Active Galactic Nuclei

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SUMMARY
Observational evidence of the structure of active galactic nuclei, and the physical conditions in them, is reviewed, with particular emphasis on optical data. The importance of photoionization by high-energy photons is stressed. Dust seems to play a considerable rôle. X-ray measurements have added greatly to our knowledge of these objects. There are several indications of a tipped, cylindrically symmetric, disc-like structure rather than a spherically symmetric structure. The velocity field is an important constraint that must be predicted by any complete, physical model.

1 INTRODUCTION
Seyfert galaxies, the most frequent type of galaxies with active nuclei, make up only a very small minority of all galaxies. They number perhaps 1 per cent of the giant galaxies, or a few per cent of the giant spirals (Simkin, Su & Schwarz 1980). Very large amounts of energy are released in their nuclei, more than can be accounted for by the stars they contain; they are very interesting from this point of view. Also, an increasingly large fraction of the most luminous optical galaxies are active galaxies (Meurs 1982). A very large proportion of the most luminous radio sources, ‘radio galaxies’, belong to this class, and essentially all quasars and QSOs we know. Understanding them will go far towards helping us understand the Universe.

2 SEYFERT GALAXIES
A Seyfert galaxy is defined by the properties of having a bright, semi-stellar or stellar nucleus, and a spectrum including relatively broad emission lines covering a wide range of ionization. A recent paper by Morgan & Dreiser (1983) shows, in an excellent series of drawings, the continuous increase in contrast between nucleus and galaxy from relatively low-luminosity Seyfert galaxies like NGC 4151 to relatively high-luminosity quasars like 3C48 in which faint ‘fuzz’ or other signs of what is apparently a more or less normal underlying galaxy have been detected by imagery to very faint light levels. All the spectra discussed or shown in the present paper are of the nucleus and the region immediately around it, taken with the Shane 3-m reflector of Lick Observatory using a slit 2·7 × 4·0 arcsec.

The only plausible interpretation of the widths of the emission lines is Doppler broadening by mass motions. Seyfert 1 galaxies are defined as having very broad permitted lines, and narrower forbidden lines (Khachikian & Weedman 1974). An example is Mrk 1243, whose spectrum is shown in Fig. 1. Typical full widths at zero intensity (FWO1) of the H I, He I, He II
and Fe II lines are $10^4 \text{ km s}^{-1} \approx 0.03 \text{ c}$. Extremes range from $\sim 4 \times 10^3$ to $\sim 3 \times 10^4 \text{ km s}^{-1}$, that is, up to $\sim 0.1 \text{ c}$. In Seyfert 1 galaxies the forbidden lines typically have full widths at half-maximum (FWHM) $\sim 5 \times 10^2 \text{ km s}^{-1}$, noticeably broader than in ‘normal’ galaxies but narrow in comparison with the very broad permitted lines. In the remainder of this review, these widths $\sim 5 \times 10^2 \text{ km s}^{-1}$ are referred to as ‘narrow’; it must be remembered that they are ‘broad’ in comparison with the emission lines in non-active galactic nuclei.

Seyfert 2 galaxies on the other hand are defined by the property that their permitted lines and forbidden lines have similar widths, $\sim 5 \times 10^2 \text{ km s}^{-1}$, like the forbidden lines alone in Seyfert 1 galaxies (Khachikian & Weedman 1974). Except for these widths, the emission-line spectra of Seyfert 2 galaxies are quite similar to these of planetary nebulae, as the early observers recognized (Slipher 1917; Hubble 1926; Seyfert 1943). An example is Mrk 1157, whose spectrum is shown in Fig. 2. However, Seyfert galaxies in many cases have a wider range of ionization than planetary nebulae, with [O I] and [S II] strong, as well as [Ne V] and [Fe VII] in many cases, particularly Seyfert 1s.

Planetary nebulae are close, resolved and basically understood, although many problems certainly still remain (see, e.g. Flower 1983). They are photoionized by ultraviolet radiation from their central, hot stars, with temperatures up to $3 \times 10^5 \text{ K} \approx 30 \text{ eV}$. The temperature in the ionized gas,
however, is set in the relatively narrow range \( \sim 1-2 \times 10^4 \text{K} \approx 1 \text{ eV} \) by the equilibrium between photoionization heating and radiative cooling. The planetary nebula itself is a shell cast off by a star of initial mass perhaps 1–4 \( M_\odot \), at the end of its nuclear burning stage, in the process of becoming a white dwarf. The elemental abundances are approximately normal (for the population to which the planetary belongs), except that they are usually somewhat enriched in He, strongly enriched in N, and sometimes also enriched even more strongly in C. These abundances indicate some (but not complete) contamination by nuclear burning of the material that now makes up the nebular shell.

We do not understand Seyfert galaxies in the same way. For any type of astronomical object three basic questions that must be answered are:

1. What is it? Describe it.
2. How does it work? What are the main physical processes that govern its structure and observed properties?
3. How does it evolve? How did it form? How is it changing now? How will it end?

We know approximate answers to these three questions for most types of stars, \( H\alpha \) regions, planetary nebulae (as indicated above), etc. We do not yet understand Seyfert galaxies in the same way, and answering these questions is the goal of all our studies. Planetary nebulae and \( H\alpha \) regions may be regarded as test objects for many of the physical concepts and methods used to seek answers to these questions for active galactic nuclei.
3 PHOTOIONIZATION

The emission-line spectra of Seyfert 2 nuclei can be understood as resulting from photoionization (Collin-Souffrin 1978; Koski 1978). Spectral diagnostics give \( T \approx 1-2 \times 10^4 \) K, far too low for collisional input of energy to the observed ionization levels, and \( N_e \approx 10^4 - 10^5 \) cm\(^{-3}\). From these physical parameters and the observed luminosities in the recombination and forbidden lines, the size of the ionized region can be estimated as \( 10^2 - 10^3 \) pc. A few of the closest Seyfert 2 galaxies can be resolved, and for them these calculated sizes are roughly confirmed. Although no collection of hot stars will produce the observed emission-line spectrum from the resulting photoionized gas (as evidenced by the fact that planetary nebula and H II region spectra do not match Seyfert 2 galaxies), a power-law type spectrum extending far to the ultraviolet will. Featureless continua of the form \( L_\nu \propto \nu^{-\alpha} \), with \( \alpha \approx 1.0 - 1.5 \) are suggested by continuum observations in the observed optical region. Extrapolation of this spectrum to high energies gives about the right distribution of ionization, and also about the right number of ionizing photons to balance the recombinations observed through the H I lines (Osterbrock & Miller 1975; Davidson & Netzer 1979). X-ray observations (of Seyfert 1 galaxies) suggest that an even better representation of the photoionizing featureless continuum may be a combination of two power laws, with \( \alpha \approx 1.5 \) at low energies, and \( \alpha \approx 0.6 \) at high energies (Mushotzky 1982; Ferland & Mushotzky 1982).

The ideal, which we do not yet have, would be a complete physical theory of the photoionizing source in active galactic nuclei. Such a theory would predict the input radiation spectrum, and a check of the picture would be the emission-line spectrum calculated from it. This is the present state of our understanding of planetary nebulae; the input photoionizing spectra for the best models are calculated from model atmospheres of the central stars, which depend on their masses, radii, luminosities and elemental abundances. These parameters in turn can be calculated, at least in principle, from the initial mass and evolutionary history of the parent star. Years ago, planetary nebula models were calculated assuming simple black-body spectra, with the temperature an arbitrary parameter, more or less analogously to the assumed power-law input spectra of active galactic nuclei models today.

In addition to pure Seyfert 1 and 2 galaxies, there are many Seyfert galaxies whose profiles combine broad and narrow components. One example is NGC 5548, whose spectrum is shown in Fig. 3. Other similar objects cover almost all possible relative strengths of the broad and narrow H I components (Osterbrock & Koski 1976). To indicate that their spectral properties are, in a sense, intermediate between the two main types, we have called these objects Seyfert 1.5 galaxies (Osterbrock 1977a). The narrow emission-line spectra of Seyfert 1 and 1.5 galaxies are similar to those of Seyfert 2s, but often go up to higher levels of ionization. They have been quantitatively studied by Cohen (1984), who confirmed that they also can best be understood in terms of photoionization. He suggested, from the differences in ionization, that the Seyfert 2 featureless continua may have cut-offs (or down-turns) in their spectra at energies \( h\nu \sim 10^3 - 10^4 \) eV, while the Seyfert 1 galaxies do not.
A very important observational problem is that Seyfert galaxies have, in addition to their emission-line and featureless-continuum spectra, integrated stellar absorption-line spectra of more or less 'normal' galaxies. Thus, to measure accurately weak emission lines, it is necessary to eliminate accurately the underlying absorption-line spectrum. The importance of this process has been demonstrated by Goodrich & Osterbrock (1983), in two specific examples, Mrk 744 and Mrk 1066. In general we try to decompose each observed Seyfert-galaxy spectrum into three components: an emission-line spectrum, an integrated-stellar galaxy spectrum and a power-law featureless continuum. A graphical example of such a decomposition is shown by Shuder (1981).

A general result of this type of analysis is that typical Seyfert 1 galaxies have much stronger featureless continua than typical Seyfert 2 galaxies (Osterbrock 1978). There must be a physical connection between a strong 'power-law' continuum source and the existence of broad wings on the H I lines – that is, the existence of dense gas with high internal velocities.

4 THE BROAD-LINE REGION

In Seyfert 1 (and broad-line radio galaxies, which will be discussed in the next section), the H I, He I, He II and Fe II broad lines are all permitted lines; no broad forbidden lines have been certainly measured. The only known interpretation is that the density is so high in the broad-line emitting region or regions that all forbidden lines are collisionally de-excited. This implies \( N_e \gtrsim 10^3 \text{ cm}^{-3} \) in the broad-line region. In essentially all Seyfert 1 and 1.5
galaxies that have been observed in the ultraviolet with the \textit{IUE}, C III $\lambda$ 1909 has a broad profile similar to those of the permitted lines (Wu, Boggess & Gull 1983). This implies $N_e \lesssim 10^{10} \text{ cm}^{-3}$, so $N_e \approx 10^9 \text{ cm}^{-3}$ is a reasonable estimate for the density in the broad-line region. The temperature is not well determined from any spectral diagnostics, but $T \approx 10^4 \text{ K}$ is a reasonable estimate. With these parameters the mass in the broad-line regions of typical Seyfert 1 galaxies are quite small, $M \approx 10^3 - 10^2 \, M_\odot$, and the characteristic sizes also, $R \lesssim 1 \text{ pc}$. These results depend only weakly on the assumed $T$. No broad-line region has been resolved by direct imaging from the Earth. Several Seyfert 1 galaxies have broad lines that have varied in strength and for profile in times as short as months, indirectly confirming that their broad-line regions are not over a few light months in size (see, e.g. Capriotti, Foltz & Peterson 1982; Antonucci & Cohen 1983).

The energy input mechanism to the broad-line region is not known for certain. However, spectrophotometric measurements show a very close proportionality between $L_{FC}$, the luminosity of an active galactic nucleus in the featureless continuum, and $L_{H\alpha}$, its luminosity in the total H$\alpha$ emission line, broad plus narrow together (Osterbrock 1978). This relationship holds for Seyfert 1, 1.5 and 2 galaxies, BLRG and NLRG, QSOs and quasars (Yee 1980; Shuder 1981). It is exactly the relationship expected if the featureless continua all have approximately the same form (the same exponent $\alpha$ if all were power laws, for instance) and photoionization were the dominant input process to the broad-line regions as well as the narrow-line region. Thus, the observations strongly suggest, but do not prove, that photoionization is important in the broad-line regions. Since the broad-line region is so much smaller than the narrow-line region, it is impossible to avoid concluding that the former is closer to the central photoionizing source. Thus, at least in some directions, only photons that pass through the broad-line region can reach the narrow-line region. All photoionization models of active galactic nuclei incorporate this feature.

Furthermore, the constant of proportionality in the observed relationship between $L_{FC}$ and $L_{H\alpha}$ is approximately the same as that expected for photoionization by a power law with exponent $\alpha \approx 1.1$, if the H I lines are emitted in pure recombination and the ‘covering fraction’, or fraction of ionizing photons emitted by the central source that are absorbed, $\Omega \approx 1$. Actually the real situation must be more complicated than this. Most of the lower luminosity objects are Seyfert 2 and NLRG, in which the density is low enough so that pure recombination, although not exactly correct, is a good approximation. However in the higher luminosity Seyfert 1 and BLRG, and in the QSOs and quasars, the densities in the broad-line regions are so high that radiative transfer and collisional effects involving excited levels increase the efficiency of radiation of H$\alpha$. This is shown for instance, in Table 1, based on approximate models calculated by Kwan & Krolik (1979, 1981) and by Drake & Ulrich (1980). It can be seen that in the dense broad-line regions the efficiency of H$\alpha$ production may be higher by as much as a factor of 8 than in the low-density narrow-line regions. This suggests, therefore, that the covering factor decreases from $\Omega \approx 1$ for low luminosity active galactic nuclei to $\Omega \approx 0.1$ at the highest luminosity QSOs quasars.
TABLE I

*Efficiency of Balmer-line emission for photoionization*

<table>
<thead>
<tr>
<th>Density $N_0$ cm$^{-3}$</th>
<th>Ionization parameter $\Gamma$</th>
<th>Photon ratios $H_{\alpha}$ $H_{\beta}$</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4 \times 10^9$</td>
<td>0.03</td>
<td>0.45 0.12</td>
<td>(Brocklehurst 1971)</td>
</tr>
<tr>
<td>$2 \times 10^9$</td>
<td>0.01</td>
<td>1.1 0.19</td>
<td>(Kwan &amp; Krolik 1981)</td>
</tr>
<tr>
<td>$1 \times 10^9$</td>
<td>0.06</td>
<td>3.3 0.53</td>
<td>(Kwan &amp; Krolik 1979)</td>
</tr>
<tr>
<td>$1 \times 10^{10}$</td>
<td>0.006</td>
<td>3.4 0.56</td>
<td>(Drake &amp; Ulrich 1980)</td>
</tr>
</tbody>
</table>

TABLE II

*Typical active galactic nucleus parameters*

- $M_{\text{stars}} = 10^9 M_\odot$
- $M_{\text{ionized gas}} = 10^7 M_\odot$
- $L_{\text{ion}} = 10^{12} L_\odot$

On black hole picture requires:

- $M_{\text{black hole}} = 10^8 M_\odot$
- $\dot{M} \approx 1 M_\odot \text{yr}^{-1}$

The luminosities of typical active galactic nuclei are greater than can be accounted for by the luminosities of the stars estimated to be present from the absorption-line spectra. Typical values are shown in Table II. Thus the observed luminosity does not result from H burning or any kind of nuclear burning in ordinary stars as we understand them. The energy source hence is very likely to be gravitational in origin. It is usually thought to be an accretion disc surrounding a black hole (see, e.g. Rees 1977, 1978). An attractive feature of this picture is that the mass of the black hole derived on this assumption, together with the size of the broad-line region derived from the density arguments as given above, predict under gravitational binding typical velocities $\sim 10^4$ km s$^{-1}$, comparable with the observed values. What is needed, of course, is a complete physical model, from which the radiation field, particle and plasma output, ionization of the gas outside the accretion disc, velocity field, and all observable parameters can be calculated for comparison with observational measurements.

5 RADIO GALAXIES

Many radio galaxies, strong radio sources, have active galactic nuclei with emission-line spectra very similar to the spectra of the radio-quiet Seyfert galaxies. Radio galaxies are far less numerous per unit volume of space, perhaps only 1 per cent as abundant as Seyfert galaxies. The optical spectra of radio galaxies may be divided into two groups, analogous to Seyfert 1 and 2 galaxies (see Grandi & Osterbrock 1978 and earlier references given there). The narrow-line radio galaxies (NLRG) have narrow permitted and
forbidden lines, similarly to Seyfert 2 galaxies. In fact whatever differences there are between the optical spectra of NLRG and Seyfert 2s are very minor indeed (Koski 1978; Cohen & Osterbrock 1981). However, morphologically the Seyfert 2 galaxies are nearly all spirals, that is disc objects, while the NLRG are nearly all cD, D, or E galaxies, that is spheroidal objects.

The broad-line radio galaxies (BLRG) on the other hand, have broad permitted lines and narrow forbidden lines, similarly to Seyfert 1 galaxies. However, typical BLRG have quite strong narrow H α components superimposed on their broad profiles, and are thus more nearly analogous to Seyfert 1·5s than to Seyfert 1s. Furthermore, the broad profiles in the BLRG tend to be more irregular, and more flat-topped, than in typical Seyfert 1 or 1·5 galaxies. Morphologically, the Seyfert 1 galaxies are nearly all spirals, like Seyfert 2s, while the BLRG are nearly all N galaxies, objects with very bright, almost stellar nuclei, and for which little more can be said about the rest of the galaxy (Morgan & Dreiser 1983). In addition, spectrophotometric measurements show that in BLRG the broad Hα/broad Hβ line ratios are on the average considerably larger than in Seyfert 1 or 1·5 galaxies, while the Fe II/Hβ ratios are on the average considerably smaller than in Seyfert 1s and 1·5s (Grandi & Osterbrock 1978). All these spectral and morphological differences must be clues to the physics of the processes in which radio plasma is generated in and/or escapes from the central sources in active galactic nuclei. Unfortunately, we do not yet understand these clues. Both the Hα/Hβ and Fe II/Hβ differences could possibly be understood as resulting if there is more dust intimately involved with the ionized broad-line gas in radio galaxies than in Seyfert 1 galaxies. Such dust would both cause reddening, increasing the observed Hα/Hβ ratio, and lock up Fe atoms, weakening the Fe II emission in deep partly ionized regions of the broad-line clouds.

Although Seyfert galaxies are radio quiet, they are not radio zero. Many of them can be detected as weak radio sources. Early surveys showed that Seyfert 2 galaxies are, on the average, stronger radio sources than Seyfert 1 galaxies (Sramek & Tovmassian 1975; de Bruyn & Wilson 1976, 1978). Meurs (1982), who observed a complete optical magnitude-limited sample of Seyfert galaxies, strongly confirmed this result.

Meurs used spectral classifications in which the galaxies were divided into only two types, Seyfert 1 or 2. We have Lick spectra of nearly all the galaxies he observed, which had been classified into the types Seyfert 1, 1·5, 1·8 or 1·9 (see below), and 2. Meur's collected photographic magnitudes $m_p$, and measured radio fluxes (or upper limits) at 1415 MHz, $S_{1415}$, were converted into optical-radio frequency 'colour indices' by the relationship

$$P - RF = m_p + 2.5 \log S_{1415}(mJy) - 18.0.$$  

(The constant was chosen merely to put the centre of the distribution near $P - RF = 0$.) Histograms of the observed distributions of $P - RF$ are plotted separately for the different types of Seyfert galaxies in Fig. 4. Observed objects are enclosed by the solid lines; objects not detected and for which only upper limits to $S_{1415}$, and thus to $P - RF$, are available are enclosed by dotted lines. It can be seen that the Seyfert 2 galaxies are, or average, much more efficient as radio sources per unit optical light than the Seyfert 1
Fig. 4. Histograms of distribution of optical to radio-frequency colour index, P–RF, for Seyfert 1, 1.5, 1.8, 1.9, and 2 galaxies separately. Solid lines enclose objects for which both P and RF are measured; dashed lines enclose additional objects not detected in the radio-frequency region and for which the upper limit was used – they could be further to the left in this diagram, but not to the right.

Galaxies. Furthermore, the Seyfert 1.5 galaxies are obviously intermediate in this property. Although there are too few Seyfert 1.8 and 1.9 galaxies for statistical significance, comparison of the Seyfert 1, 1.5 and 2 galaxies confirms that the relative strength of the narrow emission lines is strongly correlated with radio emission. Thus in both radio-loud radio galaxies, and radio-quiet Seyfert galaxies, strong narrow emission lines are closely associated with radio emission (Osterbrock 1977b). It seems most likely that the physical explanation is that the conditions under which ionizing photons from the central source can get out into the narrow-line gas are the conditions under which radio plasma can get out from the central source also.

From the available statistical information, it appears that there is a smooth, continuous transition from the most luminous nuclei of Seyfert 1 galaxies to radio-quiet QSOs, and from the most luminous nuclei of BLRG
to quasars (Weedman 1977; Meurs 1982). These statistics, the X-ray data and the optical imagery of faint 'fuzz' (nebulosity) around QSOs all strongly suggest that essentially the same physical phenomenon is occurring in the nuclei of Seyfert 2 galaxies, Seyfert 1 galaxies and QSOs, with luminosity increasing in that order, but with considerable overlap (Hutchings et al. 1982; Kriiss & Canizares 1982). Thus QSOs appear to be the most luminous examples, embedded in the nuclei of galaxies, probably spirals. Quasars seem to bear the same relationship to BLRG, but the picture is not completely clear, because some discrepancies remain in the weakness of the expected absorption-line galaxy spectrum, and the absorption features that are observed in some cases (Miller 1982; Boroson, Oke & Green 1982). Only two QSOs are known which have H I emission lines with FWHM as in Seyfert 2 galaxies (Stocke et al. 1982; Foltz et al. 1984). Evidently if the featureless-continuum luminosity of the active galactic nucleus is so large that the galaxy cannot be detected (by normal visual inspection of a Palomar Observatory Sky Survey plate of the object) and it is classified as narrow as a QSO, the featureless continuum is nearly always also so bright that broad H I emission lines are practically certain to be present.

6 EMISSION-LINE GALAXIES

Many spiral galaxies have emission lines in the spectra of their nuclei, but are not Seyfert galaxies. Their nuclei are generally not as luminous as in Seyfert galaxies, nor are their emission-line widths as large as in the spectra of Seyferts. Their spectra do not cover a wide range of ionization. They are like the spectra of H II regions or low-ionization planetary nebulae. An example is Mrk 1259, whose spectrum is shown in Fig. 5. There is no doubt

![Spectrum of the nearly edge-on Seyfert 1 galaxy NGC 4235](image)

**Fig. 5.** Spectrum of the nearly edge-on Seyfert 1 galaxy NGC 4235, *above*, λλ3500–5900; *below*, λλ4700–7200 in the rest system of the object. Scales and units as in Fig. 1.
these galaxies are photoionized by stars with temperatures ranging up to $3\text{--}5 \times 10^4 \text{K} \approx 2\text{--}4 \text{eV}$ (Sargent 1970, 1972; French 1980). Thus there are O stars in the nuclei of many spiral galaxies, in contrast to M31, the closest example studied so thoroughly by Baade, and to many other spirals. A very few galaxies have Wolf–Rayet features in the spectra of their nuclei, indicating large bursts of formation of massive stars within short intervals of time in the not too distant past (Allen, Wright & Goss 1976; Kunth & Sargent 1981; Osterbrock & Cohen 1982).

Naturally, properties like emission-line width, range of ionization, and relative brightness of nucleus vary smoothly, and it is difficult if not impossible to define an exact lower limit to an active galactic nucleus. Heckman (1980) studied a large group of emission-line galaxies, mostly spiral, with relatively low ionization, which he called 'Liners'. He considered them as probable cases of shock-wave ionization, that is the conversion of kinetic energy into heat in collisions between masses of gas in the nuclei of these galaxies. This is particularly interesting because Heckman also believed that the Liners form a continuous sequence (in physical properties) with Seyfert 2 galaxies.

More recently, however, Ferland & Netzer (1983) and Halpern & Steiner (1983) have shown by specific model calculations that the typical Liner spectra can be better fitted by photoionization models, similar to those for Seyfert 2 galaxies, with a power-law input, but with luminosity lower by a factor $10\text{--}10^2$. Also, recent surveys of the spectra of nearby, bright galaxies by Phillips, Charles & Baldwin (1983) and by Keel (1982) agree that many of these spirals have weak emission-line spectra that have weak Seyfert 2 characteristics, and that can best be fitted by photoionization models of the type described just above.

Most of the Liners have emission-line spectra so faint, particularly the [O III] lines, that it has proved very difficult to measure the weak lines, such as $\lambda 4363$, that are the most important diagnostics for discriminating between photoionization and shock heating. However Osterbrock & Dahari (1983) were able to measure these lines in two galaxies, Mrk 266 SW and Mrk 1066, that are close to the lower end of the Seyfert 2s. Their emission-line spectra showed better quantitative agreement with the photoionization models than with shock-wave models. The comparison, at least qualitatively, would be even better if these objects had relatively low-energy cut-offs in their photoionizing spectra. This suggests that there is a progression in how far the ionizing spectrum extends into the ultraviolet, from Seyfert 1s, through Seyfert 2s, to Liners.

All the observational phenomena we see in Seyfert galaxies is also evidently occurring at a lower level in many more galactic nuclei, not yet recognized as Seyferts. Particularly in the lower intensity ones, the observed emission lines probably result partly from gas photoionized by the featureless-continuum source characteristic of active galactic nuclei, extending far into the ultraviolet, and partly from gas photoionized by hot stars.

7 HIGH IONIZATION AND X-RAYS

Many Seyfert 1 galaxies have strong [Ne v] and [Fe vii], with ionization potential (to produce these ions) $\sim 100 \text{eV}$. The observations strongly
suggest that they are produced by photoionization, along with the other ions of lower ionization potential. A significant fraction of these galaxies also show [Fe x] 6374, with IP = 234 eV, and [Fe xi] 7892, with IP = 262 eV (Wilson 1979; Grandi 1978). The highest ionization Seyfert 1 galaxy presently known, III Zw 77, shows these lines as well as [Fe xiv] 5303, with IP = 361 eV (Osterbrock 1981a). This galaxy has relatively narrow broad lines, and relatively weak Fe II, making detection of λ5303 simpler; it may be weakly present but blended beyond recognition in some of the other Seyfert 1s with strong [Fe x] and [Fe xi]. In III Zw 77, relative strengths of [Fe vi] and [Fe vii] lines from different upper levels suggest the temperature is in the range expected from photoionization, but is too low for collisional energy input, although this conclusion is not secure because the reddening correction is uncertain (Osterbrock 1981a). The published analysis was worked out with older values of the collision strengths and transition probabilities, but it remains essentially unchanged with the most recent and presumably most nearly accurate ionic parameters for [Fe vii] recently published by Nussbaumer & Storey (1982).

Very simplified models with a power-law input spectrum $L_\nu \propto \nu^{-\alpha}$ with $\alpha = 1.24$ suggest that the observed strength of [Fe x] 6374 can be understood as resulting from photoionization, but that [Fe xiv] 5303 cannot. More sophisticated calculations are clearly desirable. In NGC 3783 (Wilson 1979; Pelat, Alloin & Fosbury 1981; Atwood, Baldwin & Carswell 1982) and in III Zw 77 (Osterbrock 1981a) there is a well-defined correlation between increasing ionization potential and increasing line width up to [Fe x] 6374 and [Fe xiv] 5303. On the photoionization picture this would indicate higher velocities closer to the central radiation source, again as expected under gravitational binding. However, the observed correlation can alternatively be interpreted as a correlation of critical density for collisional de-excitation with velocity, so the picture is not completely clear.

The energies of photons that can ionize up to [Fe x], [Fe xi] and [Fe xiv] are in the soft X-ray region. Within the past decade the entire field of X-ray astronomy has opened up very quickly. It is now known that essentially all bright Seyfert 1 and BLRG are strong X-ray sources, and that very nearly all highly luminous X-ray galaxies are Seyfert 1 or BLRG (see, e.g. Wilson 1979). To date no good observational correlation has been reported between X-ray luminosity of an active galactic nucleus and level of ionization in the optical spectrum. Very probably this means the geometry within the source is an important factor.

There is, however, a very good correlation between the luminosity in the broad component of the H I emission lines, or H$\alpha$ in particular, and the X-ray luminosity (Elvis et al. 1978; Wilson 1979). A few nearby X-ray galaxies, originally reported as Seyfert 2 or narrow emission-line galaxies, turned out to have very weak, originally undetected broad H$\alpha$ components, and thus confirmed this correlation (Veron et al. 1980; Shuder 1981). Quite recently the very weak broad H$\alpha$ component in M81 (Peimbert & Torres-Peimbert 1981; Shuder & Osterbrock 1981) has been observationally matched by the very low X-ray luminosity measured for this object, extending the correlation even fainter (Elvis & Van Speybroeck 1982). There are no confirmed
detections of Seyfert 2 galaxies as X-ray sources, but from available data it is impossible to be certain whether this means their spectra turn down more steeply than Seyfert 1s or not.

8 SEYFERT 1·8 AND 1·9 GALAXIES

A small, but non-negligible fraction of Seyfert galaxies have quite weak, but detectable, broad Hα emission components, along with fairly strong Seyfert 2-type emission lines. Some of these galaxies have extremely faint, but detectable, broad Hβ emission also, while in others the broad Hβ cannot be seen even on high-quality scans. I have called such objects Seyfert 1·8 and 1·9 galaxies, respectively, to indicate that they are much closer to Seyfert 2 galaxies than typical Seyfert 1 or even Seyfert 1·5 objects (Osterbrock 1981b). A total of 11 such Seyfert 1·8 and 1·9 galaxies are now known, out of approximately 120 Seyfert 1 and 1·5 galaxies, and 50 Seyfert 2 galaxies with observed spectra of the same general quality (Goodrich & Osterbrock 1983; Osterbrock & Dahari 1983). In all observed Seyfert 1·8 and 1·9 galaxies the broad Hα/broad Hβ ratios are very large, typically ~7–9, not ~3 as in Seyfert 1 or 1·5 galaxies. This large ratio suggests, though it does not prove, that reddening by dust is particularly important for the broad H I emission lines of the Seyfert 1·8 and 1·9 galaxies.

These Seyfert 1·8 and 1·9 galaxies are not, however, a group of objects seen largely edge-on, in which the observed reddenings result from interstellar dust in their galactic planes. In this connection Keel (1980) first noted that typical known Seyfert galaxies are not distributed with random inclinations to the line of sight. He estimated axial ratios b/a for a large group of Seyfert galaxies, and for a comparison group of spirals of comparable angular size. Keel found that, as a group, the Seyfert galaxies are significantly more nearly face-on than random by chosen spiral galaxies. His statistical results, fully discussed in his paper, are summarized briefly by the medians and averages in Table III. The most plausible interpretation, as Keel noted, is that interstellar dust in and near the planes of nearly edge-on Seyfert galaxies, makes them more difficult to discover. The most nearly edge-on Seyfert 1 galaxy in his sample, NGC 4235, with b/a = 0·13, does show very strong reddening of its broad Balmer H I emission lines, and was in fact recognized as a Seyfert 1 galaxy only fairly recently (Abell, Eastmond & Jenner 1978). Its spectrum, shown in Fig. 5, does not appear similar to the spectra of Seyfert 1·8 and 1·9 galaxies; in NGC 4235 the narrow lines and the galaxy spectrum as well as the broad lines are strongly affected by extinction.

Lawrence & Elvis (1982) studied a sample of X-ray galaxies, which have only narrow emission lines (NELXG). They showed the NELXG are, as a group, more nearly edge-on than the known Seyfert 1 galaxies. Their statistical results are also briefly summarized in Table III. Lawrence & Elvis (1982) interpreted these NELXG as objects in which dust, near their galactic planes and near the central broad-line region, is responsible for the extinction.

For comparison, axial ratios b/a were also estimated for all the optically selected Seyfert 1·8 and 1·9 galaxies by O.Dahari on the Palomar Observatory Sky Survey plates. His results are listed in Table IV, and the overlap with the few also included in Keel's sample gives some idea of the uncertainty of
TABLE III
Axial ratios b/a of various groups of galaxies

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of galaxies</th>
<th>Median b/a</th>
<th>Average b/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Seyferts (Keel 1980)</td>
<td>93</td>
<td>0.62</td>
<td>0.62</td>
</tr>
<tr>
<td>Comparison group (Keel 1980)</td>
<td>93</td>
<td>0.55</td>
<td>0.57</td>
</tr>
<tr>
<td>Seyfert 1 near (Keel 1980)</td>
<td>52</td>
<td>0.65</td>
<td>0.60</td>
</tr>
<tr>
<td>Comparison group (Keel 1980)</td>
<td>52</td>
<td>0.48</td>
<td>0.48</td>
</tr>
<tr>
<td>NELXG (Lawrence &amp; Elvis 1982)</td>
<td>5</td>
<td>0.33</td>
<td>0.41</td>
</tr>
<tr>
<td>Seyfert 1.8 and 1.9</td>
<td>11</td>
<td>0.67</td>
<td>0.63</td>
</tr>
</tbody>
</table>

TABLE IV
Estimated b/a of Seyfert 1.8 and 1.9 galaxies

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>b/a</th>
<th>b/a</th>
<th>b/a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dahari</td>
<td>Keel</td>
<td>Mean</td>
</tr>
<tr>
<td>Mrk 423</td>
<td>0.77</td>
<td>0.65</td>
<td>0.71</td>
</tr>
<tr>
<td>Mrk 471</td>
<td>0.66</td>
<td>0.63</td>
<td>0.64</td>
</tr>
<tr>
<td>Mrk 516</td>
<td>0.71</td>
<td>—</td>
<td>0.71</td>
</tr>
<tr>
<td>Mrk 609</td>
<td>0.97</td>
<td>0.60</td>
<td>0.78</td>
</tr>
<tr>
<td>Mrk 728</td>
<td>0.67</td>
<td>—</td>
<td>0.67</td>
</tr>
<tr>
<td>Mrk 744</td>
<td>0.54</td>
<td>—</td>
<td>0.54</td>
</tr>
<tr>
<td>Mrk 883</td>
<td>0.80</td>
<td>—</td>
<td>0.80</td>
</tr>
<tr>
<td>Mrk 1018</td>
<td>0.70</td>
<td>0.40</td>
<td>0.55</td>
</tr>
<tr>
<td>Mrk 1179</td>
<td>0.78</td>
<td>—</td>
<td>0.78</td>
</tr>
<tr>
<td>Mrk 1218</td>
<td>0.31</td>
<td>—</td>
<td>0.31</td>
</tr>
<tr>
<td>V Zw 317</td>
<td>0.49</td>
<td>—</td>
<td>0.49</td>
</tr>
</tbody>
</table>

these estimates. The median and average values show that the Seyfert 1.8 and 1.9 galaxies are distributed much like the overall group of known Seyfert galaxies, or of Seyfert 1 galaxies, and are not as a group more nearly edge-on. The most straightforward interpretation is that in the Seyfert 1.8 and 1.9 galaxies the dust that reddens the broad emission lines is not aligned with their galactic planes. This then suggests that the dust may be aligned with the broad-line regions, but that these regions are not all aligned with the principal planes of the galaxies in which they are located. Clearly it would be highly desirable to measure the X-ray fluxes of the Seyfert 1.8 and 1.9 galaxies and compare them with those of the NELXG.

9 OVERALL INTERPRETATION

Seyfert galaxies and active galactic nuclei are not completely understood and any interpretation must be partial. The following represents the best working picture I can form, but is not necessarily accepted by all workers in the field. The main energy input we do understand. In the narrow-line region almost certainly, and in the broad-line region probably, it is photo-ionization by a hard spectrum that extends far into the ultraviolet. The Seyfert 1s, Seyfert 2s and Liners have, on average, decreasing luminosity of the featureless-continuum source, in that order. Apparently they also have, on average, cutoffs decreasing in energy in the same order, but not completely correlated with luminosity.
We hope to learn more about the detailed mechanisms operating within the source from detailed comparisons of models, calculated on well-defined physical pictures. Few such models yet exist.

We do not understand the geometrical structure of the emitting regions. A physical picture that fits many facets of the observed data is that the broad-line regions are cylindrically symmetric, not spherically symmetric. If it is a flattened disc, the escape of both radio plasma and ionizing photons mainly through the conical sectors along the axis can explain many of the observed correlations (Osterbrock 1978; Cohen 1983). However, since there is not a correlation (or anticorrelation) between the axial ratios of the galaxies and the FWHM or FWOI of the broad emission lines from their active nuclei, the broad-line regions should probably be regarded as tipped with respect to the planes of the galaxies. There are observational and theoretical reasons for believing such nuclei with inclined axes of symmetry (or of angular momentum vectors) can occur (Tohline & Osterbrock 1982). In some Seyfert galaxies the weak radio emission appears, with high angular resolution, to emerge from the nucleus along 'jets' that are not perpendicular to the plane of the galaxy, strongly suggesting the existence of a structure in the very central part of the nucleus whose rotation axis differs from that of the rest of the galaxy (Ulvestad, Wilson & Sramek 1981; Booler, Pedlar & Davies 1982).

A schematic picture of such a tipped broad-line disc, surrounding a photoionization source shown as a flat accretion disc, is shown in Fig. 6. The highly inhomogeneous structure of the narrow-line region, indicated indirectly by the observational data, is also shown schematically. The picture is not to scale; the broad-line region must be relatively much smaller than shown. Very probably it is also inhomogeneous, but this could not be rendered in the drawing. Probably, also, the broad-line region goes over continuously into the narrow-line region in of density, internal-velocity field, and inclination. This is a picture, not a model; what is needed is a well-defined physical model from which predictions can be calculated and compared with observations.

Fig. 6. Schematic drawing of side view of narrow line gas, distributed in 'clouds' or condensations in a cylindrically symmetric disc, with the broad-line gas in a tipped disc at its centre. The photoionization source is the smaller disc at the centre of the broad-line region. The latter is optically thick to ionizing radiation along most, but not all rays near its equator, but not along rays near its axis. The more remote clouds are not as highly ionized on their faces as the clouds closer to the photoionizing source.
One of the strongest arguments for abandoning spherical symmetry in active galactic nucleus models is that there is such a wide range of observed broad-line widths in Seyfert 1 galaxies. Although the FWHM range up to $6 \times 10^3$ km s$^{-1}$ in objects like Mrk 279, 704, 876 and 926, they range down to $6 \times 10^2$ km s$^{-1}$ in Mrk 359 and Akn 564 (Osterbrock & Shuder 1982) and in Mrk 42 (shown in Fig. 7). No strong correlation to line width with other properties of the nuclei has been found, but there is a weak correlation (with large scatter) of increasing FWHM with increasing luminosity (Shuder 1984). This strongly suggests that an aspect effect is important in the observed line widths.

One of the important features any acceptable model must predict is the observed line profiles. Probably the most widely accepted physical picture at present is the radiation pressure-driven wind model. Simplified spherically symmetric models of this type give forms of the line profiles in relatively good agreement with observations (Blumenthal & Mathews 1975; Capriotti, Foltz & Byard 1980). However, they do not explain the lack of correlation of FWHM with luminosity. Perhaps a cylindrically symmetric wind model, with obstacles in the plane of the (tipped) broad-line region, and flow out along its axis is the next type of model to explore.

Another, less widely accepted picture, is that the velocity field observed in the broad-line region is primarily rotational (Osterbrock 1978; Shields 1978). On the simplest picture of this type, the calculated profiles disagree.
badly with the observations (Capriotti et al. 1980). However, more sophisticated pictures of this general type seem to give better agreement with the observational data (Jones & Raine 1980; van Groningen 1983). This picture should also be explored further. Perhaps a combination of rotation with a wind along the axis will be the ultimate solution. In any case, it is clear that while calculations from pictures will be helpful in the search the final solution must be a well-defined, physically calculated model.

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