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Ubiquitous Disks in AGN

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Abstract.
Disk-like structures have been inferred to exist in the nuclei of galaxies over the entire range in nuclear activity. These form the essence of the Unified Scheme, which has had great success in accounting for AGN of a wide variety of perceived types. Recent progress along this front is summarized, including new polarimetric results, high-angular resolution optical imaging, and interferometry at radio wavelengths.

1. Introduction

"There are certain queer times and occasions in this strange mixed affair we call life when a man takes this whole Universe for a vast practical joke...and more than suspects that the joke is at nobody's expense but his own."
- H. Melville, "Moby Dick"

The Universe of 1851 knew nothing of quasars and accretion disks, yet truer words could not have been spoken had Ishmael been a modern astrophysicist. Prior to the early 1980's, much of the work on active galactic nuclei (AGN) concentrated on distinct *classes* of object. These categories were largely extrinsic in nature, with classification hinging, e.g., on whether or not an object was resolved in optical images; on the presence or absence of broad emission lines; on the existence of powerful, steep-spectrum radio lobes; or of a flat-spectrum compact radio nucleus. While most scientists considered the possibility of relationships between various classes, evidence that the "joke" was up – that the distinctions were more perception than substance – came from a most unlikely corner: the somewhat arcane field of polarimetry. The discovery by Miller & Antonucci (1983) of broad permitted lines and a featureless continuum in the polarized spectrum of the prototypical Type 2 (narrow-line) Seyfert NGC 1068 established 3 remarkable facts:

- NGC 1068 contains a broad-line region (BLR) which is *obscured* from direct view,
- the nucleus is surrounded by an asymmetric distribution of scattering particles, and most importantly,
- NGC 1068 would appear as a Type 1 object (broad+narrow lines) if it were seen from a different perspective. Hence the "unification" of objects of Type 1 and 2.

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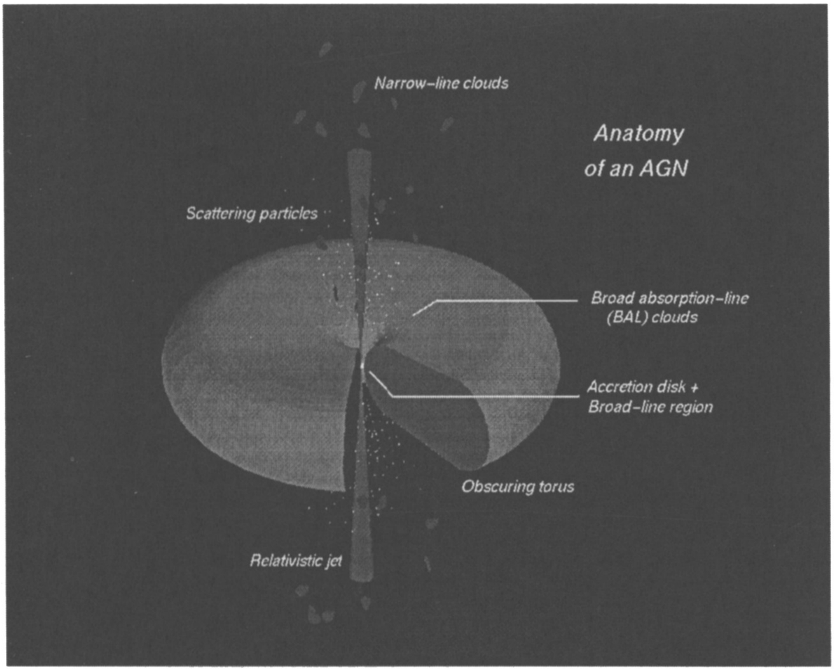

Figure 1. The generic model. Type 2 objects result from a viewpoint near the plane of a dusty torus, which hides the accretion disk and broad-line region from direct view. These are seen only in polarized light upon reflection off particles in the vicinity of the poles. Type 1 objects, with both narrow and broad emission lines, result from more polar perspectives. The presence of an extensive relativistic jet is one ingredient which distinguishes radio-loud from radio-quiet objects.

In the years following that discovery, obscuring/scattering structures have been inferred in other Seyferts, radio galaxies and quasars, and in galaxies whose primary output appears at infrared wavelengths. Just the recognition of that work would require more real estate than has been allotted to this review, moreover excellent summaries exist (e.g. Antonucci 1993). Some recent results are discussed by Hough, Young, and Corbett et al. elsewhere in this volume. This paper highlights some recent work which examines the resiliency of the "Unified Scheme" at extremes in the luminosity of the central engine. Satellite and interferometric instruments are now providing high-angular resolution information which directly tests the generic model and may one day shed light on the mechanism(s) which drive and collimate the relativistic outflows from some sources.

2. The Unified Model

Given the topic of this colloqium, it is perhaps not surprising that the unified model for AGN should closely resemble accretion structures believed to exist in young stellar objects. One rendition is shown in Figure 1. The components scale

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as follows: a $10^9 M_\odot$ black hole has a Schwarzschild radius roughly the size of our solar system. This is closely surrounded by an accretion disk and BLR with a diameter less than 1 pc. The obscuring torus is thought to have a half-opening angle of $30° - 60°$ as seen from the central source and extend out to $\sim$100 pc. Narrow-line regions (NLR) have been traced to kpc distances from the nuclei of some AGN, with the scattering region generally located closer in. Of course, in some radio-loud objects, the relativistic jet powers immense lobes with Mpc dimensions.

The NLR is visible to all outside observers, and in radio-loud sources often appears elongated along roughly the same direction as the emitting lobes. An observer lying within the opening angle of the torus will observe the classic broad + narrow-line spectrum of a QSO and catalog the object as a Type 1 source. If the vantage point is included within the narrow beaming cone of the relativistic jet, strongly polarized and variable Doppler-boosted synchrotron emission may dominate the observed continuum from X-ray to radio wavelengths. This results in an Optically Violent Variable Quasar or BL Lac object. On the other hand, a location near the toroidal plane will not see the BLR and accretion disk directly, and the object will receive a Type 2 designation. In this case, the true composition of the nucleus might only be revealed in scattered light, polarized by the reflection of broad-line emission and the featureless continuum off electrons and/or dust grains located above the plane. It is important to note that although a cartoon like Fig. 1 is a useful mental tool, the accretion "disk" and "torus" may not be distinct entities (Konigl & Kartje 1994).

3. A Color-Magnitude Diagram for AGN

Every student of astronomy appreciates the utility of the H-R diagram in understanding stellar structure and evolution. It can also be put to good use in portraying the range in properties of active galaxies. In Figure 2 is displayed a selection of representative objects in a color-magnitude format where the ordinate is an estimate of the nuclear luminosity in solar units and the abscissa is the observed IR to optical flux ratio (essentially $F(60\mu m)/F(0.5\mu m)$). Several characteristics are evident. First is the tremendous range in nuclear activity. Five orders of magnitude separate the lowest luminosity source shown, the LINER nucleus of the nearby spiral galaxy NGC 4258, and the most powerful QSOs and infrared galaxies. [The object at $>10^{14}\ L_\odot$ is the heavily obscured hyperluminous infrared galaxy (HLG) F10214+4724, a lensed source (Elston et al. 1994)]. Seyfert galaxies – like the aforementioned NGC 1068 near $L_{\rm nuc} \sim 10^{11}\ L_\odot$ – are intermediate objects. Second, the observational classes are not well-separated. Seyferts overlap the luminosity range of QSOs, and radio-loud (bold-face) and -quiet sources are well-mixed. Finally, since nuclear emission reprocessed by the dusty torus emerges isotropically in the infrared, the Unified Scheme predicts that the color axis will be related to the viewing angle to the torus, with more highly inclined objects appearing on the right-hand side of the diagram. Polarization would be expected to correlate with $L_{\rm IR}/L_{\rm opt}$ too. It is (Hines 1994).

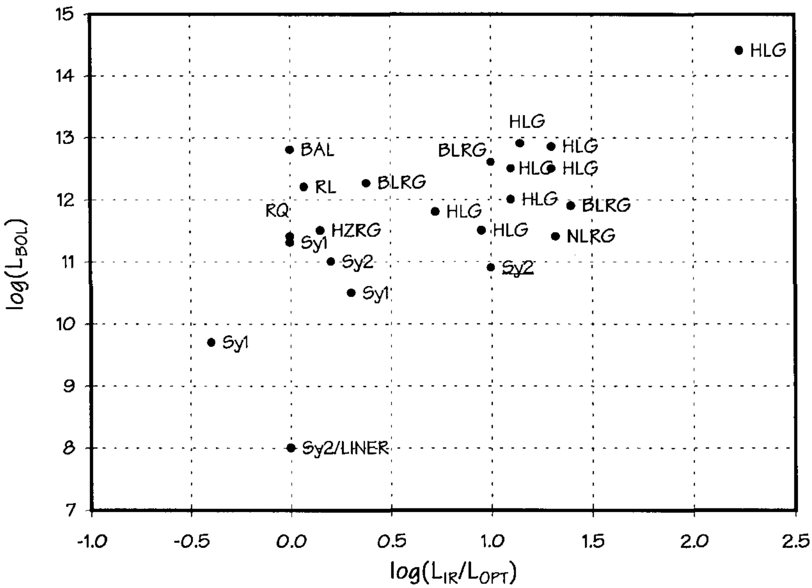

Figure 2. A crude color-magnitude diagram for a representative selection of objects, showing the wide range in activity level exhibited by AGN and the overlap among objects of various observational classes.

4. Hyperluminous Infrared Galaxies and the Lack of QSO 2's

One argument which has been lodged against the general applicability of the Unified Scheme is the lack of narrow-line (Type 2) objects of quasar luminosity among traditional lists of AGN. From the above comments, such sources would be expected to be powerful in the infrared but comparatively faint at shorter wavelengths. A sample of sources which fit this bill was identified in the *IRAS* dataset by Low et al. (1988) and studied in detail by Hines (1994). These hyperluminous infrared galaxies (HLGs) tend to have narrow emission lines and are often strongly polarized. Moreover, in several cases, broad emission lines can be discerned in polarized light or at near-IR wavelengths. A case in point is the object F15307+3252, discussed by Hines et al. (1995). Though the visual magnitude is only 19.8, the total nuclear luminosity of this $z = 0.926$ source is a whopping 10^{13} $L_\odot$, placing it among the most luminous galaxies in the known universe. The optical flux spectrum (Figure 3) is dominated by Seyfert 2-like permitted and forbidden lines of width $\Delta v < 2000$ km s^{-1}, however in polarized flux a blue continuum and strong Mg II λ2798 feature with a FWHM of ~10,000 km s^{-1} are evident. The existence of a buried QSO nucleus seems clear.

The number of HLGs is small, but *IRAS* also sampled a very small region of space with adequate sensitivity. Sanders (1992 and references therein) estimates that the space density of galaxies in the local universe with $L_{\rm IR} > 10^{12}$ $L_\odot$ is comparable to that of nearby QSOs. Therefore, depending on the assumed torus opening angle, the IR-luminous galaxies could well represent the mis-directed

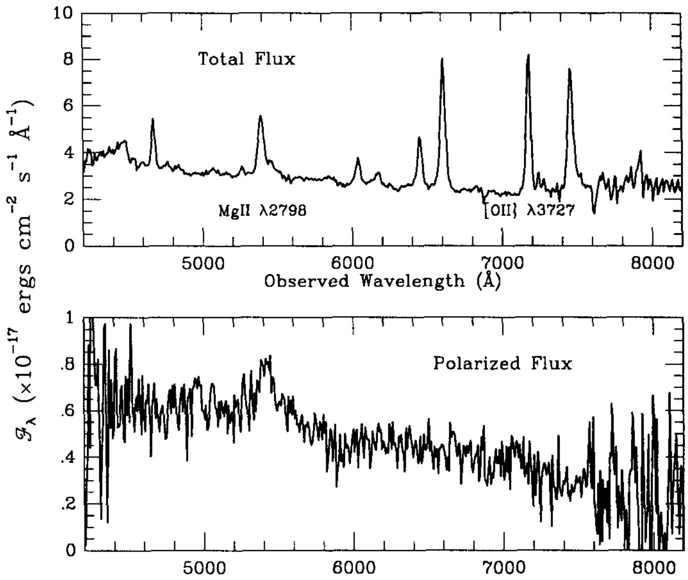

Figure 3. The polarized and total flux spectra of the Sy 2-like hyperluminous *IRAS* galaxy F15307+3252. Note the presence of broad Mg II emission in the polarized flux. Adapted from Hines et al. (1995).

QSOs which elude standard survey techniques because most of their flux appears in the infrared. If so, the space density of QSOs could be more than a factor of 2 higher than current estimates suggest.

5. Grazing Lines of Sight

If a Type 1 spectrum is observed from a line of sight which penetrates the donut-hole and a Type 2 spectrum occurs for an edge-on view what might an intermediate vantage point present? This question has been considered in regard to the Broad Absorption Line QSOs – objects which show strong absorption features extending tens of thousands of km s^{-1} to the blue of the principal resonance transitions. The BALQSOs are quite common, comprising as many as 10% of all radio-quiet QSOs. In general, they exhibit continuum and emission-line properties very similar to non-BALQSOs (Weymann et al. 1991) but the low-ionization absorbers tend to show a redder continuum such as might occur from transit through intervening dust (Sprayberry & Foltz 1992). These characteristics are consistent with a view of the nucleus which is only partially obscured by intervening material. The additional fact that they are much more likely to show significant static optical polarization ($P \gtrsim 2\%$; Hines, Schmidt, & Smith 1996) argues, in the context of the Unified Scheme, for a generally high inclination angle. The absorbing clouds might then represent material ablated off the underlying torus.

Spectropolarimetric studies have been presented for several BALQSOs in an effort to test this hypothesis. These include the prototype PHL5200 (Stockman, Angel, & Hier 1981; Goodrich & Miller 1995; Cohen et al. 1995), CSO 755 (Glenn, Schmidt, & Foltz 1994), the *IRAS* QSO 07598+6508 (Hines & Wills 1995), 0105−265 (Cohen et al.), and the lensed source H1413+117 (Goodrich & Miller). In all cases the polarization of the emission-line flux is weak or nonexistent, as expected for a perspective which provides some unobstructed lines of sight to the nucleus. Occasionally, the degree of polarization rises dramatically in the deep absorption troughs, implying less dilution and thus that the BAL clouds absorb a larger fraction of direct light than scattered light. Notably, all authors are led to a picture involving a disk-like geometry seen nearly edge-on.

6. Nearby AGN at High Angular Resolution

Spacecraft observations are now probing deep into the hearts of nearby AGN at high angular resolution. These are invariably weak sources in which starlight dilution can be very important. Nevertheless, *HST* has been effective at imaging structures which closely resemble the torus depicted in Fig. 1. Certainly the most impressive is the ~100 pc radius obscuring donut in the nucleus of the elliptical galaxy NGC 4261 (Jaffe et al. 1993), which has now yielded dynamical evidence for a central mass concentration of $5 \times 10^8\ M_\odot$ (Ferrarese, Ford, & Jaffe 1996). The axis of this donut is nearly coincident with the radio jets, leaving little doubt that the torus is related to the innermost workings of the nucleus. Additional examples of this type are presented by Ford elsewhere in this volume.

A powerful new tool being applied to the study of AGN is VLBI imaging and spectroscopy in the light of maser emission of the water molecule. In this conference, Maloney reviews the dozen or so known cases and, using the nearby spiral galaxy NGC 4258 as an example, highlights the remarkably detailed information which can be gleaned from these sources. NGC 4258 contains a string of masing knots, oriented essentially E-W on the sky in 3 clumps covering 3 distinct intervals of radial velocity. The clumps represent the tangential and radial locations in an edge-on rotating (accretion) disk where the pathlength through the molecular gas is sufficient to sustain the maser mechanism. Fitting the radial velocities and locations to Keplerian orbits, Miyoshi et al. (1995) find the most compelling evidence to date for a nuclear black hole – in this case a binding mass of $3.6 \times 10^7\ M_\odot$ inside a radius of 0.13 pc.

The nucleus in NGC 4258 is virtually dormant by comparison with classical AGN. In Figure 2 we have suggested a nuclear luminosity of only $\sim 10^8\ L_\odot$. Nevertheless, Wilkes et al. (1995) were able to isolate a compact core of (weakly) polarized flux. The electric vector of this emission is aligned precisely with the E-W axis of maser emission on the sky, such as would be produced by scattering off material above and below an edge-on obscuring torus. Neither bear any relation to the orientation of the galaxy as a whole, whose major axis is canted at a PA of nearly 150°.

The spectrum of polarized flux from the nucleus of NGC 4258 is shown in Figure 4. Evident here is a blue ($P \times F_\nu \propto \nu^{-1.1\pm0.2}$) continuum plus emission lines of of [O III], Hα+[N II] and perhaps [O I] and [S II]. In polarized flux, the emission lines have a much higher equivalent width than in total flux, radically

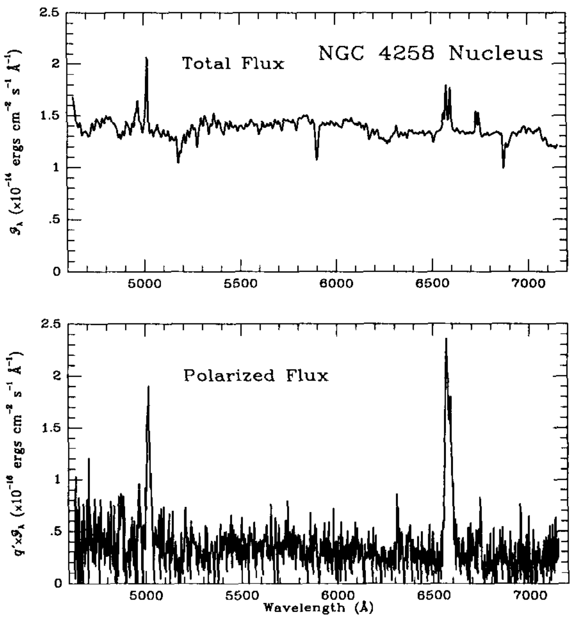

Figure 4. The spectrum of total flux *(top)* compared with that of polarized flux *(bottom)* for the inner few arcseconds of the low-luminosity nucleus of NGC 4258. From Wilkes et al. (1995).

different line ratios, and they are broader. In fact, the measured FWHM is $\sim$1000 km s^{-1}, very similar to the radial velocity of the orbiting maser gas.

Although the polarized emission lines in NGC 4258 are resolved, they fall short of the tremendous widths seen in the canonical QSO/Seyfert 1. What's more, forbidden transitions are clearly represented in the scattered light. This is not a unique case: Ferrarese et al. (1996) find that the $0\farcs12$ (17 pc) diameter compact core at the center of the dust disk in NGC 4261 displays emission lines of [O I], [O III], [N II], [S II], and the Balmer series with widths of 1000 – 2000 km s^{-1}. It would appear that the lowest-luminosity AGN may be lacking in a classical BLR. Although this conclusion could be regarded as a breakdown of the Unified Scheme, it might also explain part of the difficulty of detecting broad emission lines in the spectra of BL Lac objects.

The presence of elongated regions of narrow-line emission surrounding the nuclei of active galaxies is now well-known. This is manifested as an "alignment" between emission-line images and radio structure, and in the context of the Unified Scheme results from ionizing radiation and possibly shocks streaming outward through the hole of the torus. Under the hypothesis of an obscuring torus, the position angle of polarization implies that the "ionization cones" in NGC 4258 should bracket the nucleus in a virtually N-S direction. Very recently, this prediction has been confirmed through near-UV (λ3000) broadband imagery with the Planetary Camera of WFPC2. In the central 5″ (170 pc) shown as Figure 5 is a tiny UV-bright fan which opens to the north. The smallness of the fan, $\sim$6 pc, is no doubt due to the weakness of the central engine in this galaxy.

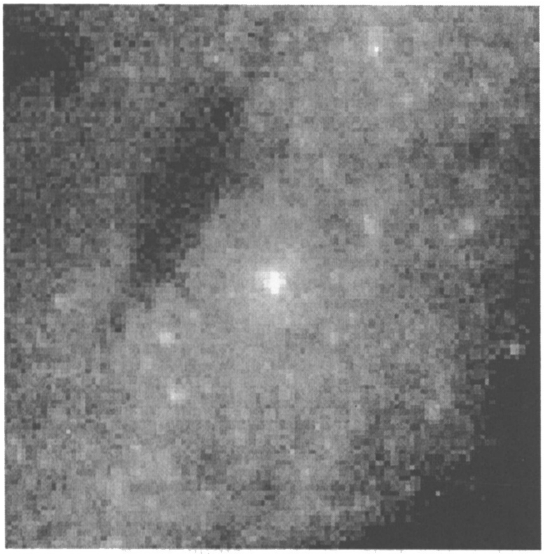

Figure 5. The central 5″ (170 pc) of a broadband UV WFPC2 image of NGC 4258. The ~6 pc fan opening to the N is interpreted as a tiny "ionization cone" emerging through the hole of the obscuring torus. The S half of the bicone is presumably obscured by the torus.

Of interest is the lack of a southern side to the bicone. In a poster presented at this conference, Herrnstein et al. identify a weak K-band continuum (~20 GHz) source displaced slightly to the north of disk center with the base of the northern radio jet. Though the jets are symmetric on the large scale, a southern side to the continuum source is also not seen. Obscuration of the southern halves by the intervening disk probably explains the one-sidedness of both UV and GHz-continuum structures.

7. Conclusions

We are finding that the Unified Scheme is sufficiently robust to weather observational tests on galactic nuclei ranging in luminosity from a thousandth that of a respectable stellar disk to the most powerful objects in the universe. In several cases, the generic model is validated by polarimetric evidence for an obscuring torus *and* the appearance of ionization cones in the same object. In NGC 4258 we have been able to carry this diagnosis one step further by establishing a geometric relationship between the torus and a disk of molecular gas orbiting a compact object whose mass exceeds $10^7\ M_{\odot}$.

Perhaps we should call this "first-order" unification. The next challenges will be to understand the radio-loud/radio-quiet distinction – including the effect of galaxy type on the radio output, to examine the possibility of a dependence of torus opening angle on source luminosity, and to investigate the apparent lack of canonical broad-line regions in the weakest sources. In addition to the pow-

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erful new observational tools which are being applied to these problems, further progress will require a better theoretical understanding of the flow of matter and energy in accretion disks and especially of the critical interface between the disk and the compact central object. It is through the synthesis of ideas in workshops of this type that such new insights will likely emerge.

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Discussion

N. Arav: Recent polarization observations by Patrick Ogle (Marshal Cohen's group) show at least 1 BALQSO with very low polarization. This goes against the edge-on viewing angle of BALQSOs in the unification model.

G. Schmidt: Our survey of 44 BALQSOs has also found a number of objects with $P \ll 1\%$. Presumably, there are complications not included in the simple Unified Scheme which result in the presence of polarization being only a statistical trend [I note that not all Seyfert 2's are polarized, nor do all which are polarized show broad emission lines in polarized flux].

D. Meier: Is it still true that BAL quasars tend to be radio quiet? If so, how can the BAL phenomenon be explained as a simple viewing angle effect?

G. Schmidt: To my knowledge the BAL phenomenon per se is restricted to radio-quiet objects. However, there is a class of radio-loud quasar sometimes termed "associated absorbers" which may represent an analogous phenomenon. The poster by Aldcroft at this meeting describes some recent work which explores this idea.