ACTIVE GALAXY UNIFICATION

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1. INTRODUCTION

Most bright galaxies are spirals, like our own, and in the nearby well-studied cases they reveal the beautiful and intricate grand-design spiral patterns that are both familiar and appealing (e.g., Sandage & Tammann 1981). At the centre of a few out of every hundred spirals there is also an extremely bright point of light. This point can be so bright that it can outshine the entire stellar output of the disc and bulge of the galaxy, and this enormous luminosity is produced from an exceedingly small volume indeed. This thesis studies aspects of these active galactic nuclei (AGNs) that inhabit some spiral galaxies.

Most likely, the power is provided by the release of gravitational energy as gas in the galaxy nucleus spirals inward towards a black hole of large mass (~ 10^8 $M_{\odot}$; Zel'dovich & Novikov 1965). The gas is continually sheared as inner orbits move faster than outlying ones. Close to the black hole, the viscous dissipation grows strong enough to heat the gas to incandescence at optical and X-ray wavelengths (Shakura & Sunyaev 1973). The disc of accreting material then radiates the enormous optical luminosity that we see (up to ~ 10^{41} W, H_0 = 75 km s^{-1} Mpc^{-1}; Hagen et al. 1992). Optical synchrotron emission from relativistic electrons is also important in some AGNs.

Although most AGNs seem to share these same sources of power, they present to us a variety of guises. For example, some AGNs produce powerful radio emission whilst others do not. Some produce broad optical emission lines, or high optical polarization, or are particularly variable, or produce powerful X-ray and gamma ray emissions, whilst others do not. AGNs seem to know about the type of host galaxy in which they reside, and take on certain characteristics accordingly (e.g., spiral galaxies host radio-quiet AGNs only, and blazars are found only in elliptical host galaxies). The causes of these diverse appearances are the focus of much current research.

The taxonomy of AGNs groups together objects that share certain combinations of these properties. The zoo of nomenclature is now home to the beasts shown in Fig 1.1. Such naming schemes occasionally prove particularly useful, where they reflect differences in the underlying physics. For example, the distinction between starbursts and all other AGNs provides insight, as starbursts and AGNs are driven by different processes. In contrast, it seems less useful to distinguish between, for example, type 1 Seyfert galaxies and radio-quiet quasars (described later). These seem to be the same process, differing only in optical luminosity.

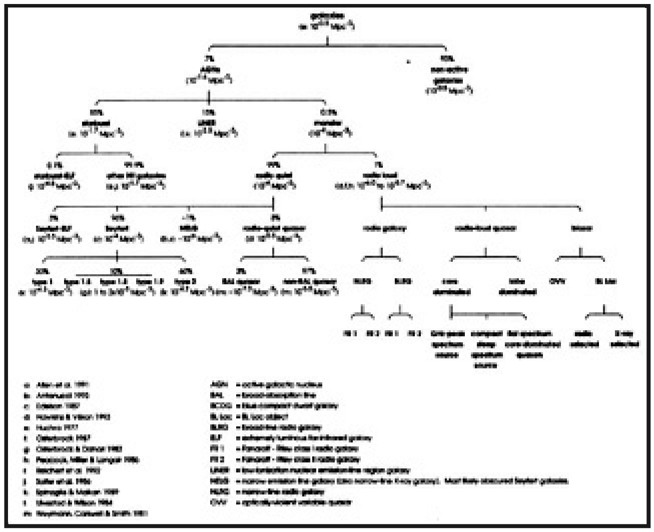

Figure 1.1 The main active galactic nuclei that are currently recognised. Space densities, compiled from the literature by ALR, are only approximate and depend on survey depths and incompleteness. However, they should serve for the purpose of introduction.

Understanding which of these distinctions reflect fundamental differences and which are interesting illusions is a central challenge. Some AGN classes might be related by evolution (e.g., extremely luminous far-infrared galaxies (ELFs) might evolve into quasars with time). Others may be related by variability (e.g., type 2 Seyferts might be type 1s in which the central source has switched off momentarily). Many may appear different only because of our viewing angle. (AGNs obscured by patchy dust look different viewed end on or side on. Relativistic jets also have aspect-dependent appearances, due to Doppler boosting.) This thesis considers the "Seyfert" and "ELF" classes and, among other things, looks at possible relationships between these and other AGNs.

2. SEYFERT GALAXIES

Seyfert galaxies were first isolated as a class by Seyfert (1943), although their unusual emission line spectra had been noticed earlier (e.g., Mayall 1934 and references therein). These otherwise normal spiral galaxies drew attention for their uncommonly luminous nuclei, and for their powerful high-excitation emission lines. (The emission lines come from clouds within a few hundred pc of the central source and are ionized by the intense radiation produced by the AGN core, e.g., Osterbrock 1987.)

Two types of Seyfert galaxy were recognised by Khachikyan & Weedman (1971), based on the widths of their emission lines. Both Seyfert types produce powerful narrow forbidden lines from high excitation species like [O III] and [Ne V]. Some Seyfert galaxies also produce broad (~ 10000 km s^{-1}) Balmer lines, whilst in others these lines are narrow (250 to 1000 km s^{-1}). Such systems are called type 1 (Sy1) or type 2 (Sy2) Seyferts respectively. Later, the intermediate types 1.5, 1.8 and 1.9 were recognised, based on the simultaneous presence of both broad and narrow components to the Balmer lines (e.g., Osterbrock & Dahari 1983).

According to the widely accepted picture of Seyfert nuclei, there are two physically distinct line-emitting regions. The broad-line region (BLR) lies close to the central continuum source, within tens of light days (Peterson et al. 1992). It has a mass of ~ 50 $M_{\odot}$, densities of 10^{14} to 10^{18} m^{-3}, temperatures of $\leq 4 \times 10^4$ K, and cloud speeds of 10^3 to 10^4 km s^{-1} and produces the broad Balmer series. The narrow-line region (NLR) spans tens to hundreds of pc, has a total mass of 10^5 to 10^6 $M_{\odot}$, densities of $10^{9.5\pm1}$ m^{-3}, temperatures of 1×10^4 to 5×10^4 K, and cloud speeds of ~ 250 to 1000 km s^{-1} (Osterbrock 1987; Lawrence 1987; Haniff, Wilson & Ward 1988). Between these two regions no emission lines are seen, for reasons that are poorly understood but may involve dust absorption (Netzer & Laor 1993).

The absence of forbidden lines in the BLR is due to the relatively high density of the BLR plasma. Large density leads to many collisions during the lifetimes of the excited states and collisional de-excitation is likely. In that event, the energy is carried off as kinetic energy and the forbidden transitions do not radiate.

Such spectroscopic properties are an important input to unification schemes. Before reviewing those schemes I will first introduce the extremely luminous far-infrared galaxies (ELFs), which are studied later in this thesis and are related to Seyfert galaxies.

3. EXTREMELY LUMINOUS FAR-INFRARED GALAXIES

ELFs are remarkable objects, discovered independently by a number of groups soon after the IRAS catalogue was released (see Norris, Allen & Roche 1988). These optically undistinguished galaxies produce the bulk of their enormous luminosities at far-infrared (FIR) wavelengths (30 to 300 μm). They are probably AGNs or bursts of star formation cloaked in a large mass of gas and dust that reprocesses most of the optical photons to the FIR. This "laundering" can make it difficult to distinguish between possible alternative power sources. This has lead to considerable debate recently over the roles played by starbursts (introduced below) and Seyfert nuclei in powering ELFs and the question is not yet resolved (e.g., Harwit et al. 1987; Sanders et al. 1988b; Condon et al. 1991).

Starburst galaxies convert large fractions of their interstellar medium (ISM) into stars at a furious and unsustainable rate. In contrast, star formation in most galaxies is a well regulated, orderly, slow process. Starburst galaxies produce large optical luminosities from the combined output of many high-mass stars. The bursts are sometimes triggered by galaxy-galaxy interactions.

Despite the obscuring dust, parts of the life cycle of ELFs have been established. The progenitors of ELFs are thought to be normal spirals, since ELFs are rich in gas and dust. Clearly, the presently observed luminous phase must be only transitory. If ELFs are powered by starburst activity then the star formation would exhaust any reasonable supply of ISM in about 10^8 yr (Chapter 6).

ELFs are often involved in interacting systems, appearing disturbed and displaying tidal tails. Interactions are efficient at driving large amounts of ISM inwards and concentrating it into the nuclear region. There, it forms a reservoir to feed star formation or an AGN. Interactions do this by tidally inducing a bar in the stellar distribution of one or both galaxies; Barnes & Hernquist 1991. Bars can funnel ISM efficiently inward since parcels of gas ahead of the bar feel a component of gravitational attraction back towards the bar. The gas decelerates and falls down the potential well. Supporting these numerical results, large concentrations of molecular material have been seen within the central kpc in many ELFs by millimetre-wave interferometers (Sanders et al. 1988a).

The future in store for ELFs is not so clear. Sanders et al. (1988b) suggest that ELFs are the progenitors of quasars and that they currently harbour AGN cores that are hidden by powerful dusty circumnuclear starbursts. According to this view, they will evolve to blow away the surrounding gas and dust. Then, as the starburst fades, the full glory of the embedded quasar core will be revealed to our view.

4. ACTIVE GALAXY UNIFICATION

Many schemes have been proposed to unify active galaxies. They have in common the thought that only a few underlying physical properties might account for the great range of AGN characteristics that we see. Indeed, some striking patterns of behaviour between various AGN types are suggestive. The present state of understanding has been likened to the years leading up to the construction of the periodic table; the patterns are tantalising but the meaning is only beginning to emerge.

Ways that AGNs might be related are discussed in the excellent reviews by Lawrence (1987) and Antonucci (1993). Lawrence summarizes a promising unified model as follows. "There is only one type of Active Galactic Nucleus (AGN). The observed variety arises from three degrees of freedom: (1) Dust opacity, which produces the distinction between Type 1 and Type 2 AGN. (2) Viewing angle of a relativistic jet, which produces the distinction between blazars and Type 1 AGN. (3) Duty cycle of activity (i.e., fraction of time spent "on") which produces the distinction between radio-loud and radio-quiet AGN ... A fourth degree of freedom is, of course, the overall luminosity." However, many aspects are still controversial, For example, Wilson & Colbert (1994) suggest that the dichotomy of radio power is intrinsic and depends on the angular momentum of the central black hole. Also, Singal (1993) questions whether the viewing angle of a relativistic jet can unify radio-loud objects.

Four schemes have been proposed to unify the two main types of (radio-quiet) Seyfert galaxies (Lawrence 1987):

- The BLR gas might simply be lacking in type 2 Seyferts (Osterbrock & Koski 1976). Varying quantities of BLR gas are present in the intermediate "Lick" types.
- Seyferts might be powered by extremely hot short-lived massive stars, and by the supernovae into which they eventually evolve (e.g., Terlevich 1992).
- The Seyfert types may be an evolutionary sequence. (A few Seyferts have made spectacular and fast changes between

Seyfert types, in which the BLR switches off or on over periods as short as several months, e.g., Alloin et al. 1985).

- Type 2 Seyferts might harbour a BLR and central continuum source, but these are obscured from view in some directions (Antonucci & Miller 1985).

The first model is probably part of the story. Some type 1 Seyferts have been seen to switch off and, in these, the difference between the Seyfert types seems to be a genuine lack of a BLR. The presence of polarized broad lines in other type 2s (see below) shows that not all Sy2s lack a BLR, and therefore this model is only part of the story.

Lawrence argues that the second model runs into trouble because such schemes do not explain the similarity of the NLR line ratios in Sy1s and Sy2s. Further, it does not explain the linear radio structures seen in Seyferts. Also, Peterson et al. (1992) finds that variability time-scales and possibly the unchanging BLR line profiles argue against this model.

The third model is clearly part of the story. The observed transitions between Seyfert types are too rapid to be caused by obscuration, and so it seems that the AGN shuts down, perhaps due to a momentary lack of fuel. However, there is more involved to explain the hidden BLR in some Sy2s. Also, Lawrence claims that the NLR excitation should be different from that observed if the AGN spends much of its time switched off.

The final model is currently the most popular, although it too is clearly not the whole story. Obscuration forms the essence of this orientation unification scheme. A torus of dense obscuring gas and dust is thought to girdle the continuum source and BLR. Looking down the axis of the torus we can see right into the BLR and accretion disc. However, when viewed edge-on, the torus blocks our view of the BLR and absorbs hard X-rays, and so the AGN looks like a type 2 (Fig 1.2). This same torus blocks ionizing photons from reaching the NLR in some directions, hence explaining the cone-shaped NLRs that are sometimes seen.

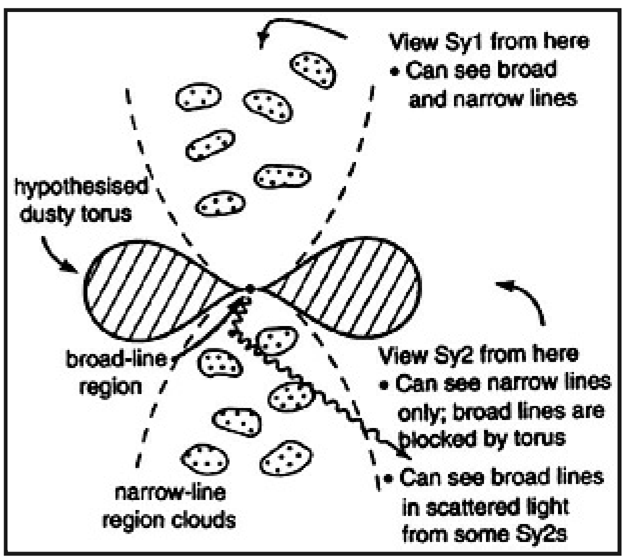

Figure 1.2. Cross-section through the structures proposed by unified models to explain the main Seyfert galaxy characteristics.

The history of orientation unification is reviewed by both Lawrence (1987) and Antonucci (1993). Both attribute to Rowan-Robinson (1977) the first explicit argument that Seyferts are a single class, differing only in dust opacity. He suggested that varying amounts of dust surround the optical core and attenuate the broad-line-producing regions. Later, Veron et al. (1980) and Shuder (1980) found that narrow emission-line galaxies (NELGs) have faint broad lines and Mushotzky (1982) found they have large X-ray-absorbing columns, and so NELGs were identified as obscured type 1 Seyferts. Osterbrock (1981) inferred the importance of dust in intermediate Seyferts from their large Balmer decrements. Lawrence & Elvis (1982) also invoked obscuration to make the BLR invisible in type 2 Seyferts. However, this was rejected by Ferland & Osterbrock (1986), who found that the featureless continuum light in type 2 Seyferts is unreddened, using the similarity of the X-ray - UV spectral index to that of Sy 1s and low-redshift quasars. The situation up to the early 1980s was summarized by Osterbrock (1984). He sketched a working picture of Seyfert nuclei that featured a cylindrically symmetric BLR, from which radio plasma and ionizing photons escape along the axis and produce conical structures. The axis of symmetry is tipped relative to the galaxy disc. Antonucci & Miller (1985) found hidden polarized broad lines in the type 2 Seyfert NGC 1068 and suggested that "the continuum and broad-line regions are located inside an optically and geometrically thick disc. Continuum and broad-line photons are scattered into the line of sight by free electrons above and below the disc." This is perhaps the strongest single piece of evidence for orientation unification of Seyfert galaxies. The unreddened featureless continuum in Sy2s found by Ferland & Osterbrock (1986) is naturally explained in this picture. Photons are scattered into our line of sight from a "mirror" that has an unobstructed view of the nucleus.

There is now much evidence to support this model, as follows.

Some Sy2s show hidden BLRs. More examples like NGC 1068 have been found (Miller & Goodrich 1990), bringing the total to five and establishing this result more securely.

The featureless continuum is stronger in Sy1s than in Sy2s. Sy 1s have bright star-like nuclei, whereas in Sy2s the featureless continuum and broad lines are weak or absent (e.g., Lawrence 1987). Further, Sy2s that display polarized broad lines also display a weak featureless continuum with the same polarization as the broad lines. This can be understood as something obscuring our direct view of Sy2 nuclei and only scattered light from the AGN remains visible.

X-ray absorbing columns are large in Sy2s and small in Sy1s. The X-ray spectra of the few detected Sy2s and intermediate types reveal large absorbing columns ($> 10^{26}$ m^{-2}), whereas Sy1s have $< \sim 5$ to 30×10^{24} m^{-2} (Mushotzky 1982; Pounds et al. 1990; Rao, Singh & Vahia 1992). Sy2 X-ray luminosities are correspondingly low. However, NGC 1068 has a normal Sy1-like X-ray / broad-line flux density ratio (Elvis & Lawrence 1988; Lawrence 1987), which suggests that it harbours an obscured Sy 1 core with X-rays and BLR visible by scattering.

All Seytert types possess an NLR. If the Seyfert types are intrinsically different then the similarity of the NLR properties (Cohen 1983) becomes coincidental.

The NLR clouds see a stronger ionizing flux than we see directly. The optical-UV continuum flux required to ionize the NLR of Sy2s is much larger than that seen directly (the photon-deficit problem; Neugebauer et al. 1980; Binette, Fosbury & Parker 1993). This can be explained by invoking anisotropic absorption around the continuum source, although other solutions have been suggested (Binette et al. 1993).

NLRs are cone-shaped. In the well-resolved cases, NLRs are sometimes cone-shaped (Pogge 1989; Evans et al. 1991, 1994). It seems that the ionizing radiation is roughly collimated before emerging into the NLR, perhaps due to an obscuring torus, or "prebeaming" by the accretion disc or its atmosphere (Kriss, Tsvetanov & Davidsen 1994). The NLR appears smaller in Sy1s than Sy2s which is consistent with projection effects expected from the standard orientation unification model (Evans 1994).

NLR excitation argues against switched-off Sy1s. The space density of Seyferts is now known to be ~ 2:1 in favour of Sy2s. Lawrence (4987) claims that switched-off type 1 theories have difficulty explaining such a ratio since they predict NLR excitation properties that are different from those observed.

Variability differs between Seytert types. Broad-line Seyferts produce a powerful featureless continuum that is variable on time-scales of weeks. In contrast, narrow-line Seyferts produce featureless continua that are either weak or non-existent, and do not vary (Lawrence 1987). This is consistent with both having variable cores that are directly visible only in Sy1s. It can further be understood since any scattered continuum light in Sy2s would be averaged over the large scattering region, reducing the variability.

Some arguments have been raised against the obscuration hypothesis, as follows.

No torus has yet been seen in a Seyfert galaxy. One torus has been found, in the powerful radio galaxy NGC 4261 (Jaffe et al. 1993). However, its size (~ 120 pc outside diameter) is larger than that implied for Seyfert galaxies, and so we may not yet have seen the long-sought torus. However, the absence of tori is probably due to the difficulty of making such an observation. Strictly, a toroidal geometry is not required. One only needs something that will cover the central continuum source and BLR, but not the scattering region or the NLR.

The light absorbed in NGC 1068 is not re-radiated. Cameron (1993) found that NGC 1068 is much weaker in the mid-IR than expected if a torus was degrading much featureless continuum light into the infrared. They propose an "absent-torus" model to avoid this difficulty and still keep the orientation unification idea. Work by Storchi-Bergmann, Wilson & Baldwin (1992) found no such IR deficit in the Seyfert NGC 3281, although they lacked the spatial resolution available to Cameron et al.

Some Seyferts change type rapidly. The rapid changes between types made by a few celebrated Seyferts were too fast to be caused by a cloud moving into our line of sight, and so an Intrinsic change in the AGN is implied. Perhaps then, many type 2s could be switched-off type 1s.

NGC 4151 is a Sy1, yet is viewed outside the NLR cone. The orientation model invokes the same torus to block our view of the BLR and to collimate the ionizing photons going into the NLR. Orientation unification incorrectly predicts that NGC 4151 should be a Sy2 since our line of sight lies outside the opening angle of the NLR cone (e.g., Evans et al. 1994).

The scattered BLR is missing in many Sy2s. According to the unified model, when Sy2s display a featureless continuum component, it is not seen directly but is scattered into our line of sight. If so, one expects photons from the BLR also to be scattered from the same "mirror" into our line of sight. However, only rarely does this occur (Cid Fernandez & Terlevich 1993).

Overall, orientation seems to be an important part of the story, but other factors also contribute.

There are parallel unification schemes that consider radio-loud AGNs. One such scheme unifies Fanaroff-Riley (FR) class II radio galaxies with the radio-loud quasars (Barthel 1994) and another unifies FR I radio galaxies with BL Lac objects (Urry & Padovani 1994). These schemes invoke relativistic beaming in a jet, rather than extrinsic dust obscuration as used by Seyfert unification schemes. According to the FR II - radio-loud quasar scheme, the parent population consists of FR II radio galaxies. When viewed close to end-on, such radio galaxies should look like radio-loud quasars because the radio jets become more prominent due to Doppler boosting, the lobe separation reduces due to foreshortening by projection, the optical core dominates the host galaxy, and we can see into the BLR. Similarly, FR I galaxies seem to be the parent population of BL Lac objects since their isotropic properties (e.g., extended radio luminosities, optical emission-line widths, and host galaxy morphologies) are similar. When the jet is pointed directly at us, the Doppler boosting becomes extreme, and one sees a point source that swamps the parent galaxy. This is accompanied by high polarization, a strong featureless nonthermal optical continuum, and rapid variability. These schemes will not be considered in more detail here as this thesis mostly treats radio-quiet objects. (Although called "radio-quiet", Seyferts are not radio-silent and are readily studied at radio wavelengths in subsequent chapters.)