PHYSICS, STRUCTURE, AND FUELING OF ACTIVE GALACTIC NUCLEI\textsuperscript{1,2}

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ABSTRACT

Some aspects of recent results on the nature of active galactic nuclei are reviewed. The importance of photoionization by a hard spectrum containing high-energy photons, extending to the X-ray region, is emphasized. Time-variation studies plus spectral line ratios show that simple models cannot satisfy all the observational constraints, and some of the suggested more sophisticated models are briefly described. Observational and theoretical results which emphasize the importance of interactions between galaxies in refueling the accretion disks about massive black holes at their centers are reviewed.

Key words: Seyfert galaxies–active galactic nuclei

1. Introduction

In this review paper the connections between active galactic nuclei and nebular astrophysics will be emphasized. Because of the limited space available, only selected topics can be included in the review; obviously, the particular selection made represents a somewhat personal point of view. A considerably longer review, essentially completed in mid-1990, is Osterbrock 1991.

One important topic is the continuity from QSOs through Seyfert galaxies to LINERs and from quasars through radio galaxies. This continuity has been particularly emphasized from the morphological point of view by Morgan & Dreiser 1983, and from the spectroscopic point of view by Schmidt & Green 1983, who simply define \( M_B = -23 \) as the absolute magnitude which separates QSOs from Seyfert 1 galaxies. Although there is continuity all along this sequence, that does not necessarily mean that these objects are all scaled versions of one and the same model any more than O stars, M2 V dwarfs, and M2 ια supergiants are all scaled examples of a single model. Although the most luminous QSOs are very rare in space, and Seyfert 1 galaxies comprise only about 1% or 2% of all spirals, the low-luminosity LINERs are much more frequent. For instance, Keel 1983a has found in a careful survey of a well-defined sample of 93 spiral galaxies that one was a Seyfert 1, four were Seyfert 2s, and about half of the remainder were LINERs. All the rest, mostly later-type spirals, had \( \text{H \eta} \)-region-type emission lines, indicating photoionization by early-type stars, which may have prevented detection of still more, weaker LINER-type spectra. Furthermore, Keel 1983b found that a significant fraction of these LINERs have weak broad Hα profiles, similar to those found in many other LINERs by Filippenko & Sargent 1985.

2. Spectra

Seyfert 2 galaxies have “broad” but “narrow” emission lines, typically with full widths at half-maximum (FWHM) of order 300 to 500 km s\(^{-1}\), although many examples exist up to 1000 km s\(^{-1}\) or down to 200 km s\(^{-1}\).

Typically they indicate relatively high ionization (strong \([\text{O \pi}] \lambda 5007/\text{Hβ} \)), plus strong low-ionization lines such as \([\text{O \i}] \lambda 6300,6364, \ [\text{S \pi}] \lambda 6717,6731, \ [\text{N \ii}] \lambda 6548,6583\), in comparison with the more common starburst or \( \text{H \eta} \) region galaxies. Seyfert 1 and 1.5 galaxies have, in addition to their much broader permitted emission lines of \( \text{H \i}, \text{He \i}, \text{He \ii}, \text{and Fe \ii} \) (with FWHM ~ \( 10^3 \)–\( 10^4 \) km s\(^{-1}\)), narrow-line spectra very similar to Seyfert 2s, but often with stronger high-ionization lines such as \([\text{Ne v}] \lambda 3346,3426 \) and \([\text{Fe vii}] \lambda 5721,6087\), indicating ionization to \( \sim 100 \) eV and \([\text{Fe x}] \lambda 6375 \) and \([\text{Fe xi}] \lambda 7892\), indicating ionization to \( \sim 250 \) eV. An example is Markarian 9, discussed by Grandi 1978. However, a few Seyfert 2 galaxies, such as Markarian 1388, have nearly equally strong high-ionization lines (Osterbrock 1985).

The diagnostic line ratios clearly show that the source of ionization in the narrow-line emitting region (NLR), and much of the energy input to it, is photoionization by a hard spectrum which extends to the X-ray energy region, as summarized for instance by Osterbrock & Mathews 1986, who give many references to the original papers. It is not certain that the highest ionization lines, such as those of \([\text{Fe x}] \) and \([\text{Fe xi}] \), result from photoionized re-
gions rather than collisionally heated coronalike regions, but their strengths correlate well with those of the [Fe vii] and [Ne v] lines, which almost certainly do come from photoionized regions. Although the main energy input to the emitting gas is by photoionization, it is possible that there is some additional heating by relativistic electrons associated with the radio-emitting plasma. This input mechanism tends to raise the temperature somewhat above the equilibrium value set by the balance between photoionization alone and radiative cooling, as discussed by Ferland & Mushotzky 1984 and Cesar, Aldrovandi & Gruenwald 1985.

The best way to distinguish between ACN-type emission-line spectra and H II-region or starburst-type emission-line spectra is by quantitative diagnostic ratios of the type originally suggested by Baldwin, Phillips & Terlevich 1981. The best ratios for this purpose in the optical region are [N ii] λ6583/Hα, [S ii] (λ6716 + λ6731)/Hα, and [O i] λ6300/Hα, each vs. [O iii] (λ4959 + λ5007)/Hβ. All these ratios are only slightly affected by errors in calibration or extinction correction. Large collections of these ratios show a well-defined division between the two types of photoionization spectra, as demonstrated and discussed by Veilleux & Osterbrock 1987.

With CCDs it is now possible to obtain good spectra of AGNs in the near-infrared spectral region out to 11000 Å, and fairly large numbers of objects have been observed by Morris & Ward 1988 and by Osterbrock, Shaw & Veilleux 1990. In this region [S πi] λλ9069,9531, analogous to the more familiar [O πi] λλ4959,5007, are strong in essentially all observed Seyfert galaxy nuclei. [O ii] λλ7320,7330 and [Ar iii] λλ7136,7751 are fairly strong in most of these objects, and [Ni ii] λ7378 is also observed in nearly all of them, as found by Halpern & Oke 1986. It is possible to use the red and near-infrared line ratios alone to separate AGNs from H II regions and starburst galaxies. An example, from a paper currently in preparation by Osterbrock, Tran & Veilleux, which includes many new near-infrared measurements, is shown in Figure 1.

The very broad H I, He I, He II, and Fe II lines of Seyfert 1 galaxies, including Lø, as well as C III] λ1909 and C IV λ1549 are emitted in the much smaller, denser broad-line regions (BLR). Here collisional and radiative-transfer effects are quite important. The best working hypothesis is that they also are photoionized, but this is not as certain as it is for the NLR. Estimates of the sizes of the emitting regions, from their densities and luminosities, are of order 10^2 pc for the NLR and 10^{-1} pc for the BLR, as spelled out in detail, for instance, by Osterbrock 1991.

3. Light Variations and BLR Sizes and Dimensions

Many Seyfert 1 nuclei have been observed to vary irregularly in light, on time scales of years, months, weeks, and even a few days. This provides the opportunity to obtain information on the sizes and geometries of their BLRs. A good summary of this topic has been published by Peterson 1988, and quite a few new results have appeared since then. The basic physical idea is that the

![Diagram of emission-line spectra](image-url)
observed featureless continuum of the central nuclear source is the extension of the high-energy photoionizing continuum into the observable spectral region. Thus, variations in the observed continuum are signals of variations in the photoionizing continuum, which cause changes in the ionization in the BLR. They can be observed in the broad emission lines, modified by the time scale for propagation of light through the BLR, $\tau = R/c$. For a thin, spherical shell of radius $R$ centered on the nucleus, this is exactly the time lag which gives the best cross correlation between the continuum and line variations, as derived by Gaskell & Sparke 1988. In any more complicated situation, it is a characteristic time scale of the variation.

The first observational recognition of these variations in the broad-line profiles and strengths was based on spectra taken at intervals of months or even years. Systematic investigation of BLRs requires observations taken much more frequently and, hence, large teams of observers working with many telescopes, or a telescope dedicated entirely to this project. A close approximation is the set of observations of the nearby, bright Seyfert 1 galaxy NGC 5548, made by the combined IUE team of very many observers, assigned at close, regular time intervals. The first results, published by Clavel et al. 1991, indicate different time delays for different lines, corresponding to $R = 4$ to 10 light days for $\lambda\Omega\pi(\lambda 1640$ and $\lambda\Lambda\pi(\lambda 1240, 12 light days for $H \beta$ and $\lambda\lambda(\lambda 1549$, approximately the same for C IV $\lambda\pi(\lambda 1909, and $\sim 30$ light days for C III $\lambda\pi(\lambda 1907$ in several planetaries observed by Eeibalman et al. 1980, 1981 with the IUE. A quantitative limit can best be obtained from the line ratio C III $\lambda\lambda(\lambda 977/C III$ $\lambda\pi(\lambda 1909, predicted as $\approx 4$ at $N_e = 10^{15} \text{ cm}^{-3}$, but $\approx 0.3$ at $N_e = 10^{10} \text{ cm}^{-3}$, both at $T = 15,000 \text{ K}$, a plausible temperature for the C $^+$ zone in BLRs. There are few observations of QSOs in which C III $\lambda\lambda(\lambda 977 might be detected, for a fairly narrow range of redshift is required to bring this wavelength into the region observable with the IUE but not allow the $\Lambda\Lambda$ forest of $H \lambda$ absorption lines to destroy it. Spectra exist for about ten QSOs in the range $0.3 < z < 0.6$ on which C III $\lambda\lambda(\lambda 977, if present, could be seen in IUE data rereduced by Kinney et al. 1991 and by Gondhalekar, but this line is not detectable in any of them. A quantitative upper limit for these ten QSOs is $\lambda\pi(\lambda 977 < 0.5$ corresponding to a mean electron density $N_e < 3 \times 10^{10} \text{ cm}^{-3}$, a value derived from the model BLRs calculated by Rees, Netzer & Ferland 1989 and by Ferland & Persson 1989. Thus, if these QSOs and the Seyfert 1 nuclei observed for light variation have similar electron densities, there is a clear contradiction between the time-delay and emission-line model results.

Undoubtedly this indicates that less drastically simplified models are necessary to interpret both the variations and the emission-line spectra. One possible alternative is that the geometry is highly anisotropic and that all the rays from the photoionizing nucleus to the parts of the BLR observed be within a core of half angle $\theta$ about the ray directly from the nucleus to the observer. In such a structure the phase lag is $\tau = R(1 - < \cos \theta >)/c$, which can be much less than $R/c$. For instance, $\tau = 0.1 R/c$ for $\theta = 25^\circ$, a cone with a full opening angle $\approx 50^\circ$. This anisotropic interpretation has been favored by Perez, Penston & Moles 1989a, b. Since a large fraction of well-observed Seyfert 1 nuclei do vary, this would require that they be observable essentially only within this cone. It would require that the “other” side not be observable, cut off by an opaque equatorial plane, and that the BLRs not be observable from outside this relatively narrow cone about their axes. Cylindrically symmetric, or “torus”, models of this type are discussed in the next section.

4. Torus Model

It has been generally accepted for many years that the most plausible energy source in an AGN is the accretion
disk around a central massive black hole and that, correspondingly, the structure of the BLR and the NLR are more likely to be roughly axisymmetric than spherically symmetric. There are many observational indications that the directions of the axes of the central source, of the BLR, and of the NLR are not strongly correlated with one another, as summarized for instance by Osterbrock & Mathews 1986. This is easy to understand because of the vastly different masses of these three objects, roughly $10^{6.5} \text{M}_\odot$, $10^{12} \text{M}_\odot$, and $10^9 \text{M}_\odot$, respectively, for a representative nucleus. The mean radii and, hence, the angular momenta per unit mass of these regions are quite different, and also are the mean epochs in the past at which the material now in these regions arrived there. As will be discussed further in Section 7, the fueling of AGNs is probably episodic and occurs in interactions with other galaxies, so it is quite plausible that these various angular-momentum vectors be in different, uncorrelated directions.

A very great step forward in understanding the structure of some if not all AGNs was provided by the spectro-polarimetric measurements of NGC 1068 by Antonucci & Miller 1985 and by Miller 1988. They found that the spectrum in plane-polarized light of this well-known Seyfert 2 galaxy shows the broad emission lines of H\textsc{i} and Fe\textsc{ii} characteristic of a Seyfert 1 galaxy. They interpreted this polarized Seyfert 1 spectrum as coming from a “hidden BLR”, which cannot be observed directly from the direction of the Sun because of heavy extinction (or “reflection”) deep within the AGN, from which it emerges along the axis and is scattered in all directions by free electrons outside the BLR. The observed polarization direction agrees with the interpretation that the broad emission-line photons have emerged along the axis of the jet as mapped in the radio-frequency spectral region. As Antonucci & Miller 1985 pointed out, this interpretation may apply not only to NGC 1068 but also to many or all Seyfert 2s as well. Thus, their interpretation is related to earlier suggestions that different types of Seyfert galaxies are similar objects, seen from different aspects (Lawrence & Elvis 1982; Lawrence 1987). It goes beyond them in providing a definite physical picture based on new observational data. Many theoretical studies and interpretations of AGN spectra, from the X-ray spectral region to the infrared, have been made on the basis of this hidden-BLR picture, for instance by Krolik & Begelman 1988, Krolik & Lepp 1989, and Miller, Goodrich & Mathews 1991.

On this picture, it is clear that not only the optical radiation from the BLR but also ionizing photons from the central source itself would be expected to escape preferentially along the axis of the disk, or jet, as suggested earlier for instance by Osterbrock 1978. Long-slit spectra taken by Baldwin, Wilson & Whittle 1987 clearly reveal the AGN-type emission-line spectrum of gas photoionized by a hard source, extending to the X-ray region, projected onto the face of NGC 1068, but distinct from the starburst-type emission-line spectra of the H\textsc{ii} regions in this galaxy. Likewise, Fabry-Perot [N \textsc{ii}] images of this same galaxy by Cecil, Bland & Tully 1990 show this same component, photoionized by the hard spectrum from the nucleus, in addition to the H\textsc{ii} regions.

The best way to see these “ionization cones”, the regions photoionized by the hard photons emerging from the nucleus, in directions about the axis defined by the nucleus of the jet, is provided by the ionization maps of NGC 1068 and other Seyfert 2 galaxies published by Pogge 1988, 1989a. They were produced by dividing an [O \textsc{iii}] image (emphasizing the AGN-type spectra) by an H\alpha + [N \textsc{ii}] image (emphasizing the H\textsc{ii}-region-type spectra) and clipping at the right isophote level to preserve the ionization cones but remove the starburst regions. Four of the eleven Seyfert 2 galaxies which Pogge studied in this way show either one-sided or two-sided ionization cones of this type, and two others show something similar but not obviously conical distributions. The mean [full] opening angle of the ionization cones is about 50°, which on the physical picture described above is determined by the relative height and diameter of the torus. An independent determination of this same ratio by Osterbrock & Shaw 1988, from the relative numbers of Seyfert 1 and Seyfert 2 galaxies, interpreted with a similar model, agrees very well with this value.

Close association of the position angle of the radio jet with the axis of the NLR and the interpretation of this direction in terms of the escape of ionizing photons from the central source has been particularly studied and put on a quantitative basis by Unger et al. 1987, using long-slit spectra, and by Haniff, Wilson & Ward 1988 and Wilson, Ward & Haniff 1988, using direct images. They lend considerable support to the idea that many, if not all, Seyfert 2 galaxies do contain a hidden BLR and, if observed from another direction, might well appear as Seyfert 1 galaxies. This would mean that interpreting the radiation from AGNs as spherically symmetric is incorrect. Rediscussion of the luminosity functions of Seyfert 1 and of Seyfert 2 galaxies from this point of view is clearly in order.

Evans & Dopita 1986 found from their long-slit spectra of NGC 1068 that the gas in its ionization cone shows ionization up to [Ne \textsc{v}] $\lambda$3426, even out to distances 2 kpc from the nucleus, but that He \textsc{ii} $\lambda$4686, though present, is weak. Bergeron, Petitjean & Durret 1989 extended this result with many more spectra and interpreted it in terms of a radiation field with a cutoff toward lower energy at $h\nu \sim 0.2$ keV, presumably resulting from absorption of the lower-energy photons by H\textsc{i}, He\textsc{ii}, and He\textsc{iii} within the NLR, closer to the nucleus.

Further confirmation of the torus model of NGC 1068 is provided by some of the first images taken with the
Hubble Space Telescope, using its planetary Camera. After processing, these images yield angular resolutions \( \leq 0.1' \). An [O III] image shows the narrow emission-line emitting gas extending close into the nucleus, in the position angle of the radio-frequency jet. The emission-line “clouds” are very well correlated in position with the radio-frequency “knots” and lie within the extension of the one-sided ionization cone known from the ground-based work into the apparent nucleus. This HST image is shown and discussed in detail by Evans et al. 1991. A continuum image, taken by Lynds et al. 1991 with a filter which cuts out all strong emission lines, does not show an unresolved, quasi-stellar nucleus as would be expected if it were directly resolvable. Instead, the nucleus is resolved, with FWHM \( \sim 0.15' \) (\( \sim 11 \) pc at the distance of NGC 1068). This value is consistent with the torus model, in which the nucleus is observable only indirectly, by dust scattering.

5. AGNs and Galaxy Interactions

Very few AGNs are found in dense clusters of galaxies, but they do exist in less compact clusters, as reported by Peterson 1982, 1987. Presumably this results from interstellar gas, the probable source of fuel for the accretion disks of AGNs, being swept out of the galaxy by the intergalactic, intracluster gas. That many Seyfert galaxies are distorted spirals, that many are barred or have nearby “companion” galaxies, and that many are in pairs or interacting systems are early findings by Adams, Simkin, Vorontsov-Velyaminov, and others as summarized and referenced in detail, for instance, by Osterbrock & Mathews 1986. The most straightforward interpretation of these results is that noncircularly symmetric interactions can deliver gas to the center of such a galaxy, with essentially zero angular momentum, as is necessary to refuel (or continue to fuel) the accretion disk around a black hole.

Dahari 1984, from a statistical study of a well-defined sample of nearly Seyfert galaxies, found these objects approximately five times as likely to have “companion” galaxies, as “normal” (non-Seyfert) galaxies drawn from his comparison sample. An even greater factor applies for very close companions of comparable size to the Seyfert or field galaxy. Here a “companion” does not necessarily mean a gravitationally bound object, as in a double star, but a galaxy that is nearby (within specified limits) in position and radial velocity (to the extent measurements of the latter are available). A companion galaxy is either passing by and will escape or will spiral in and be captured within a relatively few orbital periods, because of the very many internal degrees of freedom which can be excited. The problems with a statistical study of this type lie in defining a comparison sample of non-Seyfert but otherwise similar galaxies (which may be impossible) and in the “background correction” for projected apparent companions which are actually some distance behind or in front of the galaxy being investigated.

Fuentes-Williams & Stocke 1988 found the opposite result from Dahari, working with a smaller sample with larger average redshift or distance. They used an older, less complete list of Seyfert galaxies, which was especially incomplete in Seyfert 2s. Very recently MacKenty 1989, 1990 has made another statistical investigation, using a newer and presumably even more nearly complete sample of Seyfert galaxies. His result agrees with that of Dahari, that they are more likely to have companions than his comparison sample of average field spiral galaxies. MacKenty also found that starburst galaxies are equally likely with Seyfert galaxies to have companions, emphasizing the role that interstellar matter undoubtedly has in fueling and refueling both star formation in large complexes and “activity” in the nuclei of Seyfert galaxies.

Both Petrosian and MacKenty 1989 found that Seyfert 2 galaxies are more likely to have companions than Seyfert 1 galaxies are. (This may be related to the higher luminosity of Seyfert 1 nuclei, making the magnitude difference between the primary and companion greater.) The sample used by Fuentes-Williams and Stocke was deficient in Seyfert 2s, which may account for their not finding the higher percentage of companions which Dahari and MacKenty did. Even more recently Rafanelli & Marziani 1991, using the Veron-Cetty & Veron 1985 catalog of Seyfert galaxies, have again confirmed an overabundance of close companions among these objects.

Interacting galaxies (as defined by the distortions and other apparent results of interactions in their images) tend to have an excess of AGNs, but strongly interacting systems do not. This result has been found, for instance, by Kennicutt & Keel 1984, Keel et al. 1985, and Buschke 1986, as well as by Dahari and MacKenty in the references cited above.

Many examples of interactions can be found in images of “low-redshift QSOs”, for instance by Hutchings & Crampton 1990 and earlier references listed there. Many AGNs also occur in loose groups, such as Stephan’s “quintet”. Some “multiple-nuclei” Seyfert galaxies are known, which appear to be close collisions in progress. Some may be actual mergers. In other cases only an apparently single nucleus is observed, yet the galaxies have pronounced tidal tails. Very probably these are interacting galaxies in which the two nuclei are too close to be resolved. All these situations are discussed in considerable detail, with many references to the original papers, by Fricke & Kollatschny 1989. Evidently they are all situations in which gravitational interactions between galaxies or mergers can result in the delivery of interstellar gas and dust with essentially zero angular momentum to the near vicinity of an accretion disk about a central black hole.
N-body calculations, e.g., by Byrd et al. 1986 and Byrd, Sundelius & Valtonen 1987, reproduce semi-quantitatively the association of the strength of the perturbation (proportional to the ratio of mass of perturber to mass of galaxy and inversely proportional to the cube of the ratio of the radius of the galaxy to the distance of their closest approach) with the presence or absence of an AGN. These results thus suggest that many galaxies “bare” massive black holes in their nuclei, only awaiting fueling to become active. The most recent calculations, described by Hernquist 1989a, are based on a hybrid $n$-body numerical-hydrodynamics code. They show many situations in which close, slow approaches of galaxies can lead to interactions in which gas is delivered close to the nucleus with significantly reduced angular momentum.

### 6. Masses

Accretion-disk models can be fitted to the featureless continuum in QSOs and Seyfert 1 nuclei, specifically to the “big blue bump”, which generally peaks in the ultraviolet. The simplest model to calculate is a geometrically thin, optically thick disk. Such a model, with its two parameters, mass $M$ and mass accretion rate $\dot{M}$, provides a significantly better fit for high-luminosity QSOs (whose continua are least affected by underlying galaxy absorption-line spectra) than does a blackbody, with its two parameters $L$ and $T$. However, nearly all the published models predict a large discontinuity at the H I Lyman limit, $\lambda 912$, either in emission or absorption, as found most recently by Laor & Netzer 1989. In the few QSOs observed to test this prediction, by Antonucci, Kinney & Ford 1989, the strong absorption discontinuities were not found, casting doubt on the applicability of these thin-disk models.

However, if this Lyman-limit discrepancy is supposed capable of solution by more detailed models, fitting the rest of the featureless continuum can be used to determine the black-hole masses. The results found by Sun & Malkan 1989 by this procedure are that AGNs with strong observed continua, QSOs and Seyfert 1s, have masses that are in the range $M \approx 10^6$ to $10^8 \text{M}_\odot$, and luminosities which tend to be close to the Eddington luminosity, $L \approx L_E$. For the less-luminous Seyfert 1 galaxies the masses tend to be smaller, $M \approx 10^{7.5}$ to $10^{8.5} \text{M}_\odot$. Their luminosities $L$ are usually only a few percent of $L_E$.

These values of the masses roughly agree with those estimated from broad-emission velocity widths, with distances (sizes of the BLR) taken from photoionization models, as reviewed for instance by Osterbrock & Mathews 1986. There is no information on the masses of black holes in Seyfert 2 galaxies, for nearly all their featureless continua are too weak to fit accurately, and the NLRS are so large that the gravitational force of the stars dominates over that of the black holes. It would certainly be extremely valuable to try to fit the very few Seyfert 2 spectra in which the featureless continuum can be observed and also to deconvolve the observed polarized-light spectrum of NGC 1068 over a long wavelength interval, to further test the “hidden Seyfert 1” model.

### 7. Fueling

As discussed in Section 5, there are many observational indications that nuclear activity is associated with galaxy interactions. There seems little doubt that the physical process responsible for this association is the ultimate delivery of interstellar matter near the nucleus. Probably in many cases there is a preexisting massive black hole, quiescent because it has previously exhausted all the available fuel. No doubt in others a new black hole is formed. For interstellar matter to reach or form an accretion disk around a massive black hole requires it to approach to within a distance $\sim 10^{-2}$ to $10^{-3}$ pc. This means losing very nearly all its angular momentum on the scale of the galaxy, $\sim 10$ kpc. Rather than occurring all at once in a single process, it seems more plausible that this loss takes place in several successive stages along the lines outlined by Hernquist 1989b. The hierarchy he suggests begins with galaxy formation, mergers, and perturbations on the scale of the whole galaxy. From there noncircularly symmetric perturbations, such as bars and perturbations by companions, can reduce the angular momentum of some of the material so that it falls to distances $\sim 1$ kpc. From here self-gravitational disk interactions can reduce the angular momentum of some of the material still further, allowing it to fall to $\sim 10^3$ pc. Hernquist suggests that at this scale (comparable with the scale of the nucleus) star formation in starbursts may occur. This would allow the remaining gas to contract more rapidly, perhaps forming a dense star cluster and ultimately a black hole or, perhaps, an accretion disk about a preexisting black hole.

There are many observations which indicate that starbursts and nuclear activity are linked, as emphasized for instance by MacKenty 1989. However, there is also good evidence that at the detailed level nuclear star formation and nuclear “activity” tend to occur in different types of galaxies, as discussed by Pogge 1989. At any rate, the idea of a hierarchical series of processes proposed by Hernquist, with many alternate pathways from the galactic scale to the nuclear scale, is a good one. A somewhat similar overall picture has also been published by Shlosman et al. 1990. Detailed numerical calculations and comparison of observations of specific objects with predictions of specific models will no doubt be the path of progress in understanding further the nature of AGNs in the next several years.

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