UNIFIED MODELS: RELIGION AND SCIENCE

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1. My Personal Religious Conversion to Unification

The Unified Model states that the classification of individual AGN is a function of orientation, and that orientation effects are key to understanding the different classes. In its most extreme form, it states that every AGN has a featureless continuum (FC) source and a broad line region (BLR), both enclosed in an opaque torus. The torus is perpendicular to the associated radio structure axis. For the powerful radio sources (in Elliptical galaxy hosts), the jets undergo bulk relativistic motion, giving rise to phenomena such as superluminal motion associated with the blazar class. All strong radio sources have diffuse double radio lobes, although in the blazars one is sometimes seen projected onto the other. To take this to the extreme, we can suppose that all opaque tori are made of dust[1] and have the same opening angle and that the radio jets are all narrow and have the same bulk-motion Γ factor.

Many issues related to Unified Models have been reviewed in Antonucci 1993. Here I will just summarize very briefly the arguments which I followed most closely and found compelling. (I take such a narrow track not just for personal aggrandizement but also to get on to some relatively new information.) Although the model seems to be qualitatively correct for most sources, well-documented deviations are known, and they have interesting consequences and applications. Three of these deviations are discussed in Section 2.

1.1. Seyfert 1's and 2's

Many Seyfert 2's show Seyfert 1 spectra when the polarized flux alone is plotted, and the optical polarization position angles lie perpendicular to the associated radio axes. This has been interpreted to mean that these Seyfert 2's have featureless continuum ("FC") sources and broad line regions (BLR's) like Seyfert 1's, but that they are enclosed in opaque tori oriented perpendicular to the radio sources, and are seen only by reflection off material in the polar directions. It follows from the

[1] We've recently learned that NGC 4151 has a hard-edged ionization cone, strongly suggestive of shadowing by an opaque torus (Evans et al 1993). We know both from the appearance of the cone, and the fact that the HI column density in the line of sight is $>> 10^{17}$ (Kriss et al 1992), that we are outside the cone. Thus I'm confident NGC 4151 would be a Seyfert 2 if observed below 912Å. The fact that the FC and BLR are seen directly in the optical implies that gas opacity is operating in this case, at least for our sight line (as Evans et al conclude).

T. J.-L. Courvoisier and A. Blecha: Multi-Wavelength Continuum Emission of AGN, 301–309.

Copernican Principle that at least some Seyfert 1's are equivalent objects, viewed from a polar direction.

In the case of NGC 1068, starlight subtraction indicated that the FC polarization was wavelength independent at 16% indicative of electron scattering (Miller & Antonucci 1983, McLean et al 1983). This was verified by Wuppe data (Code et al 1992) and new UV spectropolarimetry by Hubble Space Telescope (Antonucci, Hurt & Miller 1993). Specifically, the FC should dominate throughout most of the range of the HST observations, with just a little starlight contribution near 3000Å. Therefore, we should be able to overplot the polarized flux (divided by 16%) on the total flux and get a perfect match, independent of wavelength except for a modest divergence at the red end. Figure 1 shows that this expectation has been borne out.

1.2. Blazars and Normal Double Radio Sources

The same basic phenomenology was seen in the Narrow Line Radio Galaxy 3C234, before the NGC 1068 data were understood, and the torus (or occultation/reflection model) was first based on 3C234 back in 1982. There was one subtle difference which will become important for Section 2: There was some evidence that the BLR polarization was significantly higher than the FC polarization (Section VI b of Antonucci 1984).

At the same time another unification scheme was being debated for the radio loud sources. The flat-spectrum core dominant sources generally show superluminal motion. Also, in most cases, the core synchrotron spectra dominate the spectral energy distribution all the way into the optical region, leading to a blazar classification.

The beam model was proposed to account for superluminal sources: the moving components were said to be ejected relativistically from the cores, almost in the direction of Earth, producing an illusion of faster than light motions. It was further supposed that these superluminal jets were identifiable with the (apparently) weaker jets linking cores to lobes in normal double radio sources. The blazars were simply the ones seen from nearly the jet direction (Blandford & Rees 1978).

The blazar/normal double unification obviously predicted that the blazars should show diffuse radio halos or foreshortened doubles in high dynamic range maps, because they must also have the double lobes in this model. Several groups started detecting such diffuse radio emission (including Ian Browne, John Wardle, Jim Ulvestad and others). Ulvestad and I did a major search, gathering data on all the objects known at the time of the Angel and Stockman (1980) review paper on blazars. We had enough data that we could argue that this unification *must* be qualitatively correct.

Our argument went as follows. Suppose the superluminal, roughly linear radio cores of blazars are highly anisotropic and beamed towards Earth (arguably just the "conventional physics" assumption). Suppose also that the diffuse and often two-sided halos were emitting roughly isotropically. The data show that several blazars have sufficient flux *in their diffuse halos alone* to merit a place in the 3C category.

By the first assumption above, these are aimed closely in Earth's direction; there must be many more equivalent objects which are not. By the second assumption, the misdirected equivalents must be in the 3C catalog. The only things in the 3C catalog with big powerful diffuse radio sources are the normal doubles. In fact, there are about the right number so that most or all are misdirected blazars, if the blazar emission is as isotropic as in "narrow cone" models. (Cohen 1990 later tightened the noose on "wide cone" models with better VLBI maps.)

1.3. Paradoxes ... and Resolution

In the mid 1980's most radio astronomers considered the quasars and Narrow Line Radio Galaxies to be distinct classes, and when testing the beam model statistically, they considered only blazars and quasars. They found various statistical anomalies which can all be expressed as a dearth of quasars in the sky plane. For example, the asymmetry of the arcsec scale jets in normal double radio quasars could in principle be explained by beaming, but it was argued that quantitatively the jet/counterjet ratios were observationally constrained to be too large, too often. A robust and picturesque second example comes from the depolarization/jet side anticorrelation. This seemed supportive of the beam model, but, as Laing (1988) pointed out, "The sources observed here must be oriented within about 45° of the line of sight...to generate sufficient asymmetry in path length between the two lobes, and this is consistent with the observed asymmetry in the jets."

Barthel (1989) emphasized that all of these problems are greatly alleviated if we admit the possibility that luminous narrow line radio galaxies are quasars in the sky plane. Some early radio polarization mapping was consistent with this (e.g. the inner parts of both lobes, rather than all of one lobe, seem to be depolarized in 3C234: Strom et al 1985). And, of course, the spectropolarimetry arguments show that this identification must be true at some level. Recent optical polarization imaging of distant luminous radio galaxies argues very strongly that this is true for many of them (e.g. Tadhunter et al 1992, Jannuzi & Elston 1991, and di Serego Alighieri et al 1993).

My conclusion is that the Unified Model is qualitatively correct and it is now a religion.[2] However, we can rule out the simplest version on many grounds, including those discussed below.

[2] Our religion is called the Unification Church by Archbishop Barthel. Also on this topic, Cardinal Laing would like to receive suggestions regarding appropriate vestments.

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2. Science Finds Deviations from Unification Dogma

2.1. Low Redshift FRII Statistics

In the simplest version, the unification of double-lobed radio quasars (and Broad Line Radio Galaxies) with Narrow Line Radio Galaxies is true for all objects of both classes, and they all have the same opening angle for the obscuring torus. This has been ruled out as follows.

The 3CRR catalog is essentially complete and completely optically identified. It is also selected mostly by lobe emission, because of the low frequency of the survey (178MHz). These properties make it ideal for comparing a sample of objects which are to be identified in unification schemes.

Barthel (1989) has compared the 3CRR Narrow Line Radio Galaxies (all FRII) and quasars in the $0.5 < Z < 1.0$ range all of which are FRII. The former have twice the space density on average, and half the projected linear size. These and other properties are consistent with the assertion that all of these objects have FC sources and BLRs enclosed in opaque tori with opening angles of 45°. Such a unification can resolve the statistical anomalies associated with the beam model as applied to quasars alone, as described above. It is now known from the polarization imaging of distant luminous narrow line radio galaxies that high perpendicular polarization is common. This is probably due to reflected light from objects which must (by the Copernican Principle) be quasars. Thus Barthel is qualitatively correct, and perhaps quantitatively correct in the parameter space he studied.

I'll cite three subsequent papers which test the Barthel pattern at lower redshift. Kapahi (1990; see also Lawrence 1993, Fig. 1) shows that for $0.25 < Z < 0.5$, the Narrow Line Radio Galaxies become more predominant numerically over the broad line objects, and the difference in average projected linear size vanishes. By contrast, Gopal Krishna and Kulkarni (1992) find that the size difference remains, and holds from $0.1 < Z < 2.0$, if we look at the upper envelope of the size distributions at each redshift. They justified the focus on the upper envelopes partially because it eliminates the complicated, contentions and pernicious Steep-Spectrum Compact (SSC) sources. They also made adjustments to the observed sizes for the power of the sources, though I think this was a smaller effect.

Singal (1993) reconsidered the issue, focusing on average size, but modifying the Kapahi analysis to exclude SSCs and core-dominant sources. His Figure 2 shows all of the issues very clearly: the "good" behavior of the size distributions at $1 < Z$, $0.5 < Z < 1$, and in the upper envelope of the $Z \lesssim 0.5$ data. But it also shows that for the relatively low luminosity, nearby objects, there are many "extra" small Narrow Line Radio Galaxies, which apparently do not participate in the unification with broad line objects in any significant way! Barthel (1993, p.c.) speculates that they may be the "optically dull" ones, without luminous high-ionization narrow lines. That's well worth checking.

A worthwhile study would be to consider an isotropically-selected sample in which the blazar/quasar unification alone leads to statistical anomalies. Would the quasar/NLRG unification hold sufficiently for that sample to solve these problems? That is the key question, and I'm optimistic about the answer.

2.2. The Strange Case of Cygnus A

This is the extremely luminous prototypical Narrow Line Radio Galaxy at a redshift of only 0.056. Stockton (1993) points out that you have to go out to $Z = 1.00$ before you find a more luminous radio galaxy, despite the volume factor $\cong Z^3$ and the strong cosmological evolution working for you. It may be like the extremely luminous distant radio galaxies. We are lucky to have it.

Baade and Minkowski discovered the double nucleus of Cygnus A in 1951. Later it was shown that both nuclei are spatially resolved; that the NW nucleus is almost entirely high-ionization line emission while the SE nucleus is almost entirely Featureless Continuum; and that the true center of the system as marked by the flat-spectrum radio core is between the two optical nuclei. A slightly smoothed but not deconvolved HST image of the double nucleus in the 3360Å region is shown in Figure 2.

Pierce and Stockton 1986 showed very convincingly that the dilution of Population II stellar absorption lines, and hence the FC, is spatially resolved in the SE nucleus. There is no evidence for hot stars, so they proposed that the FC is light reflected from a hidden quasar. This makes a lot of sense in the light of the unified model. Broad permitted lines do not show in polarized flux however (Goodrich and Miller 1989, Jackson and Tadhunter 1993). One could imagine that the reflection region consists of very hot electrons which broaden the reflected lines beyond recognition. However, I think the off-nuclear polarization ($\sim$1%) is just too low for spatially-resolved scattering. We have HST UV polarization imaging and spectra on the shelf which should help to test this further.

We recently found another puzzle, almost a paradox, regarding Cygnus A. If we see the flat-spectrum radio core through a molecular torus, we should see CO in absorption very easily. In fact, independent of the unified model, we supposedly know there are at least 50 magnitudes of extinction in front of the nucleus ((Djorgovski et al 1991, Ward et al 1991), and the X-ray absorption column is also large (Koyama 1992; D. Harris 1993, p.c.). Again, we expect to see CO absorption, but we do not (Barvainis & Antonucci 1993).

The observations could be accommodated by a torus composed of clouds which have very narrow internal velocity dispersions, which each cover a small fraction of the radio core, and which have a covering factor near one and not much larger. The space between the clouds must be very free of molecules. This stretches our imaginations just about to the breaking point. Rees (1993, p.c.) has suggested that the rotational excitation temperature could be very high despite a low kinetic temperature, owing to the strong radio source. In that case, stimulated emission largely cancels absorption, as is common with HI. We are considering this intriguing suggestion quantitatively.

2.3. WHY THE FEATURELESS CONTINUUM IS EXTENDED IN GENERAL!

A very interesting and unexpected subtlety in the data on almost all of the "reflected light" objects is the following. The polarized flux shows the broad permitted lines at their normal equivalent widths. We would therefore expect in the simplest case that this would also be true in the total-flux spectra corrected for contaminating starlight. In other words, if the FC and the BLR are seen only in reflection, then their ratio in total nonstellar flux should be normal. But that is not the case! The BLR is generally polarized *much more* than the FC, so that it hardly shows up in total nonstellar flux, while it has normal strength in polarized flux.

The size of the effect in the objects of Tran, Miller and Kay 1992 is very large. Mrk 477 is typical. The polarized flux spectrum looks just like a Seyfert 1. But, while P(BLR)$\gtrsim$ 20%, P(FC) is only $\sim$1%! The most likely explanation is that part of the FC source is exposed and so part of the FC flux is reaching us directly, greatly diluting the fractional polarization of the FC. The exposed component is *energetically insignificant* and is visible only because the torus is blocking a large majority of the direct FC flux. However, it provides a crucial clue that the fundamental emission process is diffuse and not entirely ultracompact as in, say, accretion disk models with sizes of order the gravitational radii. Tran and Miller refer to the exposed part of the Featureless Continuum as "FC2".[3] (Sources here are Tran, Miller and Kay 1992 and Miller 1993.)

Can the exposed part of the FC come from a source unrelated to the central energetically-dominant part, for example, hot stars? Unlikely because the total-flux FC, dominated by the exposed part, has the same spectral energy distribution as the polarized flux, from the hidden part. Both have the shape of Seyfert 1 spectra rather than that of hot stars.

The shocking implication of this is that at least a minor part of the FC source is larger that the BLR! A large FC source would be a good explanation of why the observed continuum *never* shows a Ly edge due to the BLR clouds (Antonucci, Kinney, & Ford 1989; Tytler 1993 (p.c.)). The FC may actually come from clouds extending throughout the emission line regions. If their emission is thermal, as suggested, for example, by the very steep soft X-ray cutoffs,[4] the clouds are then probably optically thin emitters. Such a scenario has been proposed on other grounds by, e.g., Antonucci and Barvainis 1988; Ferland, Korista and Peterson 1990; Barvainis 1993; and Binette, Fosbury, and Parker 1993.

If the FC source is indeed optically thin and extended, with at least a small fraction arising above the occulting torus, then it should be sufficiently strong and extended in the radio to be directly mappable. Barvainis and I have proposed this observation to the VLA.

[3] Similarly, the constant soft X-ray excess seen in Seyfert 2's (e.g. Mulchaey et al 1993) may have low polarization, and be dominated by this exposed component in most cases.

[4] Two recent arguments that the optical/UV light is the same component as the soft X-ray excess are given by Walter and Fink 1993, and A. Orr et al, this meeting. A counterargument has been given by Lee et al 1993.

There are two other important implications of Tran et al 1992 for the torus model. First, a low total FC polarization is not inconsistent with seeing a normal Seyfert 1 spectrum in polarized flux. This encourages us to believe that the Seyfert 1/2 unification may be universal. Second, the percent polarization of the *reflected* light, as shown directly by the BLR, is generally very high, as expected for a thick obscuring torus rather than, say, a warped disk.

3. Conclusions

The Unified Model is qualitatively correct, correct to "zeroth order," but far from the whole story of active galactic nuclei.

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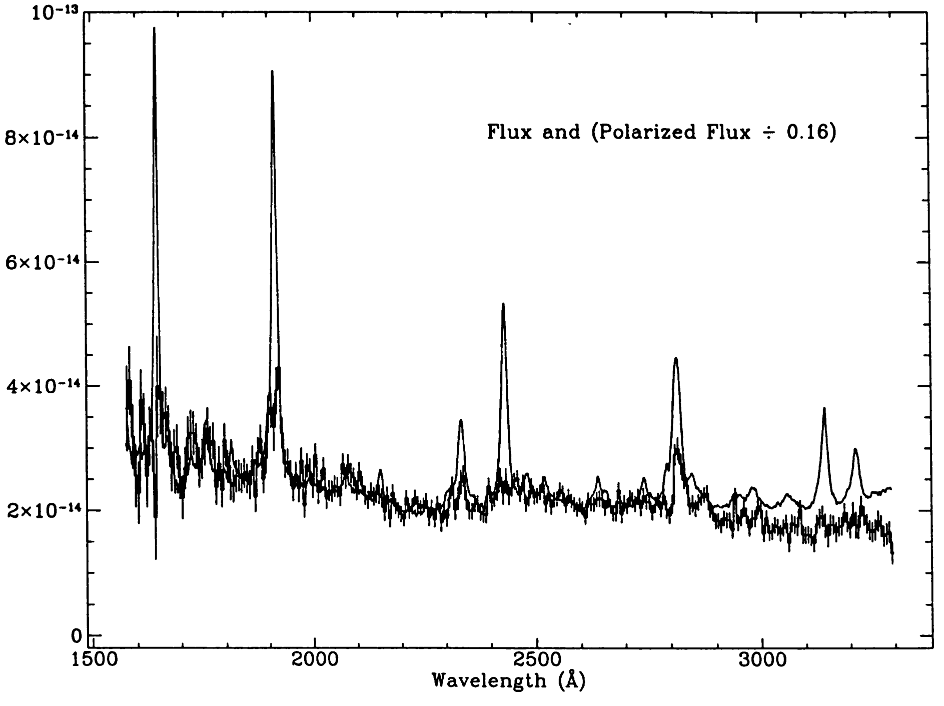

Figure 1 - Total Flux and polarized flux of NGC 1068 in the ultraviolet

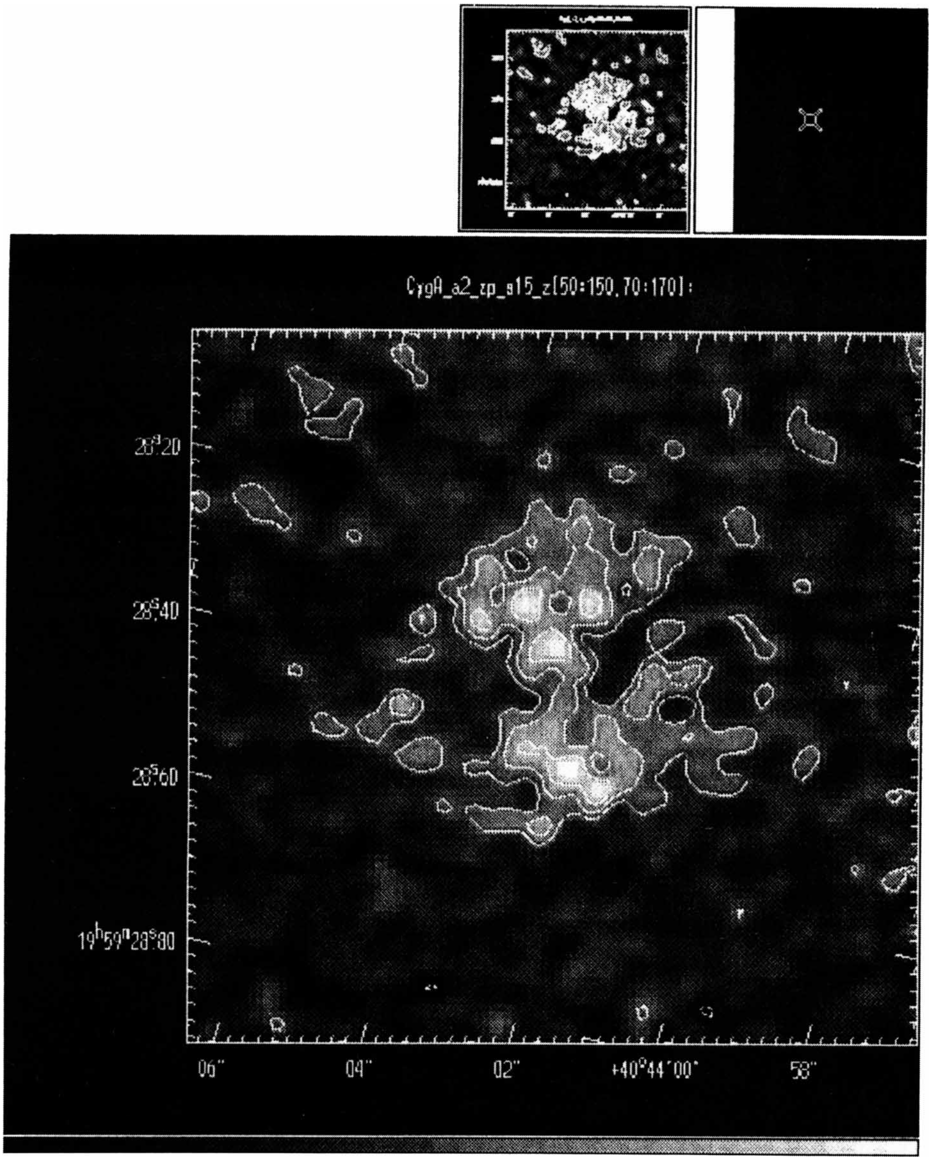

Figure 2 - Preliminary HST image of Cygnus A at 3360Å; no deconvolution, $\sigma = 0''.12$ Gaussian smoothing.