

## Seyfert Galaxies

In many respects Seyfert galaxies are similar to any other galaxy, except their nuclear regions show unusual properties: they can be much brighter and their spectra show strong emission lines of high excitation. Such nuclei are called ‘active’, and so Seyfert galaxies belong to the wider category of ‘ACTIVE GALAXIES’ or, more specifically, they have ‘ACTIVE GALACTIC NUCLEI’ (AGN). Seyferts were, in fact, the first type of active galaxy to be discovered.

In the zoo of AGNs the power of the nuclear activity spans a wide range. Within this zoo, Seyferts show intermediate levels of activity, being more powerful than LINER galaxies but less powerful than QUASARS. Seyferts also join the majority of active galaxies in being ‘radio-quiet’, with radio luminosities  $10^3$ – $10^4$  times weaker than the ‘radio loud’ category, which includes RADIO GALAXIES and radio quasars.

Over the past 20 years much effort has gone into finding Seyfert galaxies amongst the more normal galaxy population. Efficient ways to detect Seyferts include looking specifically for galaxies with bright UV emission, bright x-ray emission, or unusual far-infrared colors, since these are common characteristics of Seyferts. The fraction of galaxies with active nuclei depends on the level of activity: moderate luminosity Seyferts make up  $\sim 1$ – $2\%$  of nearby bright galaxies, lower luminosity Seyferts make up  $\sim 10\%$ , while LINERs make up  $\sim 40\%$ . Currently, about 800 Seyferts are known, though the number continues to rise.

From a wide range of studies, a picture has emerged of the structure of the central regions of Seyferts. Briefly, the gravitational field of a supermassive ( $10^6$ – $10^9 M_\odot$ ) black hole provides the ultimate energy source, as gas falls inwards via a luminous accretion disk (see SUPERMASSIVE BLACK HOLES IN AGN). A small region of fast moving clouds surrounds this central engine, spanning a few light days or weeks, while a larger region of slower moving clouds extends out a few hundred to a few thousand light years. In some cases, oppositely directed collimated jets of low density gas plow into the surrounding galaxy, accelerating the interstellar medium and creating jet-like or linear radio structures. In at least some Seyferts, dense gas and dust shroud the innermost regions, hiding them from our direct view, though the nuclear radiation escapes in other directions to light up gas and dust residing much further out in the galaxy.

The conditions that give rise to Seyfert activity are still under debate. While Seyferts are found in a wide range of galaxy types, they are more commonly found in reasonably luminous early-type spirals (e.g. types S0/a, Sa, Sb in the Hubble classification scheme). It seems, therefore, that prerequisites favoring Seyfert activity include a massive galaxy bulge and the presence of an interstellar medium. There is also evidence that Seyferts prefer galaxies with an asymmetric gravitational field arising from a bar or other distortion, possibly induced by a nearby companion galaxy. Such distortions

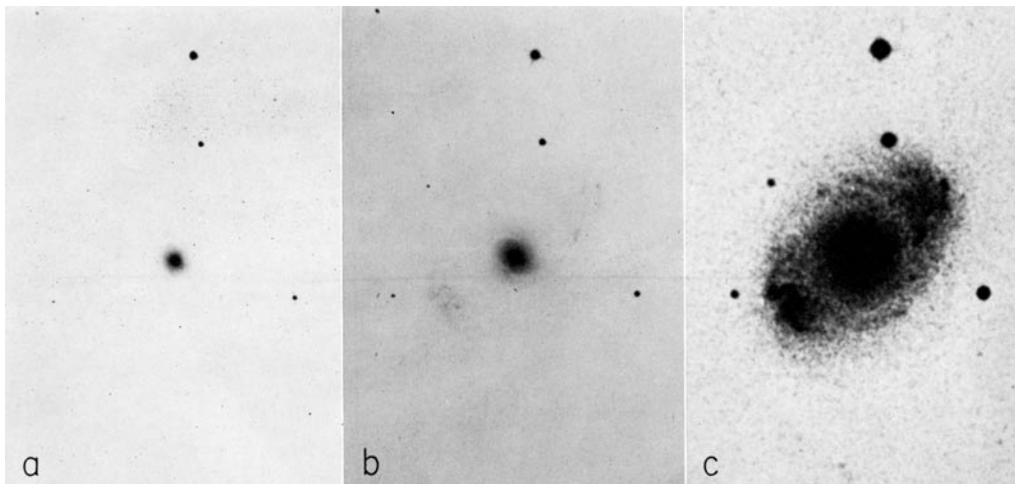
are thought to be instrumental in funneling gas down to the nuclear regions where it can then fuel the central black hole.

### Discovery, classification and detection

The early identification of nearby Seyfert galaxies rested on two observational properties—their unusual nuclear spectra and their unusual nuclear brightness. While studying galaxy spectra for his PhD work in 1908, Fath noted strong emission lines in the spectrum of the nucleus of NGC 1068. These observations were confirmed in 1917 by Slipher and by 1926 Hubble had added two more galaxies with similar spectra: NGC 4051 and NGC 4151. In 1932 Humason noted that NGC 1275 had a bright starlike center, but it wasn’t until 1943 that CARL SEYFERT recognized a distinct class of galaxies with unusually bright and concentrated nuclei, and studied in detail six of the 12 then known cases (NGC 1068, 1275, 3516, 4051, 4151, 7469), leading to the group’s name: Seyfert galaxies (see figure 1). Seyfert’s spectra showed emission lines which were not only unusually strong, but also unusually wide. Interpreting the width of the spectral lines as Doppler shifts caused by motion of the ionized (line emitting) gas implied gas velocities in some objects of several thousand  $\text{km s}^{-1}$ , far higher than velocities found in normal galaxies. A further subtlety Seyfert noticed was that in some objects the hydrogen lines were broader than the other lines.

Little work was done until the 1960s, when it became clear that Seyfert galaxies shared a number of properties with the then recently discovered quasars. At this time, quasars posed a serious theoretical puzzle. While their high REDSHIFTS implied great distance and therefore high luminosity, their brightness had been found to vary from month to month, indicating that the region producing all this energy was only a few light months across—tiny compared to the rest of the galaxy. The puzzle of how so much energy could emerge from so small a volume was sufficiently acute that some astronomers even questioned whether the quasar redshifts were true indicators of distance, leading to the so-called ‘redshift controversy’. Although this controversy has since been resolved in favor of large distances it might never have been as problematic if Seyfert galaxies had been better studied in the early 1960s, since they are clearly low redshift counterparts to the quasars. Not only are their spectra basically similar, but in 1968 NGC 4151 was found to vary in brightness, confirming a highly compact nuclear energy source. As more Seyferts and quasars were discovered, their separation in luminosity narrowed and finally even overlapped. Continuity had been established and, for most astronomers, the reality of the quasar distances and luminosities was no longer in doubt.

In 1974, Khachikian and Weedman identified two types of Seyfert galaxy on the basis of the widths of the nuclear emission lines. Figure 2 shows example spectra of each Seyfert type. While spectra of type 2 Seyferts have a single set of relatively narrow emission lines, in the spectra of type 1 Seyferts the hydrogen and helium



**Figure 1.** Three photographs of NGC 4151 taken with increasing exposures (a, b, c) showing its unusually bright nucleus—an important characteristic used in the early identification of Seyfert galaxies. (Taken from Morgan W W 1968 *Astrophys. J.* **153** 27)

lines have an additional much broader component. In the simplest cases, the broad component is either absent (Seyfert 2) or strong and dominant (Seyfert 1). With better data it became clear that there is a wide range in the relative strength of the broad and narrow emission lines, and this led Osterbrock in 1981 to refine the Seyfert classification by introducing intermediate types. A good place to establish the classification is with the hydrogen  $H\beta$  line at rest wavelength 4861 Å. As the broad component of  $H\beta$  becomes weaker relative to the narrow component, the Seyfert type changes from 1 to 1.2 to 1.5 to 1.8. For Seyfert 1.8 galaxies, weak broad wings are just visible at the base of  $H\beta$  while for Seyfert 1.9 galaxies they are only visible on the  $H\alpha$  emission line at 6563 Å. In practice, these Seyfert sub-types have not been formally defined but instead give an overall indication of the degree to which the broad component is present.

Although there are a number of Seyfert properties that depend on Seyfert type, perhaps the most noticeable is the ‘white light’ continuum coming from the nucleus. In normal galaxies the nuclear continuum is mostly starlight, but in active galaxies there can be additional emission, often blue in color and with few or no absorption features. This component is much stronger in Seyfert 1s, weaker in Seyfert 2s, and may even be undetectable in the lowest luminosity Seyfert 2s. Although we refer here to the optical continuum emission, this component extends into the UV and x-ray, and so emission in these spectral bands can also be quite different for Seyfert 1s and Seyfert 2s.

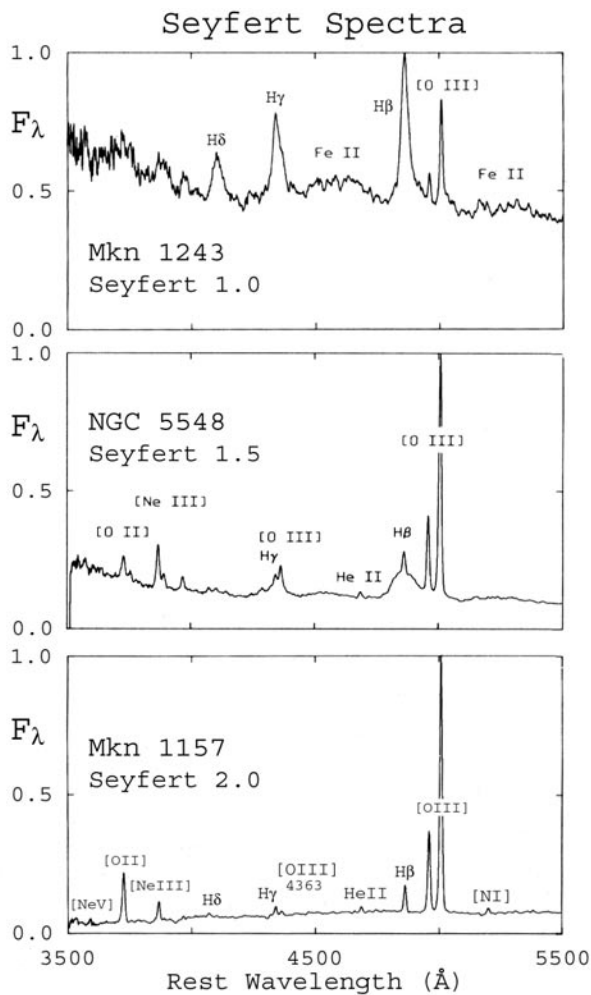
Bearing in mind the principal features which distinguish Seyfert spectra from normal galaxy spectra—strong broad emission lines and a blue continuum—we can now follow the history of how Seyferts have been identified over the past 40 years.

As outlined above, the first Seyferts were discovered essentially by accident when a galaxy spectrum was noted as being unusual. The first survey which identified many

Seyferts was that of Markarian and collaborators at the Byurakan Observatory in Armenia, during the period 1962 to 1981. This survey used a technique known as Objective Prism Spectroscopy to find galaxies with unusually blue continuum emission. The telescope was a 1.3 meter Schmidt telescope with a thin prism bolted over the entrance aperture. This combination gives relatively wide field photographs in which each star and galaxy appears as a small spectrum. In this way, the spectra of many galaxies can be studied quickly, and those which appear unusual noted and listed. The survey covered  $\sim 10\,000$  square degrees and yielded 1500 galaxies with blue continua, of which  $\sim 10\%$  were Seyferts (the remainder were mainly STARBURST GALAXIES, blue because of the presence of young massive O and B type stars). Because of the emphasis on blue continuum, the Markarian Seyferts contain a relatively high proportion of Seyfert 1s (about 50%) and rather luminous Seyfert 2s.

Since x-ray emission is common in active galaxies, x-ray surveys provide an effective means to find Seyferts. Starting in the late 1970s surveys have included those of the Ariel V, HEAO-1, Einstein and ROSAT satellites. Some of these were all-sky surveys, some included deeper pointed observations, some were sensitive to hard x-rays (2–10 keV) and others to soft x-rays ( $\sim 0.2$ –4 keV). In general, x-ray surveys tend to find Seyfert 1s since their nuclear continuum emission is stronger than in Seyfert 2s.

In 1982, the IRAS satellite provided a huge list of galaxies which were relatively bright in the far infrared (25–100  $\mu\text{m}$ ). Although bright infrared flux by itself is no guarantee of Seyfert activity, the ‘color’ of the infrared emission can help distinguish between Seyfert and normal galaxies: normal galaxies have colder dust ( $\sim 30$  K) than Seyfert galaxies ( $\sim 100$ –300 K) in which nuclear activity provides an additional heating source. Thus, IRAS-selected galaxies with ‘warm spectra’ have yielded many Seyferts.



**Figure 2.** Spectra of three Seyfert galaxies illustrating the difference between Seyfert 1, 1.5 and 2 classes. Principal emission lines are labeled, with square brackets indicating forbidden lines. (Adapted from Osterbrock D E 1984 *Quart. J. R. Astron. Soc.* 25 1.)

Since Seyferts belong to the radio-quiet group of active galaxies, radio surveys at high flux levels tend not to find Seyferts, but rather radio galaxies. Deeper radio surveys, however, do pick up more Seyferts but along with many star-forming galaxies. On further study, the presence of a compact core with flatter spectral index increases the chance that the galaxy is a Seyfert.

Perhaps the most reliable method of finding Seyferts, though also the least efficient, is optical spectroscopy of galactic nuclei. In the early 1990s the CfA redshift survey of about 2000 galaxies brighter than about magnitude 14–15 found about 2.5% to be Seyferts with an even mix of Seyfert 1s and 2s. Using smaller apertures and higher quality data, the deep Palomar survey of the nuclei of nearly 500 bright galaxies from the RSA catalogue yields about 10% Seyferts, including many of lower luminosity. In the near future, the SLOAN DIGITAL SKY SURVEY will surely find many more.

A catalog of all known Seyferts has been maintained by Veron-Cetty and Veron, and at its last edition (1998) about 790 Seyferts were listed with redshifts  $< 0.1$  and brighter than  $17^m$  in V.

### Overall structure and geometry

In this section we give a brief outline, without justification, of the basic structures found in Seyfert galaxies; brief because similar material is given elsewhere in this encyclopedia and also because more detailed descriptions of some of the structures are given in subsequent sections.

Figure 3 gives a cartoon of the structures nested from innermost to outermost. The region sizes probably scale with luminosity, larger for quasars and smaller for low luminosity Seyferts and LINERs. The values given are rough guides for the case of moderate luminosity Seyferts.

The ultimate origin for the energy which drives nuclear activity is thought to lie in the gravitational field of a central supermassive black hole of mass  $\sim 10^7$ – $10^8 M_{\odot}$ . Gas falls into the black hole via an accretion disk, which radiates powerfully across much of the electromagnetic spectrum. The disk may span from a few Schwarzschild radii to a few thousand Schwarzschild radii, probably with x-ray emission coming from the inner parts, UV and optical from further out. It is this radiation which floods out into the galaxy and ionizes any surrounding gas, causing it to radiate emission lines. The innermost region of ionized gas resides a few light days from the center, and contains gas with density  $\sim 10^9$ – $10^{12}$  atom  $\text{cm}^{-3}$  moving with speeds of a few thousand  $\text{km s}^{-1}$ . Doppler shifts therefore lead to broad emission lines—hence the name: Broad Line Region (BLR). Outside the BLR, on scales from one to a few pc lies thick dense gas, possibly in the form of a torus. This gas blocks radiation coming from the innermost regions, which can only escape out of the equatorial plane along the torus axis. This partially collimated radiation field emerges further into the galaxy to ionize gas residing in a region out to a few kpc. In this region, the gas has a lower density  $\sim 10^2$ – $10^6$  atom  $\text{cm}^{-3}$  and moves with speeds of a few hundred  $\text{km s}^{-1}$ , leading to narrower emission lines—hence the name: Narrow Line Region (NLR). Because of the partially collimated radiation field, the NLR often appears elongated or even biconical, with axis matching that of the central radiation field. When a radio source is present it is often elongated, aligned with the NLR axis, and has approximately the same size. The radio source emerges from the inner regions as a bipolar flow, accelerating and possibly shocking some of the gas in the NLR. The entire NLR and associated radio structure usually fill a region a few kpc across within the bulge of the host galaxy, but randomly aligned with respect to obvious galactic structures and orientation. If there is a more extended gaseous component, it can be illuminated by the central ionizing radiation field, leading to faint extended emission, sometimes showing conical or biconical form. This is the so-called Extended Narrow Line Region (ENLR).

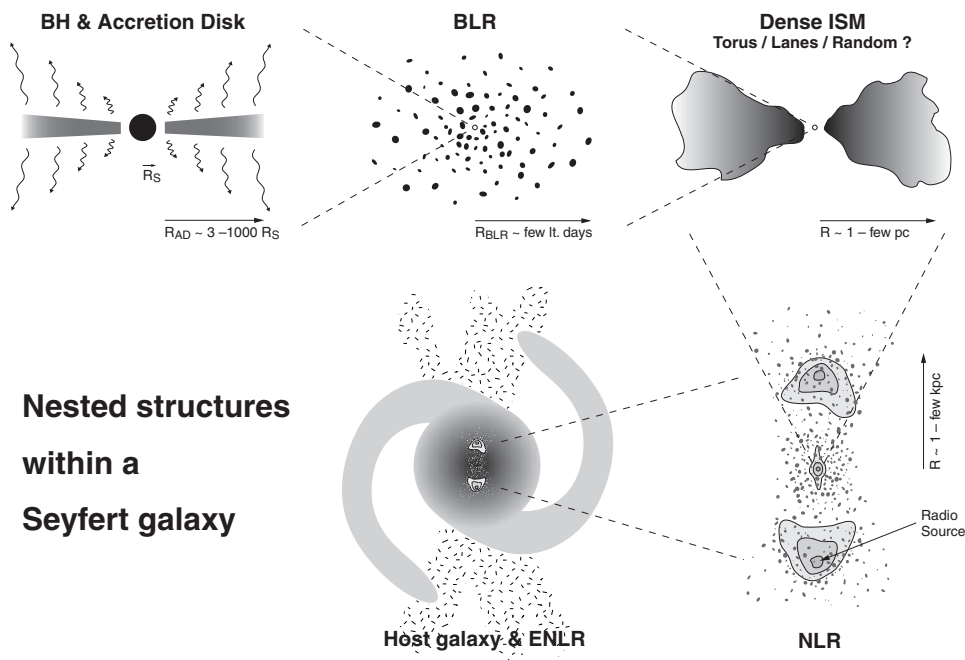


Figure 3. Cartoon illustrating the nested structures thought to be present within Seyfert galaxies.

Inherent in this picture is a lack of spherical symmetry, rooted in the anisotropic emergence of both radiation and radio emitting flows. The origin of the anisotropy might arise in either of two ways: (a) an intrinsic nuclear axis perhaps defined by the black hole spin and/or the accretion disk, and (b) partial obscuration by dense gas which blocks radiation in some directions but not in others. For Seyferts, partial obscuration is thought to be important. The simplest geometry envisioned is a thick disk or torus a few parsecs in size and aligned with the central engine axis. More recently, images from the Hubble Space Telescope (HST) have shown that dust lanes and filaments are common in the central few hundred parsecs, particularly in Seyfert 2s, raising the possibility that less coherent obscuration on these larger scales might also be important. Either way, the fact that the nuclear radiation can only emerge along particular lines of sight raises an interesting possibility which was first noted in 1978 by Osterbrock: namely, that Seyfert 2s might actually be Seyfert 1s but oriented in such a way that our view to the central region is blocked. Stated slightly differently, the same Seyfert galaxy might appear as a Seyfert 1 from some directions and a Seyfert 2 from others. This constitutes a ‘Unification’ scheme, since apparently different classes of objects are ‘unified’ into a single class. The important topic of unification arises in a number of contexts in the study of active galaxies and is discussed at length in ACTIVE GALAXIES: UNIFIED MODEL. Here we give a brief outline of the evidence supporting the particular case that many (though perhaps not all) Seyfert 2s are in fact hidden Seyfert 1s.

First, the emission line regions of Seyfert 2s, on both large scales (ENLR) and small scales (NLR), are often

elongated, with a subset showing sharp edges and even conical or biconical form. These patterns are consistent with dense nuclear gas casting shadows in a strong central ionizing radiation field. When visible, the cone opening angles are  $\sim 40^\circ-80^\circ$ , suggesting  $\sim 25\%$  of the surrounding sky sees the nuclear regions. Good examples of this are found in NCG 1068, NGC 5252, MKN 78, MKN 573.

Extending this topic further, one can use spectroscopy of the ionized gas to show that *it* sees a significantly brighter central radiation source than *we* see. There are two approaches. In the first, emission line strengths from extended gas are used to infer both the gas density and its degree of ionization. Knowing the distance between this gas and the central source then allows one to estimate the (ionizing) luminosity of the central source. This luminosity is often significantly greater than the luminosity we see directly, along our line of sight. The second approach uses the total  $H\beta$  luminosity coming from all regions to estimate the total ionizing luminosity of the central source. This luminosity is again often found to be significantly greater than the luminosity we infer from our own line of sight to the nucleus.

The third and perhaps most dramatic piece of evidence involves taking spectra of light that was initially moving out of the nucleus in one direction but then got reflected into our line of sight. This provides a sort of periscope, allowing one to look around a corner and into the nucleus from a different direction. The mirrors of the periscope are dust particles or electrons in the surrounding gas which scatter light in all directions, some

of which comes towards us. Since the scattered light is so faint compared to the normal light we need a way to isolate it. Fortunately, the scattering process also induces polarization, and so a spectrum of the polarized light shows just the scattered component. Remarkably, for many of the brighter Seyfert 2s these polarized light spectra show Seyfert 1 form: strong non-stellar continuum and broad hydrogen and helium lines. The classic discovery was for NGC 1068 by Antonucci and Miller in 1983, but since then many other examples have been found.

A fourth approach is to compare the nuclear x-ray emission of Seyfert 1s and 2s. Consistent with unification, soft x-ray spectra show significant absorption towards Seyfert 2s but little or none towards Seyfert 1s. Furthermore, at higher x-ray energies where absorption isn't important, the spectra of Seyfert 1s and 2s are often quite similar, with ratios of x-ray to optical flux much higher for the Seyfert 2s, as expected if the optical emission is blocked but the hard x-rays are not.

Finally, there is some evidence for the nuclear obscuring material itself. When water masers are detected, they tend to be in Seyfert 2s. These sources form in dense warm molecular gas with long paths in our line of sight, consistent with an edge-on disk geometry. Also, infrared spectra are often dominated by thermal emission from warm dust. Although some of this originates on NLR scales, some comes from much smaller scales. The fact that the total luminosity of many Seyferts, particularly Seyfert 2s, is dominated by the thermal infrared is consistent with the obscuration picture: much of the nuclear luminosity is absorbed by gas and dust whose principal mode of cooling is in the far infrared.

Assuming, for the moment, that all Seyfert 2s contain hidden Seyfert 1s, then we can ascertain the extent of the obscuration by comparing the relative number of Seyfert 2s (obscured) with Seyfert 1s (unobscured). In practice, it is important (and difficult) to select an unbiased sample of Seyferts using a property that is *not* thought to depend on orientation. Possibilities include radio flux, far-infrared flux, host galaxy magnitude, and narrow emission line flux, though none are ideal. With some uncertainty, the ratio of Seyfert 2s to Seyfert 1s found in such samples is roughly 2–5 to 1, suggesting  $\sim 20$ –30% of the sky sees an unobscured view of the nucleus, consistent with other estimates based on the opening angle of emission line cones.

Whether *all* Seyfert 2s contain hidden Seyfert 1s is still an open question. Arguments against full unification of the two classes focus either on the absence of expected properties (for example, most Seyfert 2s have lower polarization than expected), or the fact that properties which should be the same in Seyfert 1s and 2s are not (for example, host galaxy morphology, and possibly radio luminosity).

### Relation of Seyferts to other AGN

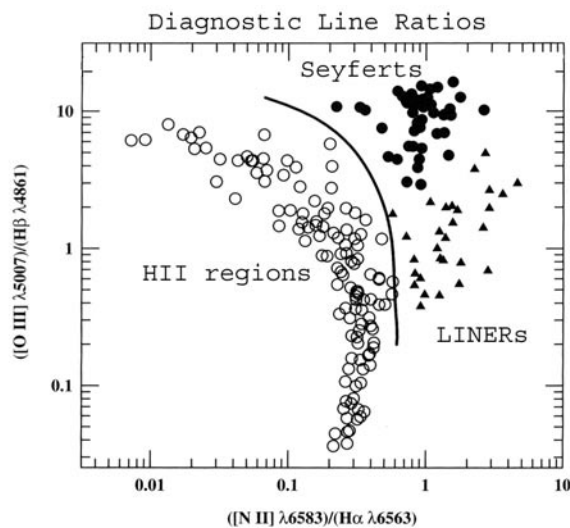
To the newcomer, it may seem that there are an annoyingly large number of names for different classes of active galaxy,

of which 'Seyferts' are only one class. This situation has arisen for a couple of reasons: (a) nuclear activity seems to have some genuine range of character, and (b) historical development is never clean and different approaches have naturally focused on different manifestations of activity. In hindsight, it is now possible to group the various categories in a more or less natural way which depends on two or three fundamental aspects of the activity itself: total luminosity, radio luminosity and variability. While these aspects are discussed in ACTIVE GALAXIES: OVERVIEW and ACTIVE GALACTIC NUCLEI: VARIABILITY, here we give a brief overview of the different classes of AGN, intending to locate Seyferts in their proper place.

Consider first the enormous range in total luminosity of AGN:  $\sim 10^{39}$  erg s<sup>-1</sup> ( $M_B \sim -10$ ) at the lowest detectable end, up to  $\sim 10^{47}$  erg s<sup>-1</sup> ( $M_B \sim -30$ ) at the highest. Seyferts span the low to intermediate range, overlapping somewhat on the high end with quasars. Since it now seems that Seyferts and quasars form a continuous physical sequence, any attempt at a formal separation is somewhat arbitrary. Although a morphological criterion is usually adequate (quasars have point-like appearance) close scrutiny of low redshift quasars often reveals galactic 'fuzz' in ground-based images or clear host galaxies in HST images. For this reason, a luminosity criterion is sometimes chosen to delineate Seyferts and quasars. There is no consensus, but threshold values of  $M_B \sim -23$  or  $L_B \sim 10^{44}$  erg s<sup>-1</sup> are typical. While Seyferts and quasars may be physically similar, differences do seem to occur with increasing luminosity, including longer variability timescales indicating larger emission regions, the apparent loss of the 'type 2' class, and some line strength changes including the relative weakening of both broad and especially narrow lines relative to the continuum.

Turning to lower luminosities, although one of the lowest luminosity AGNs is in fact a Seyfert (NGC 4395,  $M_{B \text{ nuc}} \sim -10$ ) most of the low luminosity AGNs belong to the 'LINER' class. This group was originally identified by Heckman in 1980 from a spectroscopic survey of a large number of bright nearby galaxies. A high fraction were found to have weak emission with low overall degree of ionization, hence the name: Low Ionization Nuclear Emission Line Regions, or LINERs. The exact nature of LINERs is still unclear, with evidence for an active nucleus in at least  $\sim 20\%$ : a compact nuclear UV source seen in HST images; a compact though weak nuclear radio source; or weak broad line emission visible at the base of H $\alpha$ . A major uncertainty is the ionization mechanism for the gas. Possibilities include shocks or photoionization by either a weak nuclear UV source, very hot young stars or very hot evolved stars.

Shortly after the identification of LINERs, a method for classifying emission line regions was introduced by Baldwin, Phillips and Terlevich and subsequently refined by Veilleux and Osterbrock. They used a number of diagrams which plotted the ratio of one pair of emission line fluxes against another pair. Figure 4 shows one of these diagrams and nicely illustrates how three major



**Figure 4.** One of several useful diagnostic diagrams which help distinguish between different classes of emission line object. (Adapted from Peterson B M 1997 *An Introduction to Active Galactic Nuclei* (Cambridge University Press), figure 2.3, p 26).

emission region types occupy different places on the diagram; in this case Seyferts separate from LINERs around  $[\text{O III}] \lambda 5007 / \text{H}\beta \sim 3$  while Seyferts and LINERs separate from H II regions around  $[\text{N II}] \lambda 6584 / \text{H}\alpha \sim 0.6$ . These line ratio diagrams also provide a suitable place to compare observations with theoretical models. For example, the H II REGION sequence matches models of gas clouds with a range of metallicities photoionized by radiation from OB associations with a range of ages. Similarly, Seyferts and LINERs form a sequence that matches gas which is photoionized by a power law spectrum with a range of intensities; the highest excitation Seyferts correspond to the most intense nuclear radiation field. The apparent continuity of Seyferts and LINERs on these diagrams supports the possibility that at least some LINERs are simply low intensity Seyferts.

Turning now to radio properties, Seyferts belong to the majority ( $\sim 90\%$ ) of AGN in being *radio quiet*—more luminous than normal galaxies but  $\sim 10^3$ – $10^4$  times fainter than radio-loud AGN. The closest radio-loud counterparts to Seyferts have similar optical luminosity and are called Broad Line Radio Galaxies (BLRG) and Narrow Line Radio Galaxies (NLRG), with optical spectra very similar (though not identical) to Seyfert 1s and Seyfert 2s respectively. At higher optical luminosity, we have radio-loud quasars, and at lower optical luminosity we have radio galaxies whose spectra are often LINER-like. Although most radio galaxies have huge radio sources which extend well outside the host galaxy, some have much smaller radio sources comparable in size to, though much more powerful than, the Seyfert sources (these are called, depending on details, Compact Steep Spectrum (CSS), Compact Double (CD) or Gigahertz

Peaked Spectrum (GPS) sources). It is quite likely that similar physical phenomena are occurring in the Seyferts and these compact powerful sources—both are embedded in a dense gaseous environment and probably interacting strongly with it. Thus, studying one may help understand the other.

The fundamental reason why  $\sim 5$ – $10\%$  of AGN become radio-loud is still not understood, though it is probably related in some way to the interesting fact that radio-loud and radio-quiet AGN tend to inhabit different types of host galaxy: ELLIPTICAL and SPIRAL GALAXIES respectively. It has been suggested that the radio-loud AGN have rapidly spinning (Kerr) BLACK HOLES which drive powerful jets along the spin axis, and these jets generate the powerful radio source. Conversely, slowly rotating (Schwarzschild) black holes cannot drive such jets and so remain radio-weak. The link between black hole spin and host galaxy type could arise from the fact that the elliptical hosts have formed from the merger of two spirals along with the merger of their two black holes to form a single rapidly rotating black hole.

Finally, Seyferts have little relation to the highly variable ‘BLAZAR’ classes of AGN: BL Lac objects, OVV (optically violently variable) quasars and HPQs (high polarization quasars). These are all radio-loud objects and, under the unified scheme for this category, are thought to be seen looking directly down a powerful jet where relativistic Doppler boosting enhances the luminosity, variability and polarization of the continuum.

### Black holes and continuum emission

It is worth noting that the evidence for black holes in Seyferts and other AGN is mostly indirect: large variable luminosity; relativistic jets with a stable axis; high energy spectra. Ideally, one would study gravitational dynamics of near-nuclear stars or gas. While this has been possible in a number of normal or weakly active galaxies, it is very difficult for most Seyferts simply because of the bright nuclear light and uncertain nature of the gas motions. With many ongoing HST observations, the case is now building for black holes at the centers of most (perhaps all) luminous galaxies, with black hole mass a few per cent of the bulge mass. It would be ironic if the discovery of black holes in most normal galaxies gave the most convincing evidence, by continuity, for their presence in AGN.

Two methods might provide a better approach to detecting black holes in Seyferts. The first method is to measure the dynamics of water masers in the dense warm gas close to the center. The classic case is NGC 4258 (not, in fact, a Seyfert galaxy), which provides the best case to date for a supermassive black hole, but other possible examples are increasing in number. The second method is to study the Fe  $K\alpha$  x-ray emission line profile at 6.4 keV. In several cases it is very broad and double peaked, suggesting its origin in a nuclear accretion disk at a few tens of Schwarzschild radii. An important goal will be to use profile fits to infer not only the mass of the hole but also its spin and orientation.

The energy released from matter falling towards the central black hole emerges in both bulk flows and photons; the latter yields, either directly or indirectly, the observed nuclear continuum emission. Perhaps the most noteworthy aspect of AGN continua is their extremely wide spectral range, with approximately equal energy per decade of frequency from far infrared to 100 keV x-rays (five decades) with extensions to radio and  $\gamma$ -ray energies in about 10% of AGN (not usually Seyferts). To a first approximation, the continuum shape can be described as a power law,  $f_\nu \propto \nu^{-\alpha}$ , with index  $\alpha \sim 0-1$ , with several features superposed. These features include: (a) a ‘Big Blue Bump’ (BBB) comprising a rise below  $\sim 4000 \text{ \AA}$  peaking in the UV or (unobservable) EUV and dropping to rejoin the underlying continuum in the soft ( $\sim 0.5 \text{ keV}$ ) x-ray region (the ‘soft excess’); (b) an infrared peak rising from  $\sim 1 \text{ \mu m}$ , peaking at  $\sim 25-60 \text{ \mu m}$  and falling again at  $\sim 0.3 \text{ mm}$ ; (c) a rise at the highest energies  $\sim 5-200 \text{ keV}$  with cut-off at even higher energies.

The interpretation of these various components is still somewhat uncertain, though there seems to be a general consensus. The underlying power law might be generated by the synchrotron self-Compton process: a population of relativistic electrons not only generates low energy photons via the synchrotron process but then inverse-Compton scatters these same photons up to higher energies. A related model for the x-ray power law involves inverse-Compton scattering of optical-UV photons produced in the ACCRETION DISK by electrons in a hot corona above the disk. The BBB is thought to arise from thermal emission from the accretion disk, with progressively higher energy photons coming from higher temperatures at smaller radii. Although the overall BBB feature can be nicely fitted by disk models, some expected disk signatures are *not* seen: a strong Lyman edge at  $912 \text{ \AA}$ ; high polarization; and significant phase delays between flux variations at different wavelengths. For this reason alternatives have been suggested, such as an optically thin bremsstrahlung component. The infrared peak, which can be very strong in some objects (e.g. NGC 1068), is thought to arise in most cases from thermal emission from dust. The rise longward of  $\sim 1 \text{ \mu m}$  suggests hot dust close to its sublimation temperature at  $\sim 2000 \text{ K}$ , possibly located within  $\sim 1 \text{ pc}$ . At longer wavelengths ( $\sim 25-60 \text{ \mu m}$ ) the dust is cooler and probably located in or near the NLR. Finally, the x-ray rise might come from reflection of the underlying power law off ‘cool’ gas, either the accretion disk or the dense obscuring torus. A byproduct of such reflection is fluorescence of the Fe  $K\alpha$  emission line at  $\sim 6.4 \text{ keV}$ , which can be quite strong.

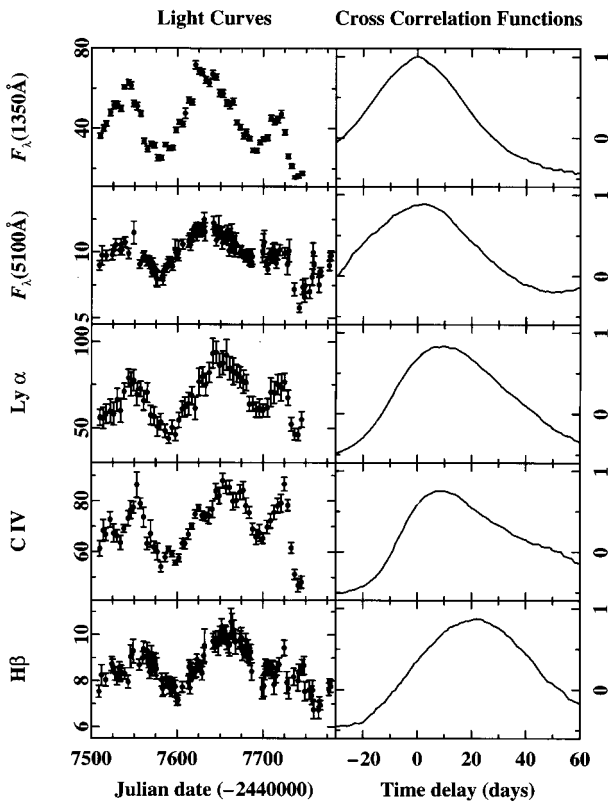
The observed blue-UV continuum in Seyfert 2s deserves further comment since, as we have discussed, the nuclear contribution should be hidden behind an obscuring torus. Why, then, do many Seyfert 2s have a sufficiently strong UV excess to show up in the Markarian survey? The reason is that much of the blue-UV light in Seyfert 2s is *extended*, coming from the inner few kpc. The origin of this continuum is still under some

debate, but it seems there are at least several contributions. Polarization observations indicate that part of the emission is scattered from the hidden nucleus. The remainder (sometimes called ‘FC2’, for Featureless Continuum 2) may be a combination of near-nuclear star formation, Balmer continuum emission from the ionized gas, and continuum emission from hot post-shock gas associated with the radio source.

### Broad line region

A defining characteristic of Seyfert 1 spectra is the presence of broad emission lines, including the Balmer lines, He II  $\lambda 4686$  and He I  $\lambda 5876$  in the optical, and Ly $\alpha$   $\lambda 1212$ , C IV  $\lambda 1549$ , C III]  $\lambda 1909$  and Mg II  $\lambda 2800$  in the near UV. In the early 1980s it was found that the Balmer line strengths in Seyferts and quasars form a single tight correlation with the non-stellar continuum strength, confirming a basic connection between the two: continuum emission photoionizes the BLR gas which then produces line radiation. An estimate of the gas density in the BLR comes from the absence of any broad components on the forbidden lines. These so-called ‘forbidden’ emission lines come from electron transitions which cannot occur via the fast electric dipole mode (which requires a quantum number change  $\Delta l = \pm 1$ ). With only slower modes of transition available (e.g. magnetic dipole), the ions are vulnerable to collisional deexcitation in a high density gas where the mean time between collisions is small. The ‘critical density’,  $n_{\text{crit}}$ , above which collisional deexcitation becomes important varies widely for different lines, so one can bracket the gas density in the BLR by noting which lines have broad components and which do not. For example, while the [OIII]  $\lambda 4363$  line with  $n_{\text{crit}} \sim 3 \times 10^7 \text{ cm}^{-3}$  has no broad component the semiforbidden CIII]  $\lambda 1909$  line with  $n_{\text{crit}} \sim 3 \times 10^{10} \text{ cm}^{-3}$  does, implying a gas density in the BLR somewhere in the range  $10^{7.5}-10^{10.5} \text{ cm}^{-3}$  (see below for a refinement of this estimate). In contrast to the forbidden lines, the so-called ‘permitted’ lines arise from fast ( $\sim 10^{-8} \text{ s}$ ) electric dipole transitions with correspondingly high critical densities  $\sim 10^{17} \text{ cm}^{-3}$ . Such lines, which include those due to recombination, are therefore easily produced in the BLR gas.

In the last decade, Seyfert variability studies have significantly helped develop our picture of the BLR. In these studies, the emission lines and continuum are repeatedly measured over periods of many months. Because of the finite size of the region, it takes time for a change in the central continuum brightness to reach the BLR gas and thereby cause a change in the emission line. Allowing for light travel delays between the continuum source and BLR gas and between the BLR gas and us, it is in principle possible to reconstruct the distribution of line emission and velocity field throughout the BLR. In practice, this full ‘reverberation mapping’ has not yet been possible, but instead simple time delays have been measured in the response of each emission line to the continuum, and these delays indicate an approximate region size. The most well studied object is the Seyfert



**Figure 5.** Variability in NGC 5548 over a period of 280 days in 1988–89. Left panels show changing fluxes in the continuum (upper two) and emission lines (lower three), while the right panels show the cross correlation of each flux curve with the UV continuum (uppermost left panel). Note that while the optical and UV continua vary together, the Ly $\alpha$ , C IV  $\lambda$ 1550 and H $\beta$  emission lines lag behind by increasing amounts, H $\beta$  being delayed by about 20 days. These lags indicate the size of the BLR (about 20 light days) and the fact that it is radially stratified, with C IV produced preferentially at smaller radii and H $\beta$  at larger radii. (Taken from Peterson B M 1997 *An Introduction to Active Galactic Nuclei* (Cambridge University Press), figure 5.6, p 86).

1.5 galaxy NGC 5548, for which delays of  $\sim 2$ –10 days are found for the highest ionization lines (e.g. He II  $\lambda$ 1640, C IV  $\lambda$ 1549) and  $\sim 10$ –20 days for the lower ionization lines (e.g. Ly $\alpha$ , H $\alpha$ , H $\beta$ , CIII]  $\lambda$ 1909), indicating a radially stratified BLR with size  $\sim 2$ –20 light days (figure 5). Surprisingly, these size estimates were a factor of ten smaller than previous estimates based on photoionization calculations (see below). The reason for the discrepancy is now understood: not only does stratification undermine the simple photoionization estimate but the densities in the BLR are probably higher than previously thought (e.g.  $\sim 10^{11}$  cm $^{-3}$  in the C IV  $\lambda$ 1459 emitting region).

Since the ionization structure in the BLR is roughly the same from object to object (because the line ratios are similar), we infer that BLR sizes must increase for more luminous objects. Using the C IV  $\lambda$ 1549 data from NGC 5548 as fiducial, the form of the dependence is  $R_{\text{BLR}} \sim$

$10h_0L_\lambda(1350 \text{ \AA}, 40)^{1/2}$  light days, where  $h_0$  is the Hubble constant in units of  $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $L_\lambda(1350 \text{ \AA}, 40)$  is the continuum luminosity at  $1350 \text{ \AA}$  in units of  $10^{40} \text{ erg s}^{-1} \text{ \AA}^{-1}$ . Since, roughly speaking, quasars are  $\sim 100$  times more luminous than Seyferts, they have BLRs which are  $\sim 10$  times larger, perhaps a few light months to a light year across.

In the 1980s photoionization models were developed which aimed to reproduce the observed emission line strengths. In general, these calculations consider a power law (or AGN-like) continuum impinging on a thick slab of gas. At a given depth in the cloud, ionization and thermal equilibrium conditions are evaluated, together with the emitted line spectrum. Absorption of the incoming ionizing continuum is calculated and the modified continuum enters the next zone deeper in the cloud. The calculation repeats for ever deeper zones in the cloud until the gas is sufficiently cool and/or neutral that no more emission is produced. Overall, the ionization degree drops into the cloud, becoming suddenly more neutral at a depth corresponding to the classical Strömgen depth (where the total number of ionizing photons is balanced by the total number of hydrogen recombinations). However, unlike H II regions ionized by hot stars, AGN continua also have a high energy component which penetrates beyond the Strömgen depth to create an extended partially ionized zone in which many low ionization lines are produced. Usually, the emergent spectrum from a single cloud is compared to observations, though more recently cloud ensembles spanning a range of conditions have been considered in an attempt to match the stratified nature of the BLR.

Several parameters help define these photoionization calculations. The most important is the ‘radiation parameter’, defined as the ratio at the cloud front of the ionizing photon density to the hydrogen density:  $U = N_{\text{ion}}/n_{\text{H}}$ , where  $N_{\text{ion}} = Q/4\pi r^2 c$  where  $Q$  is the number of ionizing photons produced by the central source per second, and  $r$  is the distance to the cloud. Other relevant parameters are gas density, cloud thickness, ionizing spectral shape and element abundances. Optimum fits suggest that for Seyfert 1s,  $U \sim 0.04$  and  $n_{\text{H}} \sim 10^{11} \text{ cm}^{-3}$ . Estimating cloud thickness is more difficult. The fact that in variable objects the emission lines follow the continuum tells us the clouds are at least optically thick to the ionizing radiation, i.e. they are at least thicker than the Strömgen depth  $S \sim Uc/n_e\alpha_{\text{B}} \sim 5 \times 10^{10} \text{ cm}$  where  $n_e$  is the electron density and  $\alpha_{\text{B}}$  is the case-B hydrogen recombination coefficient ( $\sim 2.5 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$ ). Matching the low ionization strengths requires the extended partially ionized region to be a few times deeper—perhaps a few times the diameter of our Sun. There is also evidence, it should be said, for an optically thin component to the BLR gas, coming from studies of line ratio and profile variability.

It is possible to estimate some other properties of the BLR line-emitting gas, starting with the basic equation for the production of H $\beta$  by recombination:  $L_{\text{H}\beta} =$



$h\nu_{H\beta}n_en_H\alpha_{H\beta}V$  where  $h\nu_{H\beta}$  is the energy of each H $\beta$  photon,  $n_e$  and  $n_H$  are the electron and proton densities,  $V$  is the volume of ionized gas, and  $\alpha_{H\beta}$  is the recombination coefficient for H $\beta$  ( $\sim 3 \times 10^{-14} \text{ cm}^3 \text{ s}^{-1}$ ). Since the mass of ionized gas is simply  $M = m_p n_H V$  where  $m_p$  is the proton mass, we find an ionized gas mass and volume of  $\sim 0.1 M_\odot$  and  $10^{45} \text{ cm}^3$  for a typical H $\beta$  luminosity  $\sim 10^{42} \text{ erg s}^{-1}$  and BLR gas density  $\sim 10^{11} \text{ cm}^{-3}$ . Taking the BLR radius of 10 light days from the variability measurements given above, we find that the ionized gas occupies only  $f_c \sim 1.5 \times 10^{-5}$  of the BLR volume ( $f_c$  is called the filling factor). If we assume the gas is in the form of clouds with diameters a few times the Strömgen depth ( $d_c \sim 5 \times 10^{11} \text{ cm}$ ) we derive a number of clouds  $N_c \sim V/d_c^3 \sim 10^{10}$  which collectively intercept a fraction of the central radiation of  $C_c \sim N_c d_c^2 / 4\pi r^2 \sim 0.3$  ( $C_c$  is called the covering factor). In this picture, then, the BLR is sparsely filled by a large number of small clouds which collectively intercept  $\sim 30\%$  of the ionizing radiation.

The velocity field in the BLR is poorly understood, despite the fact that the emission line profiles clearly have Doppler origin. Profiles have approximately logarithmic form (flux  $\propto \log \Delta\lambda$ ) often with slight asymmetry and/or substructure, with full widths at half maximum (FWHM) anywhere from 1000 to 10 000  $\text{km s}^{-1}$  and maximum wing widths of up to 30 000  $\text{km s}^{-1}$ . Lines in the same object can have slightly different shape (e.g. He II  $\lambda 4686$  is often broader than H $\beta$ ), indicating both velocity and ionization stratification in the BLR, with higher velocities at smaller radii. One approach has been to fit each line by the sum of two components, one broad and one very broad with possible blueshift. These fits support the decrease in velocity for lower ionization gas, and point to a slight radial velocity component, although profile variability studies suggest that radial flow is *not* a dominant component of the velocity field. If the velocities are gravitational, estimates of central mass  $M \sim rv^2/G \sim 10^7\text{--}10^8 M_\odot$  with some evidence for a correlation between central mass and luminosity. The luminosities derived amount to  $\sim 1\%$  of the Eddington luminosity, which is the natural upper limit to accretion-powered energy release when outward radiation pressure just balances inward gravitational force, limiting further accretion.

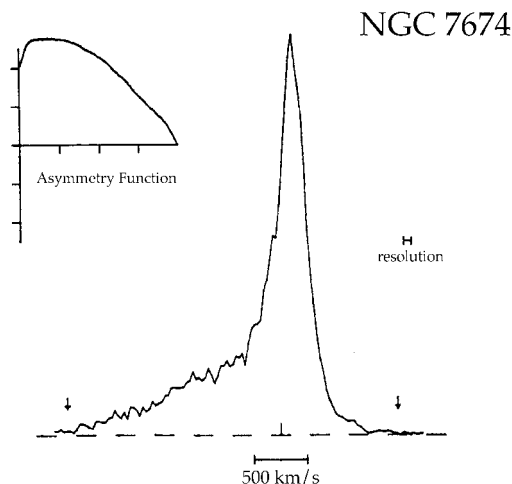
The geometry of the BLR is also poorly understood, with spherical or flattened cloud distributions as obvious possibilities, including a thin but flared disk, although the absence of very narrow lines expected for face-on disks weighs against this last possibility. The origin and evolution of the cloud system are also poorly understood. Possibilities that have been explored include a two-phase medium in which the clouds are in pressure balance with a hot intercloud medium; clouds may be confined by magnetic forces; clouds may form in cooling post-shocked gas; clouds may even comprise the extended atmospheres of giant stars. Each of these has its strengths and weaknesses, and we must await further work to clarify the true situation.

### Narrow line region

In the spectra of Seyferts, the narrow forbidden and permitted emission lines come from a region well outside the BLR, spanning a few tens of pc to a few kpc called the ‘Narrow Line Region’ (NLR). Unlike the BLR, therefore, ground-based telescopes can often resolve the outer parts of the NLR while HST has provided some detailed images and spectra. The mere presence of forbidden lines tells us that gas densities are lower than in the BLR. At these lower densities the physics of line production is simpler and line ratios may be used to estimate physical properties of the ionized gas. Classic examples include the two line ratios: [S II]  $\lambda\lambda 6717/6731$  and [O III]  $\lambda\lambda 5007/4363$  which yield electron densities  $\sim 10^3\text{--}10^4 \text{ cm}^{-3}$  and electron temperatures  $\sim 1\text{--}2 \times 10^4 \text{ K}$  respectively. Such simple estimates must be viewed with caution, however, because they represent weighted averages over a wide range of conditions: for example, gas densities probably rise from  $\sim 10^2 \text{ cm}^{-3}$  on kpc scales to  $\sim 10^{6\text{--}8} \text{ cm}^{-3}$  in the inner regions. More sophisticated approaches follow the same strategy as for the BLR: photoionization calculations evaluate conditions within a single gas cloud and, in more recent work, integrate over a distribution of cloud properties. As with the BLR gas, much of the NLR gas is thought to be optically thick to the ionizing radiation, although studies of the He II  $\lambda 4686/\text{H}\beta$  ratio indicate the presence of some optically thin gas. In trying to match these calculations to observations, sequences of models are evaluated with a range of radiation parameter and/or relative mix of optically thick to optically thin gas. Typical values for the radiation parameter found for the NLR are  $U \sim 0.01$ , with some evidence for higher values in Seyfert 1s than Seyfert 2s.

Repeating the analysis for the BLR, we can derive crude estimates for the global properties of the NLR gas. Taking as fiducial,  $L_{\text{H}\beta} \sim 10^{41} \text{ erg s}^{-1}$ , a gas density of  $\sim 10^3 \text{ cm}^{-3}$  and NLR size of  $\sim 100 \text{ pc}$ , we obtain a mass of ionized gas of  $\sim 10^7 M_\odot$  with filling factor  $\sim 10^{-2}$ . The Strömgen depth in the clouds is  $\sim 10^{18} \text{ cm}$ ; there are  $\sim 10^6$  clouds with integrated covering factor  $\sim 1$ . While the numbers are far from precise, they do indicate that the amount of gas is dynamically unimportant, that it only sparsely fills the region, and that it intercepts a significant fraction of the ionizing radiation.

As the name suggests, the emission lines from the NLR have ‘narrow’ Doppler widths, with FWHM  $\sim 200\text{--}800 \text{ km s}^{-1}$  (a few lie outside this range). The emission line shapes are almost always more peaky than Gaussian, and most have an asymmetry with the base and wing stronger and more extended on the blue side than the red (figure 6). This asymmetry tells us that, at least for the higher velocity, more nuclear gas, there is a radial flow and part of the region is obscured by dust. If the far side of the region is obscured by intervening dust, then the flow is *outwards* (the visible near side is blueshifted). If the clouds themselves contain dust, and the line emission comes from the side of the cloud facing the central source, then the flow is *inwards* (we cannot see the clouds on the near side



**Figure 6.** The [O III]  $\lambda 5007$  emission line profile from the nuclear region of NGC 7674 provides an extreme example of an asymmetric blue wing. A velocity scale, line median, instrument resolution and asymmetry function are also shown.

since we look into their backs). Recent observations have shown that the optical and infrared forbidden lines have similar asymmetries, showing that the dust is still opaque even at these long wavelengths. The preferred scenario is thick nuclear dust, possibly in a dense disk, blocking the far side and indicating an outflow. The outflow might be driven by a nuclear wind or be related to the jets which give rise to the radio source. For those Seyferts with relatively strong double or triple structured radio sources it is often possible to see separate red- and blueshifted emission components close to the radio lobes, indicating bipolar driven outflows. In these objects, the integrated line profile can be particularly structured and broad, with base and core widths up to  $\sim 1000 \text{ km s}^{-1}$  (examples include NGC 1068, MKN 3, MKN 78). For most objects, however, there is good evidence that the majority of the NLR gas, as measured by the [O III]  $\lambda 5007$  profile core width (FWHM), is moving in the gravitational field of the bulge of the host galaxy. The evidence includes the fact that the profile peaks and cores are close to the rest frame of the galaxy, and that there are good correlations of the [O III]  $\lambda 5007$  emission line width with (a) rotation velocity of the galaxy, (b) bulge luminosity and (c) bulge stellar velocity dispersion. Stated simply, galaxies with massive bulges have relatively broad forbidden lines (e.g.  $\sim 500 \text{ km s}^{-1}$ ), while galaxies with low mass bulges have relatively narrow forbidden lines (e.g.  $\sim 200 \text{ km s}^{-1}$ ). Galaxies with relatively strong double or triple radio sources tend to stand off these correlations with yet broader lines, due to bipolar flows. For the gravitationally dominated gas, it is still unclear whether the predominant motion is rotation or random, though probably both occur.

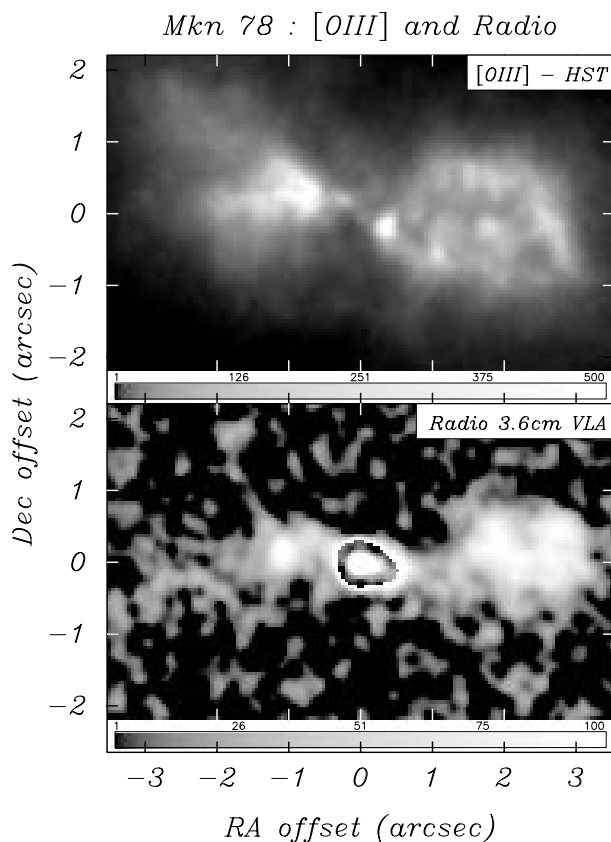
Not all emission lines have the same profile shape, and in general lines of higher ionization and/or higher critical density tend to be broader with a higher degree of

asymmetry. This indicates that, like the BLR, the NLR is stratified with the higher velocity, more nuclear gas having higher density and ionization degree. It is conceivable, though not yet shown convincingly, that a continuous sequence of conditions connects the inner NLR to the BLR.

The spatial structure of the NLR emission has been studied using emission line imaging, both from the ground and using HST. In this technique, images are taken through two narrow pass filters, one centered on the color of the emission line (ON band) and one centered on the nearby continuum (OFF band). By subtracting the OFF band from the ON band one is left with a pure emission line image. Furthermore, by dividing two emission line images such as [O III]  $\lambda 5007$  and  $H\beta$  one can generate a map of the gas excitation which clearly highlights AGN-related emission ( $[\text{O III}]/H\beta \sim 10$ ) and distinguishes it from star formation emission ( $[\text{O III}]/H\beta < 3$ ). Such images indicate that the NLR is often elongated, with an axis parallel to the radio axis. Indeed, for those Seyferts with well developed radio sources the NLR emission is closely related to the radio source, with brighter emission either coincident with jets and jet bends, or surrounding and sheathing radio lobes, sometimes with a curved 'bow shock' appearance. Spectroscopic studies show higher velocities for this radio-related emission, indicating strong dynamical interaction and an overall bipolar outflow, but also including split lines near jets, possibly indicating lateral expansion away from the jet. A good example of close radio/emission line association is Markarian 78 (figure 7).

The close association between line and radio emission in the NLR raises the important possibility that the gas is ionized, at least in part, by shocks arising in the interaction. Although early calculations of slow shocks could only match LINER-like spectra, more recent calculations of fast ( $\sim 500 \text{ km s}^{-1}$ ) shocks can match Seyfert-like spectra. A key feature of these calculations is the production of UV and x-ray radiation, both line and continuum, in the hot post-shock gas. This radiation then photoionizes gas both behind the shock and in front of it, yielding a spectrum quite similar to that observed in Seyferts. At present, 'photoionizing shocks' and standard power law photoionization (possibly including optically thin gas) give an equivalently good match at least to the optical lines, though there is some hope that UV lines will help discriminate between the models, as long as the uncertainties introduced by dust reddening are not too great.

Returning to the emission line images and excitation maps, a number show sharp edges which outline parts of a cone, or bi-cone if it occurs on both sides. As described earlier, this seems to indicate a partly shadowed nuclear source of ionizing radiation. These emission regions can extend out to considerable distances,  $\sim 15\text{--}20 \text{ kpc}$ , where they are termed the 'Extended Narrow Line Region' or ENLR. This emission has high excitation and narrow lines of low velocity, suggesting it is simply undisturbed ambient gas residing either in the disk of the galaxy or in the galactic environment. The fact that most



**Figure 7.** HST [O III] emission line image and VLA radio image of the Seyfert 2 galaxy Mkn 78 showing close spatial association. Note that a dust lane crosses the nucleus, hiding the most nuclear [O III] emission. Gray scale numbers are proportional to flux, with the radio core rescaled by a factor of five for clarity. For this galaxy 1 arcsec  $\sim$  1 kpc ( $h_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ). (Data courtesy of M Whittle and A S Wilson.)

ENLRs lie well beyond any radio source and can show conical form suggests they are ionized by the central UV radiation source. Recently, however, careful estimates of the required UV flux suggest that at larger radii there may be an additional source of ionization, though what this is is not yet known.

A final pragmatic theme is the frequent need to correct measured spectra for the effects of reddening by dust. Fortunately, the NLR Balmer line strengths are expected to be close to their theoretical values, and so any deviation can be attributed to reddening. For example, the  $H\alpha/H\beta$  flux ratio should be  $\sim 2.8$  (the ‘Case B’ value, though a more detailed calculation gives 3.1) and so a measured value of, say,  $R$ , yields an estimate for the absorption due to dust of  $A_V \simeq 6.8 \log_{10}(R/2.8)$  magnitudes in the V band, where the coefficient depends on the reddening law (Whitford’s law in this case). Knowing  $A_V$  allows one to correct the observed spectrum, using the same reddening law  $f(\lambda)$ , where  $A_\lambda = A_V \times f(\lambda)$ .

### Hosts, environment and triggering

While the previous sections have concentrated on the anatomy of activity in Seyfert galaxies, there remains an important question: why are some galaxies active while others are not? Although we cannot yet answer this question with confidence, two or three lines of enquiry help pave the way forward. The first is to ask whether Seyfert host galaxies are unusual in any way; the second is to ask whether any active properties correlate with any host galaxy properties; and the third is to identify mechanisms which might send gas down to fuel the nuclear regions. In this area, empirical studies are difficult because of the statistical weakness of the effects and the presence of sample and control biases.

Perhaps the one clear result concerns the morphological type of the host galaxies: Seyferts favor early-type spirals, S0–Sbc, clearly avoiding late-type spirals and, to a lesser extent, ellipticals. Interestingly, LINERs show a similar distribution (with somewhat more ellipticals), while radio galaxies are almost exclusively elliptical or S0. In all these cases, more luminous galaxies are more likely to be active. It seems, therefore, that an important condition for the onset of activity is a relatively massive bulge. There is also a tendency for active galaxies to be disturbed in some way and/or have a nearby companion—both being conditions which may lead to nuclear fueling. The neutral gas content (atomic and molecular) of Seyferts is basically normal, though Seyfert 2s may have more molecular gas and associated star formation than otherwise similar non-active galaxies. Recent HST images have also shown that Seyfert 2s tend to inhabit later Hubble types and have more nuclear dust lanes than Seyfert 1s. This suggests a modification to the standard unification scheme: Seyfert 2s simply have more nuclear dust than the Seyfert 1s and are therefore more likely to be obscured, rather than being identical except for our viewing angle.

It is worth noting a few active properties which do (or don’t) correlate with host galaxy properties. First is the axis of nuclear activity, as defined by the radiation field and/or radio source. Overall, there appears to be little alignment of this axis with the large scale disk or bar of the host galaxy. Recent evidence, however, suggests that for later Hubble types there *is* an alignment with the host disk, while for early Hubble types the alignment is with smaller scale nuclear gas or dust disks or lanes whose more random orientation probably reflects recent merger or infall history. Because the NLR resides within the galaxy bulge, it is perhaps not surprising that some NLR properties correlate with bulge luminosity, for example emission line and radio luminosities. The origin of these correlations is not yet clear, but might involve a number of properties which depend on bulge mass (i.e. depth of gravitational potential): emission region volume, gas and radio source pressures, mass loss rate from bulge stars, and mass of central black hole. More easy to understand is the dependence of NLR emission line width on bulge mass, since the gas velocities are largely gravitational. An interesting wrinkle on this last result is

that disturbed galaxies have even broader emission lines, confirming that such disturbances can affect gas motions in the inner regions. Perhaps more fundamental is a possible correlation between nuclear (active) luminosity and host galaxy (or more likely, bulge) luminosity—low luminosity Seyferts reside in lower mass bulges than quasars. An obvious explanation is that more massive bulges have more massive central black holes, a result supported at least in part by recent black hole mass measurements in more normal galaxies.

Perhaps the central theoretical problem has been to understand how gas moves from far out in the galaxy disk down to the innermost regions where it can accrete onto the black hole—a loss in ANGULAR MOMENTUM by a factor  $\sim 10^5$ ! Early work focused on bars as a means of draining angular momentum from gas, via shocks and dissipation. It is at present unclear how important this particular mechanism is since, although studies have been somewhat ambiguous, there seems to be no tendency for active nuclei to prefer barred galaxies. More recently, Barnes and Hernquist have shown, using computer simulations, that galaxy encounters and mergers can be particularly effective at sending gas into the nuclear regions. The tidal fields resulting from the encounter help create a gaseous bar which lags behind a stellar bar. The gravitational torque on the gas robs it of angular momentum and it falls inwards, losing up to  $\sim 99\%$  of its angular momentum. At smaller radii it is unclear what happens: gas may build up and become unstable to self gravity and/or there may be bars within bars which help funnel the gas to ever smaller radii. Once in an accretion disk, however, Balbus and Hawley have shown that magnetically driven turbulence provides enough viscosity to drive the gas inwards to the black hole.

### The future

We now briefly identify several themes likely to be pursued in the coming years. (a) The hunt for black holes will continue, aiming to establish a demographic perspective—how do black hole mass and spin relate to AGN or host properties? (b) How does the inner accretion disk function, and how does it play a role in generating the continuum emission? (c) Much remains to be done to find out the structure and velocity field of the BLR—ideally, its kinematics will be dominated by black hole gravity giving another handle on the properties of the central object. (d) The root cause of the apparent unification of Seyfert 1s and 2s needs to be clarified—is the torus model too simple in the light of the recent HST observations showing more distributed dust lanes in Seyfert 2s? (e) We need to refine our picture of the NLR, and in particular the importance of the radio emitting jets—clearly the jets accelerate the gas, but do they also ionize it? (f) What is the nature of the extended UV continuum in Seyfert 2s, and is enhanced star formation associated with nuclear activity? (g) Finally, we would like to know how activity is triggered in more detail. Although interactions are now known to send gas to the central kpc, how does it get from there to the pc scale and beyond?

Clearly, these are exciting times in the study of Seyferts.

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