PLANETARY NEBULAE AND SEYFERT GALAXIES - SIMILARITIES AND DIFFERENCES

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ABSTRACT. Knowledge gained in the study of planetary nebulae has been, and can be further, transferred to understanding active galactic nuclei. Photoionization is the main energy-input mechanism in the narrow-line regions, and probably although by no means certainly in the broad-line regions as well. There are many detailed differences because of the much "harder" input spectrum in active galactic nuclei, compared with planetary nebulae. A tentative model of the structure of the gas distribution in a Seyfert-galaxy nucleus is presented.

The concept of Seyfert galaxies dates back to the paper in which Seyfert (1943) stated that a very small proportion of galaxies have spectra showing many high-ionization emission lines localized in their nuclei. These emission features are similar to those found in planetary nebulae, as Seyfert reported. Invariably, these galaxies contain very luminous nuclei. Of the workers before Seyfert, Hubble (1926) had particularly remarked on the planetary-nebula-like emission-line spectra of three of them, NGC 1068, 4051, and 4151. Thus the earliest spectroscopic observers already noted the close similarity between the emission-line spectra of Seyfert galaxies and planetary nebulae. Many more galaxies, indeed at some level or other, nearly all spiral and irregular galaxies, have in their spectra the generally lower ionization-level emission lines of H II regions.

Since planetary nebulae, and the mechanisms by which their emission-line spectra are formed are fairly well understood (although not completely so), it is clearly advantageous to use the knowledge gained from these objects in analyzing and interpreting Seyfert galaxies. In particular, there are many planetary nebulae in our Galaxy, some of them quite close to us, which can easily be resolved, while very few Seyfert galaxies are close enough for us to get any resolved optical information on their emission-line emitting nuclei. Thus planetary nebulae may be regarded not only as interesting objects in themselves, but as guides and test objects to understanding the structure of Seyfert galaxy nuclei.

Clearly not only the similarities must be studied, but the differences as well. One obvious dissimilarity between the spectra of

Seyfert galaxies and planetary nebulae is in the widths of their emission lines. Part of the standard definition of a Seyfert galaxy is that the emission lines be strong and broad (Weedman 1977); actually this means in practice noticeably broader than in typical galaxies, whose line widths are often approximately 300 km/sec full width at half maximum (FWHM). Planetary nebulae of course have much smaller line widths, typically 50 km/sec FWHM, resulting from expansion (Wilson 1948).

Seyfert galaxies may be classified into two types from their spectra. Seyfert 1 galaxies are those in which the H I emission lines are noticeably broader than the forbidden lines, such as [O III] λλ4959, 5007, while Seyfert 2 galaxies are those in which the H I and forbidden emission lines have similar widths (Khachikian and Weedman 1974). Radio galaxies, the optical counterparts of strong radio sources, have bright nuclei and emission-line spectra similar in many ways to Seyfert galaxies (Baade and Minkowski 1975), although they are much rarer per unit volume of space. They also can be divided into two groups, broad-line radio galaxies, (BLRG), with H I emission lines noticeably broader than the forbidden lines, as in Seyfert 1 galaxies, and narrow-line radio galaxies (NLRG), with H I and forbidden emission lines with similar widths, as in Seyfert 2 galaxies (Osterbrock, Koski and Phillips 1976). Seyfert galaxies and radio galaxies together are usually referred to as active galaxies. QSO's (quasistellar objects), and quasars (quasistellar radio sources) are clearly similar to them in many ways and are often included within the class of active galactic nuclei.

The FWHM of the emission lines in Seyfert 2 and NLRG cover a broad range, approximately 300 to 1200 km/sec, with a typical value of about 500 or 600 km/sec. There is no systematic difference between the widths in the two groups. Note that NGC 1068, which has a FWHM 1200 ± 150 km/sec, is often cited as a typical Seyfert 2, but actually is no more so than NGC 7027 is a typical planetary nebula (Koski 1978; Cohen and Osterbrock 1981; Shuder and Osterbrock 1981).

In Seyfert 2 and NLRG the measured H I Balmer-line ratios are generally steeper than predicted by recombination theory. However, just as in planetary nebulae, the differences between the observed and recombination gradients can generally be ascribed to interstellar reddening. In well observed objects several different H I line ratios generally give approximately the same amount of extinction (Osterbrock and Miller 1975; Koski 1978; Cohen and Osterbrock 1981). However, very recent measurements of [O II] and [S II] line ratios, comparing lines in the violet and red spectral regions, yield on the average somewhat lower amounts of extinction (Malkan 1982). If the interpretation is correct, they suggest that Hα/Hβ = 3.6 ± 0.3, somewhat larger than the recombination value 2.9. The method of deriving the amount of extinction is based on the assumption that the effective electron densities and temperatures in the [O II] and [S II] are the same, which is questionable, but a range of model calculations, of the type described below, could be substituted for this assumption. Another assumption in all the reddening calculations is that the wavelength dependence of the extinction in active galactic nuclei is the same as in our Galaxy. This is by no means obvious, but probably is not too serious when the results are used only to interpolate the extinction as a function of wavelength.

It seems well established that the ionization mechanism in the Seyfert 2 and NLRG is photoionization by a "hard" spectrum, extending to high energies (Collin-Souffrin 1978). The most convincing evidence for the conclusion that photoionization is important is that the electron temperature T calculated from [O III] and [N II] emission-line ratios is in many cases of order 1-2 x 10^4 K. Particularly for [O III], this is much smaller than the temperature expected under conditions of "collisional ionization", that is, direct input of mechanical energy which is converted into heat, and thermal ionization under relatively low-density conditions. On the other hand, temperatures of this order are expected to result from photoionization over a wide range of input spectra, because of the strong thermostatic effect of cooling by collisionally excited line radiation. No star or mixture of stars could give the wide range of ionization, from [O I] and [S II] to [Ne V] and [Fe VII] observed in many Seyfert 2 and NLRG. On the other hand, a power-law, featureless-continuum spectrum, extrapolated from observational data in the optical region to the extreme ultraviolet, will give just this type of spectrum. Often the featureless continuum, which must be determined by decomposing the observed continuous spectrum into normal-galaxy and power law components, can be represented as $F_\nu \propto \nu^{-\alpha}$, with $\alpha \approx 1$. Qualitatively, the high-energy photons of such a power-law continuum, beyond the exponential tails of the continuous spectra of even the hottest known stars, will produce highly ionized species close to the source, as well as a long partially ionized zone in which [O I] and [S II] will be the strongest optical lines emitted (Mitton 1972). Furthermore, the number of ionizing photons in such an extrapolated power-law spectrum is sufficient, in all well observed cases, to balance the total number of recombinations indicated by the H I emission lines (Osterbrock and Miller 1975; Costero and Osterbrock 1977; Koski 1878).

Calculated photoionization models, with input spectra of the form $L_\nu \propto \nu^{-\alpha}$, with $\alpha \approx 1$, do approximately agree with the observed emission-line spectrum of the Crab Nebula, known from the work of Woltjer (1958) to be photoionized by a synchrotron power-law continuum, agrees well with the emission-line spectra of Seyfert 2 and NLRG, except for the He I and He II lines. They are stronger in the Crab Nebula because of the high He abundance in this object. An even better match to the active-galactic-nuclei spectra is provided by a linear combination of the spectra of the Crab Nebula and of the planetary nebula NGC 7027 (Koski 1978). Since NGC 7027 has a very hot central star, this indicates that the photoionization continua in Seyfert 2 and NLRG probably turn down somewhat at high photon energies.

Seyfert 1 and BLRG have broad H I, He I and He II emission lines with FWHM in the range 1 - 7 x 10^3 km/sec, and with full widths at zero intensity (FWOI) ranging up to 2.8 x 10^4 km/sec. Here it is not so clear what the energy input to the ionized gas is. There are essentially no diagnostics that give information on T, or on electron density except that it is so high that all forbidden lines are collisionally deexcited, requiring $N_e \gtrsim 10^8$ cm^{-3}. A few Seyfert 1 galaxies observed with the IUE (Wu, Boggess and Gull 1982), and many high redshift quasars and QSOs show broad C III] λ1909 emission. This requires $N_e \lesssim 10^{10}$ cm^{-3} in the broad-line regions of these objects, and presumably of all Seyfert 1 and BLRG.

The best working hypothesis is that the main ionization source in the broad-line regions (BLR) is also photoionization. This is based on the linear relationship over several powers of ten between the luminosity in the Hα or Hβ emission lines, summed over the total profile, broad plus narrow components (Yee 1980; Shuder 1981; see also Osterbrock 1978). This is just the relationship expected from photoionization by an ultraviolet spectrum that is the extension, with more or less the same power law, of the observed optical featureless continuum (Searle and Sargent 1968). The photoionization interpretation is not required by this observation; any source of ionization that is directly proportional to the optical featureless continuum would also satisfy the data. Photoionization is simply the most straightforward explanation. It requires that the ratio of the number of ionizing photons emitted by the source to the number of Hβ or Hα photons emitted by the ionizing gas be essentially constant.

For pure recombination, this means that the "covering factor" or fraction of ionizing photons observed by the gas be constant from the Seyfert 2 and NLRG at lower luminosities, through Seyfert 1 and BLRG at intermediate luminosity, to low redshift QSOs and quasars that are the highest luminosity objects in which Hβ or Hα has been measured and compared quantitatively with the optical featureless continuum. Furthermore, for a covering factor $\Omega/4\pi = 1$, the exponent in the power law $L_\nu \propto \nu^{-\alpha}$ must be $\alpha \gtrsim 1$; this can be accepted for the Seyfert and radio galaxies but for high-luminosity QSOs and quasars, in which the Lyman limit at λ912 is directly observable, the data suggest $\Omega/4\pi \approx 0.3$ is more likely (Yee 1980). This would require an index $\alpha \gtrsim 0.6$. If this value of the exponent were used for all the objects, it would suggest that the luminosities in the featureless continuum of the Seyfert galaxies have been undercorrected for reddening by dust. An alternate interpretation would be that $\Omega/4\pi$ varies smoothly from ~ 1 at low luminosities to ~ 0.3 at high luminosities, and that the number of Hα or Hβ photons emitted per photoionization varies smoothly in just such a way as to compensate the change in covering factor. The third interpretation of course is that processes other than photoionization also transfer energy from the source to the gas, and lead ultimately to emission of H I line photons, in just such a way as to mimic photoionization. Understanding this puzzle is a necessity to understanding active galactic nuclei, QSOs, and quasars.

The Balmer decrements of the broad H I lines in BLRG and Seyfert 1 galaxies cannot be matched by recombination plus reddening alone. At the high densities of the BLR, Lα excapes only slowly and both the 2^2S and 2^2P terms of H I are populated; both collisional excitation and radiative-transfer effects involving these levels are therefore expected to occur and thus to modify the relative intensities of the lower Balmer lines (Netzer 1975; Osterbrock, Koski and Phillips 1975, 1976). Yet, although there is a scatter about the reddening line considerably larger than the observational errors, the broad-line

Balmer decrements on the average approximately follow it, indicating that dust also does play an important role (Osterbrock 1977).

In QSOs and quasars (Baldwin 1977) and in several Seyfert 1 galaxies observed with the IUE (Wu, Boggess and Gull 1980), the measured Lα/Hβ ratios are much different from the recombination values. These measurements provide extremely important additional information for sorting out the effects of optical depths in the lines, collisional excitation, and dust on the emission processes in the BLR. Infrared measurements of H I provide still further information (Soifer et al. 1981). Theoretical treatments taking all these effects into account are inevitably very complicated and involve massive calculations, even though the physical situation assumed is necessarily highly simplified (Davidson and Netzer 1979; Collin-Souffrin, Dumont and Tully 1982). Yet surely, in the end, they will be necessary for understanding the BLR. Dust clearly may be very important, not only in modifying the emergent radiation from the BLR, but also by its effects in scattering and absolving ionizing and line radiation within that radiation. It should not be omitted from the calculations for supposed "simplicity" (Osterbrock 1979).

Many Seyfert galaxies have intermediate-type spectra, with H I line profiles combining strong broad and narrow components. These objects are often referred to as Seyfert 1.5 galaxies, to indicate they combine with characteristics of Seyfert 1's and 2's. Examples can be found with almost any relative strengths of broad and narrow components (Osterbrock and Koski 1976; Osterbrock 1977). They are included in the very good proportionality relationship between featureless continuum and Hα or Hβ luminosities if the total, broad plus narrow, H I profiles are measured. Most of the BLRG have Balmer-line profiles with strong narrow-line components, more nearly similar to Seyfert 1.5 galaxies than to Seyfert 1's (Grandi and Osterbrock 1978).

The narrow emission-line spectra of Seyfert 1 galaxies are very similar to those of Seyfert 2 and NLRG. The equivalent widths of the narrow lines in the Seyfert 1's are relatively smaller, however, indicating that not as large a fraction of the ionizing radiation reaches the narrow-line region (NLR) (Osterbrock 1978). Also, detailed study shows that in many cases the [O III] (λ4959 + λ5007)/λ4363 ratio is relatively small, indicating either a relatively high T in the NLR, or alternatively if $T \approx 1\text{-}2 \times 10^4$, a relatively high N_e ($N_e \approx 10^6 - 10^7$ cm^{-3}). Because of the continuity of the narrow-line spectra, and the fact that many of these objects and many more of the Seyfert 2 and NLRG have [O III] ratios that do indicate $T \approx 1\text{-}2 \times 10^4$ and $N_e \lesssim 10^4$, it has been argued that photoionization is the main energy-input mechanism to the NLR in all these objects, and that therefore $T \approx 1\text{-}2 \times 10^4$ in all of them. On this interpretation the objects with relatively small (λ4959 + λ5007)/λ4363 are objects with relatively high N_e in their NLR. However, from comparisions of [O III] and [Ne III] emission-line strengths, Heckman and Balick (1979) have suggested that T instead may be higher in the objects with relatively strong λ4363. Some observational evidence to support this conclusion has been found by Cohen (1981) from additional spectrophotometric measurements of intermediate-type Seyfert galaxies.

The indicated higher temperatures in the NLR of many Seyfert 1, 1.5 and BLRG suggests that an additional heating mechanism is effective in them. It may be the radio plasma which, in the BLRG, is streaming out from the nuclei to the radio-emitting lobes, generally symmetrically placed far outside the optical galaxy, at opposite ends of the axis of rotation (see e.g. Miley 1980). There are many indications that Seyfert 1 and 1.5 galaxies are objects in which similar plasma is generated at the nucleus but does not get outside the galaxy to the lobes, perhaps because it is ejected in directions along which it encounters more ambient gas and is slowed down or stopped (Ulvestad, Wilson and Sramek 1981). If the ultraviolet radiation field is sufficiently intense, the main ionization process will be photoionization, but additional heat will be delivered to the ionized gas by the frictional slowing down or stopping of the ionized gas. This will tend to raise its temperature without significantly raising the level of ionization. Theoretical work in this direction would be of great interest in exploring this possible difference between Seyfert galaxies and planetary nebulae.

As to the level of ionization, [Ne V] and [Fe VII] are observed in many Seyfert 1 and 1.5 galaxies, but few Seyfert 2's. [Ne V] is observed in several planetary nebulae, and [Fe VII] only weakly in a few. The energies required to produce these ions are 97 and 99 ev respectively. This suggests there may be a cut-off or turndown of the ionizing continuum in Seyfert 2 galaxies around 100 ev (Cohen 1981). [Fe X] and [Fe XI] are observed in a significant number of Seyfert 1 and 1.5 galaxies and [Fe XIV] in the unusual high-ionization Seyfert 1 object III Zw 77. They are not observed in any planetary nebulae. The ionization energies to produce them are 234, 262, and 361 ev respectively. Simplified calculations show that all these observed lines can be produced in photoionization models with power-law sources, and the observed correlations suggest, but do not prove, that they are formed in this way (Grandi 1978; Osterbrock 1981a). The line widths are larger for the high-ionization lines, and since they must be formed close to the source of ionizing photons, this suggests that gravitational accelerations are important (Wilson 1979, Osterbrock 1981a).

The [Fe X] and [Fe XI] emission lines indicate ionizing photons at least up to 300 ev in many Seyfert galaxies, and [Fe XIV] up to at least 500 ev in III Zw 77. These are X-ray energies. Within the past decade measurements made in space have shown that every Seyfert 1 or 1.5 galaxy is an X-ray source, and that nearly every galaxy observed with X-ray luminosity above some threshhold is a Seyfert 1 or 1.5 (see e. g. Culhane 1978). There is a very good correlation between the luminosity in the broad component of Hα and the X-ray luminosity. "Pure" Seyfert 2 galaxies are weak or non-existent X-ray emitters; a few Seyfert 2 or narrow emission-line galaxies identified as X-ray sources turned out on close inspection with high-quality data to have very weak but definitely present broad components of Hα emission (Shuder 1980, Veron et al. 1980). There is not a good correlation between the X-ray luminosity of a galaxy and the strength of the high-ionization optical lines [Fe X], [Fe XI], and [Fe XIV]. Perhaps this is because when photoionization occurs it destroys the ionizing photon.

Very high quality X-ray measurements are now becoming available for many Seyfert 1 and 1.5 galaxies, and their interpretation may be expected to provide good information on the geometrical structure, orientation and covering factor in these objects, particularly in the BLR (Lawrence and Elvis 1972; Mushotzky 1982; Maccacaro, Perola and Elvis 1982).

Abundances of the elements cannot be measured in Seyfert galaxies with the precision possible in planetary nebulae, because we do not yet know the detailed structure of the galactic nuclei, and therefore cannot calculate accurate models for them. Standard diagnostic methods, as used in the early planetary-nebula work, show the abundances are approximately "normal" in Seyfert and radio galaxies. The most readily apparent difference between the spectra of Seyfert galaxies and planetary nebulae is that in some of the former the [Fe VII] lines are relatively strong, while in the latter they are invariably weak, as mentioned above. This can be traced to the fact that the Fe abundance is approximately "normal" in Seyfert galaxies, while it is considerably subabundant in the gas in planetaries. The straightforward interpretation is that the missing Fe is locked up in solid components in dust particles in planetaries, but not in Seyferts (Shields 1975). Quite recently Gaskell, Shields and Wampler (1981) have found evidence that Fe, Si, Al, Mg and C all have normal abundances in quasars, and have argued that since none of these elements are depleted as in planetary nebulae and the interstellar medium, there is no dust in quasars or in the BLR of active galactic nuclei, which they take to be physically similar. Since the same reasoning would seem to show that there is no doubt in the NLR either, from the normal abundance of Fe, while there is strong evidence that dust is there and weak suggestions of dust in the BLR as well, the question must be regarded as still open.

All the active galaxies have detectable featureless continua, which can be found by decomposing the observed spectrum into emission lines plus a normal-galaxy spectrum with absorption lines plus a power-law continuum (Koski 1978; Yee and Oke 1978; Shuder 1981). In Seyfert 1 and BLRG the featureless continuum is usually very strong. Typically the fraction of the continuous spectrum near Hβ in the featureless continuum is $f_{FC} \gtrsim 0.9$, or in many cases undetectably different from 1. For typical Seyfert 2 and NLRG on the other hand, $f_{FC} \lesssim 0.1$ to 0.4. Thus there is a very strong correlation between the presence of broad emission-line components, and the presence of a strong featureless continuum. This correlation suggests that the physical mechanism that produces the high velocities observed in the BLR is intimately connected with the mechanism that produces the featureless continuum. Cyg A is the outstanding exception to this correlation; recent high-quality spectral scans show it has $f_{FC} \gtrsim 0.6$, above the upper limit of previously observed NLRG (Osterbrock 1982). In its radio properties also, Cyg A is more similar to the N galaxies that are BLRG, than to the cD and E galaxies that are NLRG like itself (Grandi and Osterbrock 1978).

An interesting group of objects, recognized only relatively recently, are Seyfert galaxies with weak broad Hα emission components, and in some cases very weak broad Hβ emission, combined with fairly strong narrow emission-like spectra. All of them have fairly small f_{FC}. Since these properties are close to but not identical with those of Seyfert 2's, I have called them Seyfert 1.8 or 1.9 galaxies (Osterbrock 1981b). The broad-line component Hα/Hβ ratios are very large in all these objects, suggesting that extinction by dust is important in the BLR. However the galaxies in which they are found are not, as a group, seen nearly edge-on, as is, for instance NGC 4235, a Seyfert 1 galaxy that shows the effects of strong extinction by dust in its plane (Abell, Eastmond and Jenner 1978). In addition to the five published examples of Seyfert 1.8 or 1.9 galaxies (Osterbrock 1981b), more recently classified objects of this type are Mrk 728, 744, 766, 1179, and 1218.

A very striking difference between the spectra of Seyfert 1 and BLRG is that the former usually show strong Fe II emission, while the latter almost invariably do not (Osterbrock 1977, Grandi and Osterbrock 1978). The Fe II profiles are either the same as the H I broad-line profiles or slightly narrower than them; the Fe II emission lines are clearly associated with the BLR but perhaps are weighted slightly more strongly toward the lower-velocity parts of it (Phillips 1977, 1978a). Analysis of the optical Fe II emission multiplets alone seemed to favor slightly resonance-fluorescence as their excitation mechanism (Phillips 1978b). However, more recent comparisons of the ultraviolet, higher-excitation multiplets with the optical ones have greatly strengthened the idea that the Fe II emission arises by collisional excitation in heated, mostly neutral regions (Collin-Souffrin _et al_. 1979, 1980; Wills, Netzer and Wills 1980; Grandi 1981).

The great majority of galaxies that show emission lines in their spectra are objects in which the photoionization source is early-type stars. At a low enough level, essentially every late-type spiral galaxy and irregular has emission lines of this type. Many of these objects have O-type stars even in their nuclei, which are thus giant H II regions. Some of them have so many stars that the nebular emission lines are very strong, and radio and X-ray emission can be observed from the integrated effect of the supernova remnants in them. These are the "star-burst" nuclei of Weedman _et al_. (1981). Most early-type spiral galaxies also have nuclear emission lines; in general they have larger [N II]/Hα and [S II]/Hα ratios than the H II region galaxies. It has been suggested that the interstellar gas in these early-type spirals is collisionally ("shock") heated (Heckman 1980). However, further observational and theoretical study makes it seem much more likely that in fact the gas is photoionized by a featureless, power-law continuum, with a much lower luminosity than in typical Seyfert galaxies, and thus essentially undetectable in the integrated-galaxy optical-continuous spectrum (Keel 1982).

In the active galaxies, the line profiles are broader than in nearly all such narrow emission-line galaxies. Still, the narrow-line profiles of active galactic nuclei are barely resolvable with most scanner data obtained to date, and only the line widths have been determined (e.g. Koski 1978; Shuder and Osterbrock 1981; Feldman _et al_.

1982). Recently, considerably higher-resolution measurements have revealed that the narrow lines are characteristically asymmetric, with a sharper fall-off to the red than to the blue. An interpretation in terms of extinction by dust in the NLR, with the gas flowing radially outward, is suggested by these profiles (Heckman et al. 1981). Several other groups are actively making similar profile measurements, and it is clear that they will add greatly to our understanding of active galactic nuclei.

Likewise an atlas of broad-line profiles in Seyfert 1 galaxies has recently been published by Osterbrock and Shuder (1982). They exhibit a very great range of widths, and are symmetric in some cases, asymmetric to the red in others, and to the blue in still others. Although it is difficult to draw any but the most general information from the profiles alone, they will clearly be extremely useful in testing any models that are calculated from definite physical pictures, as for instance Capriotti, Foltz and Byard (1979) or Raine and Smith (1981)..

Perhaps the most widely adopted basic idea is that the observed high velocities result from radial, radiation-pressure driven flows (e.g. Blumenthal and Mathews 1975). An alternate picture is that the emitting regions are flattened, perhaps by rotation (Shields 1977; Osterbrock 1978). Recent very high angular-resolution measurements with the VLA of some of the nearest Seyfert galaxies show that the regions of weakly radio-emitting plasma in these objects, which appear to be closely associated with the NLR, have disk-like distributions associated with the planes of the galaxies. In some cases, there appear on the VLA maps two small, oppositely directed "jets", which lie along a line that is not the same as the rotation axis, but rather is inclined to it. This suggests that there may be an inner, small disk-like structure, with size of order of 1 pc, whose rotation axis is tipped with respect to that of the rest of the galaxy (Wilson and Willis 1980; Ulvestad, Wilson and Sramek 1981). It is natural to associate this small region with the BLR, and Tohline and Osterbrock (1982) have given theoretical and observational evidence that supports such a tipped structure.

A pictorial representation of such a model is shown in Figure 1. The tipped BLR is shown crosshatched; at its center is the photoionization source, perhaps an accretion disk around a black hole. The BLR is supposed to be optically thick to ionizing radiation along nearly all rays in its equatorial plane, but not at its poles, so that ionizing photons mostly escape only within a cone about this axis, which is also the axis along which radio plasma can escape. In a nearly "pure" Seyfert 1 galaxy the optical depth of the BLR is large and the cone shrinks to an angle of nearly 0^o; in the opposite extreme the disk is optically thin in all directions, the object is a nearly pure Seyfert 2, and the cone opens out to 90^o. The NLR is composed of density condensations, each of which is mostly highly ionized on the face toward the photoionization source. Each condensation is optically thick, and is only slightly ionized on the side facing away from the source. The most distant condensations are not as highly ionized at their front faces as those nearer the source. The BLR has a similar structure, consisting of condensations also.

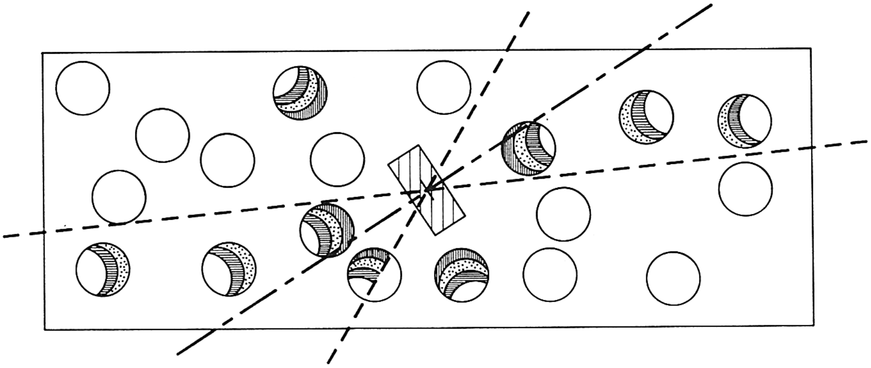

Fig. 1. Schematic drawing of model for gas distribution in active galactic nuclei.

The drawing is an extreme simplification; there are many more condensations than shown, and the fraction of them that are struck by ionizing radiation varies smoothly with angle. The only slightly ionized regions of the dense condensations in the BLR are the Fe II emitting regions; presumably they are heated by plasma. In the BLRG, on the other hand, the observations suggest that the flow is along the rotation axis out into the radio lobes, and perhaps better collimation in this situation leads to less of the neutral parts of the condensations being heated in this way. On this picture the Seyfert 1.8 and 1.9 nuclei might be understood as cases in which the tipped BLR is seen nearly edge on, so that there is strong extinction in its outer parts, but the main galaxy is not, so the NLR has on the average no more extinction than in typical Seyferts.

The entire model is highly schematic. Much further work will be necessary to make it physically definite, and to test it. There are clearly additional complications - for instance, spectropolarimetric measurements show that although in NGC 4151 the forbidden lines and the narrow components of the H I lines have the same polarization (Schmidt and Miller 1980), in NGC 1068 the forbidden lines and permitted lines have different polarizations, indicating that they cannot arise in identical regions (Angel et al. 1976). NGC 4151 is a fairly typical Seyfert 1.5; NGC 1068 is an abnormal Seyfert 2. Clearly many problems remain, but one may hope by combining data from all spectral regions either to reject this type of model, and pass on to a better one, or to find that it meets, at least for a time, all the observational tests. The ultimate aim is to understand the structure and physical nature of all the emitting regions, and of the mechanisms by which energy is "generated" (assembled and released) almost certainly by gravitational processes. The ionizing radiation emitted by the central source, perhaps as a function of position and angle, must be the input spectrum that leads to the observed emission-line spectrum.

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ALLER: The presence of strong [Fe VII] and [Ca V] lines in the spectra of Seyfert galaxies suggests that there is little loss of refractory elements from the gas phase. This differs from the situation in PN, where Fe and Ca are depleted. However, observations show that dust is present in Seyferts! How might these facts be explained?

OSTERBROCK: There is no doubt that the [Fe VII] lines are stronger in Seyfert 1 galaxies than in PN. The [Fe VII] line profiles are basically the same as those of other lines formed in the narrow-line emitting regions. Yet the Balmer decrements show that dust is present in or very near the narrow-line regions. Perhaps the dust in Seyfert 1 galaxies differs from that in PN, or perhaps it is just outside the ionized regions.

PEIMBERT: What are your views on the evolution of galaxies with broad-line emitting regions?

OSTERBROCK: Essentially all Seyfert galaxies are spirals, and nearly every Seyfert is a SB spiral, or is distorted, or has a close companion galaxy. Evidently, the deviation from a circularly symmetric gravitational field is necessary for the Seyfert phenomenon to occur. Thus, it seems possible, and perhaps likely, that every spiral galaxy with these properties will, given enough time, ultimately become a Seyfert.

Recent spectral studies of "normal" spiral galaxies, particularly by William C. Keel at Lick Observatory, have shown that many of them have emission line spectra that can be understood in terms of photoionization by a power law spectrum ($L_\nu \propto \nu^{-\alpha}$), but with a luminosity much smaller than in typical Seyferts. These objects can thus be regarded as "weak" examples of the Seyfert phenomenon. Perhaps, in some of them, the energy source will grow and they will become fully developed Seyferts. In others, the energy source may remain weak or become exhausted.

SEATON: To what extent can the anomalous Balmer decrements be explained by reddening? The basic theory of recombination spectra has been pursued further for Seyferts than for PN, particularly by including effects of line transfer. Perhaps studies of PN have something to gain from the work on Seyferts in this field.

OSTERBROCK: In the narrow-line regions, the Balmer decrements can be fitted pretty well by recombination plus reddening. In the broad-line regions, deviations from the recombination decrements are large and seem to indicate that reddening, collisional excitation (from n = 1 and n = 2), and radiative transfer effects all play a role. Many theoretical computations, from one side or another of this problem, have been made, but the real physical situation is undoubtedly much more complicated than that assumed in the models.

NUSSBAUMER: Have the electron temperatures in the narrow and broad-line regions been reliably determined?

OSTERBROCK: In many cases, yes, for the [O III] and [N II] narrow-line emitting regions. Also, in one case (III Zw 77), from [Fe VII], although the result is uncertain because the reddening correction is not known. In the broad-line regions, there are no good diagnostics, although the Fe II lines indirectly indicate $T \approx 10^4$ K, and the broad-line spectra of the brighter Seyferts that have been observed with

IUE (and in QSO's with large red-shift, in which the ultraviolet spectrum can be observed) indicate that $1 \times 10^4 \lesssim T \lesssim 2 \times 10^4$ K is consistent with the observed C III] and C IV line strengths.

SURDEJ: With your proposed model, how can you escape the conclusion that Seyfert 1 (Seyfert 2) galaxies are galaxies seen edge-on (face-on)?

OSTERBROCK: In the proposed model, the main velocity field in the broad-line region is rotation, but there is a smaller "turbulent" velocity field. This produces the finite height of the broad-line region shown in the Figure. Thus, viewed even from along the axis, the broad-line profiles are significantly wider than the profiles of the forbidden lines produced in the narrow-line regions. There is a large range of line widths in Seyfert 1 galaxies, from about 0.01 c to about 0.10 c. According to the model, part of this spread arises from differences in rotational and turbulent velocities, part from projection effects. I believe that the observational data show the disks to be tipped, in many cases, with respect to the planes of the spiral galaxies in which they occur. The spectra of the Seyfert 1 galaxies with even the narrowest broad-lines typically also show Fe II emission, high stages of ionization in the narrow lines, and have small [O III] λ 5007/Hβ ratios - all of which differentiate them from Seyfert 2 galaxies.

COSTERO: It seems that the spectra of type I PN and Seyfert 2 galaxies are very similar, both showing very low and very high excitation lines. Would you comment on this?

OSTERBROCK: I agree with you. However, in Seyfert 2 galaxies, the [S II], [O I], and [N I] lines are typically stronger (relative to Hβ) than in type I PN. I believe that the photoionizing spectra are roughly the same in both types of objects but that the approximate power-law spectra, probably with a cut-off around 100 eV in the Seyfert 2 galaxies, contain more high energy photons than even the hottest central stars of type I PN, thus producing larger "transition zones" in which O^0, N^0, S^+, H^0, H^+, and electrons coexist.

ROCHE: There are clear differences in the infrared (10 μm) spectra of narrow-line galaxies and Seyferts. The former show strong emission in the narrow dust features, while the Seyferts generally have featureless continua with no direct evidence of dust emission.