models greatly. The good correlation of the continuum and broad-line variations, with a well-defined time lag, is probably the best evidence that the BLR is mostly photoionized (Peterson 1988).

Dust is important and shows up by its extinction effect on the emission-line ratios in nearly every AGN. On the average, Seyfert 2 galaxies are more heavily reddened, indicating that they have higher dust content (Dahari & De Robertis 1988). Infrared emission from “warm dust” near the nucleus, which converts significant amounts of the ultraviolet and optical radiation to infrared thermal emission, is also essentially ubiquitous in AGNs (Sanders et al. 1989). Again, on the average the thermal infrared is stronger in the Seyfert 2 objects.

3. CYLINDRICAL STRUCTURE

It has long been supposed that the characteristic structure of AGNs has cylindrical symmetry, as drawn in Figure 1, rather than spherical (Shields 1977; Osterbrock 1978). The main observational reason is that radio jet structures are seen very near the nucleus in VLA high-resolution radio maps of many Seyfert galaxies (Wilson & Ulvestad 1982; Ulvestad & Wilson 1989). High spatial resolution optical studies of the nearest objects show that the strong [O iii] emission characteristic of AGNs is strongly associated with these radio jets (Whittle 1985a). From the theoretical side, it is very difficult to imagine any way in which material from a galaxy can arrive at its center with almost precisely zero angular momentum. Nonzero
angular momentum implies cylindrical symmetry, and presumably the axis of symmetry corresponds to the jets.

The only possible energy source we know for AGNs is gravitational (unless the stars in them are very different from the stars in any galaxy we know; see § 8). The most plausible mechanism is the release of some of its energy in an accretion disk before the mass, falling toward the center, disappears into a central black hole (Lynden-Bell 1969; Rees 1977, 1984). Note that it is not at all necessary that the axis of the central part of the AGN be aligned with the overall galaxy, and in fact in most cases the jets are not (Tohline & Osterbrock 1982). Many galaxies, including our own, have warps near their centers, and probably the best way to think of the gas in an active galaxy is the BLR merging into the NLR, merging in turn into the interstellar medium in a continuous warp, with axis shifting from the jet direction at the center to the axis of the main body of the galaxy in its inner parts (Sanders et al. 1989).

A very important advance was the discovery by Antonucci & Miller (1985), that in plane-polarized radiation the Seyfert 2 galaxy NGC 1068 has the spectrum of a Seyfert 1 object, with broad Hβ and Fe II emission features. The interpretation they proposed, that there is a "hidden BLR" in the nucleus of NGC 1068 whose radiation does not escape directly to us because of strong obscuration close around it, but which does escape along the axis, and is scattered toward us (and thus polarized) by free electrons above and below the obscuration, appears to be a striking confirmation and extension of the schematic model shown in Figure 1. Furthermore the observed position angle of the plane of polarization is perpendicular (to within observational error) to the observed position angle of the jets in NGC 1068, indicating the photons do escape from the hidden BLR along the axis of the jets. Miller & Goodrich (1990) have observed this same effect in several other Seyfert 2 galaxies, and in each case with the direction of polarization perpendicular to the axis of the jets, or other elongated radio-frequency structure. This picture of an "ionization cone" along the axis of the jets, with smaller optical depth than in the equatorial plane, because there is less gas along the axis than in the equatorial plane or "torus" perpendicular to it, to which has been added very well with further observational data (Miller, Goodrich, & Mathews 1991). According to it, NGC 1068 would show a Seyfert 1 spectrum in natural light if observed from nearly the direction of the axis of its AGN. It is natural to suppose that all Seyfert galaxies may have this "universal" structure (Krolik & Begelman 1986, 1988), and on this hypothesis Osterbrock & Shaw (1989) derived an opening angle of approximately 70° for the "typical" ionization cone, from statistics of the numbers of Seyfert 1, 1.5, 1.8, 1.9, and 2 galaxies in one well-studied field. However, although some AGNs clearly do have this structure, whether in fact it is universal is another question. We shall discuss it in § 8, in the context of all the available observational data.

The ionization cones in NGC 1068 and several other Seyfert 2 galaxies have been clearly shown by long-slit spectroscopy outside the nuclei (Baldwin, Wilson, & Whittle 1987; Unger et al. 1987), and by filter photography, especially by Pogge (1988a, b). He showed that the ratio [O III]/(Hα + [N II]) is a good graphic indication of the importance of photoionization by hard radiation of the AGN spectrum, relative to photoionization by the O stars that are present in many Seyfert galaxies. In NGC 1068 and some other Seyfert 2 galaxies, only one side of the ionization cone is observed, evidently on the near side of the plane of the galaxy, while the cone on the other side is obscured by dust in that plane. In other, more nearly edge-on Seyfert 2 galaxies both sides of the ionization cones appear on the [O III]/[Hα + [N II]) images. The mean opening angle of the ionization cones in the four Seyfert 2 galaxies in which Pogge (1989) observed these structures is approximately 50°.

The ionization cone in NGC 1068 is especially well documented, having been observed spectroscopically in [Ne V] λ3426 by Evans & Dopita (1987) and Bergeron, Petitjean, & Durretet (1989; who found an opening angle of about 80°) from the ground, and in N v λ1240, C iv λ1549, and He ii λ1640 by Truong & Bruhweiler (1991) from the IUE satellite. Furthermore, Evans et al. (1991) obtained an [O III] image with the Hubble Space Telescope. Heavily processed to minimize the effects of the spherical aberration, it shows the inner part of the ionization cone down to a scale of a fraction of an arcsecond (1″ ≈ 70 pc). It is resolved into many small clouds, as expected in analogy with all other observed ionized "nebulae" in our own and other galaxies. These authors derived an opening angle of 65° ± 20° from their observation of the NGC 1068 ionization cone.

Of the Seyfert 2 galaxies Pogge (1989) observed in this way, eight showed extended emission. Of these eight, four showed ionization cones, all aligned with the radio jet axis. On the other hand, of nine Seyfert 1 galaxies he also observed, only three showed extended emission, and none of these appeared to be an ionization cone seen end on. This appears to be an argument against a single, universal model, as discussed in § 8. However, the sample is small and not statistically significant, so the result is suggestive, not conclusive.

4. VELOCITY FIELD

One of the most interesting current problems in AGN research is to map and understand their velocity fields. These have been studied to date in all but the nearest Seyfert galaxies only by studying their observed line profiles quantitatively, in terms of the dependence of their widths and asymmetries at various intensity levels. Many of these papers have been reviewed by Osterbrock (1991). Outward flow from the nucleus, whether radial, conical, or cylindrical, will give the observed blueward asymmetry of the emission lines, if dust in the plane perpendicular to the axis obscures the outward-flowing gas on the other side (Osterbrock 1988). An overall model, with a wind-accelerated flow outward near the axis of the inner NLR, a jet compressed flow further out, a rotational, gravity-dominated component in the outer NLR, warped with respect to the inner region, and possibly a slow, inward, gravity-dominated flow in the inner NLR, as proposed by Veilleux (1991) in his Figure 24, seems to fit nearly all the observed data. Whittle (1992b, c) has also particularly emphasized the importance of gravitational forces on the NLR velocity field, as shown by the correlations between "host" or "parent" galaxy luminosity and bulge luminosity with quantitative measures of the observed emission-line profiles.

In the BLR on the other hand there is no preferred asymmetry, red or blue. Thus rotation and/or random "turbulence" probably dominate the velocity field, and no single model with inflow or outflow fits all of the observed objects, as reviewed more extensively by Osterbrock (1991). However, in many higher luminosity QSOs and quasars differences are observed between measured wavelengths (or observed redshifts) of high-ionization lines, such as C iv λ1549, N v λ1240, and low-ionization lines such as Mg ii λ2800 (Gaskell 1982; Wilkes 1986). These differences certainly indicate a structure in which
the mean ionization conditions and velocity field are correlated, presumably through distance from the central source, and can most plausibly be interpreted in terms of a small net infall velocity, rather than outflow (Kallman & Krolik 1986; Corbin 1990). This may be compared with the situation in broad absorption line QSOs (BALQSOs), which make up about 12% of the total number of QSOs. The BALQSOs are defined as QSOs with broad C iv λ1549 absorption features, blueshifted by several thousand km s$^{-1}$ with respect to the emission-line peak. They appear to be in other ways similar to "normal" QSOs, and the preferred interpretation is that they are not an intrinsically different class of objects, but more probably are similar objects seen from a different viewing angle (Weymann et al 1991). The blueshifted broad C iv absorption lines indicate outflow in the direction in which we are viewing them. According to this interpretation, $f = \Omega / 4\pi \approx 0.12$ is the fraction of the total solid angle subtended at the BLR by regions of outflow in these high-luminosity objects, while the remaining $1 - f$ is subtended by areas of slow inflow. If the gas densities over these areas are comparable, the ratio of inflow to outflow velocities would be the inverse ratio of the covering factors, $(1 - f)/f \approx 7$.

Time variations in the broad-line profiles, following variations in the continuum (presumably including the photoionizing radiation, as discussed in § 2) should distinguish between inflow or outflow. Most published papers have found neither, but Crenshaw & Blackwell (1990) reported, from the IUE monitoring of NGC 5548 by Clavel et al. (1991), that a drop in the continuum by a factor 2.9 was followed by a drop in the flux in C iv λ1549, in which the red wing dropped first, with a delay $8 \pm 2$ days, followed by the blue wing, with a delay of $13 \pm 3$ days. They interpreted this result as indicating inflow, with a velocity of 4500 km s$^{-1}$ in the "central" BLR, with radius 9 light-days. Similar results were found earlier for this same object and for NGC 4151 by Gaskell (1988), and Koratkar & Gaskell (1991) from less closely sampled observations. However, from later, more closely sampled observations of NGC 4151, Clavel et al. (1990) found that the blue and red wings of C iv vary simultaneously, and that they respond more rapidly than the core of the line to continuum variations. Thus they argue against net inflow or outflow and indicate that the velocity dispersion increases inward toward the central source.

Finally, we should note that it is much more likely that the BLR and NLR are our names for the extremes in a continuous distribution of density, with many condensations and fluctuations, than that they are two distinct, physically separate regions.

5. CONTINUITY

As emphasized in the Introduction, QSOs and Seyfert 1 galaxies appear to form a continuum, the distinction between them based more on historical circumstances than on a sharp physical division in their properties. This has been emphasized by Morgan & Dreiser (1983). The most sensible method of separating QSOs and Seyfert 1 nuclei is by an arbitrary definition in terms of their luminosity. Following Schmidt & Green (1983), Véron-Cetty & Véron (1989), and others, we adopt $M_B = -23$. This corresponds approximately to $10^{45.6}$ ergs s$^{-1} \approx 10^{12} L_\odot$ in the optical, ultraviolet, and near-infrared spectral regions. The "bolometric correction" is unusually large for AGNs because they radiate over such a wide frequency range, from X-ray (and $\gamma$-ray in the few objects observed in this region) to the far-infrared and radio-frequency regions. The overall luminosity of a "typical" nucleus with $M_B = -23$ is thus approximately $10^{46.3}$ ergs s$^{-1} \approx 5 \times 10^{12} L_\odot$.

Similar continuity exists between the radio-loud quasars and radio galaxies, both less abundant by a factor $\sim 10^2$ than the radio-quiet versions mentioned above. Among the galaxies there is a marked difference in form; the Seyfert galaxies are essentially all spirals, while the radio objects are N, C, D, or E galaxies.

There are only very few high-luminosity Seyfert 2 galaxies. Only one is known with optical absolute magnitude more luminous than the QSO limit, E 0449 - 184, with $M_B = -23.2$ (assuming $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$), (Stocke et al. 1982). Another highly reddened Seyfert 2, IRAS 20460+1925, has $M_B = -22.2$ corrected for extinction. But it is not a typical Seyfert 2 galaxy. With its strong infrared continuum (eradiated by dust), it has total luminosity $L \approx 1.7 \times 10^{13} L_\odot$ (assuming the same $H_0$), well over the limit that would make it a QSO (Frogel et al. 1989). A few other similar objects are described in § 7. The extreme paucity of high-luminosity Seyfert 2 galaxies, except for these few objects, must mean that the blocking torus decreases in angle subtended at the central source, as its luminosity increases along the sequence from Seyfert 2 nucleus to QSO (Lawrence 1987). An alternate interpretation would be that the observed luminosity is very highly aspect-dependent, and that the highest apparent luminosities occur only for objects in which the nuclear and BLR radiation escape freely in our direction.

LINERs are the relatively low-luminosity AGNs, isolated as a class by Heckman (1980). They typically also have relatively low-ionization lines, in particular, relatively small [O III] $\lambda\lambda5007/\lambda4959$ intensity ratios, and correspondingly especially large [O I] $\lambda6300/\lambda5007$ and [S II] $\lambda\lambda6716+6731/\lambda5007$ ratios. Spectroscopic diagnostics and comparison with models strongly suggest that many LINERs are simply extensions of Seyfert 2 galaxies to lower luminosities, photoionized by a weaker AGN spectrum, as reviewed, for example, by Osterbrock (1991). Many of them show weak, broad Hz emission wings, detectable only on high signal-to-noise ratio spectra, carefully processed by subtraction of galaxy integrated stellar absorption-line spectra to leave a smooth continuum and the emission lines (Filippenko & Sargent 1985). This, of course, indicates a weak Seyfert 1 component, and thus again suggests that photoionization is important. However, the objects called LINERs form a very mixed bag, and there is no doubt that among them there are also quite a few galaxies in which shock-wave heating, as a result of collisions between gas clouds, is the main energy-input mechanism. These are chiefly objects in which the emission occurs in extended regions, rather than in small nuclei (Heckman 1987). The weakest known LINERs are objects with AGN-type emission lines just above the limit of detectability, and it seems very likely that there are still more active nuclei, undetected as yet, too weak for our present techniques.

The known LINERs have been discovered or recognized in more or less random surveys, and although their number evidently increases toward lower luminosity, the luminosity function is not at all well established. An early complete survey of a well-defined sample of "normal" spiral galaxies by Keel (1983) indicated that approximately half of them showed weak AGN properties in their spectra, namely relatively large [N II] $\lambda6583/\lambda6548$ ratios (in comparison with H$\alpha$ regions and starburst galaxies). The nucleus of our own Galaxy, a spiral, cannot be
observed directly in the optical spectral region, but in the far-infrared, millimeter, and radio-frequency regions it shows many evidences of weak activity (Genzel & Townes 1987). It is almost certainly not strong enough for our Galaxy to be classified as a LINER. The nucleus of M 31 has even weaker observable indications of activity, but [N II] λ6583 can be seen in emission with high spatial resolution. Both [N II] λλ6548, 6583 are fairly strong in the nucleus of M 33. No Hα emission is detectable in either nucleus, but whatever might be present would be greatly weakened by the Hα absorption line in the integrated stellar spectrum (Rubin & Ford 1986). Careful removal of this component will be necessary to determine whether or not there is a low-level AGN component in either of these nearby spiral-galaxy nuclei.

6. BLACK HOLES

The accretion disks around black holes in AGNs should be detectable in their spectra. Most of the models have been calculated in the thin disk, z-model approximation. In these models the temperature increases inward following a power law, and the resulting calculated continuous spectrum of the disk gives a slightly better fit with the observed continuum in the optical and ultraviolet spectral regions than a blackbody does (Sun & Malkan 1989). However, these models generally predict a relatively strong discontinuity, either in emission or absorption, at the Lyman limit x12. Such discontinuities were not observed in a program designed specifically to detect them in QSOs with z > 3, for which the Lyman limit spectral region is shifted into the optical spectral region (Antonucci, Kinney, & Ford 1989). The same absence of strong absorption or emission at the Lyman limit persists in lower redshift QSOs (0.4 < z < 2.5) observed with the IUE (Kinney 1992). These observations throw into some doubt the interpretation of the continuum in terms of a thin accretion disk.

To the extent these continuum fits are meaningful, they give masses for the black holes in Seyfert 1 nuclei M ≈ 10^7.5-10^8.5 M⊙, and M ≈ 10^8-10^9 M⊙ for those in QSOs (Sun & Malkan 1989). These masses, the observed widths of the broad emission lines, and the dimensions deduced for BLRs mentioned in § 2 are roughly consistent with motion under gravity, V^2 ∝ GM/R.

The well-known Eddington luminosity

\[ L \leq L_\text{E} = \frac{4\pi G M c}{\sigma_T} = 1.3 \times 10^{38} \frac{M}{M_\odot} \text{ ergs s}^{-1} \]

is an upper limit to the luminosity of a spherical object that can be held together gravitationally by a mass M against radiation pressure, where \( m_p \) is the mass of a proton and \( \sigma_T \) is the electron scattering or Thomson cross section. From their observed luminosities and the masses derived from the accretion disk continuum fits, Seyfert 1 nuclei typically have \( L \approx 10^{41} \text{ erg s}^{-1} \), while QSOs are closer to \( L \approx L_\text{E} \) (Sun & Malkan 1989). Similar trends have been found by Padovani & Raffanelli (1988) and Padovani (1989), using photoionization models to estimate the dimensions of the broad-line regions, and the measured line widths to estimate the velocities. These methods and results are exceedingly stimulating, but are still highly model-dependent.

The mass consumption rate \( \dot{M} \) necessary to sustain a luminosity \( L \) is given by

\[ \dot{M} \approx \frac{0.1}{\epsilon} \frac{L}{5.7 \times 10^{45} \text{ ergs s}^{-1}} M_\odot \text{ yr}^{-1} \]

where \( \epsilon \) is the fraction of the mass disappearing into the black hole which escapes as radiation. Thus, for a QSO radiating at the Eddington limit, the time scale for its mass to increase (by a factor \( \epsilon \)) is

\[ \tau = 4 \times 10^7 \left( \frac{\epsilon}{0.1} \right) \text{ yr} \]

as Turner (1991) has emphasized. This is the time scale for the QSO to exhaust its available fuel, unless the supply is very large. For a Seyfert 1 black hole radiating at \( 10^{41} \text{ erg s}^{-1} \), the time scale would be 10 times longer. Thus we should think of galaxies having relatively short-lived active phases, and spending much of their lifetimes as "normal" spirals. Such behavior was conjectured by Woltjer (1959) simply on the basis of the relatively small number of active galaxies. Many of the "normal spirals" we observe must have inactive black holes which have exhausted all the available fuel, namely the gas (and dust) with suitably low angular momentum to fall close enough to the center to get into the accretion disk (Lynden-Bell 1969). There is evidence for a black hole with \( M \approx 10^6 M_\odot \) in the nearby spiral M 31 (Dressler & Richstone 1988; Kormendy 1988), and perhaps larger ones in other galaxies.

The central black hole in an AGN must be rotating with nearly the maximum allowed angular momentum per unit mass, the Kerr metric. The observations show copious amounts of ionized gas very near the rotating object. Under these conditions magnetic fields must play a role. The radio-frequency observations of synchrotron radiation from jets confirm the presence of such fields. All kinds of theoretical possibilities are open; the difficulties in calculating which of them actually occur are immense (Rees 1984). In accretion disk models the temperature increases inward toward the central black hole. Some attempts have been made to understand the X-ray emission as arising in the very innermost part of the accretion disk, nearest the black hole, but generally models calculated in this way do not predict a hard enough spectrum (Aldrovandi 1981; Fabbiano 1988). It seems much more likely that the high-energy photons are produced in and near the jet, in regions where magnetic forces are probably important (Guillop & Rees 1988). Variations in the X-ray fluxes can occur in times as short as a few hours, comparable with the light crossing time for a few times the Schwarzschild radius of a \( 10^8 M_\odot \) black hole (Yaqoob & Warwick 1991).

One very interesting result of the measurements described in § 2 is that the continuum variations at different wavelengths occur in phase. More quantitatively, in both NGC 4151 and NGC 5548 the continuum variations at \( \lambda 5000 \) follow those at \( \lambda 1350 \) with a phase lag of at most \( \Delta \lambda \leq 2 \pm 2 \) days (in both objects). Yet according to the accretion disk models, these continuum photons are predominantly emitted at different radii. If the variations were due to perturbations or instabilities in the models, they would propagate across the disk with the speed of sound, and much longer lag times (of the order of years) would be expected. Only disturbances propagating with the velocity of light can explain the observed nearly synchronous continuum variations. The same conclusion can be drawn from continuum observations of 3C 273 at \( \lambda \lambda 1250, 3440, \) and 5800 (Courvoisier & Clavel 1991). In NGC 5548 the ultraviolet continuum varies with larger amplitude than the optical; the spectrum gets harder as it gets brighter (Wamsteker et al. 1990; Clavel et al. 1991).

These results can be interpreted in terms of a disk model heated, not by frictional dissipation of kinetic energy in a thin
disk, but rather by absorption of ultraviolet and X-ray radiation emitted along the axis in and near the jets. Such a model was in fact proposed long ago by Shields (1977). X-ray measurements of AGNs, interpreted in terms of a power-law spectrum modified by absorption, and observations of Fe K-shell emission and absorption lines add strong support to this picture. Best fits to most of the Seyfert 1 galaxies observed to date are the power-law indices ($F_\nu \propto \nu^{-n}$) $n = 0.70$ over the energy range $2$–$10$ keV (Turner & Pounds 1989) and $n = 0.81$ over the lower energy range $0.2$–$2$ keV (Krupa et al. 1990), both with very small dispersion. Soft X-ray excesses, above the power law at the lowest energies ($\lesssim 0.3$ keV), are present in many objects (Wilkes & Elvis 1987; Masmou et al. 1992). This same energy region is where the strongest absorption occurs, making the detections of such soft X-ray excesses difficult. The Fe K-shell emission line observed in several AGNs can only be interpreted in terms of resonance-fluorescence, excited by the X-ray continuum incident on relatively “cold” ($T < 10^5$ K) gas (Krolik & Kallman 1987; Pounds et al. 1989). This is but one, extreme example of the “reprocessing” of high-energy photons interacting with the gas in AGNs (Guilbert & Rees 1988). The absorption at low energy determines the column density along the line of sight to the central X-ray source, typically in the range $10^{20}$–$10^{23}$ H atoms cm$^{-2}$. The overall X-ray spectra can be understood in detail on the basis of models incorporating electron-positron pair injection in a compact region, reflected and reprocessed by cold material (Zdziarski et al. 1990).

A quite detailed disk model, aimed at fitting all these optical, ultraviolet, and X-ray data, has been proposed by Collin-Souffrin (1991, 1992). It includes relativistic jets along the axis through the black hole, with a thick hot disk, supported by radiation pressure, possibly unstable, extending out to $10^4$ Schwarzschild radii ($R_S$). Most of the X-rays are emitted from this hot disk. Some strike the thin disk, stable and supported by gas pressure, which extends outward from there to $10^5$ $R_S$; others, originally radiated in directions away from the thin disk, may be scattered by the surrounding hot dilute medium back toward this disk. The inner part of this region (out to $\sim 10^2$ $R_S$) itself emits the ultraviolet continuum, as in the thin disk models. Further out in this disk is the BLR ($10^2$–$10^4$ $R_S$).

A wind, flowing away from the disk, is the region in which the high-ionization broad lines such as C IV, 1549 are emitted. The lower broad ionization lines, including H$\alpha$, H$\beta$, and Fe II come from the partly ionized regions further out, at the top and bottom of the disk, photoionized by the hard X-ray photons. The Lyman discontinuity may be much weaker in this type of model, because the region in which it forms is more nearly isothermal, heated from without by the ionizing radiation and from within by frictional dissipation, than in the standard thin disk models. Thus in this model much of the continuum and broad emission-line radiation comes from the accretion disk itself.

This model is by no means completely worked out physically, particularly the structure of the central thick, hot disk, and the form of the X-ray spectrum it emits. But as a heuristic picture it seems to agree the best with many observed features of AGN spectra, over a wide range of energies. It appears to be the best working hypothesis at the present time and certainly deserves further testing. Probably in time it will be disproved by further observations and will yield to a still more complicated model which preserves many of its features, but goes beyond them. One very interesting theoretical suggestion is the possible existence of long-lived vortices on the surfaces of AGN accretion disks (Abramowicz et al. 1992). They could in principle explain many of the observed features of the X-ray variability and other continuum features; further calculations are clearly indicated.

7. Evolution

Years ago Vorontsov-Velyaminov (1977) and Adams (1977) pointed out that many Seyfert galaxies are distorted. Simkin, Su, & Schwarz (1980) confirmed this result from a photographic survey of 30 nearby Seyfert galaxies and also noted that many of them have companions or bars. Both are direct evidence of noncylindrically symmetric gravitational fields in these galaxies. Simkin et al. showed from published dynamical studies, and additional theoretical work of their own, that under these conditions some of the gas in the galaxy may lose enough angular momentum to fall close to the nucleus and thus become a potential source of fuel. Subsequent statistical studies, based on large, well-defined samples (Elmegreen, Elmegreen, & Bellen 1990), have confirmed that there is an excess number of early-type barred spirals among spiral galaxies with companions and vice versa.

Such quantitative statistical studies of the Seyfert effect are more difficult. The problem is to define a control sample of galaxies which match the Seyfert galaxies in “all” respects except that they are not Seyfert galaxies. However, three different statistical studies have concluded that there is an excess of Seyferts among galaxies which have nearby “neighbors” or “companion galaxies,” and that there is an excess of galaxies with nearby neighbors among the Seyfert galaxies (Petrosian 1982; Dahari 1985; MacKenty 1989, 1990). The contrary result, that there is not such an excess of nearby companions among Seyfert galaxies, was found by Fuentes-Williams & Stocke (1988). The reason for this difference is not clear; all four papers chose their control sample in different ways, and objections can be marshaled against any of them. Fuentes-Williams and Stocke drew their sample of Seyfert galaxies from relatively early catalogs of such objects, and it is therefore deficient in Seyfert 2 galaxies. Both Petrosian and MacKenty found Seyfert 2 galaxies more likely to have companions than Seyfert 1 galaxies (Dahari did not find a statistically significant difference), and this is no doubt at least part of the reason for the discrepancy. Certainly the weight of this evidence favors an association between the Seyfert phenomenon and a galaxy having a nearby “companion,” which means physically a galaxy close enough to interact gravitationally with the galaxy in question.

There are many examples of the apparent results of gravitational interactions in images of Seyfert galaxies reproduced in the papers by Adams, Vorontsov-Velyaminov, and Simkin et al. mentioned above. A more recently published example is NGC 7592 (Rafanelli & Margiani 1992). For more distant objects the linear resolution is necessarily poorer, but fine-seeing CCD images (especially those taken with the Canada-France-Hawaii telescope at Mauna Kea), processed carefully, show convincing examples of companions, interactions, and mergers as well. A short, selected list is given in Table I. The descriptions are abbreviated forms of those given by the authors of the papers listed, based on comparisons with calculations of galaxy interactions going back to Toomre & Toomre (1972).

Note that “starburst galaxies” or H $\alpha$ region galaxies also tend to have companions, and to show the effects of inter-
actions. MacKenty (1989) has studied this issue quantitatively and found no statistically significant difference between the tendency of Markarian Seyfert and non-Seyfert (predominantly starburst) galaxies to have “companions,” though both types do have this property significantly more than “normal field galaxies.” The close connection between Seyfert activity and starburst galaxies and regions was particularly emphasized by Weedman (1983). There are differences in detail, however, as the AGNs tend to be found in intermediate-type galaxies, while the pure starburst nuclei more frequently occur in late-type spirals (Keel 1983; Pogge 1988b).

A physical picture that links many of these observational results is based on the hypothesis that many galaxies have inactive black holes at their nuclei. These nuclei turn active only when they are refueled by an interaction which delivers gas with nearly zero angular momentum (on the scale of the galaxy). Only such gas can be captured near the center and releases energy in the process of ultimately falling into the black hole. Probably some of the energy is radiated from the accretion disk (not necessarily a thin one), the rest from other cylindrically symmetric structures, such as the jets, near the black hole. Without an interaction, a perturbation, or a merger, which can take up or exchange angular momentum, an “initially” bare AGN (meaning it has used up all the gas close enough to the center to get into the accretion disk or near the black hole in a previous AGN episode) will remain inactive. Refueled by an interaction it can “reactivate” itself. The time scale for an AGN to decay is, as discussed above, \( \sim 10^9 \) yr, comparable with the dynamical time scale of a galaxy.

Star formation also occurs as a result of such interactions. The gas does not need to be delivered as close to the nucleus; the scale of observed nuclear star formation events is \( \sim 10^2 \) pc rather than a fraction of a parsec as for AGNs. The observational data, as emphasized by Kennicutt & Keel (1984), Keel et al. (1985), Dahari (1985), and Bushouse (1986, 1987), show that the more distorted, more strongly perturbed, or more recently merged objects are starburst but not AGN galaxies. Evidently either the more violent collisions do not deliver much gas nearly to the black hole with nearly zero angular momentum, or, more likely, to do so takes a long enough time that the immediate, strongest tidal effects have begun to damp out before the AGN stage is reached. Sanders et al. (1988b) interpret the “ultraluminous infrared galaxies” which they isolated as objects with \( L > 10^{12} L_\odot \) that emit the bulk of their radiation at infrared wavelengths as “the origin of quasars.” From their images and spectra, these objects are clearly strong interactions and mergers in progress of dust-rich systems. So long as we understand “origin” to mean “this time around,” and “quasars” to mean “AGNs,” the name is probably correct. There may well have been, and probably was, a preexisting black hole in one or both of the new interacting galaxies which has been refueled by the interaction.

Numerical simulations of these processes have been carried out. Byrd et al. (1986) showed that galaxy interactions can cause tidal instability, leading to inflow from the main body of a model galaxy to its central region, for companions roughly matching the estimated masses and separations found observationally by Dahari (1985) to be significant in the Seyfert galaxy statistics. Byrd, Sundelius, & Valtonen (1987) found from further numerical model calculations that there is generally a delay from the time the strong tidal perturbation begins to the time the infalling material reaches the nucleus, and that the inflow occurs spasmodically rather than continuously. The time scales of the initial delay and of the intervals between refueling episodes are \( \sim 10^8 \) yr, comparable with the dynamical time scales of the galaxy, and with the expected lifetime of an AGN before it exhausts its fuel supply. Similar results were found in quite independent calculations by Noguchi (1988).

Tidal interactions cause perturbations on the scale of the whole galaxy (\( \sim 10 \) kpc), but Lin, Pringle, & Rees (1988) have analyzed and discussed how the nonaxisymmetric gravitational instability they trigger can work down to much smaller dimensions (\( \sim 10^2 \) pc). Further self-gravitating instability, perhaps associated with the burst of star formation, may further reduce the angular momentum of some of the mass still further, to the range necessary for it to fall to the potential fueling region (\( \sim 1 \) pc). These and other alternate processes are discussed in detail, with some examples from computed numerical models, by Hernquist (1989a, b). A somewhat similar discussion, also emphasizing the importance of non-circularly symmetric perturbations, especially interactions and bars in barred spirals (which presumably results from interactions), has been given by Shlosman, Begelman, & Frank (1990). Barnes & Hernquist (1991) have presented further numerical calculations simulating mergers of gas-rich disk galaxies, which show graphically how torques from the stars, together with energy losses by collisional processes and radiation by the gas, result in a considerable fraction of the gas mass ending up near the center. It is clear that in such interactions and perturbations the axis of the remaining galaxy need not be at all the axis of the interaction, the axis of the AGN fuel, or its result on a scale of 1 pc.

Observational results from many authors, discussed and referenced, for example, by Osterbrock (1991), agree that there are few if any AGNs in dense clusters of galaxies, or in the dense central regions of looser clusters. No doubt gas has been stripped from galaxies in these regions by the intergalactic medium. In addition the high relative velocities of galaxies in clusters reduce the strength of their interactions (that is, of their tidal interaction and capture cross sections, and of their interaction times). In the less dense, outer parts of loose clusters, the relative numbers of Seyfert galaxies are comparable with their numbers in the general field, while in small, loose groups the numbers are similar to those among field galaxies with “companions.” Here the slower, more numerous interactions evidently dominate over any possible stripping by intergalactic matter.

If most Seyfert galaxies have resulted from fueling or refueling by interactions, it is obvious to ask whether they all have. Certainly they are not all observed to have companions, as the statistical studies mentioned above all agree. But no doubt some have already merged, and others have traveled far enough away after perigalacticion to be outside the radius...
which each study defines as the upper limit to the distance of a “companion,” to reduce the contamination by background objects. Other companions may be too faint to have been observed with the available telescopes and imaging systems, yet massive enough to produce an effective interaction. Byrd et al. (1987) claim that, allowing for such effects, 75% or more of Seyfert galaxies may have “companions,” and that the morphological types of the few isolated Seyfert galaxies are consistent with their being the results of recent galaxy mergers. Xanthopoulos & De Robertis (1991) have obtained high-quality CCD images of eight of the small fraction of Seyfert galaxies which appear to be completely isolated. Carefully searched on these images, two of these eight in fact do appear to have distant companions, one other one has a bar, three others plus the two with companions have hints of a bar, and two others are “slightly elongated” or with a “jetlike” projection, that is, images of recent interactions. Only one of the eight, Mrk 1388, shows no sign of a bar, elongation, or companion. But it is classified as an E galaxy by Xanthopoulos & De Robertis, and thus may be the result of a merger. Thus at least for this small sample, it appears that every Seyfert galaxy can be interpreted as resulting from an interaction, although the evidence does not require this interpretation in every case.

Note that the mass of the black hole increases in each interaction, and hence its Eddington luminosity $L_E$ increases also. The evolution during one interaction, refueling episode may be “formation” or “appearance” as an ultraluminous infrared galaxy with a Seyfert 2 spectrum (as observed in these objects), followed by evolution as some of the dust clears away by sublimation in the radiation field or by decay back to a plane, to either a Seyfert 1 or Seyfert 2, depending on the angle of view and the remaining amount of dust. Then as the supply of fuel begins to diminish and with it the luminosity, this object could evolve toward a lower luminosity Seyfert 2, then to a LINER as $M$ approaches zero, and finally to a “normal spiral.” In other, still less extreme interactions, either a Seyfert 1 or Seyfert 2 may form (depending on orientation of the observer), followed by evolution to a Seyfert 2 as the luminosity decreases, and then to LINER.

In this connection a table of the statistics of perturbation strengths as a function of Seyfert galaxy type is instructive. As the best available existing published source we use the compilation by Whittle (1992a). As he states, this sample is defined as the Seyfert galaxies for which reasonably accurate line-width measurements are available, and thus is somewhat inhomogeneous, but within each Seyfert galaxy type this should not cause a problem. We use the Seyfert types from Table 2 of Whittle (1992a). For the strength of the perturbation Whittle lists in his Table 3 two quantities, DC, the “distortion class,” representing how disturbed the galaxy appears from its optical image, and IAC, the “interaction class,” representing the presence (or absence) of an apparently massive (or less massive) nearby companion. Both these classes are given as integers, ranging from 1 (weakest) to 6 (strongest). The DC classification was defined by Dahari (1985) in his Table 3, there called “the interaction class (IAC) of single galaxies.” The IAC classification was originally defined by Dahari & De Robertis (1988) to describe in a one-dimensional scheme “the presence of a companion (relative size and proximity),” and/or the DC as stated just above. Whittle (1992a) used only the first part of this definition and compiled values of both these quantities from Dahari & De Robertis (1988). He also reclassified many of the objects, using the best images available to him, either published, or from newer CCD images, as described in his § 8.3. There he also defines the “perturbation class,” PC, as the maximum of DC or IAC. It is this single parameter which is used in our Table 2. All the Seyfert galaxies from Whittle’s Table 2 are included for which at least one of the DC or IAC is listed in his Table 3. Note that he uses the spectral type Seyfert 1.2, which we no longer use at Lick; on our system most of these Seyfert 1.2 objects would be classified as Seyfert 1.5, and the remainder as Seyfert 1.

The first three sets of two columns of Table 2 in the current paper each list for each PC the number $n$ of galaxies of the Seyfert type listed (1, 1.2, and 1.5, respectively) and the corresponding decimal fraction $f$ of the total number of galaxies of that type. These three types are grouped together in the next pair of columns, headed Seyfert 1 +1.2 +1.5; these are the objects which would all be classified as Seyfert 1 on a system which included only 1 and 2. There are only small numbers of Seyfert 1.8 and 1.9 galaxies in any sample, including Whittle’s; they are grouped in the next pair of columns. Finally, the Seyfert 2 galaxies are listed in the last pair of columns. It can clearly be seen that the Seyfert 2 galaxies include a larger percentage of the strongly interacting systems (PC = 5, 6, 7), while the Seyfert 1 +1.2 +1.5 group includes a larger percentage of the moderately interacting systems (PC = 4, 5). The same trend appears to be present along the whole sequence Seyfert 1, 1.2, 1.5, 1.8 +1.9, 2, although the numbers of objects are too small to be certain of this, particularly for the Seyfert 1.5 (Whittle’s classification) and Seyfert 1.8 +1.9 groups.

Clearly the evolution of Seyfert galaxies cannot be derived from these statistics. But at least they do not contradict the refueling idea sketched above, that some AGNs may evolve along the path Seyfert 2 $\rightarrow$ Seyfert 1 $\rightarrow$ Seyfert 2 $\rightarrow$ LINERs, others, “forming” (appearing when refueled) as Seyfert 1

<table>
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objects which then evolve Seyfert 1 → Seyfert 2 → LINERs,
and still others, forming as Seyfert 2 objects, then evolving to
LINERs. In all cases the interacting system appears as a star-
burst before the AGN appears, but not all starbursts become
AGNs. The “ultraluminous infrared galaxies,” on this inter-
pretation, are the most luminous Seyfert 2 galaxies of the first
path.

Note further that the dynamical time scale of a galaxy, a few
times $10^8$ yr, is comparable with the Eddington-luminosity
time scale of the black hole. Therefore correlating the spectral
type of AGNs with the form of the galaxy (the amount of
distortion, presence of tidal tails, position of companion, etc.)
which in principle may give the time and strength of the inter-
action should give clues to the evolution. Promising first steps
in this direction have been taken by Hutchings & Neff (1991a).
Clearly many more numerical simulations of interactions and
an overall way of classifying them will be necessary, but it is a
worthwhile goal to strive for. A very good beginning of such
a program has been reported by Burke et al. (1991). Note also
that even in the simplest case there are at least two parameters,
$M$ or $M$ (or $L/L_\odot$) of the black hole, in addition to the amount
of dust, the relative velocity, and perigalacticon distance (or
alternatively the impact parameter) of the pair, and various
orientation angles of even the simplest model galaxies. It is not
at all an easy problem to tackle theoretically.

8. ADDITIONAL THOUGHTS

Dust is evidently always present in AGNs, but less so, on the
average, in Seyfert 1 than in Seyfert 2 galaxies (Dahari & De
Robertis 1988). Even in the apparently most dust-free Seyfert
1 galaxies (as judged by extinction), the strong infrared emission
suggests that dust is present, perhaps in torus around the
nucleus. Some Seyfert 2 nuclei show only relatively little reddening in
their narrow emission-line spectra; according to the evolutionary
scheme tentatively proposed in § 7 they are in a late stage of evolution, after the Seyfert 1 stage.

Recent high-resolution CO observations of only a very few
of the nearest Seyfert galaxies to date show that CO, if detect-
able, is strongly concentrated to the nucleus, in an apparently
toroidal ring, with diameter a few $10^3$ pc (Blitz, Mathieu, &
Bally 1986; Sanders et al. 1988a; Heckman et al. 1989;
Meixner et al. 1990). This is observational evidence which sup-
ports the models sketched above.

One very interesting question is whether one unified model,
the “hidden BLR” or “torus model,” applies to all Seyfert 1,
1.5, 1.8, 1.9, and 2 galaxies. A very good discussion of this
point is given by Lawrence (1987). I would agree with him that
probably does not, although it does undoubtedly apply to
many of these objects, perhaps the majority. But in polarized
light many observed Seyfert 2 galaxies do not show the broad
H I emission lines, similar to those in NGC 1068, which are the
signature of the hidden BLR (Miller & Goodrich 1990). The
extended ionization cones seen in Seyfert 2 galaxies do not appear to be observed, from a different projection, in Seyfert 1
galaxies (Pogge 1989). The observed CO content, which should
be independent of orientation, seems to differ. From the few
examples studied to date, there tends to be more molecular gas
in Seyfert 2 than in Seyfert 1 galaxies. Also, NGC 1068, the first
example of the hidden BLR detected by its spectrum in polar-
ized light, is quite an atypical Seyfert 2. The full widths of its [O III] narrow emission lines, $\sim 850$ km s$^{-1}$ are among the
largest of any Seyfert 2 nucleus. Its X-ray spectrum is quite
usual in comparison with the few other Seyfert 2 galaxies
observed in this energy region (Kruper et al. 1990). Thus,
although many objects clearly fit the unified picture well
(Krolik & Begelman 1988), it seems most likely that they all do not.
However, the samples studied in these detailed ways were
all small, and the conclusion is by no means certain.

An alternate picture of the physical nature of AGNs is that
they are photoionized by very hot stars rather than by a
central disk and/or jet powered by a massive central object.
This is the Warmer picture, proposed by Terlevich & Melnick
(1985). It is fairly clear that a power-law spectrum $F_\nu \propto \nu^{-4}$ for
instance, can always be mimicked reasonably well by an
assumed distribution of stars of different effective tem-
peratures, so long as those temperatures go high enough to
produce hard X-rays. Stars with effective temperatures up to
$1.5 \times 10^5$ K are required. There is essentially no observational
evidence for luminous stars of nearly so high a temperature in
our Galaxy or other nearby galaxies, although a few of the less
luminous planetary-nebula central stars have temperatures
this large (e.g., Shaw & Kaler 1989). The relevance of the
Warmer picture thus depends largely on the hypothesis that
large numbers of such high-luminosity, high-temperature stars
do exist in AGNs. A very good analysis of photoionization
models calculated on this hypothesis has recently been
published by Cid Fernandes et al. (1992). The observed contin-
um and broad-line variations in many AGNs would require
nearly all these hot, high-luminosity stars to be in an extremely
small volume, presumably with time-variable extinction
around it. The rapid X-ray variations observed in, for instance,
the Seyfert 1 galaxy Mrk 618, with time scales of $\sim 10^{4.5}$ s,
would appear impossible to explain on this basis (Rao, Singh, &
Vahia 1992). Thus the Warmer idea has severe problems.
However, Terlevich, Diaz, & Terlevich (1990) have reported
that the Ca II $\lambda 8542, 8662$ absorption lines (which arise in
late-type giant and supergiant stars) are as strong in Seyfert
galaxy spectra as in normal galaxies. Hence, they conclude,
the infrared continuum is largely the integrated result of many
late-type supergiants, the evolved remnants of the young, hot
stars postulated in the Warmer picture. Further study of this
question is clearly desirable. The most recently published
version of the Warmer idea attributes the BLR to the inte-
grated effect of supernova remnants (Terlevich et al. 1992).

An alternative idea for the BLR is that the “clouds” in it are
actually the atmospheres of stars, contained by gravity rather
than by an external pressure. According to one version of this
idea they are red giant stars, according to another they are
main-sequence stars heated and “blotched” by the strong radia-
tion field of the central photoionizing source. These ideas are
discussed briefly, with references to the original papers, by

Finally, the new X-ray results just starting to appear from the
ROSAT will undoubtedly be very important in increasing our
understanding of AGNs. Much of what we know to date has
come from measurements with the earlier X-ray telescopes
in a relatively few, nearby Seyfert 1 nuclei, and only very few
measurements, mostly with rather poor signal-to-noise ratios.
The expected number of AGNs detectable by ROSAT is
$\sim 2 \times 10^5$, and the first published paper on optical identifica-
tions of ROSAT sources appears to confirm that estimate
(Bade et al. 1992). Although almost all the ROSAT published
AGN identifications to date are Seyfert 1 galaxies, undoubt-
dedly more Seyfert 2 galaxies will also be observed with it,
providing quantitative evidence on the spectra and column
densities in these objects.
9. CONCLUSIONS

Although we are far from understanding fully the nature and structure of AGNs, we have many ideas about them, based on quantitative observational data and physical theories. Our level of understanding of them may be comparable with our predecessors' understanding of stars in the 1930s. Most AGNs form one family, from QSOs and quasars at the upper end in luminosity, through Seyfert and radio galaxies, to LINERS. They are not all built on the same model, but have many general features in common. The best current working hypothesis is that the central source includes an accretion disk centered on a massive black hole, but the disk is more complicated than a simple x-model thin disk. Jets along the axis of the disk are a common feature. Much of the energy input to the surrounding gas is by photoionization from a hard spectrum, extending well into the X-ray region, emitted by the central source, probably by the combination of several different processes, but which result in, to a first approximation, a power law, to a second approximation, a broken power law, and to a higher approximation, many more complications in detail. The cylindrical structure shows up in ionization cones. Many Seyfert 2 galaxies would be observed as Seyfert 1 galaxies from a different orientation, but they do not all fit a single model.

The best current working hypothesis is that AGNs "form" or are reawakened from a previously inactive black hole in a "normal" galaxy is refueled by gas as a result of an interaction, either a perturbation or merger, with another galaxy. In some (but by no means all) such interactions, appreciable quantities of gas can be delivered near the nucleus with essentially zero angular momentum on the scale of the galaxy. Such interactions very frequently lead to nuclear starbursts, and less frequently, by a chain of steps, they can lead to AGNs. The evolution of a single AGN occurs as activation at a significant fraction of its Eddington luminosity, followed by gradual clearing of the dust and decay of the luminosity or comparable time scales, to the LINER stage and inactivity. This is followed, on the average after a much longer time interval, by reactivation of the now larger-mass black hole, in the next interaction of its "parent galaxy" with another galaxy. Further measurements over the entire observable spectral or energy region, with larger telescopes, will undoubtedly add further to our knowledge of these powerful, enigmatic objects.

I am deeply honored and sincerely grateful to the American Astronomical Society for choosing me as its Henry Norris Russell Lecturer for 1991. I am very grateful to the National Science Foundation for its partial support of my AGN research over the years, most recently under grants AST 86-11457 and AST 91-23547, and to the University of California for its continued support. I am especially grateful to my faculty colleagues William G. Mathews and Joseph S. Miller, postdocs (as they were) Bruce Balick, Steven A. Grandi, James M. Shuder, Michael M. De Robertis, and Richard A. Shaw, graduate students Alan T. Koski, Mark M. Phillips, Ross D. Coates, and D. Danz, and postdocs (as they were) Bruce Balick, Steven A. Grandi, James M. Shuder, Michael M. De Robertis, and Richard A. Shaw, graduate students Alan T. Koski, Mark M. Phillips, Ross D. Coates, and D. Danz.
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