UNIFIED SCHEMES FOR RADIO-LOUD AGN: RECENT RESULTS[1]

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ABSTRACT. After briefly summarizing the main tenets of unified schemes of Active Galactic Nuclei, I review some recent results in the field of unification of radio-loud sources, both for the low-luminosity (BL Lacs and Fanaroff-Riley type I radio galaxies) and high-luminosity (radio quasars and Fanaroff-Riley type II radio galaxies) populations.

1. Introduction

It now seems well established that the appearance of Active Galactic Nuclei (AGN) depends strongly on orientation. Classes of apparently different AGN might actually be intrinsically similar, only seen at different angles with respect to the line of sight. The basic idea, based on a variety of observations and summarized in Figure 1 of Urry & Padovani (1995), is that emission in the inner parts of AGN is highly anisotropic. The current paradigm for AGN includes a central engine, surrounded by an accretion disk and by fast-moving clouds, probably under the influence of the strong gravitational field, emitting Doppler-broadened lines. More distant clouds emit narrower lines. Absorbing material in some flattened configuration (usually idealized as a torus) obscures the central parts, so that for transverse lines of sight only the narrow-line emitting clouds are seen (narrow-lined or Type 2 AGN), whereas the near-IR to soft-X-ray nuclear continuum and broad-lines are visible only when viewed face-on (broad-lined or Type 1 AGN). In radio-loud objects we have the additional presence of a relativistic jet, roughly perpendicular to the disk, which produces strong anisotropy and amplification of the continuum emission ("relativistic beaming"). In general, different components are dominant at different wavelengths. Namely, the jet dominates at radio and γ-ray frequencies (although it does contribute to the emission in other bands as well), the accretion disk is thought to be a strong optical/UV/soft X-ray emitter, while the absorbing material will emit predominantly in the IR. It then follows that a proper understanding of AGN will only come through multifrequency studies (e.g., Padovani 1997).

This axisymmetric model of AGN implies widely different observational properties (and therefore classifications) at different aspect angles. Hence the need for "Unified Schemes" which look at intrinsic, isotropic properties, to unify fundamentally identical (but apparently different) classes of AGN. Seyfert 2 galaxies have been "unified" with Seyfert 1 galaxies (see Antonucci 1993, and references therein, and Granato, these Proceedings, for more recent results). As regards the radio-loud population, Fanaroff-Riley

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type I (FR I: i.e., low-power) radio galaxies have been unified with BL Lacertae objects, a class of AGN characterized by very weak emission lines, while Fanaroff-Riley type II (FR II: i.e., high-power) radio galaxies have been unified with radio quasars. In the latter case, flat-spectrum radio quasars (FSRQ) are thought to be oriented at relatively small angles w.r.t. to the line of sight ($\theta \lesssim 15°$), while steep-spectrum radio quasars (SSRQ) should be at angles intermediate between those of FSRQ and FR II radio galaxies.

This paper is *not* meant to be a review of unified schemes: the interested reader might consult, for example, the reviews by Antonucci (1993) and Urry & Padovani (1995). My aim is to discuss some of the very recent results in the field of unified schemes for radio-loud AGN which have appeared in the literature in the last year or so (and therefore were not included in Urry & Padovani 1995).

2. BL Lac - FR I Unification

2.1. Broad lines in BL Lac (or "When is BL Lac not a BL Lac?")

Vermeulen et al. (1995) have discovered a broad Hα line in BL Lacertae, the class prototype itself, comparable in luminosity and velocity width to that of the Seyfert 1 galaxy NGC 4151. Although weak, broad emission lines have been previously detected in other BL Lacs (Stickel et al. 1993), the presence of such a line in BL Lacertae itself has attracted the attention of many BL Lac pundits. The main distinguishing feature of BL Lacs is in fact their weak, or even absent, emission lines, generally characterized by equivalent widths for the stronger lines $W_\lambda < 5$ Å. The question then is: Is BL Lac still a BL Lac? The reassuring answer is: Yes. The newly detected broad line, in fact, has $W_{H\alpha} = 5.6 \pm 1.4$ Å, consistent with the 5 Å limit.

This detection, however, has some quite interesting implications for our understanding of BL Lacs (and of AGN in general: see Salvati, these Proceedings). This relatively strong line should have been detected in previous spectra, taken when the source was of roughly similar brightness. Corbett et al. (1996) have estimated that the Hα luminosity (and equivalent width) must have increased by a factor of 4 from earlier observations. If the source of ionization were related to the non-thermal continuum, the equivalent width of all emission lines should be independent of the ionizing power, as both line and continuum luminosity would be proportional to it. Corbett et al. (1996) then suggest the presence of an additional, variable continuum source: the observed $W_{H\alpha}$ could in fact be explained by an accretion disk whose flux is only 4% of the non-thermal, beamed continuum at the wavelength of Hα. Such a small contribution to the total flux in the optical band affects only slightly the shape of the optical continuum by flattening the slope in the 3,500 – 7,000 Å range, but should produce a marked depolarization of the synchrotron component (assuming thermal emission is unpolarized). This is a strong prediction of the model although, as Corbett et al. point out, this dilution might be difficult to detect due to the strong variability of the wavelength dependence of the synchrotron polarization observed in BL Lacs.

The possibility that BL Lacs possess an accretion disk, even though its contribution to the total flux might be quite small, is suggestive. Furthermore, the presence of broad lines in BL Lacs, and the lack of them (to the best of my knowledge) in FR Is, might provide the only evidence, so far, of the presence of an obscuring torus in low-luminosity radio sources. Finally, the detection of an emission line at the same redshift as the host galaxy absorption lines shows that at least BL Lac (and all the other objects sharing this property: see e.g., Stickel et al. 1993) is not gravitationally micro-lensed (Urry & Padovani 1995).

2.2. BL Lacs (or lack thereof) in Abell Clusters

Owen, Ledlow & Keel (1996) have looked for BL Lacs in 183 low-luminosity radio galaxies in relatively rich ($\sim 60\%$ of richness class 1 and 2) clusters at $z < 0.09$. They found no object which met the "standard definition" of BL Lacs, based on a measure of a non-thermal component (4000 Å break $\lesssim 25\%$) and weakness of the lines ($W_\lambda < 5$ Å), although they found 4 objects with weak evidence for non-thermal activity (4000 Å break $\sim 33 - 43\%$: typical ellipticals have break values $\sim 50\%$), two of them with relatively strong lines (unlike BL Lacs). Owen et al. expected 8 BL Lacs on the basis of a relativistic beaming model (Urry, Padovani & Stickel 1991) or 3/18 at $P > 10^{32}$ erg s^{-1} Hz^{-1} simply on the basis of the observed luminosity functions of FR Is and BL Lacs. Their null results are inconsistent with these expectations at the $> 99\%$ and 95% level respectively, apparently putting in serious trouble the BL Lac – FR I unification. This inconsistency might be at least partly related to the definition of a BL Lac, which is likely to be not that clear-cut and should perhaps be slightly relaxed, for example by increasing the value of the 4000 Å break (as pointed out by Marchã et al. 1996). More importantly, it seems now quite likely that BL Lacs avoid the richest clusters (at least at low redshifts: e.g., Pesce, Falomo & Treves 1995; Smith, O'Dea & Baum 1995; Wurtz et al. 1996b) and reside mostly in relatively poor (richness class ~ 0) clusters, which however seem to include a large fraction of FR I galaxies (Hill & Lilly 1991). This behaviour, although still unexplained, is nevertheless consistent with the findings of Wurtz, Stocke & Yee (1996a) that most BL Lacs have host galaxies too faint to be bright cluster galaxies (BCGs) in rich clusters: their host galaxy magnitudes are more typical of BCGs in poorer clusters, which are less luminous.

In summary, the sample of Owen et al. (1996) probably included a large number of unlikely BL Lac hosts: the significance of their null results should then be re-evaluated.

2.3. X-ray selected vs. Radio-selected BL Lacs (or HBL vs. LBL)[2]

It has long been recognized that BL Lacs appear to come in two versions, one being more extreme, having larger optical polarization, core-dominance, and variability, and usually associated with objects selected in radio surveys, the so-called radio-selected BL Lacs (RBL). The less extreme version, mostly selected in X-ray surveys, was then obviously named accordingly (X-ray-selected BL Lacs: XBL). This division was clearly not satisfactory, as it was not based on intrinsic physical properties but solely on the selection band, and did not uniquely characterize a source. Recent all-sky surveys, in

[2] This is a big topic, currently hotly debated in the literature, which is impossible to address in detail in such a short contribution. Therefore, after introducing the problem, I will simply refer to some recent papers on the subject.

fact, include many BL Lacs previously selected at radio frequencies and which could then now be classified both as RBL *and* XBL. Padovani & Giommi (1995; see also Ledden & O'Dell 1985 for the first subdivision of BL Lac classes based on L_x/L_r) have then proposed to classify BL Lacs in HBL (or high-energy peak BL Lacs) and LBL (or low-energy peak BL Lacs), based on a simple division in terms of their X-ray-to-radio flux ratio. This reflects their different multifrequency spectra, with LBL (most RBL) having a peak (i.e., emitting the bulk of their energy) at infrared-optical frequencies, and HBL (most XBL) having a peak at ultraviolet-X-ray frequencies. Note that such a distinction does not mean that there are two separate BL Lac classes: it is more likely that there is a continuous distribution of, for example, peak frequency, which turns out to be bimodal because of selection effects.

What is the relation between the two classes? This is being (and has been) discussed by various authors (see Padovani & Giommi 1995 and Urry & Padovani 1995, and references therein). Briefly, the two opposite views are that: 1. LBL are *intrinsically* more numerous ("different energy distribution" scenario); 2. HBL are *intrinsically* more numerous ("different angle" scenario). In the former view, radio selection gives an "unbiased" view of the BL Lac population (in terms of population ratios) and HBL and LBL are oriented w.r.t. the line of sight within approximately the same angles. In the latter, X-ray selection is unbiased, and HBL are seen at larger angles. Currently available samples are not deep enough to overthrow the balance in favour of one or the other of the two explanations, which diverge in their predictions only at relatively faint radio and X-ray fluxes.

Some of the recent papers on the subject include: Padovani & Giommi (1996) and Lamer, Brunner & Staubert (1996), on the different *ROSAT* spectra of HBL and LBL, which are consistent with their different multifrequency spectra; Sambruna, Maraschi & Urry (1996) on, amongst other things, the difficulty in explaining the observed differences in the multifrequency spectra of HBL and LBL only by changing viewing angle; Kollgaard et al. (1996) on radio constraints to the two pictures, which would seem to favour the "different angle" hypothesis. Finally, Wurtz et al. (1996a) find no differences in the host galaxy properties of HBL and LBL, while Fossati et al. (these Proceedings), present yet a new explanation for the relation between HBL and LBL.

3. Radio Quasar - FR II Unification

3.1. Linear sizes of radio galaxies and quasars

The question of the comparison between linear sizes of radio galaxies and quasars lies at the core of unified schemes: if radio quasars are oriented at small angles to the line of sight, then they should have systematically smaller large-scale radio structures than radio galaxies, thought to be in the plane of the sky. A simple relation exists between the ratio of median sizes of radio galaxies and quasars, r_θ, and the half-opening angle of the obscuring torus (or equivalently the critical angle w.r.t. the line of sight separating the two classes), θ_c. (In fact, the smaller θ_c, the higher will be r_θ.) The critical angle is also obviously related to the quasar fraction f_q ($f_q = 1 - \cos\theta_c$), from which it follows that r_θ and f_q have to be inversely related (that is the smaller f_q, the smaller θ_c, the higher

r_θ). The important point of Barthel's (1989) paper was to show that both r_θ and f_q were consistent with a critical angle $\simeq 45°$ for the 3C sample at $0.5 < z < 1.0$. Barthel's findings were criticized by some authors, particularly by Singal (1993), who argued that not only the quasar fraction seemed to be redshift dependent but the apparent agreement between the angles inferred from the number ratios and those derived from the linear sizes disappeared extending the comparison to other redshift ranges.

It must be stressed that the whole subject of linear sizes of radio sources is quite complex, having been addressed by many authors quite often with contrasting results (see Neeser et al. 1995 for a very good description of some of the selection effects which can affect this sort of analysis). As summarized in Urry & Padovani (1995) and discussed in Singal (1996), various solutions to the problems raised by Singal (1993) have been proposed. Singal (1996), however, examining the quasar fractions observed in low-frequency radio samples, noted that not only the quasar fraction decreases at lower fluxes (which would show that a single θ_c is untenable) but the ratio of median sizes of radio galaxies and quasars actually seems to *decrease* as well, contrary to the expectations of unified schemes. In other words, while r_θ should be inversely dependent on f_q, r_θ actually *increases* with f_q (see Figure 2 of Singal 1996). Note that no change of θ_c with redshift or power will bring the data in agreement with the predictions of unified schemes, as the observed dependence is opposite to the predicted one.

Does this mean that unified schemes are totally wrong? Apparently not, if one takes into account the evolution of the single radio sources. Recent results (e.g., Fanti et al. 1995; Readhead et al. 1996) suggest that radio sources grow in size during their active phase, with an accompanying decrease in power due to expansion losses. Gopal-Krishna, Kulkarni & Wiita (1996) have parameterized this behaviour, with the further assumption that the half-opening angle of the torus depends on luminosity (which could be explained by the fact that more powerful engines "erode" away the inner parts of the torus: see Urry & Padovani 1995 and references therein). The result is that Gopal-Krishna et al. can explain the apparently anomalous relation between r_θ and f_q pointed out by Singal (1996) with reasonable input parameters. Within this model, the median radio sizes of quasars can actually approach, or even exceed, that of radio galaxies, as reported by Singal (1996) for some samples.

Note that the inclusion of source evolution in unified schemes, which seems unavoidable, might complicate the use of the core-to-extended flux ratio, R, as an orientation indicator, as in this view the extended flux would also be time-dependent, that is R could change with time for the same angle to the line of sight.

3.2. Infrared spectroscopy of radio galaxies

There are some ways to overcome the presence of obscuring material and be able to see the central engine even in Type 2 sources. One of these is spectropolarimetry, where one looks for broad lines in that small fraction of the nuclear flux which is in some cases "reflected" towards our line of sight by dust and/or electrons. Recent results in this field are discussed by Cimatti, these Proceedings. I concentrate here on another way to see through the dust by moving to longer wavelengths, where the torus becomes more transparent: infrared spectroscopy. Infrared broad lines have been detected before in

Type 2 radio sources (see Urry & Padovani 1995 for references) but it is clear that one would like to be able to answer such questions as: How many Type 2 sources actually show broad lines when observed in the infrared? What is the distribution of BLR extinction in these sources? The best way to address these points is through the use of an unbiased, flux-limited sample, such as that studied by Hill, Goodrich & DePoy (1996). These authors present infrared spectrophotometry of Paα, plus optical spectroscopy of Hα and Hβ, for a flux-limited sample of 11 3CR FR II radio sources with $0.1 \leq z < 0.2$, which includes 8 narrow-line radio galaxies, 2 broad-line radio galaxies, and one quasar. Infrared broad lines are detected in 3 narrow-line radio galaxies (or $\sim 40\%$ of the Type 2 sources), and extinction values are derived for narrow and broad lines. The distribution of broad-line extinction, A_V, is in reasonable agreement with a simple unification model. Extension of this work to higher redshifts (and therefore luminosities) should permit a direct test of the idea that the half-opening angle of the torus increases with power (see Sect. 3.1). If that is the case, at higher powers there should be fewer sources with relatively large extinctions ($A_V \gtrsim 5$), as compared to their lower power counterparts.

4. Across the two Schemes

4.1. Relation between BL Lacs and Flat-spectrum radio quasars

The relation between BL Lacs and FSRQ is not clear. The two classes share similar properties (apart from the presence of strong emission lines in the latter class). Sambruna et al. (1996) have suggested a continuity in the multifrequency spectra of HBL, LBL, and FSRQ, with the frequency of the peak of the emission shifting to higher values for decreasing luminosities. This continuity seems to have been severely weakened by the discovery of "HBL-like" quasars (Padovani, Giommi & Fiore, these Proceedings), that is of radio quasars (including some FSRQ) with multifrequency spectra similar to those of HBL. Padovani, Giommi & Fiore (1997) have also found that, contrary to previous results, even the soft X-ray spectra of FSRQ and BL Lacs of the LBL type are similar. Finally, Vagnetti (these Proceedings), has presented his latest results on the possible evolutionary relation between the two classes.

5. Open Questions - Hot Topics and Conclusions

I have listed here some of the open questions/hot topics on which work is in progress. These will be hopefully discussed at the next Italian meeting on AGN, to be held in 1998!

- Obscuration in FR Is. The presence of broad lines in at least some BL Lacs (Sect. 2.1) indicates that some obscuring material must be present in FR Is (as well as in FR IIs). A SAX core program will address this issue. Also, ISO observations of FR Is should provide further constraints.

- BL Lac (and FR I) environment. As stressed in Section 2.2, it might well be that BL Lacs avoid the richest clusters. More work in this field is needed, as the samples used to study the environment of BL Lacs are still relatively small. Various ongoing projects will address this point in more detail. Comparable studies on the environment of FR I radio galaxies using sizeable and well defined samples should also be performed.

- HBL/LBL dichotomy. As mentioned in Section 2.3, we need deeper and larger BL Lac samples to address this point. Amongst the various groups working on this, both Perlman, Padovani, Giommi, et al. (1997) and Caccianiga, Maccacaro, Wolter, et al. (these Proceedings) are cross-correlating X-ray and radio catalogues to select new BL Lac (and FSRQ) samples.
- (Spectro)Polarimetry of complete samples of radio-galaxies. As mentioned in Section 3.2, spectropolarimetry allows one to see emission from the nuclear region, particularly broad lines, even in Type 2 sources. So far, however, spectropolarimetric studies have concentrated on individual, sometimes peculiar, sources. We would need a spectropolarimetric study of a complete, well-defined sample, to quantify how common reflected broad lines are, for example. As far as I know, nobody is doing this, but I hope that I am misinformed on this! Tadhunter et al. and di Serego Alighieri et al., however, are carrying out a polarimetric study of a complete sample of radio sources, which should still give interesting, quantitative information.
- VLBI studies of complete sample of radio sources. These are important to study, among other properties, the distribution of superluminal speeds to estimate beaming parameters and constrain unification. Various surveys are in progress, for example the Caltech-Jodrell Bank survey of strong ($0.7 < f_{6cm} < 1.3$ Jy) radio sources (e.g., Polatidis et al. 1995) or the survey of low-power radio galaxies by the Bologna group (e.g., Venturi et al. 1995).

In conclusion, the unification of radio-loud sources is a very active field, with interesting results appearing even on a relatively short time scale. In 1995 alone, about 65 papers on beaming and unification of radio sources have been published (51 in refereed journals), an all-time record judging from the data relative to the last ten years (source: Astrophysics Data System). Various modifications to our relatively simple and idealized unification picture seem to be in order: not all FR I radio galaxies might host BL Lacs, after all, but probably only those in relatively poor clusters; obscuring material might be present in FR I radio galaxies as well, and not only in their higher-luminosity counterparts; not unexpectedly, radio sources do evolve in time, growing in size and dimming in power, which might help solving some inconsistencies in their linear sizes relative to those of radio galaxies; infrared broad lines are indeed detected in about half of the low-redshift narrow line radio galaxies; but we still do not know if BL Lacs of the LBL type are intrinsically more numerous than BL Lacs of the HBL type!

Finally, although so far unified schemes for radio-loud and radio-quiet AGN have been considered separately, there might be some connection between the two. Falcke, Sherwood & Patnaik (1996) have recently suggested that relativistic boosting, normally associated with radio-loud AGN, might be present in the radio cores of some radio-quiet sources as well. This idea, with its far-reaching implications, might open up new research paths which could help us to solve the long-standing problem of the radio-loud/radio-quiet dichotomy of the AGN population.

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