Revista Mexicana de Astronomía y Astrofísica, **26**, 65-72 (1993)

THE NATURE AND STRUCTURE OF ACTIVE GALACTIC NUCLEI. II

Donald E. Osterbrock
University of California Observatories, Lick Observatory,

RESUMEN

Se describe nuestro conocimiento actual de la naturaleza y estructura de los núcleos activos de galaxias (NAGs) basado principalmente en espectroscopía óptica, pero incluyendo resultados de muchos autores que cubren el intervalo completo de longitudes de onda observables. Se hace énfasis en la importancia del polvo en los NAGs y se discuten las ideas actuales de su distribución y su efecto en los espectros observados. Se discute el modelo de toro, la polarización y la naturaleza de 'Seyfert 1 escondida' en NGC 1068 y en al menos otras dos galaxias Seyfert 2. Es muy probable que la mayoría de los *QSOs*, galaxias Seyfert y *LINERs* formen una familia, y que haya muchos NAGs débiles aún no detectados en galaxias aparentemente normales. Se describe a grandes rasgos una hipótesis de trabajo que involucra reabastecimiento de combustible en NAGs mediante interacciones de galaxias.

ABSTRACT

Our current understanding of the nature and structure of active galactic nuclei is described, chiefly on the basis on optical spectroscopy, but including results of many authors, covering the entire observable wavelength of energy range. The importance of dust within the AGNs is emphasized, and current ideas of its distribution and of its effect on the observed spectra, are discussed. The torus model, polarization, and the "hidden Seyfert 1" nature of NGC 1068 and at least some other Seyfert 2 galaxies are discussed. It is likely that most QSOs, Seyfert galaxies and LINERs form one family, and there may be many as yet undetected low-luminosity AGNs in apparently normal galaxies. A working hypothesis, involving refueling of inactive galactic nuclei through galaxy interactions, is sketched.

Key words: **GALAXIES – ACTIVE — GALAXIES – NUCLEI — GALAXIES – SEYFERT**

1. INTRODUCTION

Active galactic nuclei (AGNs) are the most luminous objects in the universe. Thus they are the most distant members we can observe, and also the most powerful energy sources we know. For both these reasons we need to understand them physically. They radiate strongly over a very wide frequency or wavelength range, and observational measurements in all spectral regions have aided in understanding them. My own expertise is in optical and near infrared spectroscopy, and I have recently reviewed the subject chiefly from this point of view, but bringing in results from the other spectral regions in two invited papers (Osterbrock 1991, 1993). In the present review I have tried to summarize very briefly the main points covered in these papers, and to discuss in more depth the most recent progress in the field. Only a few of the references given in the earlier two reviews are repeated here; for additional citations to the primary published papers they should be consulted.

AGNs form, so well as we understand them, one family of objects, though we call the most luminous ones quasistellar objects, QSOs (many astronomers use the word quasars, originally applied only to quasistellar radio sources), and the less luminous ones Seyfert galaxy nuclei. That they form one family does not mean that they are all identical, scaled versions of the same object, any more than that all stars, from dwarfs to supergiants and from spectral type M to spectral type O are all scaled versions of the G2 V Sun. Rather it means that, so far as we understand them, they are similar in their physical nature, in the sense that stars are.

According to the most recent complete sample drawn from the CfA redshift survey, slightly over 1% of the galaxies more luminous than M_{Zw} (essentially the same thing as M_B) = —18 have AGNs (Huchra & Berg 1992). However, the fraction increases rapidly at higher luminosities. Approximately 2% of the galaxies more luminous than —19 have AGNs, approximately 3% of those more luminous than —20, approximately 13% of those more luminous than —21, and essentially all of those more luminous than —22. Note also that there may be many more AGNs at lower luminosity levels, which are very hard to detect (Filippenko & Sargent 1985). Their total number, and luminosity function, are among the most interesting current problems in this field.

In the study of any class of astronomical object three questions naturally arise:

1. What is it? Describe it.
2. How does it work? What physical principles govern it?
3. How does it evolve? How did it form? How long will it live? How will it die?

Obviously the third question is difficult to answer before the answers to the first two are reasonably well known, but that has not inhibited may astronomers and physicists in the past, nor will it inhibit the author of the present paper.

2. SPECTROSCOPY

The optical emission-line spectra of Seyfert galaxy nuclei were originally classified into two types. Seyfert 1 spectra have broad permitted lines of H I, He I, He II, Fe II, etc., and narrow forbidden lines of [O III], [N II], [Ne III], [O II], [O I], [S II], [Ne V], etc. Seyfert 2 spectra have narrow permitted and forbidden lines. Some objects however have well-defined composite profiles of the permitted emission lines, particularly H I, with a broad component and a narrow component superimposed on it. These are classified Seyfert 1.5. Some have very weak broad components of Hα and Hβ, the latter broad component in particular only barely visible on ordinary spectral scans. These are classified Seyfert 1.8. Some even more extreme objects exist in which the broad Hβ emission component is so weak as to be undetectable, or nearly so, and the broad Hα component is weak but detectable. These are classified Seyfert 1.9 galaxies. Many authors, however, continue to use only the primary Seyfert 1 or 2 classification.

The narrow emission-line spectra of the Seyfert 1 and Seyfert 2 spectra are approximately the same, covering a wide range of ionization from [O I], [S II], [N II], [O II], etc. through [O III] to [Ne V], [Fe VII], and in some objects [Fe X] and [Fe XI]. There is some tendency for the Seyfert 1 nuclei to have, on the average, somewhat higher levels of ionization than the Seyfert 2's. These observed spectra lead naturally to a simple model of a Seyfert 1 nucleus containing a broad-line region (BLR) in which the internal velocities (presumably some combination of rotation, random "turbulence", and inflow and/or outflow) are high, of order 10^3 to 10^4 km s^{-1}, and a narrow-line region (NLR) in which the internal velocities are smaller, of order a few times 10^2 km s^{-1}. In the BLR the density must be relatively high (since all the forbidden lines are evidently greatly weakened by collisional deexcitation), of similar order of magnitude to the densities in the solar (and stellar) chromosphere(s). In the NLR the density must be considerably lower (since the forbidden lines are strong), of similar order of magnitude to the densities in nebulae.

Many line profile studies show that in most objects the density of the ionized gas in the NLR decreases outward (in the mean), and that the level of ionization also decreases outward (in the mean). But the gas is evidently clumped into condensations (or density maxima), with a relatively small "filling factor". Thus the highest levels of ionization probably occur only in the clouds closest to the center, but lower degrees of ionization occur both there and further out in the NLR. The same appears to be true in the BLR, but with less certainty. And there are many indications that the dichotomy in the BLR and NLR is too great a simplification. The observations seem to show that the true structure is not two separate regions, with no gas at intermediate densities, but rather a continuous distribution with intermediate densities (in the mean) at intermediate distances.

From spectroscopic diagnostics, the mean values of the temperature and density, averaged over many regions in any one NLR, are T $\approx 10^4$ K $\approx$ 1 eV, $N_e \approx 10^4$ cm^{-3}. From the observed luminosities in the individual emission lines this corresponds to a mass of ionized gas $M \approx 10^6\ M_\odot$, and a characteristic size r $\approx 10^2$ pc. Similar average values for the BLR are T $\approx 10^4$ K (with more uncertainty) and $N_e \approx 10^9$ to 10^{10} cm^{-3}, corresponding to M $\approx 10^2$ M and r $\approx$ 0.1 pc. The relatively low temperature, even at high levels of ionization, indicates that the main mechanism of energy input to the ionized gas is photoionization. The wide distribution of level of ionization indicates that the photoionization is by a hard spectrum, extending to very high energies (X-rays), with a greater proportion of high-energy photons than in even the hottest O and planetary-nebula stars we know.

The relative abundances of the elements whose emission lines are observed in AGNs are not greatly different from solar abundances, except that N may be somewhat overabundant.

In many Seyfert 1 nuclei, and some QSOs, the featureless continuum varies, on time scales of days, weeks and months, apparently nonperiodically, and the broad emission lines vary also. Evidently the ultraviolet photoionizing radiation varies along with the optical continuum, changing the ionization structure within the BLR. The delay between the continuum and broad emission-line variations gives information on the size of the ionized region, basically, its characteristic size in light days.

The earliest results from these "light reverberation" measurements chiefly showed that closer time monitoring was necessary. Recent results from large collaborations tend to give smaller dimensions for the BLRs than the figure quoted above, and hence higher electron densities, more like 10^{10} to 10^{11} cm^{-3}. The discrepancies are not large, and probably mean that more sophisticated geometrical models are needed, rather than indicating a fundamental problem. These "time-delay mapping" results show that higher-ionization lines are emitted (in the mean) closer to the nucleus than lower-ionization lines. Likewise, C III] λ1909, which can be partly collisionally deexcited, tends to come from farther out from the nucleus, again indicating that the density decreases outward (in the mean) in the BLR. The very fact that the variations of the broad lines follow the continuum variations is an indication that photoionization is an important source of energy for heating the BLR.

3. DUST

Dust shows up in extinction in the NLRs by its reddening effect on the H I Balmer decrement. Because of the large partly ionized zone in AGNs resulting from ionization by high-energy photons, which penetrate deeply into the neutral gas, collisional excitation of Hα is not negligible in AGNs, as it is in H II regions photoionized by hot stars. Accordingly, the intrinsic Hα/Hβ ratio is approximately 3.1 in the NLRs, rather than about 2.8 as in nebulae (Gaskell 1983; Malkan 1983; Gaskell & Ferland 1984). These measurements show that the Seyfert 2 galaxy spectra, on the average, are more highly reddened than the narrow-line spectra of the Seyfert 1 and 1.5 galaxies.

In Seyfert 1s the broad H I emission lines arise from recombination, modified strongly by collisional excitation and optical-depth effects, because of the high densities in the BLRs. Thus the "intrinsic" intensity ratios I(Hα)/I(Hβ) and I(Hβ)/I(Hγ), as emitted in the BLR are not independently known and the questions of reddening and the presence or amount of dust are more controversial. Early measurements of a large number of Seyfert 1 galaxies appear to show that these objects do scatter around the expected reddening line in and Hα − Hβ − Hγ diagram, suggesting that dust is present in or near the BLR (Osterbrock 1973). The dispersion, however, is so large (as expected from the combined effects of collisional excitation and Balmer-line self absorption and fluorescence) that this evidence is merely suggestive, not conclusive.

A recent careful reduction, based on the best observational data for Seyfert 2 galaxies, suggests that the intrinsic intensity rates I(Hα)/I(Hβ) may be closer to 3.4, than 3.1 as used in most recent discussions (Binette et al 1990). Further theoretical and observational studies of this point are clearly desirable.

In a very recent paper Laor and Draine (1993) conclude, from theoretical considerations on the survival of dust particles in the radiation fields and particle densities in AGNs, plus fitting the available observational data, particularly on the absence (or weakness) of the $\lambda 9.7\mu$m amorphous silicate absorption feature, that dust is not present in most BLRs. However, the result depends on necessarily simplified assumed physical conditions in the BLR, and prior experience with similar predictions in planetary nebulae, in which dense condensations apparently preserve dust, which is gradually fed into the ionized gas as these "clumps" are eroded by radiation, suggests that the result is not certain.

Perhaps the strongest suggestion that dust is present in some BLRs is provided by observations of the broad components of Hα and Hβ is Seyfert 1.8 and 1.9 galaxies. In these objects the I(Hα)/I(Hβ) intensity ratios are unusually large, suggesting strong dust extinction (Osterbrock 1981; Goodrich & Osterbrock 1983; Goodrich 1989). Several Seyfert galaxies have been observed to vary over time between Seyfert 1 or 1.5 and Seyfert 1.9, including NGC 7603 = Mrk 530 (Tohline & Osterbrock 1976), NGC 4151 (Penston & Perez 1984; see also Antonucci & Cohen 1983, whose spectra show it was a Seyfert 1.8 in December 1980), Mrk 1018 (Cohen et al 1986), NGC 2622 = Mrk 1218 (Goodrich 1989), Mrk 372 (Gregory, Tifft & Cocke 1991) and Mrk 993

(Tran, Osterbrock & Martel 1993). To explain these spectral variations in NGC 7603, Tohline & Osterbrock (1976) suggested changes of the amount of dust extinction as one of several possible mechanisms. Cohen et al (1986) rejected this mechanism in Mrk 1018 on the basis of their optical and IUE ultraviolet measurements, but Goodrich (1989), on the basis of further optical measurements, concluded that this interpretation can explain the variability of this object, NGC 7603, and NGC 2622. In a follow-up paper based on measurements of H I Paβ, Goodrich (1990) strengthened this conclusion, and showed that it also applies to IRAS 1958−183, but that the same mechanism cannot account for the variations observed in Mrk 609 and UGC 7064, which also vary between Seyfert 1 or 1.5 and 1.8 or 1.9. In these latter two objects, changes in the ionization appear to be the main cause of the observed variations in the broad H I emission lines.

Netzer & Laor (1993) have put forward the interesting idea that the separation between the BLR and NLR results from the fact that dust is present in the NLR, but cannot exist in the BLR because of the strong radiation fields there, which cause the solid particles to sublimate. Thus in the BLR much of the ionizing radiation can be converted directly into (broad) emission-line photons, while in the NLR a large part of this radiation is absorbed by dust and converted into infrared continuum radiation. The remainder goes into photoionization and thus into emission-line photons, but over a much larger length scale. Netzer and Laor (1993) show quantitatively that the luminosities, spectral energy distributions and sizes of the BLRs, together with the physical properties of the dust in AGNs so well as they are understood, are consistent with the particles sublimating approximately at the outer edge of the BLR. Of course it is highly unlikely that there is a sharp distinction in the AGNs, and it is quite plausible that many AGNs may have dust in the parts of their BLRs that are either furthest from the central source, or densest and best shielded from the radiation.

In fact, the variations mentioned above, in which the emission-line spectrum varies between Seyfert 1 and 1.9, may be interpreted on this picture as cases in which the amount of dust in the "outer" part of the BLR is varying. Even those cases in which the main cause of the observed emission-line variation is variations in the ionization parameter can perhaps result from absorption of the ionizing radiation by variations in the amounts of dust "within" the BLR.

4. DIAGNOSTICS

Starburst galaxies, which have large numbers of recently formed O stars in their nuclei, and hence large numbers of H II regions or a large region of gas photoionized by the ultraviolet radiation from hot stars, are much more frequent per unit volume of space than Seyfert galaxies. Although most of them have emission line spectra similar to he Orion nebula, some have considerably higher ionization or excitation, with intensity ratio I([O III] λ5007)/I(Hβ) as large as 5 or 6. This is as large, or larger than the value of this same ratio in many Seyfert 2 galaxies. The starburst galaxies can be distinguished from them by their narrower emission lines, by the relative weakness of [O I] λ6300, [S II] $\lambda\lambda$6716, 6731 and [N II] $\lambda\lambda$6548, 6583 in their spectra, and by the absence of [Ne V] λ3426, [Fe VII] λ6087 and [Fe X] λ 6375. Diagnostic diagrams based on these and other emission-line ratios, as pioneered by Baldwin, Phillips & Terlevich (1981) are the best quantitative method to separate starburst and Seyfert galaxies. The best ratios to use are those which are both physically significant, and involve intensity ratios of lines close together in wavelength, such as I([O III] λ5007/I(Hβ) and I([N II] λ6583)/I(Hα), thus minimizing the effects of errors in intensity calibration or in reddening correction (Veilleux and Osterbrock 1987).

In the near infrared, [S III] $\lambda\lambda$9069, 9531 are the strongest emission lines in all Seyfert galaxies and starburst galaxies, completely analogous to [O III] $\lambda\lambda$4959, 5007 in the optical spectral region. Similar diagnostic ratios involving these [S III] lines, and [O II] $\lambda\lambda$7320,7330, [S II] $\lambda\lambda$6716, 6731 in the red and near infrared may also be used for classification (Morris & Ward 1988; Kirhakos & Phillips 1989; Osterbrock, Tran & Veilleux 1992). The advantage of these near-infrared diagnostic ratios is that the lines are less affected by extinction, and can be observed even in galaxies in which the AGN is more heavily obscured by dust. However, the disadvantage is that the near-infrared spectral region observable with currently available CCDs only includes higher H I Paschen lines up to Pδ (n = 3 - 7) λ10049 and Pγ (3 - 6) λ10938, which are relatively weak, and (particularly Pδ) in a region in which the sensitivity is dropping rapidly with increasing wavelength. Hence only Hα, which is close to the [O II] and [S II] lines, but far from [S III] in wavelength, has been used as the H I member of the diagnostic line ratios.

Measurements further into the infrared of H I Pα and Brγ, H_2 molecular lines, and [Fe II] are even more advantageous. Although only few results in this region are now available, they will undoubtedly come at an increasing rate, and will be invaluable for further understanding the nature and structure of AGNs, especially in their cooler, dustier, less highly ionized regions, and the partly ionized and dissociated regions within and near them. It will be important to measure the same carefully defined regions within the galaxy in the ultraviolet, optical and infrared spectra which are compared.

5. CYLINDRICAL STRUCTURE

The inner structure of AGNs has long been regarded as having approximately cylindrical, rather than spherical symmetry. The chief observational reason is that many of the nearest Seyfert galaxies are observed to have small "jets" attached to their nuclei, on high angular resolution radio-frequency maps. These jets appear to be strongly associated with the [O III] emission. From the theoretical point of view it is hard to imagine that the gas and dust near the center have identically zero angular momentum, which suggests that there is a plane of symmetry and an axis of rotation perpendicular to it. The only sufficiently powerful known energy source is the conversion of gravitational energy into heat and radiation, and the most plausible mechanism is the release of energy by mass disappearing into a black hole (Lynden-Bell 1969; Rees 1984). Again, it is difficult to believe that on the very small scale of an accretion disk, the gas could have exactly zero angular momentum.

On the other hand, the central nuclear structure is not necessarily aligned with the overall structure of the galaxy in which the AGN is present. Many galaxies, including our own, have warps near the centers. The observed radio-frequency jets of AGNs are in general not in the same direction as the axes of rotation of the galaxies in which they lie.

This general picture, incorporated in most observationally based models of AGNs, was confirmed and greatly extended by Antonucci & Miller (1985) and Miller (1988), in their spectropolarimetric measurements of the nearby, bright Seyfert 2 galaxy NGC 1068. Their spectra show that the weak, plane-polarized radiation of this AGN has a Seyfert 1 spectrum with broad permitted H I emission lines, and Fe II blends of emission lines. The plane of polarization is perpendicular to the axis of the radio-frequency jets observed in NGC 1068. The interpretation they proposed is that there is a "hidden Seyfert 1 nucleus" in NGC 1068, invisible from our line of sight because of the large optical depth in the direction of the equatorial plane of this AGN, but from which radiation escapes along the axis. Some of this escaping radiation is then scattered by free electrons, and all of these scattered photons which reach us are polarized so that their E-vectors are, on the average, perpendicular to the axis of the jet, as observed. This is the now widely accepted "torus model".

Electron scattering was proposed as the scattering mechanism because the degree of polarization observed in the featureless continuum and broad lines is independent of wavelength in the optical region (Miller & Antonucci 1983; Antonucci & Miller 1985; Miller 1988; Miller, Goodrich & Mathews 1991). This conclusion was greatly strengthened by the ultraviolet spectropolarimetric measurements of NGC 1068 obtained by Code et al (1993) from the 1990 Astro-1 mission of the space shuttle Columbia. They found that the degree of polarization of the featureless continuum remains nearly constant down to $\lambda1500$. It does not seem possible to explain the flat polarized flux over the large spectral range covered by the combined optical and satellite ultraviolet measurements by scattering by dust. Only electron scattering can match the observed polarized spectrum.

Miller & Goodrich (1990) and Tran, Miller & Kay (1992) have observed this same "hidden Seyfert 1 nucleus" phenomenon in several other Seyfert 2 galaxies, in the optical spectral region. In each case the direction of polarization is perpendicular to the axis of the jets or other elongated radio-frequency structure.

Ionization by hard radiation from an AGN, escaping along its axis, has been observed on a large scale, comparable with the scale of the galaxy, in NGC 1068 and several other Seyfert 2 galaxies by many authors, as reviewed extensively e.g. by Osterbrock (1989, 1991).

6. ONE FAMILY

As mentioned in the introduction, AGNs seem to form one family. QSOs and Seyfert 1 galaxies or nuclei appear to be continuous in their properties. The only well-defined way to separate them is by an arbitrary division in luminosity, usually taken as $M_B = -23$ (Schmidt & Green 1983). Likewise, quasars and radio galaxies, both less abundant by a factor 10^2 than their radio-quiet equivalents, appear to merge continuously into one another in their physical properties. But the radio objects are cD, D or E galaxies (if they can be classified morphologically from their optical images), while the Seyfert galaxies are spirals. The active nuclei seem to be similar, and the differences between the radio-loud and radio-quiet objects, including their relative frequency, are probably related to the fact that spiral galaxies contain much more interstellar gas and dust than elliptical galaxies.

LINERs is the name coined by Heckman (1980) for low-ionization nuclear emission regions, galaxies with emission lines in their spectra that are lower in ionization or excitation than the typical Seyfert-galaxy lines, but that cover a wider range of ionization than H II regions and starburst galaxies. Those in which the emission lines arise in the nucleus appear to be the extension of AGNs to lower levels of luminosity, or of hardness of the photoionizing radiation. (Other LINERs, with diffuse emission spread through the body of the galaxy, are clearly cases of "shock" or collisional heating).

Although LINERs with strong emission lines are relatively easy to recognize, at fainter levels there may be many as yet undetected. Studies by Stauffer (1982) and Keel (1983) show that an appreciable fraction of all spiral galaxies reveal weak LINER characteristics, if searched carefully enough. The nucleus of our own Galaxy, though not optically observable from our position near the galactic plane, because of very heavy intervening dust extinction, does show weak activity in the infrared and radio spectral regions. However, it is so weak that our Galaxy probably would not be classified as a LINER from a position with a direct line of sight to its nucleus. The nucleus of M 31 is even weaker in its LINER or Seyfert 2 characteristics, but nevertheless on high resolution spectra, taken very close to its nucleus, shows strong [N II] emission (Rubin & Ford 1986).

7. EVOLUTION

There is a close association between starburst galaxies and Seyfert galaxies, as pointed out and emphasized by Weedman (1983). Many Seyfert galaxies have strong starburst regions near their nuclei. However, starburst galaxies are much more numerous than Seyfert galaxies, and hence it is obvious that most starburst galaxies are not Seyferts.

Both Seyfert galaxies and starburst galaxies tend to be more frequent in loose groups of galaxies, and among galaxies that have "companions", that is, other galaxies close enough to them to interact gravitationally with them. The empirical evidence for these statements, based on statistical studies, is summarized and reviewed by e.g. Osterbrock (1989, 1991). A few of these studies have reached the opposite conclusion, but the bulk of the evidence favors the statements as given. Also, many Seyfert galaxies are barred galaxies, or show other types of distortion, indicative of recent gravitational interactions.

Since starburst nuclei are more extended than Seyfert galaxy nuclei, it seems likely that the direction of evolution is from starburst to Seyfert; that some, but not all starburst galaxies become Seyferts as their nuclei contract. In general angular momentum inhibits contraction; evidently, only the objects in which angular momentum is "lost", or transferred so that some of the material ends up with near-zero angular momentum, can contract to the Seyfert nucleus stage.

The black-hole, accretion-disk picture of AGNs leads naturally to many of these observed correlations. The fundamental idea is that an existing black hole has an upper limit to its luminosity, the Eddington luminosity, dependent on its mass.

$$L \leq L_E = \frac{4\pi c G m_H M}{\sigma_T} = 1.3 \times 10^{38} \frac{M}{M_\odot}.$$

Sketchy observational data suggest that Seyfert 1 nuclei typically have black holes with $M \approx 10^{7.5-8.5} M_\odot$ and $L \approx 10^{-1} L_E$, while QSOs have $M \approx 10^{8-9.5} M_\odot$ and $L \approx L_E$. In any case the mass consumption rate is related to the luminosity, and as a result for a QSO with $L \approx L_E$, the time scale for the black hole mass to increase by a factor e is

$$\tau = 4 \times 10^7 \left(\frac{\epsilon}{0.1}\right) yr.$$

Here ϵ is the fraction of the mass disappearing into the black hole which escapes as radiation, conventionally estimated to be $\epsilon \approx 0.1$. For a Seyfert 1 radiating at $10^{-1} L_E$ the time scale τ is ten times longer. Very roughly a black hole will appreciably increase its mass, if supplied with sufficient fuel, in $\sim 10^8$ yr, or, put another way, will exhaust the available fuel, unless its amount is very large, in this time.

Hence any existing AGN is likely to "die" or "go out", in approximately this time. It will then continue its existence as an apparently normal galaxy, with a quiescent black hole in its nucleus, until it is refueled by the delivery of new mass, with nearly zero angular momentum, near the nucleus. This refueling evidently can occur most easily in the form of gas, perturbed in an interaction so that its angular momentum is changed. Some of the gas will gain angular momentum and either leave the galaxy, or form tidal tails and other distorted structures. But some of the gas will have enough angular momentum, closer to the center of the galaxy in which it remains. Further instabilities can then take over and allow the gas to fall still closer to the nucleus. These processes have been discussed and analyzed by many authors, as reviewed e.g. by Osterbrock (1989, 1991).

The result in many cases must be star formation, and in some of these, nuclear star formation. This may lead, in some cases, to still further instabilities and to some of the gas falling even closer to the central black hole. In this way a new accretion disk can form, refueling and reactivating the black hole. This currently appears the most plausible mechanism for understanding the evolution of active galactic nuclei. Since the dynamical time scale of a galaxy is typically a few times 10^8 yr, comparable with the lifetime of an AGN, we may hope to date the evolution of a nucleus by the distortion still observable in the galaxy from the interaction. In fact the available statistical results show that the most disrupted, strongly perturbed objects are starburst galaxies, but not Seyfert galaxies. Evidently the time required for the starburst nucleus to become unstable and contract enough to form or refuel an AGN is sufficiently long so that the major distortions of the galaxy itself decay before the active nucleus becomes observable.

Note that the evolution of the black hole is always toward greater mass, greater Eddington luminosity, and hence, if fuel is or becomes available, toward higher luminosity. The "ultraluminous infrared galaxies" identified by Sanders et al (1988) as "the origin of quasars" appear to be large, massive, dust-rich interacting galaxies. Most of them have Seyfert 2 optical spectra. Evidently the BLR, if present, is completely hidden in these objects. At lower levels of distortion, Seyfert 2s appear to be more dust-rich than Seyfert 1s. But the less luminous AGNs are also more commonly Seyfert 2s than Seyfert 1s. Thus the direction of evolution may be *starburst galaxy* → *Seyfert 2* → *Seyfert 1* → *Seyfert 2* → *LINER* → *quiescent* in some cases, and simply *Seyfert 2* → *LINER* in others, depending on orientation. However, several parameters are involved; the mass of the black hole, the mass consumption rate (or equivalent L/L_E, the fraction of the Eddington luminosity at which the object radiates), the amount of dust (which probably depends on the past history of the object), and the parameters of the interaction. Clearly we do not fully understand AGNs, but this evolutionary picture seems at present to be the most promising direction for further investigation.

I am indebted to many colleagues for valuable discussions and thoughts, and to the organizers of the VII LARM for inviting me to give this review. As always, I am grateful to the University of California for continued support of my research, and to the National Science Foundation for its partial support under grant AST 91-23547.

REFERENCES

Antonucci, R. R. J., & Cohen, R. D. 1983, ApJ, 271, 564
Antonucci, R. R. J., & Miller, J. S. 1985, ApJ, 297, 621
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Binette, L., Calvet, N., Canto, J., & Raga, A. C., 1990, PASP, 102, 723
Code, A. D., Meade, M. R., Anderson, C. M., Nordsieck, K. H., Clayton, G. C., Whitney, B. M., Magalhaes, A. M., Babler, B., Bjorkman, K. S., Schulte-Ladbeck, R. E., & Taylor, M. 1993, ApJ., submitted
Cohen, R. D., Rudy, R. J., Puetter, R. C., Ake, T. B., & Foltz, C. B. 1986, ApJ, 311, 135
Filippenko, A. V., & Sargent, W. L. W. 1985, ApJS, 57, 503
Gaskell, C. M. 1983, Ap Letters, 24, 43
Gaskell, C. M., & Ferland, G. J. 1984, PASP, 96, 393
Goodrich, R. W. 1989, ApJ, 340, 190
Goodrich, R. W. 1990, ApJ, 355, 88
Goodrich, R. W., & Osterbrock, D. E. 1983, ApJ, 269, 146
Gregory, S., Tifft, W. G., & Cocke, W. J. 1991, AJ, 102, 1977
Heckman, T. M. 1980, A&A, 87, 152
Huchra, J., & Burg, R. 1992, ApJ, 393, 90
Keel, W. C. 1983, ApJS, 52, 229
Kirhakos, S., & Phillips, M. M. 1989, PASP, 230, 639
Laor, A., & Draine, B. T. 1993, ApJ, 402, 441
Lynden-Bell, D. 1969, Nature, 223, 690
Malkan, M. 1983, ApJL, 264, L1
Miller, J. S. 1988, Active Galactic Nuclei, ed. H. R. Miller, & P. J. Wiita (Berlin: Springer) p. 112
Miller, J. S., & Antonucci, R. R. J., 1983, ApJL, 271, L7
Miller, J. S., & Goodrich, R. W. 1990, ApJ, 355, 456
Miller, J. S., Goodrich, R. W., & Mathews, W. G. 1991, ApJ, 378, 47
Morris, S. L., & Ward, M. J. 1988, MNRAS, 230, 639
Netzer, H., & Laor, A. 1993, ApJL, 404, L51

Osterbrock, D. E. 1977, ApJ, 215, 733
Osterbrock, D. E. 1981, ApJ, 249, 462
Osterbrock, D. E. 1991, Rep. Prog. Phys., 54, 579
Osterbrock, D. E. 1993, ApJ, 404, 551
Osterbrock, D. E., Tran, H. D., & Veilleux, S. 1992, ApJ, 389, 196
Penston, M. V., & Perez, E. 1984, MNRAS, 211, 33P
Rees, M. J. 1984, ARA&A, 22, 471
Rubin, V. C., & Ford, W. K. 1986, ApJL, 305, L35
Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. Z. 1988, ApJ, 325, 74
Schmidt, M., & Green, R. F. 1983, ApJ, 269, 352
Stauffer, J. R. 1982, ApJ, 262, 66
Tohline, J. E., & Osterbrock, D. E. 1976, ApJL, 210, 117
Tran, H. D., Miller, J. S. & Kay, L. E., ApJ, 397, 452
Tran, H. D., Osterbrock, D. E., & Martel, A. 1992, AJ, 104, 2072
Weedman, D. W. 1983, ApJ, 266, 479

Donald E. Osterbrock: Lick Observatory, University of California, Santa Cruz, CA 95064, USA.