An introduction to active galactic nuclei: classification and unification

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Abstract

In this article I present a summary of AGN classification, followed by a critical review of attempts to understand aspects of the classification in terms of orientation-based unified schemes. Concentrating on radio-loud AGN, I show that the unified schemes based on anisotropy induced both by beaming in relativistic jets and by absorption in dusty torus structures, work well in a broad-brush sense. However, they represent simplifications of a situation that is, in reality, likely to be more complex. In particular, the AGN selected in radio flux limited samples encompass a wide range of intrinsic X-ray/UV/optical/infrared properties for a given radio power, reflecting a number of variable factors in addition to orientation (e.g. large scale environment, accretion rate onto central black hole). There is also a growing recognition that AGN are dynamic, evolving objects that strongly influence their immediate surroundings, including the distribution of circum-nuclear gas and dust.

Key words: galaxies:active

1 Classification

Classification is one answer to the question of how to make sense of a phenomenon with diverse properties such as Active Galactic Nuclei (AGN). Classification is often one of the first steps taken in a scientific endeavour, and usually precedes – and indeed stimulates – understanding of the physical causes of the phenomenon in question. The history of science abounds with examples of classification as a first step in the road of understanding. Linnaeus produced a detailed classification schemes for living organisms long before they were understood as biological systems. Mendeleev developed the periodic table for the classification of the elements some forty years before it was explained in terms of atomic and nuclear structure.

The classic example of the success of the classification approach in astronomy

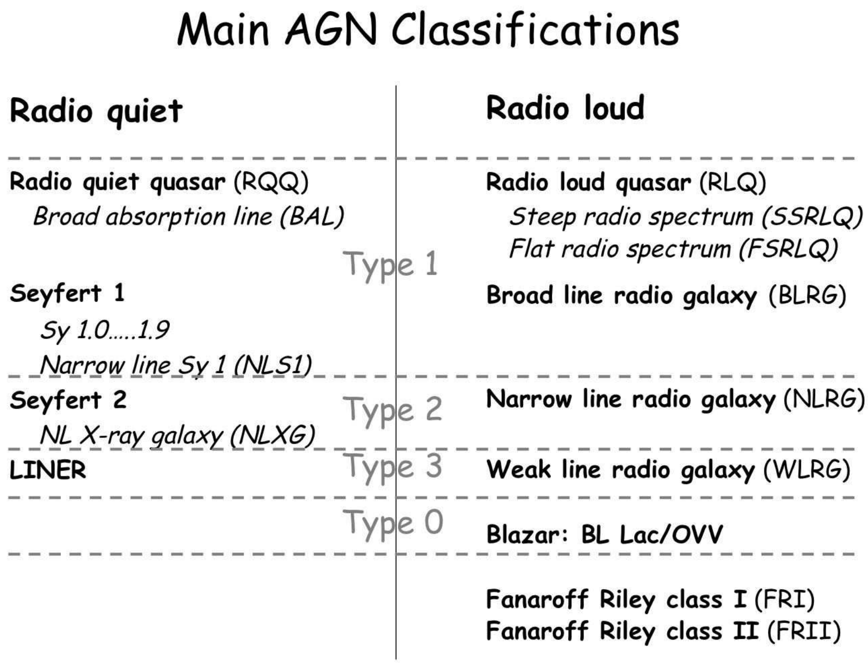

Fig. 1. The main classification labels used for active galactic nuclei. AGN with broad permitted lines detected at optical wavelengths are generally known as Type 1 AGN, while those with only narrow emission lines are known as Type 2 AGN. Lower luminosity AGN are sometimes referred to as Type 3 AGN, while those showing rapidly variability at optical wavelengths are sometimes labelled Type 0 AGN.

is stellar spectral classification. After some earlier, less successful attempts by Secchi and colleagues, in the late 19th/early 20th century the Harvard group led by Pickering, Maury and Cannon succeeded in developing the stellar classification scheme that remains widely used today. Based on the relative strengths of detailed absorption features in the stellar spectra, and the requirement that the absorption line strengths vary smoothly and continuously along the sequence, the Harvard scheme identified some important patterns in the diversity of stellar spectra but was developed independently of any physical understanding of the stars. Such understanding only came with the subsequent development of atomic physics by Bohr and others, and the development of concepts such as ionization equilibrium and excitation of energy levels by, for example, Boltzmann and Saha. These developments allowed Payne-Gaposhkin to demonstrate that the Harvard spectral classification sequence is a sequence in photospheric temperature, and that the abundances of most common elements show little variation along the main sequence. This in turn aided the interpretation of the Hertzprung-Russell diagram, which underpins much of our understanding of stellar structure and evolution.

In many ways active galactic nuclei (AGN) represent a more diverse phenomenon than stars. Whereas stars emit most of their light in the optical atmospheric window, AGN emit powerfully over the full accessible electromagnetic spectrum. In consequence, AGN were discovered and classified separately at different wavelengths as technological advances allowed new parts of the electromagnetic spectrum to be opened up for astrophysical investigation. The main recognised classifications of AGN are summarised in Figure 1.

The first recorded description of the optical spectrum of an AGN was made by Fath (1909) who noted the strong emission lines in the nuclear spectrum of NGC1068. However, the study of the nuclear regions of six unusual spiral galaxies by Seyfert (1943) represents the first systematic study of a class of AGN. The rich optical spectra of AGN generated considerable interest, and led to the eventual classification of Seyfert galaxies based on the presence (Seyfert 1 galaxies) or absence (Seyfert 2 galaxies) of broad ($FWHM > 1000$ km s^{-1}) permitted lines, in addition to narrow forbidden lines of [OIII], [OII], [OI], [NeIII], [NeV], [NII] etc. that are a feature of both classes (Khachikian & Weedman , 1974). The study of AGN gained considerable further impetus in the early 1960s following the discovery of quasars with their high luminosities, quasi-stellar appearance and optical spectra that are similar to those Seyfert 1 galaxies (Schmidt , 1963; Greenstein & Matthews , 1963).

At the lower end of the luminosity scale it was clear by early 1980s that a large proportion of otherwise normal spiral galaxies show potential evidence for active nuclei in the form of low ionization nuclear emission line regions (LINERS: Heckman , 1980). However, it remains uncertain whether all LINERS are truly AGN, or rather a subset of them represent nuclear star forming regions (e.g. Ho, Filippenko & Sargent , 1997).

Although AGN can be distinguished from stellar-photoionized HII regions based on their relatively broad emission lines and the unusual concentration of their emission towards the nuclear regions of the galaxies (c.f. Seyfert , 1943), such identification is not always clear-cut, and nowadays it is more common to identify AGN based on their emission line spectra, recognising the characteristic AGN spectra that encompass a wide range of ionization, as well as the presence of broad permitted lines some (Type 1) objects. This approach has recently been used with great success to identify many 1000's of AGN in deep wide field galaxy surveys based on fibre-fed spectrographs (e.g. Kauffmann et al. , 2003).

The development of classification schemes for radio-loud AGN (i.e. those initially identified at radio wavelengths) has in many ways paralleled that of optically-discovered AGN. Following the first optical identifications of extragalactic radio sources by Bolton, Stanley & Slee (1949) and Baade & Minkowski (1954), it became clear that these "radio galaxies" often have rich emission line spectra that are similar to those of Seyfert galaxies (e.g. Schmidt , 1963), with broad line radio galaxies (BLRG) the radio-loud equivalent of Seyfert 1 galaxies, and narrow line radio galaxies (NLRG) the radio-loud equivalent of Seyfert 2 galaxies. There is also a class of weak line radio galaxies [1] (WLRG) which, despite the signs of powerful radio jet activity, have optical emission lines of low equivalent width and ionization (Hine & Longair , 1979; Laing et al. , 1994; Tadhunter et al. , 1998) — similar in many ways to LINERS. Finally, some radio-loud AGN are classified on the basis that they show rapid variability at optical wavelengths. Collectively labelled as "blazars", these include the BL Lac Objects (which also lack emission lines that strong relative to their optical continua) optically violently variable (OVV) quasars.

To add a further layer of complexity, in addition to their optical classifications, it is also possible to classify radio-loud AGN on the basis of their extended radio structures. In the scheme developed by Fanaroff & Riley (1974), radio galaxies are classified according to whether they have extended radio structures are edge brightened or edge darkened (FRII or FRI). Significantly, FRI radio sources have radio powers that are, on average, lower than those of FRII sources, with the radio power dividing line between FRI and FRII sources falling close to the break in the radio luminosity function. The radio-loud quasars are also sub-divided on the basis of whether they are steep radio spectrum dominated (steep spectrum radio loud quasars: SSRLQ), flat radio spectrum dominated (FSRLQ), core-dominated or lobe dominated.

It is clear that the classification of AGN is complex and sometimes confusing, employing many different methods. Criteria include: the presence or absence of broad emission lines in optical spectra (e.g. Sy1/Sy2, BLRG/NLRG), optical morphology (e.g. Sy1/radio-loud quasar, BLRG/radio-loud quasar), radio morphology (FRI/FRII), variability (BL Lac, OVV), luminosity (e.g. Sy1/radio-quiet quasar, WLRG/NLRG), and spectral shape (e.g. SSRLQ, FSRLQ) [2]. The general challenges faced in the classification of AGN include the following.

- **The diversity in classification methods.** The methods used to classify objects differ both between different wavelength regions, and within a given wavelength region, often leading to more than one classification applying to each individual AGN. Although this can be confusing, considerable insight may be gained by correlating the different classifications and properties of individual sources. For example, radio-loud quasars with flat radio spectra (FSRLQ) often have core-dominated radio structures and are highly variable

[1] Following the definition of Tadhunter et al. (1998) WLRG are objects with $EW_{[OIII]} < 10$Å. Note that WLRG are sometimes labelled low excitation galaxies (LEGs).

[2] See Figure 1 for an explanation of the acronyms.

at optical wavelengths (i.e. they are are also classified as OVVs), whereas radio-loud quasars with steep radio spectra (SSRLQ) tend to have lobe-dominated radio morphologies and be less variable at optical wavelengths. Such patterns of behaviour lead to important insights in understanding the relationship between SSRLQ and FSRLQ (see below). As a further example, the fact that low power radio galaxies with FRI radio morphologies are invariably classified as WLRG at optical wavelengths provides key information about the physics of the energy generation in the central regions of such galaxies.

- **Attempting to force continuous sequences of properties into discrete bins.** A familiar problem from many fields of astrophysics is that, as part of classification, we often attempt to force objects that are actually continuous in a particular property into discrete classification bins. For example, it is now generally believed that radio-quiet quasars are high luminosity counterparts of Seyfert 1 galaxies, but there exists a continuous range in luminosity between the lowest luminosity Seyfert 1 and the highest luminosity quasar. Moreover the quasar classification is based primarily on optical morphology, whereas the Seyfert 1 classification is based mainly on optical spectroscopic properties. Therefore, it is hard to draw the dividing line in luminosity between the two classes. Similarly, because most AGN have non-thermal radio emission associated with the activity at some level, it can be difficult to draw the line between radio-loud and radio-quiet AGN. As a final example, the division between Seyfert 1 and Seyfert 2 galaxies is not always clear-cut, because the strength of the broad permitted lines relative to the narrow lines varies in a continuous manner. Hence the development of more detailed classification schemes in which Seyfert galaxies are placed into Seyfert 1.0, 1.2....1.9, 2.0 categories based on the relative strengths of their broad permitted lines (Osterbrock , 1977).
- **Classifications change.** As instrumental sensitivity improves, and new techniques are developed, classifications can change. This is particularly true of the Sy1/Sy2 or BLRG/NLRG division. With spectra covering only the the blue part of the optical window (i.e. sampling Hγ and Hβ) it can be difficult to detect the broad permitted lines, especially if the broad line AGN component is weak relative to the host galaxy stellar continuum and/or the S/N is low. In some cases high S/N spectra covering the strong Hα line, combined with accurate stellar continuum modelling and subtraction, are required to reveal the true Sy1 character of an AGN (e.g. Holt et al. 2007). The case of PKS1932-46 shown in Figure 2 illustrates this point well. Although this object was originally classified as a NLRG based on relatively low S/N blue spectra taken with the ESO3.6m telescope (Tadhunter et al. , 1993, 1998), a higher S/N spectrum taken on the 8m VLT reveals a broad Hα line above the strong stellar continuum of the elliptical host galaxy (Holt et al. , 2007). A further complication is that weak broad line components may be detected in scattered rather than directly transmitted light. In such cases, spectropolarimetry observations – which enhance the contrast of the

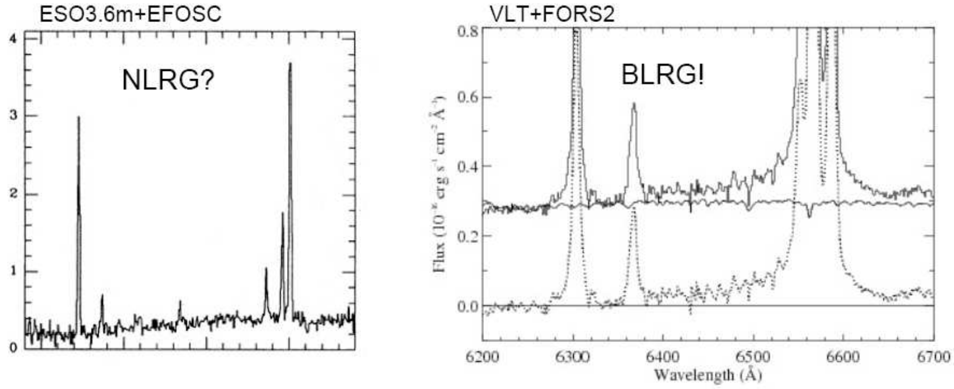

Fig. 2. Optical spectra of the southern radio galaxy PKS1932-46. The spectrum on the left was taken on the ESO3.6m telescope at blue optical wavelengths (see Tadhunter et al. 1993 for details) and shows no signs of broad permitted lines, while the spectrum on the right was taken using the ESO VLT telescope and shows clear broad wings to Hα following modelling and subtraction of the underlying stellar continuum (Holt et al. , 2007).

scattered features relative to the stellar continuum and narrow line emission – reveal the characteristic Sy1 spectrum in polarized light (e.g. Antonucci & Ulvestadt, 1985; Cohen et al. , 1999).

- **Variability.** It is often assumed that classifications are static over the lifetimes of AGN (e.g. once a Sy1 always a Sy1). However, accurate brightness measurements of AGN have only been possible over the last $\sim 10^2$yr, and this time period is short relative to the estimated typical lifetimes of AGN ($\sim 10^7 - 10^8$yr). Thus it is conceivable that AGN change classifications over their lifetimes without this necessarily being apparent over the short timeframe of the observations. In fact, some AGN are known to have shown major spectral changes on timescales of years to decades. For example, in the cases of NGC4151 and NGC7582 the optical spectra changed between Sy1 and Sy2 types over a period of a few years (Penston & Perez , 1984; Aretxaga et al. , 1999), and some LINER nuclei have been observed to develop Sy1 characteristics on a similar timescale (Storchi-Bergmann, Baldwin & Wilson , 1993; Bower et al. , 1996). By analogy with certain types of X-ray binary systems, we must also be open to the possibility that even more drastic changes (e.g. from radio-quiet to radio-loud) may take place over the lifetimes of AGN as the central energy generating regions around the central black holes cycle through different accretion states (e.g. Körding, Jester & Fender , 2006).

It is always important to bear in mind that the purpose of classification is not only to find convenient means of labelling objects, but also to search for patterns in behaviour that eventually lead to physical insights and understanding of the phenomenon in question. In this sense, there are three major "divisions" in the behaviour of AGN: the absence or presence of broad permitted lines in

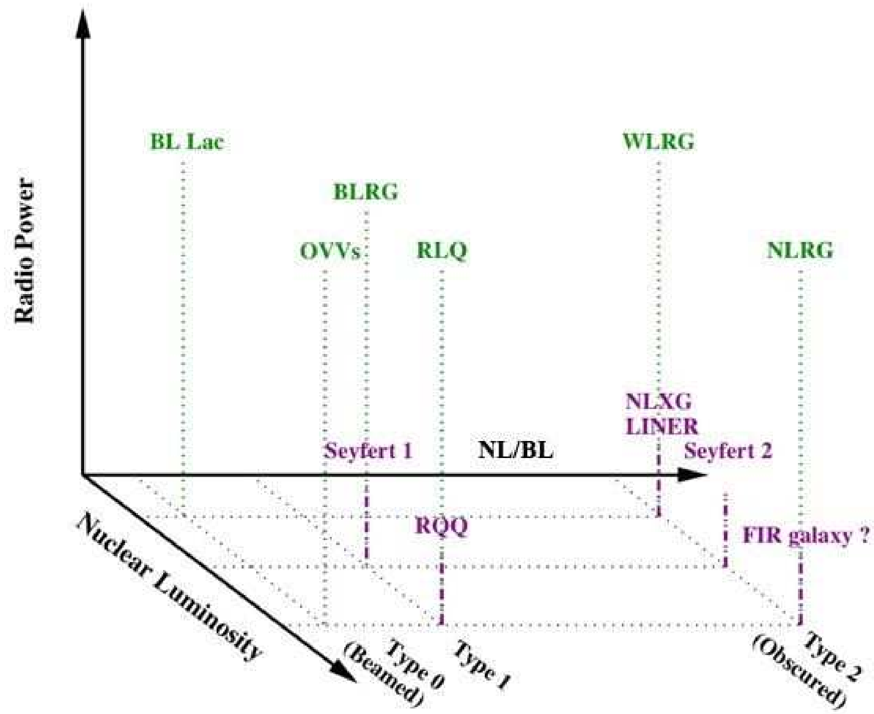

Fig. 3. A three dimensional classification for AGN, reflecting the major divisions amongst the various classes of AGN: the presence or absence of broad permitted lines, AGN luminosity, and radio loudness (acronyms explained in Figure 1).

their optical spectra, degree of radio loudness, and luminosity. Using these divisions it is possible to place AGN within the three dimensional classification scheme shown in Figure 3. This is not to say that other divisions/classification criteria are not also important, but it is the three axes shown in Figure 3 that have received the most attention to date.

Finally, while classification is concerned with making sense of the *diversity* in their properties, some of the most important insights into the nature of AGN have been gained by considering what they have in common rather than how they differ. All classes of AGN (with the possible exception of LINERS) share the properties that they are extra-ordinarily powerful, compact, long-lived and have the ability to form highly collimated jets. It has proved difficult to explain these collective properties by any other mechanism than the accretion of gas to the close vicinities of super-massive black holes (e.g. Rees , 1977).

2 Unification

If AGN classification is a first step to identify underlying patterns in behaviour, AGN unification represents an attempt to gain physical insights on the basis of that classification. In the remainder of this review I will concentrate on the development and testing of the orientation-based unified schemes for AGN over the last three decades. This is very much a personal perspective, concentrating on some recent results, and I refer the reader to the several excellent reviews by other authors in order to gain a more general overview. In particular, the review by Lawrence (1987) discusses the status of classification and unification up to the late 1980s, that by Antonucci (1993) discusses the unification of both radio-quiet and radio-loud AGN, while Urry & Padovani (1995) present a comprehensive review of the unified schemes for radio-loud AGN.

2.1 The history of the orientation-based unified schemes

The history of orientation-based unified schemes is a tale of two separate strands of development at radio and optical wavelengths that eventually came together towards the end of the 1980s.

The radio strand was stimulated by the development of very long baseline interferometry (VLBI) techniques in the 1970s that allowed the inner jets of radio-loud quasars to be mapped at milliarcsecond resolution. By combining VLBI observations made at different epochs Cohen et al. (1977) discovered that some components in the inner-jets were moving outwards relative to stationary cores with apparently superluminal transverse velocities. It was soon realised that the apparently superlumination motions are an optical illusion caused by observing relativistic jets pointing close to the line of sight. The major significance of this discovery for the unified schemes is that jets undergoing bulk relativitic motion are expected to emit their radiation anisotropically due to the relativistic abberation effect. It was also recognised that such "beaming" will lead to the appearance of a quasar changing with its orientation to the line of sight (Blandford & Konigl , 1979). This led to the proposal that radio-loud and radio-quiet quasars may represent the same class of object viewed from different directions, with radio-loud quasars observed with the radio jet pointing close to the line of sight and radio-quiet quasars observed with the radio jet pointing closer to the plane of the sky (Scheuer & Readhead , 1979). This first unified scheme is seriously flawed because we now know that the diffuse radio lobes are not moving relativistically, therefore it is not possible to "hide" the powerful, radio-emitting lobes via the beaming effect in the radio-quiet quasars. However, it prefigures much of the later development in this field.

Following on from the pioneering work of Blandford & Konigl (1979) and (Scheuer & Readhead , 1979), Orr & Browne (1982) proposed a less ambitious scheme that uses the beaming effect to explain the relationship between FSRLQ (jet pointing close to the line of sight) and SSRLQ (jet pointing further from the line of sight). The latter scheme has proved more successful in the sense that it is consistent with detection of radio haloes around the bright, compact cores of the FSRLQ – these haloes apparently representing the diffuse radio lobes viewed end-on (Browne et al. , 1982; Antonucci & Ulvestadt, 1985). It is also consistent with the later discovery of a de-polarization asymmetry in the extended radio components of radio-loud quasars that is correlated with jet sidedness (Laing , 1988; Garrington et al. , 1988) – the radio lobes are less depolarized on the side of the nucleus with the brightest jet, as expected in the case of beamed jet emission, with the depolarization caused by the magnetised hot haloes of the host galaxies or clusters of galaxies.

The second strand is based on X-ray and optical observations that provide evidence for anisotropy induced by gas and dust obscuration in the circum-nuclear regions of AGN. At around the same time as the discovery of superluminal motion in radio-loud AGN, based on infrared observations, Rowan-Robinson (1977) suggested that Seyfert 2 galaxies suffer enhanced extinction relative to Seyfert 1 galaxies. This proved consistent with later X-ray studies that revealed significant differences in the gas absorption columns of the two Seyfert types (Lawrence & Elvis , 1982). However, the first clear information about the geometry of obscuring regions was obtained by Antonucci and colleagues using optical spectropolarimetry observations of radio galaxies and Seyferts. In a pioneering spectropolarimetry study of nearby radio galaxies, Antonucci (1984) found that radio galaxies tend to fall into two groups based on their polarization properties: one – mainly comprising NLRG – in which the polarization is aligned close to perpendicular to the radio axis, the other – mainly comprising BLRG – in which the polarization is aligned closer to parallel to the radio axis. Antonucci realised that these polarization properties could be explained in terms of scattered AGN light, with the parallel alignments due to equatorial scattering by a disk that is viewed obliquely, and the perpendicular alignments resulting from polar scattering by material in the opening of an optically thick doughnut/torus-like structure. Indeed the Antonucci (1984) paper contains the first sketch of the circum-nuclear torus which is now such a key element of the unified schemes. Subsequently, Antonucci & Miller (1985) used spectropolarimetry observations of the nearby, bright Seyfert 2 galaxy NGC1068 to detect broad permitted lines in its polarized spectrum [3], confirming that it has a Seyfert 1 nucleus hidden in its core by optically thick obscuring material.

[3] In fact, prior to the work on NGC1068, a scattered broad permitted line was detected in spectropolarimetry observations of the radio galaxy 3C234 by Antonucci (1984). However, the detection in NGC1068 was more convincing.

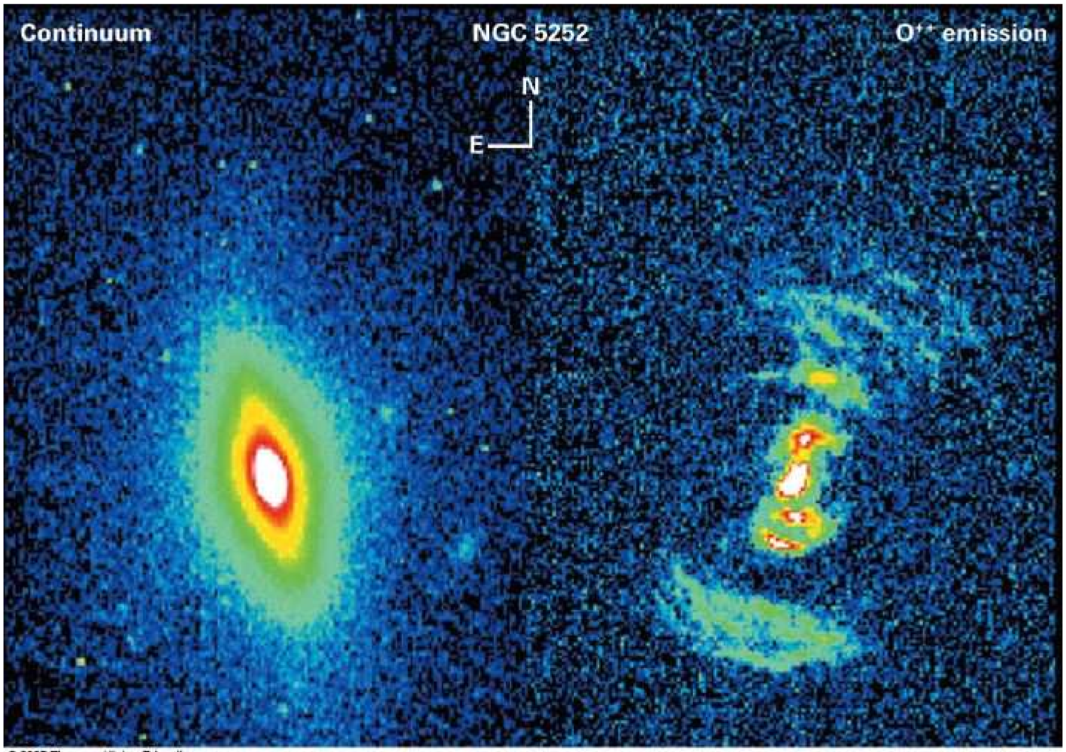

Fig. 4. Optical images of the Seyfert galaxy NGC5252. Left: optical continuum image. Right: [OIII] emission line image showing the spectacular ionization cones. See Tadhunter & Tsvetanov (1989) for details.

The idea of obscuration by a dense, optically-thick, torus-like structure was further reinforced by the detection, using deep narrow-band imaging observations, of sharp ionization cones in the extended narrow line regions of several Seyfert 2 galaxies (e.g. Pogge, 1989; Tadhunter & Tsvetanov, 1989, see Figure 4). Long-slit spectroscopic observations also provided evidence for an anisotropic ionizing continuum in the form of emission lines that were more extended along the radio axes of Seyfert 2 galaxies than in the perpendicular direction (Unger et al. , 1989).

To summarise, by the late 1980s it was recognised that two distinct mechanisms for producing anisotropy – beaming by relativistic jets, and obscuration by optically thick regions surrounding the AGN – could cause the appearances of an AGN to change with orientation relative to the observer's line of sight. Thus, on the one hand beaming could unify FSLRQ with SSRLQ, and on the other anisotropic obscuration could unify Sy1 with Sy2 galaxies. However, there was much that the unified schemes could not explain. In particular, a major lacunae for radio-loud AGN was that, despite some similarities in their radio properties (e.g. the powers of their extended radio lobes), it was not possible to unify radio galaxies with radio-loud quasars using the beaming mechanism alone. This is because some of the key components of quasar spectra that are not present in radio galaxy spectra – including the broad

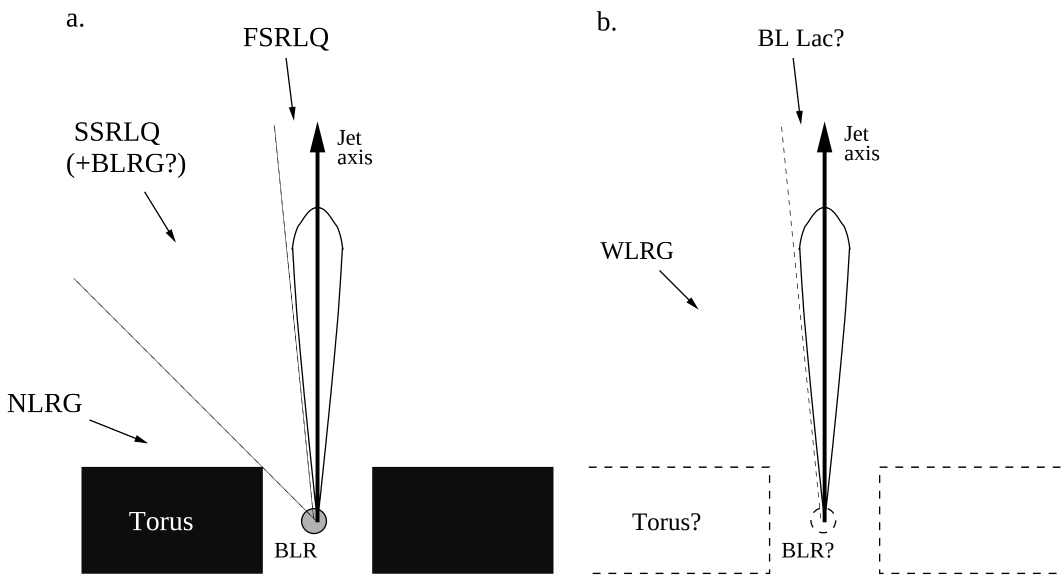

Fig. 5. Unified schemes for radio-loud AGN: (a) for objects with strong narrow emission lines; (b) for objects with weak narrow emission lines.

permitted lines and big blue bump continuum emission – are non-relativistic, and therefore not subject to the extreme beaming effect associated with the non-thermal jet components. It was soon recognised that the only way to produce a scheme capable of unifying all the major classes of powerful, radio-loud AGN was to combine the two mechanisms for producing anisotropy.

The Barthel (1989) scheme, which combines both beaming and anisotropic obscuration, is illustrated in Figure 5(a). When the radio jet is pointing at a large angle to the observer's line of sight($\geq$ 45 degrees), the bright AGN is entirely hidden by dust in the circumnuclear torus and the object is classified as a NLRG. As the jet points closer to the line of sight, the AGN becomes directly visible and the object is classified as a quasar (AGN dominates the host galaxy emission) or as a BLRG (AGN of similar brightness to the host galaxy). At even smaller angles the observer's line of sight falls within the beaming cone of the relativistic jet, the AGN emission is dominated by the flat radio spectrum, highly variable emission of the inner jet and the object is classified as an FSRLQ and/or OVV quasar.

It is important to emphasise that radio-loud AGN are particularly well-suited to testing the unified schemes. This is because samples of such objects can be selected using their extended, steep spectrum radio emission components (mainly lobes and hotspots) which, unlike the inner relativistic jet components, are not thought to be significantly beamed. Therefore, in contrast to samples of AGN selected at X-ray, optical and near-IR wavelengths, radio-selected samples of AGN – particularly those selected at low radio frequencies – are not substantially biased with respect to a particular orientation relative to the line of sight.

The basic principle of the orientation-based unified schemes is that the AGN types being unified all belong to the same parent population of AGN with similar intrinsic properties, and that differences between the observed properties of the types are due to anisotropy and orientation effects. We can define a "perfect unification principle" (PUP) which posits that all AGN within a particular unified group are identical (e.g. same intrinsic AGN power, spectrum and age; same torus properties; same jet properties; and same host galaxy properties) and that the differences between the types within the group are *solely* due to orientation/anisotropy effects. Given the observed diversity in the general population of AGN and their host galaxies, it is unlikely that such perfect unification could ever hold, but the PUP provides a useful fiducial against which we can judge the success of the unified schemes and determine which other factors are likely to be important in determining the observed properties of AGN.

Two immediate problems for the PUP when applied to the Barthel (1989) scheme for radio-loud AGN are as follows.

- **How do WLRG and BL Lac objects fit in?** At radio wavelengths WLRG are largely classified as relatively low radio power FRI radio galaxies, however, a small but significant subset have FRII morphologies (Hine & Longair , 1979; Laing et al. , 1994; Tadhunter et al. , 1998). The problem with accommodating WLRG within a Barthel-style scheme is that it is not clear how one could produce sufficient anisotropy in the narrow emission lines, for example, via torus-induced obscuration, to explain the large disparities in emission line luminosity and ionization state between the WLRG on the one hand, and NLRG/BLRG/radio-loud quasars on the other. Moreover, differences between the radio properties of the majority of WLRG (low power FRI) and the majority of NLRG/BLRG/SSRLQ (high power FRII) are not readily explainable in term of jet beaming effects. It seems certain that the WLRG are not consistent with the PUP applied to the scheme illustrated in Figure 5(a).

  It is possible that the physics of the energy generation in the central regions of WLRG are fundamentally different from those of radio-loud AGN with strong emission lines. For example, it has been proposed that the properties of WLRG are consistent with their black holes accreting at a lower rate – perhaps from the hot phase of the ISM – than the radio-loud AGN with strong emission lines which are more likely to be fuelled by cold gas accretion (Ghisellini & Celotti , 2001; Hardcastle, Evans & Croston , 2007). Alternatively, it has been suggested that distributions of gas and/or obscuring dust are different in the WLRG, with their torus properties allowing less of the emission line radiation to escape the nuclear regions (Cao & Rawlings , 2004). Note, however, the mid- to far-IR (MFIR) continuum properties of WLRG are inconsistent with the idea that they contain luminous quasar nuclei that are entirely hidden by dust at optical wavelengths (see Figure 7 below).

The fact that at least some of the properties of WLRG are similar to those of BL Lac objects (e.g. apparently weak emission lines, similar extended radio luminosities), has also lead to the proposal that WLRG should be unified with BL Lac objects rather than BLRG/radio-loud quasars. This alternative unified scheme for WLRG/BL Lac objects is illustrated in Figure 5(b). However, the detection of broad, quasar-like emission lines in some BL Lac objects (Corbett et al. , 1998), and the fact that the narrow line luminosities of BL Lac objects are often larger than those of WLRG with similar redshifts/radio powers, suggests that the situation may be even more complex (Urry & Padovani , 1995; Wills et al. , 2004).

- **The status of BLRG.** In many ways the BLRG, which have broad permitted lines as well as a non-stellar continuum at optical wavelengths, appear to be fainter versions of radio-loud quasars. Although BLRG are more common than radio-loud quasars in the local Universe ($z < 0.2$) the redshift distributions of the two types overlap, and examples of BLRG can be found at all redshifts (Tadhunter et al. , 1998). One explanation for the relative faintness of BLRG at optical wavelengths is that they suffer enhanced extinction compared with radio-loud quasars. Alternatively they may be intrinsically less luminous versions of radio-loud quasars. In the former case, the PUP can be saved if the obscuring material is associated with the less dense outer regions of the torus, and the BLRG are observed with the radio jet an angle to the line of sight that is intermediate between that of radio-loud quasars and NLRG. Certainly there is evidence from the measured ratios of broad hydrogen permitted lines, as well as optical/infrared colours and polarization properties, that at least a subset of BLRG have AGN that are modestly reddened by dust extinction (Osterbrock, Koski & Phillips , 1976; Rudy & Tokunaga , 1982; Goodrich et al. , 1992; Cohen et al. , 1999).

  However, because of their relative faintness, and the fact that some of the apparent spectral differences between BLRG and quasars may reflect intrinsic differences in their AGN rather than reddening effects, it is difficult to rule out the idea that some BLRG are instrinsically lower luminosity versions of radio-loud quasars at similar redshifts, in contravention of the PUP. Indeed, the X-ray, optical, near-IR, mid-IR and radio properties of the BLRG PKS1932-46 (see Figure 2) suggest that this object has an intrinsically low luminosity AGN compared with other radio-loud quasars at intermediate redshifts (Inskip et al. , 2007). Based on mid- and far-IR properties it has even been suggested that NLRG and BLRG represent different stages in the evolution of AGN (van Bemmel & Barthel , 2001).

  Most plausibly, BLRG represent a mixed population that comprises a combination of mildly redddened and intrinsically faint radio-loud quasars. Dennett-Thorpe, Barthel & van Bemmel (2000) have shown that the mixed population hypothesis is consistent with the radio properties of nearby BLRG.

In the following sections I discuss the various tests that have been applied to the Barthel-style unified scheme for radio-loud AGN (see Figure 5(a)) over the last two decades.

2.2 Statistical tests of unification I: orientation-dependent properties

As well as the sharp changes in the spectral, morphological and polarisation properties already noted above, we expect certain other of the observed properties of radio-loud AGN to vary with orientation, allowing tests to be made of the unified schemes. These properties include the measured maximum extents of the extended double-lobed radio emission, the degrees of core dominance of the radio sources, and the detailed emission line spectra of the quasar nuclei.

The results of the test based on the maximum measured extents of the radio sources was one of the major pieces of evidence presented by Barthel (1989) to support his unified scheme. If quasars are truly observed with their jets pointing closer to the line of sight than radio galaxies then, due to foreshortening, the measured linear sizes of their extended radio sources should be smaller for a given intrinsic radio source extent. Barthel applied this test to complete samples of radio galaxies and radio-loud quasars with redshifts $0.5 < z < 1.0$ selected from the 3CR sample and found evidence that, although each population displays a wide range in projected linear size (some quasars have radio sources with large measured extents), on average the linear extents of quasars are smaller than those of radio galaxies. However, statistically this difference is only significant at the $\sim 2\sigma$ level, and subsequently, various studies have produced less clear-cut, sometimes contradictory, results concerning the differences between the linear size distributions of quasars and radio galaxies (see Saikia & Kulkarni , 1994, and references therein). With hindsight, this is not surprising given that the radio sources in a given flux-selected sample are likely to encompass a wide range of intrinsic linear extents, reflecting the ranges of radio source ages and gaseous environments into which the radio jets are expanding. These factors reduce the sensitivity of the linear size distributions to orientation effects.

Reflecting the polar diagram of the beamed emission from the inner jets, it is also expected that, as the jet axis points closer to the line of sight, the flat spectrum radio cores should become stronger relative to the (unbeamed) extended steep spectrum radio emission. This effect can be quantified using the R-parameter that measures the ratio of the flux of unresolved core to the flux of the extended radio emission. Notwithstanding issues related to the impact of variable resolution on the accuracy of the core measurements, the results are consistent with the unified schemes in the sense that, on average, NLRG have significantly lower R-parameters than BLRG and radio-loud quasars in the 2Jy and 3C samples (Laing et al. , 1994; Morganti et al. , 1997). Moreover, the overall distribution of R-parameter estimates in the 2Jy sample is consistent with the beaming hypothesis assuming a randomly oriented parent populations (Morganti et al. , 1995). However, these are statistical results and there are significant outliers. In particular, a sub-set of the quasar/BLRG in the 2Jy sample show very weak cores (Morganti et al. , 1997). Again, the sensitivity of this test, and the overall accuracy of the R-parameter as an orientation indicator, will be reduced by the fact that the core-to-jet ratios are affected by a number of factors (e.g. environment, jet Lorentz factor, variability) in addition to orientation; these factors may vary considerably within a given flux-limted sample of radio sources.

At optical wavelengths, changes in the detailed spectra of radio quasars are also expected as the orientations of the radio jets relative to the line of sight vary. Under the assumption the broad permitted lines are emitted by rotating disk-like structures close to the nuclei, with the disk rotation axes aligned with the axes of the large-scale jets, due to projection effects, the measured velocity widths of the broad lines are expected to decrease as the jets point closer to the line of sight. The equivalent widths of the narrow emission lines are also expected to decrease as the beamed jet continuum emission becomes increasingly important. There is good statistical evidence for both effects: the velocity widths of the broad permitted lines and the equivalent widths of narrow forbidden lines are both anti-correlated with orientation-sensitive R-parameter (Wills & Browne , 1986; Jackson et al. , 1989), albeit with a large scatter that is likely to be a consequence of the range in the intrinsic emission line and radio source properties across the samples considered.

Overall, these tests based on properties that are expected to vary in a well-defined way with jet orientation show broad consistency with the expectations of the orientation-based unified schemes. The fact that they are not more sensitive and clear-cut is likely to be due to the wide ranges of intrinsic source properties within samples considered, representing violations of the PUP.

2.3 Statistical tests of unification II: orientation-independent properties

Whereas the previous section concerned statistical tests based on properties that vary with orientation, in this section I consider tests that take the opposite approach, in particular, investigating whether properties that are assumed to be isotropic and orientation-independent show significant variations between the different classes of radio-loud AGN. Any detected variations could reflect either fundamental problems with orientation-based unification or problems in the assumptions made in designing the test(s).

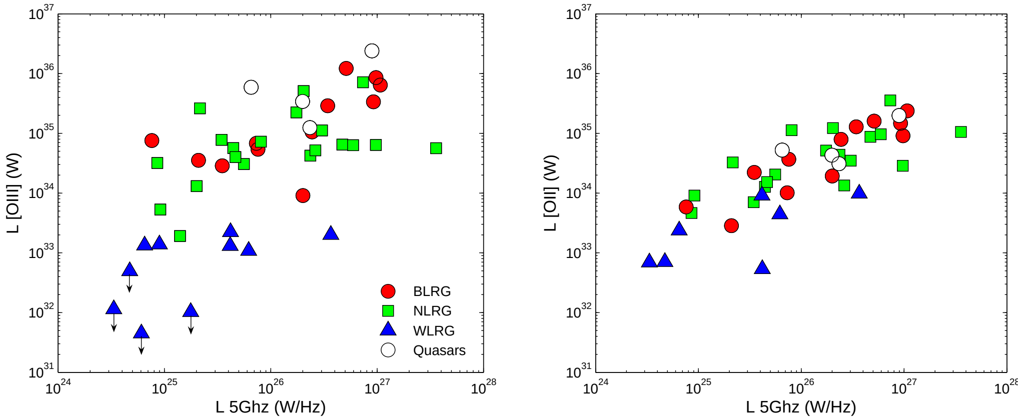

Fig. 6. Correlations between radio and emission line luminosities for the 2Jy sample with redshifts $0.05 < z < 0.7$ (see Tadhunter et al. , 1993, 1998). The sample has been selected on the basis of steep spectrum radio emission, and specifically excludes objects that are dominated by flat spectrum radio cores. Left: [OIII]λ5007 luminosity plotted against 5 GHz radio power. Right: [OII]λ3727 luminosity plotted against 5 GHz radio power. The open circles represent radio-loud quasars, the red circles BLRG, the green squares NLRG, and the blue triangles WLRG. Note that there are no significant differences between the distributions of the broad line (BLRG+quasars) and narrow line (NLRG excluding WLRG) objects on these plots, although, as expected, the WLRG are displaced towards low emission line luminosities.

The optical narrow emission lines have received considerable attention as orientation-independent indicators of AGN activity. One of the first attempts to use the emission lines to test the unified schemes was made by Jackson & Browne (1990), who compared the [OIII]λ5007 emission line luminosities of pairs of radio galaxies and radio-loud quasars selected from the 3C catalogue that were matched in extended radio power. They found that, on average, the quasar [OIII]λ5007 luminosities are a factor $\sim$10$\times$ larger than those of radio galaxies of similar extended radio power. Rather than interpreting this result as evidence against the orientation-based unified schemes, Jackson & Browne suggested that the [OIII]λ5007 emission is in fact anisotropic, due to extinction of the inner narrow line region (INLR) by the circum-nuclear torus. This was supported by the fact that the Balmer decrements provide direct evidence for significant dust extinction of the narrow lines in the radio galaxies. More recently, Haas et al. (2005) have used Spitzer observations of a small sample of radio-loud AGN to investigate the emission line anisotropy using mid-IR emission lines that are less affected by dust extinction. They find that, while there exist large differences between the mean [OIII]λ5007 luminosities of the radio galaxies and radio-loud quasars in their sample, there are no significant differences between the luminosities of the mid-IR emission lines such as [NeV]λ24.3μm for the two classes.

If the [OIII]λ5007 emission is truly affected by torus extinction, then the INLR must be relatively compact ($\sim$1 – 10 pc). Some direct evidence for a compact INLR is provided by the apparent variability of the narrow emission lines in the broad line radio galaxy 3C390.3 (Clavel & Wamsteker , 1987; Zheng et al. , 1995). The idea that the INLR is compact and hidden by the torus in NLRG is also supported by the detection of significant polarization in the [OIII]λ5007 emission lines measured in a small sample of southern radio galaxies (di Serego Alighieri, Cimatti & Fosbury , 1994). However, before concluding that the optical emission lines are anistotropic and hence do not provide a clean test of the orientation-based unified schemes, it is important to note the following:

- many of the studies that provide evidence for significant [OIII]λ5007 anisotropy employ relatively small samples that are not statistically complete;
- interpretation of the [OIII] results is affected by the status of the BLRG in the unified schemes, in the sense that, objects with intrinsically weak broad line nuclei may not be included in samples of radio-loud quasars, thus biasing the quasar samples towards broad line objects that are intrinsically luminous;
- the inclusion of WLRG in the radio galaxy samples may potentially bias them towards AGN that are intrinsically less luminous (e.g. Laing et al. , 1994);
- because of radial gradients in ionization and density, not all optical emission lines may suffer the same degree of anisotropy.

On the latter point, a study of a relatively large sample of 3C radio galaxies and quasars by Hes, Barthel & Fosbury (1993) found no clear differences between the [OII]λ3727 luminosities of radio-loud quasars and radio galaxies. As Hes et al. argue, because the [OII]λ3727 line has a lower ionization and critical density, it is likely to be emitted predominately at larger radial distances from the AGN than [OIII]λ5007, and is hence less affected by the dust obscuration in the circum-nuclear regions.

Regarding sample completeness and the inclusion of BLRG and WLRG, it is notable that in their study of a large, statistically complete sample of steep spectrum 2Jy radio sources Tadhunter et al. (1998) found no strong evidence for differences between the [OIII]λ5007 luminosities of the narrow line objects (NLRG, excluding WLRG) and broad line objects (BLRG+radio-loud quasars) of similar extended radio power. Figure 6 presents updated versions of the correlations between radio power and emission line luminosity for the 2Jy sample. It is clear that, although some of the objects at the high radio power end of the correlations with the highest [OIII] luminosities are indeed broad line objects, the [OIII] luminosity distributions of the broad line objects are similar to those of the narrow line objects, especially if the WLRG are excluded from the comparison. Consistent with the results of Hes, Barthel & Fosbury (1993), any small differences that might exist between distributions of emission line luminosities of the populations in the [OIIIλ5007 vs P_{rad} plot

(Figure 6, left) entirely vanish in the [OII]λ3727 vs P_{rad} plot (Figure 6, right). I conclude that, while it is difficult to rule out a degree of anisotropy in the [OIII]λ5007 emission from radio-loud AGN, the magnitude of effect is likely to be less than deduced in the early studies (i.e. at most a factor of a few rather than an order of magnitude).

Given the rapid decline in the dust extinction curve towards longer wavelengths, the mid- to far-IR (MFIR) wavelength region holds much promise for testing the unified schemes. As well as strong narrow emission lines (Haas et al. , 2005), thermal continuum emission from dust structures heated either by the AGN or by circum-nuclear starbursts is also strong at such wavelengths (e.g. Ogle, Whysong & Antonucci , 2006). Even allowing for the relatively large optical depths of the putative torus structures, the degree of anisotropy induced by the torus at the longer MFIR wavelengths (>30μm) should be relatively slight. Therefore we should expect narrow and broad line AGN to display similar continuum luminosities at such wavelengths.

The first attempts to investigate the MFIR properties of radio-loud AGN were based on observations made with the IRAS satellite. Unfortunately, because of the limited sensitivity, a relatively small fraction (<30%) of radio-loud AGN in the local Universe ($z < 0.2$) were detected at 25, 60 and 100μm by IRAS. However, by stacking and combining individual 25 and 60μm IRAS images for complete sub-samples of 3C objects of various radio powers and redshifts, Heckman et al. (2002, 2004) were able to compare the MFIR continuum properties of the broad- and narrow-line objects. They found evidence for significant differences between the mean and median 25μm luminosities of the broad- and narrow line objects, as expected in the case that the 25μm emission is produced at the inner face of the torus and the torus has a significant optical depth at the shorter MFIR wavelengths. Perhaps more surprising is the fact that the differences between continuum luminosities of the broad and narrow line objects persist at 60μm, despite the fact that most models predict that the torus should be relatively transparent at such long wavelengths, and in any case, the dust emitting the far-IR radiation may be located outside the inner parts of the torus. van Bemmel & Barthel (2001) have also highlighted differences between the MRIF continuum shapes of BLRG and NLRG based on ISO observations, perhaps linked to differences between the optical morphologies of the sources (the NLRG in their small sample show an increased prevalence of dust lanes).

At longer, sub-mm wavelengths — where any anisotropy due to the circum-nuclear torus should be entirely negligible — attempts have also been made to compare the continuum properties of high-z radio galaxies and quasars. In apparent accord with the Heckman et al. (1992, 1994) far-IR results for lower redshift objects, Willott et al. (2002) find that radio-loud quasars both have a higher detection rate, and are significantly more luminous, than the radio

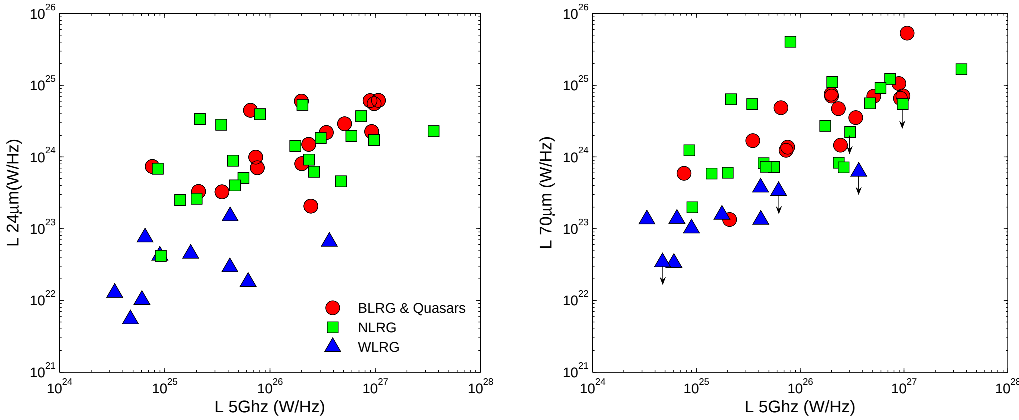

Fig. 7. Correlations between radio and MFIR luminosities for the 2Jy sample with redshifts $0.05 < z < 0.7$ (see Tadhunter et al. , 1993, 1998). Left: 24μm luminosity plotted against 5GHz radio power. Right: 70μm luminosity plotted against 5GHz radio power. The red circles represent broad line AGN (BLRG+quasars), the green squares NLRG, and the blue triangles WLRG. Note that there are no significant differences between the distributions of the broad line (BLRG+quasars) and narrow line (NLRG excluding WLRG) objects on these plots.

galaxies at 850μm in their small sample of radio-loud AGN in the redshift range $1.2 < z < 2$.

At first sight, the apprent differences between the MFIR and sub-mm properties of radio-loud quasars and radio galaxies deduced from these early studies might be taken as providing evidence against the orientation-based unified scheme, or at least suggest that the degree of anisotropy of the MFIR continuum is larger than predicted by the torus models. In the latter context, it is important to consider possible contamination of the MFIR continuum by the non-thermal emission associated with the inner radio jet components. Although the radio to MFIR SEDs of some FSRLQ with high R values suggest significant non-thermal contamination of the MFIR continuum, for the majority of radio galaxies and SSRLQ there is no evidence for such contamination (Polletta et al. , 2000; Cleary et al. , 2007). Therefore it is unlikely that non-thermal contamination alone can explain the apparent differences between the MFIR properties of the radio-loud quasars and radio galaxies. More plausibly, the differences may not be real, but rather the consequence of considering samples that are highly incomplete in terms of detections, with all the usual dilemmas concerning the inclusion of WLRG and BLRG; many of the comments made in the context the emission line studies described above also apply to the MFIR continuum studies.

Fortunately, the recent availability of Spitzer, with its orders of magnitude improved sensitivity compared to IRAS and ISO, has lead to a much higher level of completeness in terms of detections at MFIR wavelengths. Figure 7 shows the results of a deep Spitzer photometric survey at 24 and 70μm of the 2Jy sample, plotting the MFIR monochromatic luminosities against the 5 GHz radio luminosities (Dicken et al. 2008, in preparation). At the high level of completeness of detections in this survey (100% at 24μm and 90% at 70μm), there is little evidence for differences between the distributions of narrow line (NLRG, excluding WLRG) and broad line (BLRG+quasar) objects in these plots; similar results are obtained when the MFIR luminosities are plotted against the [OIII]λ5007 luminosities of the objects. These results are broadly consistent with the orientation-based unified schemes, and suggest that the degree of anisotropy in the MFIR thermal continuum of radio-loud AGN is low, even at the shorter mid-IR wavelengths (down to $\sim$24μm).

Note that, aside from sample incompleteness and potential selection biases, departures from the PUP might also result in differences between the luminosities of broad- and narrow line AGN, even if the orientation-based unified schemes are broadly correct. For example, consider the case of a radio-flux limited sample of AGN. If, as is now widely accepted (see section 3.1 below), the torus "recedes" as the AGN luminosity increases, and if there exists a spread in intrinsic AGN bolometric luminosity for a given radio power/redshift, then on average the emission line, MFIR and sub-mm luminosities for the sources observed as quasars will be higher than those measured for sources observed as radio galaxies in the same redshift range. This is because the more luminous AGN in a given redshift range have an increased chance of being observed as quasars (because of their wider torus opening angles) than the less luminous quasars.

Perhaps least ambiguous — because least likely to be affected by obscuration/anisotropy — are tests based on the properties of the AGN host galaxies and their large-scale environments. Over the last decade the study of AGN host galaxies has benefitted greatly from the enhanced resolution provided by the Hubble Space Telescope, which has allowed the first accurate comparisons of the properties of the host galaxies of radio-loud quasars with those of radio galaxies. In the most comprehensive such study to date, Dunlop et al. (2003) have found excellent agreement between the properties (luminosities, colours) of the host galaxies of quasars and radio galaxies in intermediate redshift samples matched in radio power. Although the large scale environments are often difficult to quantify, especially for samples of AGN at high redshifts, it is found that the environments of radio-loud quasars and radio galaxies are broadly consistent for flux limited samples selected at similar redshifts (Hill & Lilly , 1991; McLure & Dunlop , 2001).

In summary, tests based on (assumed) isotropic properties of radio-loud AGN present no serious problems for the broad concept of the orientation-based unified schemes. Any measured differences between the broad- and narrow line objects in these tests can be readily explained in terms of wrong assumptions (e.g. the property being examined is not genuinely isotropic), incompleteness, sample selection biases and/or departures from the PUP.

2.4 Detailed infrared, optical and X-ray observations: the case of Cygnus A

Although the statistical approach is useful for investigating whether the general properties of the populations of radio-loud AGN are consistent with the unified schemes in a broad-brush sense, detailed studies of individual sources also have an important rôle to play. In particular, by detecting the hidden quasar nuclei in the cores of galaxies otherwise classified as NLRG, such studies can provide some of the strongest evidence to support the unified schemes. In this section I will concentrate on the various detailed observational studies that have been made of the archetypal NLRG in the local Universe: Cygnus A ($z = 0.0560$).

One approach involves searching for the hidden quasar nuclei by imaging in wavelength regions that suffer less obscuration than the optical. The first success of this approach came with the detection of an unresolved compact core source in the near-nuclear regions of Cygnus A using ground-based near-IR observations (Djorgovski et al. , 1991). By comparing the measured K- and L'-band fluxes of the core source with estimates of the expected fluxes based on extrapolation of radio core data, Djorgovski et al. (1991) estimated an equivalent V-band extinction of $A_v \sim 50 \pm 30$ magnitudes towards the quasar nucleus of Cygnus A. However, a potential problem with the early ground-based observations was that they lacked the spatial resolution to distinguish the true quasar nucleus from a starlight distribution that is strongly peaked towards the nucleus. Therefore it is not surprising that more recent studies based higher resolution HST/NICMOS imaging observations of Cygnus A (Tadhunter et al. , 1999, see Figure 8), while detecting an unresolved core source at 2.3μm, provide evidence that it has a lower flux, and higher extinction ($70 < A_v < 94$ magnitudes — more in line with X-ray estimates of the absorbing column, see below).

X-ray wavelengths provide another promising window to search for hidden quasar nuclei in NLRG. Again, the power-law nucleus of Cygnus A was among the first to be studied in detail at X-ray wavelengths. Ueno et al. (1994) demonstrated that, in order to fit the hard X-ray spectrum of Cygnus A, an absorbed power-law component is required in addition to the thermal bremsstrahlung emission associated with the surrounding cluster of galaxies. The estimated absorbing column to the power-law source implies a large optical extinction of $A_v \sim 170$ magnitudes if the standard Galactic gas to dust extinction ratio applies. Using the high spatial resolution afforded by Chandra, Young et al. (2002) have confirmed that the power-law component is associated with an unresolved X-ray source in the centre of the galaxy. More

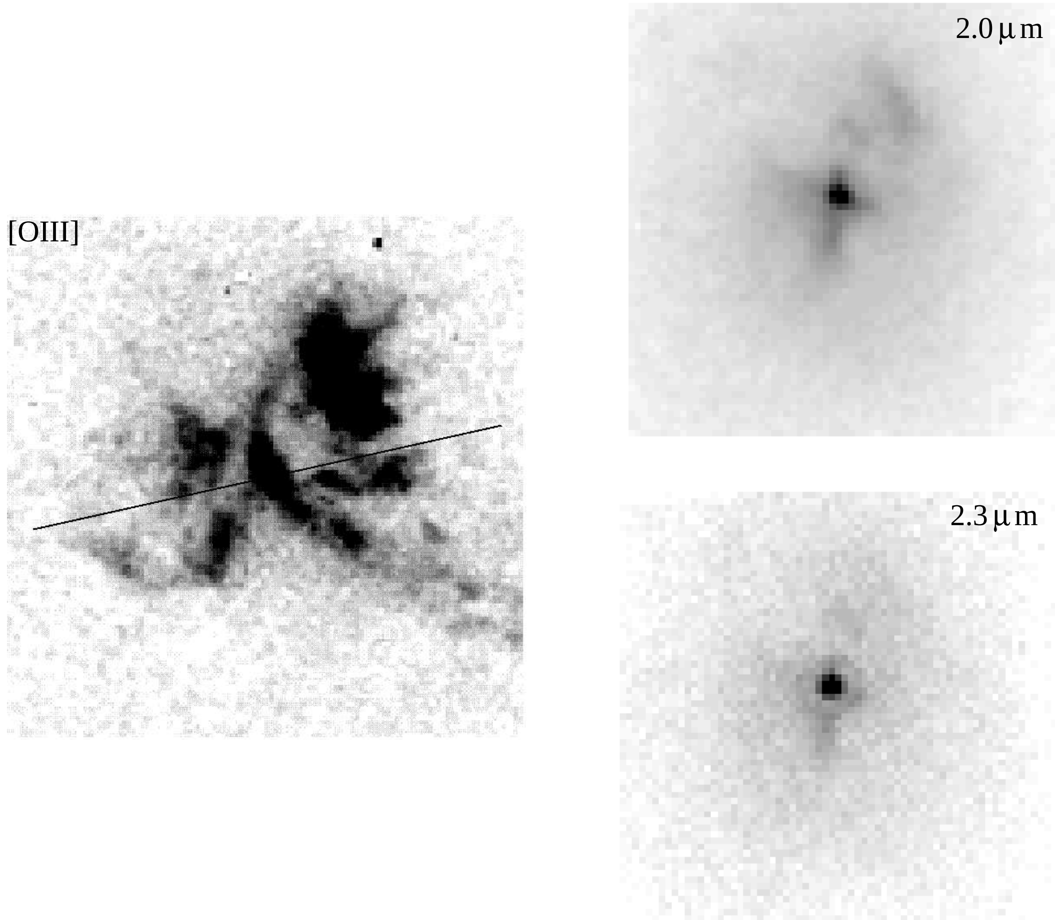

Fig. 8. Optical and infrared images of the nearby NLRG Cygnus A, taken with the Hubble Space Telescope. The narrow-band [OIII]λ5007 image shown on the left was taken with WFPC2 camera using a linear ramp filter (see Jackson, Tadhunter & Sparks , 1998, for details). The infrared images on the right were taken with NICMOS on board HST and show the clear detection of a nuclear point source component at 2.3μm, and the edge-brightening of the quasar illumination cones at 2.0μm (Tadhunter et al. , 1999). The line segment in the lefthand plot shows the direction of the large-scale radio jet axis.

recently, absorbed power-law components have been detected in a number of other powerful FRII radio galaxies (Sambruna, Eracleous & Mushotsky , 1999; Kraft et al. , 2007; Evans et al. , 2008), although we still lack observations of the large, statistically complete sample of such objects that would be required for a proper analysis of the X-ray nuclei in the general population of NLRG.

Less direct, but also important for testing the unified schemes, are observations of the extended reflection nebulae and ionization cones surrounding the

AGN. Biconical structures are expected to result from the illumination of the ISM in the host galaxies by the anisotropic continuum produced by the shadowing effect of a circum-nuclear torus. In the case of Cygnus A, at optical wavelengths there is strong evidence for both a bi-conical reflection nebula — detected in polarized light (Tadhunter, Scarrott & Rolph , 1990; Ogle et al. , 1997) — and ionization cones — detected in narrow-band emission line images centred on the wavelengths of redshifted [OIII]λ5007 and H$\alpha\lambda$6562 (Jackson, Tadhunter & Sparks , 1998, see Figure 8). Reassuringly, the opening half-angles of the cones are in line with the expectations of the unified schemes and the known inclination of the radio jets of Cygnus A relative to the line of sight. Moreover, the sharpness of the edges of the cones – which have apices close to the unresolved radio and infrared cores – provides strong support to the idea that the inner face of the torus lies within 50 pc of the quasar. The fact that sharp-edged cones are also detected in polarized light at 2.0μm demonstrates that the inner obscuring structure has a large optical depth even at infrared wavelengths (Tadhunter et al. , 2001). Together these observations provide clear-cut evidence for a compact, optically thick torus in Cygnus A that hides its illuminating nucleus from our direct view at optical wavelengths. Note, however, that other studies have challenged the idea that the central obscuring regions in all AGN necessarily comprise compact torus-like structures that are uniformly filled with dust and gas (see contribution by Elitzur in these proceedings).

Despite all these successes, the most compelling evidence for a hidden quasar nucleus in Cygnus A is provided by deep optical spectropolarimetry observations which detect the broad permitted lines characteristic of quasars in polarized light (Ogle et al. , 1997; Cohen et al. , 1999). Note that the broad lines are also present in the total intensity spectrum of Cygnus A, but are relatively faint and difficult to detect in the presence of the strong stellar continuum of the host galaxy. Scattered quasar broad lines have since been detected in several other NLRG (e.g. Cohen et al. , 1999). However, it will always be difficult to derive reliable statistics on the presence of hidden quasar nuclei in the population of NLRG using spectropolarimetry alone, because the detection of the scattered AGN component depends on a number of factors (e.g. density of scattering ISM, geometry, strength of stellar continuum) in addition to the presence of luminous illuminating quasars.

Clearly, the detailed observations of individual objects such as Cygnus A are an essential complement to the statistical studies described above; they provide the most direct evidence that individual NLRG contain hidden quasar nuclei.

3 Further problems with the simplest orentation-based schemes

The weight of evidence, both from the statistical studies of large samples and more detailed studies of individual objects, is strongly supportive of the general principles of the orientation-based unified schemes; such schemes are likely to be correct to first order. However, I have already noted some evidence for departures from the PUP based on statistical studies. In this section I highlight some further results which suggest that the simplest orientation-based unified schemes cannot hold.

3.1 Luminosity-dependent effects

One of the most glaring problems for the PUP is that the fraction of broad-line, quasar-like objects appears increases sharply with radio power/redshift in flux-limited samples of radio sources. At the lowest radio powers covered by the 3C survey few, if any, broad line nuclei are detected amongst the FRI radio galaxies, whereas at the highest radio powers $\sim$50% of sources are classified as broad line objects (Lawrence , 1991). In contrast, if all radio galaxies contain quasar nuclei (hidden or otherwise) and the properties of the torus (e.g. distance of inner face from nucleus, thickness) do not change with radio power/redshift, the fraction of objects with detected broad line nuclei should remain fixed with radio power/redshift. A plausible explanation for this discrepancy is that the properties of the torus change with radio power. In particular, on the basis of the strong correlations between emission line luminosity and radio power (e.g. Rawlings & Saunders , 1991; Tadhunter et al. , 1998), the luminosity of the quasar should increase with radio power. Then, if the radial distance of the inner face of the torus from the AGN is set by the sublimation temperature of the dust, it is expected that the radial distance of the inner face of the torus from the nucleus (r_{inner}) will increase with the radio power as the quasar becomes more luminous ($r_{inner} \propto L_{bol}^{0.5}$). This in turn will increase the opening angle of the torus and lead to relatively more broad line objects being detected at high radio powers. However, despite the plausibility of this receding torus argument (Hill, Goodrich & de Poy , 1996; Simpson , 1998), it is important to be aware of other explanations for the change in the broad line fraction with radio power.

- **The difficulty of detecting broad line AGN in low radio power objects.** Assuming that the optical emission lines are produced by AGN photoionization of the ISM, and the properties of the ISM (e.g. covering factor) do not vary much from source to source, then the emission lines should provide a good indication of the intrinsic luminosities of the quasar nuclei. In this case, even if relatively unobscured, the quasar nuclei of WLRG (all

FRI radio sources and some FRII radio sources) will be intrinsically faint, and the broad permitted lines that are characteristic of quasars at optical wavelengths difficult to detect against the strong stellar continua of the host elliptical galaxies. To date, broad permitted lines have not been convincingly detected in any genuine WLRG [4], although they have been detected in some relatively low (intrinsic) radio power objects in which the radio jets appear to be pointing close to the line of sight, including BL Lac, NGC1275 and 3C120. Currently we lack high S/N spectra for a substantial sample of FRI radio galaxies that have sufficient spatial resolution to isolate the unresolved cores detected at optical wavelengths (Chiaberge, Capetti & Celotti , 1999) from stellar haloes of the host galaxies. Such observations would be required to definitively detect any quasar-like nuclei in such objects.

- **Mixing up classes of objects that have intrinsically different AGN.** As discussed in Section 2.1 it is possible that the WLRG represent a distinct class of radio galaxies in which the AGN are capable of producing powerful relativistic radio jets without any associated quasar broad permitted lines and short wavelength continuum emission. This would imply two populations of extragalactic radio sources with fundamentally different AGN properties. If one population (represented by the WLRG) dominates at low radio powers/redshifts, and the other (represented by NLRG/BLRG/RLQ) dominates at high powers/redshifts, then this could potentially explain the observed increase in fraction of broad line objects with radio power/redshift.

Of particular relevance in this context, Grimes, Rawlings & Willott (2004) have made a comprehensive statistical analysis of the quasar fraction in a large sample of extragalactic radio sources drawn from the 3C, 6C an 7C surveys. Their study takes full account of the correlations between emission line luminosity and radio power, the scatter in the correlations, and the cosmic evolution of the radio sources. They find that, while receding torus models for single or dual radio source populations provide good fits to the data, they cannot rule out dual population models in which the properties of the torus are fixed (i.e. the torus does not recede).

It is also notable that the evidence for a varying broad line fraction with AGN power is not confined to radio-loud AGN. Using [OIII] luminosity at a proxy for AGN power, a recent analysis by Simpson (2005) of AGN selected from the SDSS survey provides evidence that the effect is also present in samples of radio-quiet AGN. However, Simpson (2005) finds that the amplitude of the effect in both radio-loud and radio-quiet samples is smaller than predicted by the simplest receding torus models in which the thickness of the torus remains

[4] A possible exception is the detection of a weak broad line component in the FRI radio galaxy 3C386 (Simpson et al. , 1996), although this results requires confirmation with higher S/N data and accurate subtraction of the underlying stellar continuum.

fixed; in order to explain the relatively mild increase in broad line fraction with [OIII] luminosity the torus is required to become thicker as it recedes from the AGN.

3.2 The extent and evolution of the circum-nuclear ISM

It is often assumed that the obscuration in the circum-nuclear regions of AGN is caused solely by gas and dust in compact ($r < 100$pc) torus-like structures, and that the distribution of ISM remains fixed over the lifetime of an AGN. Indications that both of these simple assumptions are not valid include the following.

- **Dust lanes.** For a significant fraction of powerful radio galaxies in the local Universe, high resolution HST observations reveal a more extended distribution of obscuring ISM in the form kpc-scale dust lanes (de Koff et al. , 2000).
- **Hollowed-out cones in Cygnus A.** There is clear evidence from the edge-brightening of the quasar illumination cones in Cygnus A that AGN-induced outflows have hollowed out cavities in the kpc-scale dust lane of that object (Tadhunter et al. , 1999).
- **Quasar absorption line studies.** Observations by Baker et al. (2002) reveal a higher incidence of UV resonance line absorption in compact (young), compared with extended (evolved), SSRLQ at $0.7 < z < 3$, suggesting that the distribution of absorbing ISM evolves as the radio sources expand through the haloes of the host galaxies.
- **Evidence for outflows in nearby AGN.** Spectroscopic observations of absorption lines in nearby broad-line AGN (e.g. Crenshaw, Kraemer & George , 2003), and emission lines of all classes of AGN (e.g. Heckman , 1980), show direct kinematic evidence for outflows on the kpc-scle of the NLR in the form of blueshifted features.

Overall, there is now substantial evidence that the distribution of obscuring ISM in AGN is more extensive than the compact torus structures required by the unified schemes, and also evolves over the lifetime of the AGN activity. Indeed, evolution of the circum-nuclear ISM is predicted by recent models of galaxy evolution that invoke the feedback effect associated with powerful AGN-induced outflows to explain the tight correlations between black hole mass and host galaxy properties (e.g. Fabian , 1999; di Matteo, Springel & Hartquist , 2005), as well as the shape of the galaxy luminosity function at high luminosities (Benson et al. , 2003).

A particularly interesting object, which highlights the importance of obscuration by material outside the putative torus structure as well as the evolution

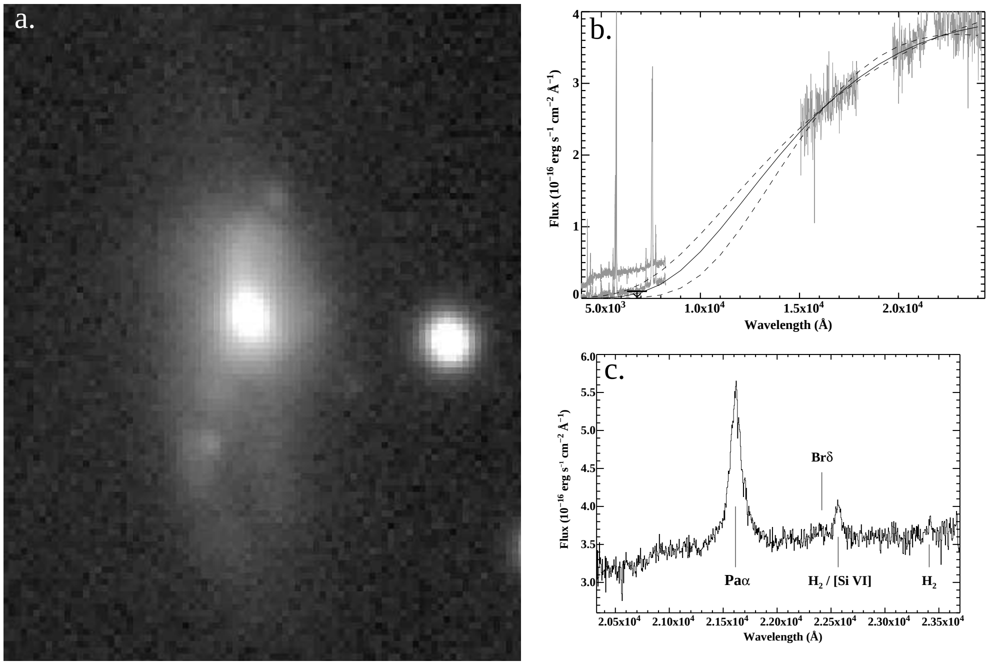

Fig. 9. Images and spectra of the proto-quasar PKS1549-79 (Tadhunter et al. , 2001; Bellamy et al. , 2003; Holt et al. , 2007). (a) R-band emission line-free image of the galaxy showing the spectacular tidal tail structures. (b) Optical to infrared spectral energy distribtion (SED) with various continuum models overlaid, illustrating the dramatic decline in the SED from near-infrared to optical wavelengths. (c) K-band spectrum showing the detection of a broad Paα emission line.

of the ISM, is the southern compact radio source PKS1549-79 ($z = 0.152$). At radio wavelengths this object shows all the characteristics of an object that has its radio jet pointing close to the line of sight, including a flat radio spectrum, one-sided radio jet pointing away from the dominant flat spectrum radio core, and evidence for variability at high radio frequencies (Tadhunter et al. , 2001; Holt et al. , 2007). On the basis of the simplest unified schemes one would expect this object to appear as a quasar or blazar-like object, with a strong non-stellar continuum and broad permitted lines at optical wavelengths. However, despite showing luminous high ionization optical emission lines that are characteristic of powerful AGN, the blue continuum of PKS1549-79 is dominated by starlight and no broad component to Hβ is detected (Tadhunter et al. , 2001). In addition, radio HI 21cm observations detect substantial HI absorption along the line of sight to the compact radio source(Morganti, Oosterloo & Tadhunter , 2001; Holt et al. , 2007). Again, the latter feature is inconsistent with the simplest unified schemes in which all the circum-nuclear obscuration is due to a compact torus.

It is only at near-IR wavelengths that the true character of the AGN in PKS1549-79 is revealed, with the detection of a broad quasar-like Paα line and a strong non-stellar continuum (Bellamy et al. , 2003; Holt et al. , 2007). Figure 9 shows the dramatic decline in the non-stellar continuum of this object between near-IR and optical wavelengths, consistent with a V-band extinction $A_v > 6.4$ magnitudes. Adding the evidence for large-scale tidal tails in optical images, substantial star formation, a large Eddington ratio, and emission line outflows, it is likely that the quasar in PKS1549-79 has been triggered relatively recently in a major galaxy merger, and we are witnessing the main growth phase of the super-massive black hole. However, the quasar-induced outflows (jets and/or winds) have not yet had sufficient time to remove the natal cocoon of obscuring dust and gas from the circum-nuclear regions of the host galaxy.

The case of PKS1549-79 illustrates in dramatic fashion that AGN are intimately linked to galaxy evolution via major galaxy mergers that trigger the activity, and AGN-powered outflows that drive the gas from the nuclear regions of the host galaxies. The detailed study of other such "misfit" objects holds much promise for our attempts to understand the co-evolution of supermassive black holes and their host galaxy bulges.

4 Conclusions

The orientation-based unified schemes are highly successful at explaining some aspects of AGN classification, in particular, the relationship between broad and narrow line AGN. Over the last 20 years they have withstood most major statistical tests. However, it is clear that they represent a generalisation, an attempt to simplify, perhaps over-simplify, a complex situation. There is much that they cannot explain (e.g. the relationship between radio-loud and radio-quiet AGN). Their main use lies in the fact that they allow us to eliminate certain variables in our quest to understand the fundamental physics, triggering and evolution of AGN. At the same time, the development of the unified schemes has yielded key information about distribution and evolution of the ISM in circum-nuclear regions. As a result, we are beginning to understand AGN as dynamic, evolving systems that have a major impact on their surroundings.

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