Radio galaxies: unification and dust properties

Peter Barthel, Ilse van Bemmel

*Kapteyn Astronomical Institute, P.O.Box 800, NL-9700 AV Groningen*

**Abstract**

The 2002 status of unification models for extragalactic radio sources is examined, with particular emphasis on the dust properties of these objects.

*Key words:* radio galaxies; unification; dust; torus

1 Introduction

Unification of active galaxies combines the mechanisms of relativistic beaming in radio jets (when present – the radio-loud objects) with anisotropy due to dust shadowing or non-spherical optically thick emission; key parameter is the aspect angle. These geometric effects, in interplay with source evolution – youth, adulthood, seniority, as well as duty cycle – provide the full framework in which we seek to explain the active galaxy populations.

In case of Seyfert galaxies, an optically thick torus was invoked in the mid 1980’s to explain the apparent differences (strength of continuum and emission line radiation) between Seyfert’s of Types 1 and 2. As for the radio-loud population of radio galaxies and quasars such tori were postulated in combination with relativistic effects in their radio jets. The model whereby quasars and BL Lac objects are favourably oriented radio galaxies has drawn considerable interest: the unification church still has many members. The review articles by Antonucci (1993) and Urry & Padovani (1997) provide excellent accounts of these models. Increased attention has been paid in the last decade to the subject of life-time evolution of active galaxies and AGN: some of that work will be dealt with here, while Biretta et al. (2002) provide an excellent full account. For a nice up-to-date summary of the general aspects of unification studies we refer to the Proceedings of the Elba workshop ”Issues in Unification of AGN” (Maiolino et al., 2002).

In this short review we will discuss new evidence from the past decade in favour or against unification of active galaxies. Furthermore, we will examine
the infrared properties of active galaxies, in order to gain insight in the physical behaviour of the dusty toroid.

2 Status of radio-loud unification models

Aspect being the key parameter in geometric unification, how do we know the aspect angle to or the inclination of an active galactic nucleus? Here radio-loudness helps because the fractional radio core strength (radio core strength normalized with total radio or extended radio luminosity) – obviously taken from kpc-resolution radio images – provides a reasonably good orientation indicator. As pointed out by Wills & Brotherton (1995), the optical core luminosity normalized with the total radio luminosity provides an additional, improved orientation indicator. In addition, radio-loud objects provide us with a radio (jet) axis: radio images permit determination of the projected source axis so only the inclination angle w.r.t. this jet axis is unknown. While radio-quiet objects occasionally display optical cone emission yielding the optical axis, that axis is generally less well constrained.

As such, unification models for radio-loud objects are further developed and encompass more seemingly different classes. Within the framework of this radio-loud meeting we will concentrate on the radio-loud populations, but mention results for radio-quiet objects where relevant.

2.1 FR I unification

The model whereby Fanaroff & Riley Class I radio galaxies at small inclination manifest themselves as BL Lacertae objects has gained considerable support from HST observations of the former. Ultraviolet/optical cores in FR I host galaxies were found to correlate with their radio cores arguing for a common, beamed synchrotron origin (Capetti et al., 2002). No evidence for slower milli-arcsec scale jets in comparison to FR II radio galaxies was found: FR I jets – or their relativistic spines – must slow down from the parsec to the kiloparsec scale (e.g., Giovannini et al., 2001). Dust disks are often observed in FR I hosts galaxies: their optical depth is much lower as compared to the opaque circumnuclear tori postulated in FR II radio galaxies (Chiaberge et al., 2002). Added to the apparent absence of broad line emission in FR I radio galaxies (at least: luminous BLR – see e.g., Corbett et al., 2000), this may mark an important distinction between the Fanaroff & Riley classes, but the distinction is blurred (e.g., Blundell & Rawlings, 2001). Further evidence is provided by the far-infrared SEDs: FR I’s are generally less far-infrared-bright than FR II’s at comparable radio luminosity (Heckman et al., 1994), by a moderate factor of ∼4. Note that the broadband optical photometric host properties differ little or nothing (Ledlow et al., 2002) and that the masses of the central black holes have no connection to radio luminosity whatsoever (e.g., Woo & Urry, 2002) – it is most likely the accretion mechanism itself that will determine the
FR nature of the radio galaxy.

Backyard FR I Centaurus A was studied in quite some detail and found to conform to the unification model (e.g., Capetti et al. 2000; Chiaberge et al. 2001). Whysong & Antonucci (2002) did however point out differences between archetypal FR I’s Centaurus A and Virgo A (M 87).

2.2 FR II unification

Barthel (1993) found substantial supportive evidence for the favourable orientation of all radio-loud quasars; most of this evidence has become stronger. This is however not equivalent with the picture whereby all FR II radio galaxies contain a QSO hidden from direct view. In fact, the evidence for the existence of a population of FR II pure-radio-galaxies – without a big blue bump – has grown. Such a population of optically “dull” FR II radio galaxies, in which the nuclear accretion activity is currently switched off or at a low level, together with the astrophysically attractive model of a receding torus (e.g., Simpson in these Proceedings) may well account for the reported number density and linear size incompatibilities between FR II radio galaxies and quasars.

Investigations into possible orientation invariants, à la Hes et al. (1996) and Baker (1997) continue to be important. Relatively weak [OIII] emission may be due to obscuration but also to a weak ionizing spectrum (e.g., Tadhunter et al. 1998). With regard to the invariance issue, the mid- and far-infrared emission remains controversial. It is still not clear to what extent this emission is suitable to test and/or constrain unification models (e.g., van Bemmel et al. 2000); see Sect. 5. The multi-component, partly anisotropic nature of the far-infrared radiation nevertheless does not provide major inconsistencies with unification models; it is however likely that a cool dust component, related to host star-formation activity plays a significant additional role.

Beautiful radiation cones have been reported, in objects varying from the nearest Seyfert galaxies to high redshift radio galaxies. These provide clear evidence for anisotropic nuclear radiation fields, with an added component of jet driven star-formation (of difficult to determine magnitude). The strength of the latter is – not surprisingly – related to the size of the radio source (e.g., Best et al. 2000). However, in the powerful radio galaxy Cygnus A there is solid evidence that the ionization cones seen in optical images are generated by an outflow, driven by the radiation pressure of the central quasar (van Bemmel, 2002).

As for the host galaxies, the HST studies carried out by the Edinburgh group have yielded strong support for the FRII unification, and also the K(z) behaviour provided consistency – see the contribution by McLure in these Proceedings. HST and ground-based studies of radio galaxy hosts by de Vries and collaborators provide in addition consistency with evolutionary models for the growth of radio sources; see Sect. 3.
Obscured AGN are required by the X-ray background: this was already pointed out in the late 1980’s and the evidence is still strong (e.g., Comastri et al., 1995). X-ray spectra will soon yield the cosmologically evolving obscuration, including the contribution from highly obscured AGN (Fabian, in Maiolino et al., 2002).

Spectropolarimetry provides the tool to proof unification. Following up on the beautiful early work by Miller, Antonucci c.s., both the Caltech and the Hatfield group obtained these proofs, for an as yet small number of objects. Polarization and obscuration/reddening appear to go hand-in-hand, cf. the models (e.g., Young et al., 1996; Cohen et al., 1999).

Observations of the archetypal FR II narrow-line radio galaxy Cygnus A were wonderfully revealing: its radiation cones were imaged with HST (e.g., Jackson et al., 1998; Tadhunter et al., 1999) whereas the hidden BLR was detected with spectropolarimetry (Ogle et al., 1997). We stress however that ultraluminous backyard radio source Cygnus A harbours a QSO of only moderate strength!

3 Effects of source evolution

Considerable effort was spent to study the nature of compact radio sources. These objects, of the Gigahertz-Peaked Spectrum (GPS) and Compact Steep-Spectrum (CSS) classes, are now thought to represent the progenitors of the large classical doubles. Whereas the latter display radio structure of supergalactic ($\gtrsim 100$ kpc) dimensions, the former are subgalactic – typically a few tens of kpc for the CSS and a few tens of pc for the GPS class. See also the contribution by Snellen in these Proceedings. Noteworthy is the determination of the spectral ages of several CSS objects (Murgia et al., 1999) which appear in agreement with their postulated youth. Cold H I gas has been detected in several CSS radio galaxies (e.g., the contribution by Vermeulen in these Proceedings); the CSS quasar class displays pronounced associated CIV absorption (Baker et al., 2002). Combined with the fact that some CSS radio galaxies and quasars radiate unusually strong far-infrared emission this has been postulated to imply a young evolutionary stage with strong star-formation (Baker et al., 2002). Well-known CSS quasar 3C 48 provides an excellent example (Canalizo & Stockton, 2000). It is likely that the radio jets, trying to find their way through the circumnuclear ISM play an important role (e.g., O’Dea et al., 2002). True (proper motion) expansion velocities, of order 100 km/sec, for compact radio galaxies have been measured, arguing for their very young ages (e.g., Owsianik et al., 1999) and a nice case of a reborn GPS in a large double lobed radio galaxy was recently reported (Marecki et al., 2002). Radio source number density data require an increasing expansion speed and/or decreasing radio luminosity with age – to tie this down, the evolutionary models for extragalactic radio sources are currently being investigated with larger samples. Overall, the global host galaxy properties of
compact and large scale radio galaxies do not show inconsistencies with the evolutionary models (de Vries et al., 2000).

Support for the occurrence of recurrent nuclear activity (duty cycle ?) is slowly accumulating (e.g., Schoenmakers et al., 2000). Given the general occurrence of massive black holes in luminous galaxies (e.g., Magorrian et al., 1998), such repetitive activity triggered by repetitive fueling is not unexpected. A multi-wavelength approach including deep optical imaging seems at order.

Broad-line radio galaxies make up an important subset of the radio galaxy population. Their nature is most likely composite: the class encompasses low-luminosity QSRs, possibly with different torus opening angles as compared to high luminosity QSRs, as well as radio galaxies with somewhat transparent, porous tori (Tadhunter et al., 1998; Dennett-Thorpe et al., 2000). van Bemmel & Barthel (2001) point out that BLRGs are characterized by the absence of star-formation: one explanation could be that some BLRG represent old, dying radio galaxies. The absence of optical synchrotron (jet) components in some BLRGs (Chiaberge et al., 2002) may be consistent with that view.

4 Very dusty sources

Intriguing recent development is the detection in X-rays of active nuclei in seemingly non-active galaxies, apart from their dusty starburst nature: NGC4945 (e.g., Guainazzi et al., 2000) and NGC6240 (Iwasawa & Comastri, 1998). Such highly obscured AGN are important in the possible evolutionary connection between starburst galaxies and AGN and may be important contributors to the X-ray background – ongoing Chandra and XMM-Newton investigations will undoubtedly shed light on these issues.

Noting that dust obscuration lies at the heart of unification models, we proceed by reviewing the status of torus models.

5 Modelling the toroid in AGN

5.1 Introduction

Key to the unification model is the obscuring torus, creating an angle and wavelength dependent anisotropy in active galaxies. The soft X-ray and UV emission from the central engine is reprocessed to infrared wavelengths by the dust in the torus. In 1983 IRAS was the first satellite to detect infrared emission from the relatively distant active galaxies. Soon after, several groups started to model this reprocessing using radiative transfer codes. Among the first to present their models are Pier & Krolik (1992), hereafter PK92. A few years later they are followed by Granato & Danese (1994), hereafter GD94 and Efstathiou & Rowan-Robinson (1995), hereafter ER95, and recently mod-
els have appeared by Nenkova et al. (2002) and van Bemmel & Dullemond (2003), hereafter BD03. The ISO satellite provided a wealth of additional data, however, only for the Seyfert galaxies these allow a good constraint of the models. For the radio-loud AGN population only few objects have a well defined broad-band SED, e.g. Cygnus A.

5.2 The early models: PK92, GD94 and ER95

To ease the radiative transfer calculations, all groups assume azimuthal symmetry, but the actual torus geometries differ among the different groups. PK92 define a so-called pill-box geometry, where the thickness of the torus is constant with radius, and the inner walls are perpendicular to the plane of the toroid. GD94 use a similar geometry, but with the possibility of having a conical hole in the center, instead of perpendicular walls. They also allow for different dust mixtures to be present in the torus. ER95 use three different geometries: a conical disk, where the thickness of the disk increases linearly with radius, an anisotropic sphere, and a pillbox with a conical hole. In all their models, the torus has a constant inner radius, causing the central opening to be circular (the opposite of the GD94 central cavity). All these ’early’ models assume Galactic dust properties.

5.3 The silicate problem

All three groups predict significant 10 µm silicate emission in type 1 active galaxies, which is not observed. The more powerful radio-loud population still lacks proper spectra, but the absence of 10 µm emission is well established by the ISO spectrometers for the Seyfert type AGN. GD94 postulate depletion of small grains by shocks in order to explain the lack of 10 µm emission in type 1’s. Only one of the ER95 pill-box model does not predict 10 µm emission.

This leads several groups to the conclusion that AGNs do not contain standard Galactic dust. The grain size distribution might differ significantly from the Galactic distribution, in the sense that AGN toroid dust is dominated by larger grains. This is first recognized by Laor & Draine (1993), and several groups have brought forth explanations for this. From UV spectra it becomes clear that also the 2200 Å absorption is shallower than expected in many AGN, consistent with the lack of small grains (Maiolino et al., 2001a).

Small grains are easily destroyed in the strong radiation field of an active nucleus. However, they should survive in the regions shielded by the torus. Several reasons have been presented in literature for the lack of small grains in AGN: most recently a clumping theory is presented by Maiolino et al. (2001b). The grains are swept up by the radiation pressure, and clump together to form larger grains.
5.4 The width problem

The early models encounter a second problem in explaining the full width of the broad-band SED observed in all types of active galaxies. Although the results from the models are generally broader than a single grey body, due to the temperature gradient in the dust, most of them are not yet broad enough. PK92 recognize this problem, and both GD94 and ER95 have tried to improve, but did not succeed.

5.5 A second component?

To deal with these issues, recent models have appeared in which the dust is no longer smooth, but clumpy (Nenkova et al., 2002), or has a non-Galactic grain size distribution (BD03). Both sets of models can produce the full observed width of the infrared SED of active galaxies, and both manage to circumvent significant 10 $\mu$m emission in models at small inclinations.

However, observational evidence is mounting that not all the infrared emission in active galaxies arises from the compact torus (see e.g., Spinoglio et al., 2002; Prieto et al., 2001). There must be a significant contribution from a second dust component, which seems to be related to star-formation in the host galaxy, i.e. at scales much larger than the radius at which the AGN can influence the dust. So far, all papers have ignored this possibility, except BD03. Such a second component may well provide a solution to the width problem in the early models. BD03 provide colour-colour diagrams for their models, showing that the observed 25–60 and 60–100 $\mu$m colours are not well fitted by single component torus models, and demand an additional dust component.

This secondary dust component might also be responsible for the lack of silicate emission observed in type 1 AGN; if the torus does produce 10 $\mu$m emission but this passes through a colder layer of dust, the resulting spectrum shows no 10 $\mu$m emission, or even a shallow absorption. However, this would require a large scale, spherical dust screen that covers all viewing angles to the nuclear regions. In the case of NGC 1068 there is no evidence of large scale silicate absorption: the nucleus seems to be the main source of the absorption. However, in this object the star-formation provides only a marginal fraction of the total infrared luminosity (Marco & Brooks, 2003), whereas it is thought to contribute at least 50% to the far-infrared emission in powerful radio sources.

For a proper understanding of dust in the nuclear regions of AGN the relative contributions of large and small scale dust need to be assessed. Decomposition will result in a better understanding of the behaviour of dusty tori in active galaxies, but also of the properties of the dust associated with star-formation in the host galaxies. Although the current generation of models is roughly consistent with observations, many important issues need to be solved. For this purpose, deep SIRTF low resolution spectroscopy data will be most welcome.
6 Conclusions

Good progress has been made during the past decade regarding aspect angle unification of radio-loud objects. The basic picture is correct, but the distinction between various classes appears somewhat blurred. The actual torus, big blue bump, and jet set-up, connected to source power and lifetime evolution, is not yet understood. The infrared might provide valuable clues, but we first need to understand how the various components contribute to the overall SED.

Acknowledgements

We acknowledge expert reading by healthy Ski Antonucci noting in passing that he fell ill just before the Workshop, leading the SOC to request the present reviewers to take over Ski’s review talk at 48h notice ..... The authors realize that this review is far from complete and does no justice to many active workers in the field. Apologies to those outside the review cone ....

References

Antonucci, R. 1993, A&AR, 31, 473
Baker, J. C. 1997, MNRAS, 286, 23
Baker, J. C., Hunstead, R. W., Athreya, R. M., et al. 2002, ApJ, 568, 592
Barthel, P. D. 1993, ASP Conf. Series, 54, 175
Best, P. N., Röttgering, H. J. A., & Longair, M. S. 2000, MNRAS, 311, 23
Biretta, J. A., Koekemoer, A. M.,Perlman, E. S., & O’Dea, C. P. 2002, NewAR, 46 (2–7)
Blundell, K. M. & Rawlings, S. 2001, ApJ, 562, L5
Canalizo, G. & Stockton, A. 2000, ApJ, 528, 201
Capetti, A., Celotti, A., Chiaberge, M., et al. 2002, A&A, 383, 104
Capetti, A., Schreier, E. J., Axon, D., et al. 2000, ApJ, 544, 269
Chiaberge, M., Capetti, A., & Celotti, A. 2001, MNRAS, 324, L33
Chiaberge, M., Macchetto, F. D., Sparks, W. B., et al. 2002, ApJ, 571, 247
Cohen, M. H., Ogle, P. M., Tran, H. D., Goodrich, R. W., & Miller, J. S. 1999, AJ, 118, 1963
Comastri, A., Setti, G., Zamorani, G., & Hasinger, G. 1995, A&A, 296, 1
Corbett, E. A., Robinson, A., Axon, D. J., & Hough, J. H. 2000, MNRAS, 311, 485
de Vries, W. H., O’Dea, C. P., Barthel, P. D., et al. 2000, AJ, 120, 2300
Dennett-Thorpe, J., Barthel, P. D., & van Bemmel, I. M. 2000, A&A, 364, 501
Efstathiou, A. & Rowan–Robinson, M. 1995, MNRAS, 273, 649
Giovannini, G., Cotton, W. D., Feretti, L., Lara, L., & Venturi, T. 2001, ApJ, 552, 508
Granato, G. L. & Danese, L. 1994, MNRAS, 268, 235
Guainazzi, M., Matt, G., Brandt, W. N., et al. 2000, A&A, 356, 463
Heckman, T. M., O’Dea, C. P., Baum, S. A., & Laurikainen, E. 1994, ApJ, 428, 65
Hes, R., Barthel, P. D., & Fosbury, R. A. E. 1996, A&A, 313, 423
Iwasawa, K. & Comastri, A. 1998, MNRAS, 297, 1219
Jackson, N., Tadhunter, C., & Sparks, W. B. 1998, MNRAS, 301, 131
Laor, A. & Draine, B. T. 1993, ApJ, 402, 441
Ledlow, M. J., N., O. F., & Eilek, J. A. 2002, ARA&A, 46, 343
Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, AJ, 115, 2285
Maiolino, R., Marconi, A., & Nagar, N. 2002, ASP Conf. Series, 258
Maiolino, R., Marconi, A., & Oliva, E. 2001a, A&A, 365, 37
Maiolino, R., Marconi, A., Salvati, M., et al. 2001b, A&A, 365, 28
Marco, O. & Brooks, K. J. 2003, A&A, 398, 101
Marecki, A., Barthel, P., Polatidis, A., & Owsianik, I. 2002, astro-ph/0209212
Murgia, M., Fanti, C., Fanti, R., et al. 1999, A&A, 345, 769
Nenkova, M., Ivezić, Z., & Elitzur, M. 2002, ApJ, 570, L9
O’Dea, C. P., de Vries, W. H., Koekemoer, A. M., et al. 2002, AJ, 123, 2333
Ogle, P. M., Cohen, M. H., Miller, J. S., et al. 1997, ApJ, 482, L37
Owsianik, I., Conway, J. E., & Polatidis, A. G. 1999, NewAR, 43, 669
Pier, E. A. & Krolik, J. H. 1992, ApJ, 401, 99
Prieto, M. A., Pérez García, A. M., & Rodríguez Espinosa, J. M. 2001, A&A, 377, 60
Schoenmakers, A. P., de Bruyn, A. G., Röttgering, H. J. A., van der Laan, H., & Kaiser, C. R. 2000, MNRAS, 315, 371
Spinoglio, L., Andreani, P., & Malkan, M. A. 2002, ApJ, 572, 105
Tadhunter, C. N., Morganti, R., Robinson, A., et al. 1998, MNRAS, 298, 1035
Tadhunter, C. N., Packham, C., Axon, D. J., et al. 1999, ApJ, 512, L91
Urry, C. M. & Padovani, P. 1995, PASP, 107, 803
van Bemmel, I. M. 2002, Ph.D. Thesis, University of Groningen
van Bemmel, I. M. & Barthel, P. D. 2001, A&A, 379, L21
van Bemmel, I. M., Barthel, P. D., & de Graauw, T. 2000, A&A, 359, 523
van Bemmel, I. M. & Dullemond, C. 2003, A&A, accepted
Whysong, D. & Antonucci, R. 2002, astro-ph/0207385
Wills, B. J. & Brotherton, M. S. 1995, ApJ, 448, L81
Woo, J.-H. & Urry, C. M. 2002, ApJ, 581, L5
Young, S., Hough, J. H., Efstathiou, A., et al. 1996, MNRAS, 279, L72