The relative frequency of broad-lined and narrow-lined active galactic nuclei: implications for unified schemes

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SUMMARY

I discuss evidence concerning the relative occurrence of narrow-lined and broad-lined active galactic nuclei (AGN), in optical, IR, X-ray, and radio-selected samples. Both narrow-lined AGN and reddened broad-lined AGN occur more frequently at lower source powers. There is marginal evidence that narrow-lined AGN were more common in the past. Narrow-lined objects have weaker [O III] at a given radio power. These data are inconsistent with the simplest ‘unified scheme’ where a similar thick molecular torus surrounds all AGN, and with the simplest modification, that the torus geometrical thickness is a function of source power. A substantial range of geometrical thicknesses must exist at all powers. Both the typical geometrical thickness and the typical optical thickness of obscuring material probably vary with source power. This may arise naturally in accretion models, as smaller black holes are more easily smothered. I speculate that the obscuring material, rather than being an orbiting torus of cool molecular matter, may be an expelled shell of gas, only the outer parts of which are dusty.

1 INTRODUCTION

There is evidence that some Seyfert nuclei contain axisymmetric obscuring structures, e.g. (Antonucci & Miller 1985; Miller & Goodrich 1990; Antonucci 1983; Tadhunter & Tsvetanov 1989; Pogge 1989; Haniff, Wilson & Ward 1988; Haniff, Ward & Wilson 1991), possibly representing a geometrically and optically thick ‘molecular torus’ (Krolik & Begelman 1986, 1988). At least some type-2 Seyferts are actually type-1 Seyferts, hidden behind such an obscuring structure (Antonucci & Miller 1985; Elvis & Lawrence 1988; Koyama et al. 1989). Similar arguments have been made to relate radio-loud quasars to radio-galaxies (Scheuer 1987; Barthel 1989). Such ideas lead to a simple ‘unified scheme’ in which all AGN possess similar molecular tori, and differ only in orientation, an idea implicit in many studies, and explicitly argued in some (Osterbrock & Shaw 1988; Krolik 1989; Barthel 1989). The term ‘unified scheme’ has also been used by Orr & Browne (1982) for the idea that core-dominated radio-loud quasars differ from lobe-dominated radio-loud quasars in the viewing angle to a relativistic jet. The two schemes are at least grossly consistent with each other in that, for example, no narrow-line objects have known to show super-luminal motion; so perhaps a large variety of AGN properties depend only, or primarily, on inclination, a hypothesis we might perhaps call the ‘Unified Unified Scheme’ (or UUS).

This paper critically examines the hypothesis that narrow- and broad-lined AGN differ only in orientation. I concentrate on the simplest diagnostic, the fraction of narrow-lined (type 2) objects f_n, found in complete samples. (In the simplest unified scheme, f_n = \cos \theta_c, where \theta_c is the half opening cone angle of the torus.) Several lines of evidence show that the simplest unified scheme cannot hold. I consider further evidence on whether simple modifications may suffice, such as \theta_c varying with luminosity, and optical thickness varying with luminosity.

2 OPTICAL AND INFRARED SAMPLES

Selection on parent galaxy magnitude should in principle give true relative densities. Table 1 shows collected statistics on AGN occurrence in galaxy samples with complete spectroscopic information. Unfortunately, even for weak Seyferts in nearby galaxies, the nuclear contribution to total magnitude is important, and larger for type 1 nuclei, which are therefore discoverable over larger volumes. Osterbrock & Shaw (1988) attempt to correct for this bias by arguing that the observed optical luminosity functions (total magnitudes, galaxy plus nucleus) of types 1 and 2 AGN are similar but with the peak shifted by \Delta M_{B} \sim 0.8, so that this reflects the typical difference in nuclear magnitude contribution. Salzer (1989) makes a similar correction. Following these authors, I apply a simple volume correction of a factor 2.82...
to the type-1 Seyfert counts for samples 1 and 2 in Table 1. This is clearly unsatisfactory but, ignoring the problem for now, type-2 nuclei seem to be ~ four times as common as type-1 nuclei, suggesting very thick tori, with θc ~ 35°.

Long-wavelength IR selection is to first order the same as selection on parent galaxy magnitude, as all spirals radiate copiously in the far-IR. Sample 5 in Table 1 therefore gives similar results to the optical samples. Samples 6 and 7, however, consist only of ultraluminous objects, presumably with negligible normal galaxy contribution. The results from these samples suggest that type-2 objects outnumber type-1 objects even more heavily. On the other hand, selection at 12 μm (Sample 8) and selection by warm colours (Samples 9 and 10) turn up type-1 and -2 AGN in even more numbers. This is not necessarily a problem for the unified scheme, since a molecular torus as thick as the one suggested by Krolik & Begelman (1986) will be optically thick even at 12 μm, so that edge-on objects are biased against.

A serious conceptual problem is whether LINERs (Low- ionization Nuclear Emission-line Regions) should be included as genuine AGN. For example, Spinoglio & Malkan (1989, reference 8) report 26 type-1 Seyferts, 32 type-2 Seyferts, and 26 LINERs. Inclusion of the latter as narrow-lined AGN would then increase fn to 0.69 ± 0.05. Another basic problem in the accounting is that long exposures seem to show faint Seyfert nuclei in a substantial minority of galaxies (Fillipenko & Sargent 1988). Within a magnitude-limited sample, one may hope to locate and classify all AGN down to some minimum intrinsic underlying power, but then an unshadowed nuclear quantity is required to make such a cut.

3 HARD X-RAY SAMPLES

Hard X-ray selection should be neutral with respect to obscuration differences for gas columns NHI up to ~ 10[^{24}] cm^{-2}. (Equivalent hydrogen columns are based on the assumptions that abundances are roughly solar, and that heavy elements are not highly ionized.) Hard X-ray sky surveys saw none of the classical nearby optically selected type-2 Seyferts, but did see one famous narrow-lined radio galaxy (Cen A). If NGC 1068 is typical, type-2 Seyferts are lacking because the molecular torus is so thick [NHI > 10[^{25}] cm^{-2}] that even hard X-rays are absorbed, and we see only the scattered fraction when looking through it (Elvis & Lawrence 1988). Presumably, deeper surveys would start to pick up such a scattered population.

However, approximately one-third of X-ray selected AGN are so-called ‘Narrow Line X-ray Galaxies’ (NLXGs), which were at first thought to be type-2 Seyferts, but in fact typically show weak broad emission at Hz and so are directly viewed but heavily reddened type-1 Seyferts (see Lawrence & Elvis 1982 and references therein). This is supported by the fact that an absorbed X-ray spectrum is seen in NLXGs, with columns in the range NHI = 10[^{22}]-10[^{23}] cm^{-2} (Mushotzky 1982; Turner & Pounds 1989). Recently several previously stubborn objects have had broad emission revealed in the Paschen lines (Blanco, Ward & Wright 1990); some still remain with no clearly proven Broad Line Region (BLR) (e.g. NGC 7582 and Cen A), but, because they are seen to have highly absorbed X-ray spectra, these objects also are assumed to be directly viewed but obscured type-1 nuclei. Two more ‘classical’ type-2 Seyferts have now been observed by the GINGA satellite. Unlike NGC 1068, they have absorbed spectra, but their columns are between that assumed for NGC 1068 and those of the NLXGs which turned up in the hard X-ray surveys (Mkn348, NHI = 10[^{21}] cm^{-2}, Warwick et al. 1989; Mkn3, NHI = 10[^{23}] cm^{-2}, Awaki et al. 1990). There seems then to be a large range in the optical thickness of material that covers AGN. The NLXGs occur preferentially at low X-ray luminosity, as does X-ray absorption, whether an object has been classified as NLXG or not (Lawrence & Elvis 1982; Mushotzky 1982; Turner & Pounds 1989). This cannot result simply from seeing a single population at various angles; the probability of being obscured varies with source power.

Two other things about X-ray absorbing material should be borne in mind. First, some AGN are known to have dust optical depths (measured by the strength of the 10 μm silicate feature) that are much smaller than expected given the X-ray column, if the absorption occurs in cool material similar to the interstellar medium (Aitken & Roche 1985). The absorbing material in these cases is then probably largely dust-free. However, the reddening and the X-ray column are correlated — very few objects are known to have an absorbing column but no apparent emission-line reddening (NGC 4151 is the prominent exception). Finally, in some AGN the column is known to vary on a time-scale of months.

<table>
<thead>
<tr>
<th>Table 1. Statistics of AGN type in optical and IR spectroscopic surveys.</th>
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<tr>
<td>PARENT SAMPLE</td>
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<tr>
<td>----------------</td>
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<tr>
<td>Sy 1</td>
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<tr>
<td>RSA subset</td>
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<tr>
<td>(B_{lim} = 12.9)</td>
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<tr>
<td>CFA redshift survey</td>
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<tr>
<td>(B_{lim} = 14.5)</td>
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<tr>
<td>Wasilewski survey</td>
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<tr>
<td>(B_{lim} = 15.7)</td>
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<tr>
<td>UM survey</td>
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<tr>
<td>Complete 60-μm sample</td>
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<tr>
<td>IRAS gals, L_{IR}&gt;10^{12} L_{sun}</td>
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<td>(Sanders et al. 1988)</td>
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<td>(Leech et al. 1989)</td>
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<tr>
<td>Total</td>
</tr>
<tr>
<td>Complete 12-μm sample</td>
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<tr>
<td>Warm IRAS gals</td>
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<tr>
<td>(De Grijp et al. 1987)</td>
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<tr>
<td>(Low et al. 1988)</td>
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<tr>
<td>Total</td>
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Notes: Errors on fn are 68% per cent confidence, based on the formula of Gehrels (1986) for fractions chosen from Poisson distributed quantities. Corrections to fn: (a) volume surveyed for Sy 1 corrected by factor 2.82 (see text); (b) correction as in the reference quoted.

4 THE 3CR SAMPLE

The safest AGN discovery method is low-frequency radio selection, sensitive to large-scale radio lobes, which are presumably both unshaded and unbeamed. A further advantage is that almost all objects are already certainly AGN of some kind. The detailed spectrum (e.g. Seyfert 2 or LINER) is then irrelevant - all we want to know is whether a BLR is present. The properties of radio-loud and radio-quiet AGN differ only in details, so it seems likely that we are on safe ground in generalizing, but we may want to be careful in making quantitative statements. A further possible worry is that radio emission is energetically a marginal aspect of the AGN phenomenon, and current radio power will depend in a complicated way on history and environment as well as intrinsic nuclear power. Nevertheless, it seems that, after all, the radio powers of quasars do correlate with their optical powers, though with a separate normalization for radio-loud and radio-quiet objects (see fig. 4 of Miller, Peacock & Mead 1990). I have also checked that optical and low-frequency radio luminosities correlate for the 3CR quasars I use below. (The narrow-line objects show no such correlation of course, as we are looking only at the parent galaxy.)

A completely identified sample is desirable. (The imposition of an optical magnitude limit produces a bias in favour of type 1 nuclei, very strongly so at high redshifts/ luminosities.) The only sample that comes close is the 3CR sample. Other, deeper, low frequency samples, such as that of Eales (1985) or Allington-Smith et al. (1982, 1988) either are not sufficiently completely identified, or have insufficient spectroscopic information for nuclear type classification. The most recent identification summary of the 3CR itself is by Spinrad et al. (1985); here I prefer to use the 3CR-based statistically complete area and flux-limited sample by Laing, Riley & Longair (1983; LRL), of 173 sources with S(178 MHz) > 10 Jy. Additional identifications and redshifts have been taken from Perryman et al. (1984); Riley, Eales & Baldwin (1984); Ellis & Purvis (1985); McCarthy et al. (1987); Le Fevre & Hammer (1988); Djorgovski et al. (1988); and Laing (private communication). Laing & Riley (in preparation) will soon publish an updated summary. Only one source remains unidentified (4C13.66) and one has only a photometric redshift (4C74.16).

Previous analyses of the LRL sample (e.g. that of LRL themselves) have grouped objects as 'quasars' or 'galaxies' but of course many of those 'galaxies' are spectroscopically identical with quasars, i.e. are broad-lined radio galaxies. In what follows below therefore I have re-classified objects, based on a literature search, according to whether or not broad lines have been seen, regardless of redshift or optical structure. I have excluded from analysis the sources 3C231 (M82) and 3C272.1 (M84), as they have luminosities orders of magnitude lower than the rest, and may have radio emission dominated by a starburst rather than by an active nucleus.

Fig. 1(a) shows the distributions of broad- and narrow-lined objects with radio luminosity. Fig. 1(b) shows deduced values of $f_{v_r}$. The sample as a whole has $f_{v_r} = 0.71 \pm 0.04$, similar to optical and IR samples, but the value is a function of luminosity. At the lowest luminosities, most objects are narrow-lined; at the highest luminosities, only half. At the lowest luminosities ($L_{178} < 10^{25}$ W Hz$^{-1}$), the assumed obscuring tori must be very thick, $\theta < 0.28$ at 84 per cent confidence. Unlike the other well-known luminosity effect, the transition from FRI to FRII structure, this seems to be a gradual, rather than an abrupt, change. (The effect remains if FRII sources alone are considered.)

Before concluding that $f_{v_r}$ varies with source power, we must ask whether there may be luminosity-dependent selection effects that influence spectroscopic classification. First, weak emission lines may be hard to see against parent-galaxy starlight for low-power sources, so that classification is altogether difficult. This may be a serious worry for objects in the first bin of Fig. 1(b), where several objects are apparently optically dull, but, above this bin, almost all objects have well-detected emission lines. There are two problems which may cause selection effects with redshift, and thus indirectly

Figure 2. Dependence of properties of 3CR radio sources on luminosity at 178 MHz, calculated assuming $H_0 = 50$, $\Omega = 1$, and $K$-corrected assuming a spectral index of 0.7. (a) Lower panel, number distribution of broad- and narrow-lined objects in sample. (b) Middle panel, fraction of objects within a given luminosity range that are narrow-lined. Error bars are 68 per cent confidence limits except for the first point (triangle, an upper limit), which being one-sided, covers 84 per cent confidence. Limits are calculated using the formulae of Gehrels (1986) for fractions chosen from Poisson-distributed quantities. (c) Upper panel, values of $V/V_{max}$ versus luminosity for broad- and narrow-lined objects. The 1 o error on the mean value in each bin was estimated using the internal variance of individual values within the bin, and is close to the theoretically expected error in all cases.

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Although this is only marginal evidence for differential evolution of broad- and narrow-lined objects, it is strong evidence against the kind of differential evolution required in the opposite direction to explain away the dependence of $f_n$ on radio power. In the first two bins of Fig. 1(b), there are 34 narrow-line objects and 3 broad-lined objects. In the last two bins, there are 36 narrow-lined objects and 33 broad-lined objects, at a mean redshift of ~1. The ratio of narrow to broad objects therefore changes by a factor 10.4, and at 95 per cent confidence by more than a factor 5.85. This would require differential evolution with $r < -2.55$, compared to the observed value of $4.1 \pm 2.44$, and so can be excluded at better than 99 per cent confidence.

To summarize, there is very strong evidence that narrow-line objects are rarer at high luminosities, and marginal evidence that they were more common in the past. The luminosity dependence of $f_n$ cannot result from a single population viewed from various angles, but could still be consistent with simple modifications of the unified scheme. The smallest modification would be that objects of the same luminosity have the same cone-angle, but that this cone-angle, changes slowly with luminosity. On the other hand, it may well be that a range of cone-angles exists at all luminosities, with of course the thick tori producing most of the narrow-line objects. Some kind of mean cone-angle may then change with luminosity, with geometrically thick tori predominating at low powers, and geometrically thin tori at high powers. Finally, it may be that not all objects have tori (or not all have optically thin tori), so that what changes with luminosity is the probability of having an optically thick torus.

If cone-angle varies simply with luminosity, we might expect that low-power objects are systematically stronger far-IR sources than high-power objects. If, on the other hand, a large range of cone-angles exists at all powers, we might expect narrow-lined objects to be stronger far-IR sources, at all radio powers. Fig. 2 shows the correlation between 60 µm and radio luminosity for LRL sources, including upper limits, but excluding a handful of core-dominated sources, for which the IR emission is almost certainly non-thermal. The broad-lined objects follow a reasonably tight correlation whose slope is not significantly different from unity. Narrow-lined objects show a large scatter, and have unfortunately only been detected so far at low powers. The majority of detections are above the line defined by broad-line objects, but in the same range of luminosity, a majority of upper limits fall below the line. No strong conclusion can be made overall, as most of the 3CR sources were not even pointed at, let alone detected, so it is not clear what selection effects remain.

A better hope is to examine narrow-line power. Jackson & Browne (1990) have argued that radio-loud AGN show the same effect as that claimed by Lawrence (1987) for type 1 and 2 Seyferts – namely that, for the same radio power, narrow-line objects are weaker in [O iii] emission – and have used this to argue against narrow- and broad-line objects being drawn from the same population. However, their analysis was based on a subjectively selected sample, and the narrow- and broad-lined objects were not even drawn from the same radio sample, although they were roughly matched pair-wise in radio power; a similar analysis with an objective sample is desirable. Rawlings et al. (1990) have defined a radio-complete sample of 39 LRL FRII radio-galaxies with

<table>
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<th>SAMPLE</th>
<th>N</th>
<th>p</th>
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<tr>
<td>All sources</td>
<td>172</td>
<td>7.0 +/- 1.4</td>
</tr>
<tr>
<td>Narrow-lined only</td>
<td>122</td>
<td>8.8 +/- 2.0</td>
</tr>
<tr>
<td>Broad-lined only</td>
<td>50</td>
<td>4.7 +/- 1.4</td>
</tr>
<tr>
<td>L_{178} &lt; 10^{27}</td>
<td>37</td>
<td>&lt;0.9 (84% confidence)</td>
</tr>
<tr>
<td>10^{27} &lt; L_{178} &lt; 10^{28}</td>
<td>37</td>
<td>9.8 +/- 4.4</td>
</tr>
<tr>
<td>L_{178} &gt; 10^{28}</td>
<td>98</td>
<td>7.1 +/- 1.2</td>
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RA > 1 hr and z < 0.5, for which they collect \([\text{O} \, \text{m}]\) measurements from their own work and from the literature. However, for our purposes this sample will not do as it stands, as it is a sample of ‘galaxies’ and contains a mixture of broad-lined and narrow-lined objects, which Rawlings et al. do not distinguish between. To make this a complete sample of radio sources, I added the four quasars which satisfy the same criteria (3C47, 3C215, 3C249.1, and 3C351); \([\text{O} \, \text{m}]\) measurements were taken from Yec (1980) and Blumenthal, Keel & Miller (1982). Fig. 3 shows the correlation between \([\text{O} \, \text{m}]\) power and radio power, and confirms the effect claimed by Lawrence (1987) and Jackson & Browne (1990), that, at a given radio power, narrow-line objects have weaker \([\text{O} \, \text{m}]\) emission. More accurately, it seems that the broad-line objects occupy the upper end of a large spread. These results strongly suggest that a large range of cone-angles exists at all powers, so that the simplest modification of the unified scheme is not sufficient. However, as the scatter in the correlation is so large, it does not tell us whether the mean cone-angle is changing with luminosity. Furthermore, \([\text{O} \, \text{m}]\) power is not likely to depend only on nuclear power and cone-angle – there may for example be sensitive dependencies on history and environment – so we must be careful in interpreting this diagram.

Another argument is as follows. If cone-angle increases with luminosity, then the greatest projection effects should occur at the lowest luminosities. Kapahi (1990) considers apparent linear sizes of the radio sources for galaxies and quasars in three redshift ranges. In the upper two ranges, galaxies are larger than quasars, confirming Barthel’s (1989) result. In the lower redshift range however, galaxies are if anything smaller than quasars. (The numbers are also consistent with similar sizes for the two groups.) It is unlikely then that these low-redshift broad-lined objects are all seen through a narrow cone. It is more likely that they have no torus, or a much thinner torus, than the narrow-lined objects.

5 DISCUSSION

It is not my intention here to develop theoretical models, but it is worth making some brief points on how luminosity-dependent effects might arise. First, an average cone-angle dependence may arise if there is a thick dusty disc in AGN whose height, to first order, does not depend on luminosity. The inner edge of the disc will be set by the radius at which dust evaporates, and so does depend on luminosity. Assuming a dust evaporation temperature of 1000 K, the radius where this is the blackbody equilibrium temperature is \(R = 0.38L_{45}^{1/2}\) pc, where \(L_{45}\) is the (UV, soft X-ray) heating luminosity in erg s\(^{-1}\). If the height of the disc is \(h\) pc, then the effective cone-angle is given by \(\cos \theta = (h/R)/(1 + h/R)\). At low powers this stays near 1.0, then changes quickly near \(h/R = 1\). For example with \(h = 1\) pc, at \(L_{45} = 1\), \(f_\theta = 0.93\), by \(L_{45} = 10\), \(f_\theta = 0.64\), and for \(L_{45} = 100\), \(f_\theta = 0.25\).

A general dependence of obscuration on source power could be a natural consequence of accretion models. Steady accretion is limited at the Eddington rate, proportional to black hole mass, but many possible methods for external supply of material (e.g. stellar mass loss through the galaxy, encounters with other galaxies) do not depend on the central black hole mass. While at times, the black hole must be unsupplied and dormant, at others, it must be smothered; furthermore small black holes are easier to smother. The nuclear absorbing material may represent a reservoir of matter that has reached the nuclear regions but cannot yet be accreted. Krolik & Begelman (1988) suggest that matter evaporated from the inner edge of their postulated torus supplies material for accretion, but find it difficult to explain (a) why some evaporated material accretes rather than leaving in an outflowing wind, and (b) how a cool rotating molecular torus remains geometrically thick. However, as we have seen, much material is free of dust, close to the nucleus, and changing rapidly. Perhaps then the axisymmetric, geometrically thick, obscuring region that we can infer from observations is not formed from inward-moving material, but from excess material that is being expelled. Outward moving
material may more easily form geometrically thick structures, and a variety of thicknesses and physical states, depending on recent history. As the outer parts cool, dust may form, as with a nova shell, or the expelled gas may sweep up a shell of ambient material, as in a supernova remnant. To first order, this may result in a spherical shell of dust, possibly broken at the poles if ejection is more energetic in these directions.

6 CONCLUSIONS

Optical and IR samples tell us that narrow-lined AGN outnumber broad-lined AGN by a factor of several. Selection by low-frequency radio power reveals that the fraction of narrow-lined AGN is a decreasing function of source power, and was possibly larger in the past. Narrow-line objects have weaker NLRs for a given radio power. Both hard X-ray and radio selection reveal a population of objects that have broad lines but are heavily reddened; these also occur more often at low source-powers. Genuine narrow-lined objects have larger X-ray absorbing columns than the reddened broad-line objects. Much absorbing material in AGN is very close to the nucleus and free of dust.

These facts are inconsistent with the simplest unified scheme, involving only the orientation of a thick molecular torus; at the least, it must be that such tori show a large range in geometrical thicknesses, but it also seems that the optical depth of such tori, and/or the probability of such a structure existing at all, varies with source power. In accretion models, we naturally expect that small black holes will produce low-power sources, and will be more likely to be smothered. Geometrically thick axisymmetric obscuring regions may represent expelled shells of material, rather than orbiting tori.

ACKNOWLEDGMENTS

Martin Elvis pointed out to me (amongst general advice and ideas) that a variation of cone angle with luminosity could result if a thick disc is of fixed height, but has an inner radius that scales with source power. I also thank Meg Urry, as this work was inspired by a workshop on AGN unification organized by her.

REFERENCES

A. Lawrence