Cosmic evolution and unified models for radio AGN

J.V. Wall 1, C.A. Jackson 2

1 Department of Astrophysics, University of Oxford, Nuclear and Astrophysics Laboratory, Keble Road, Oxford, UK OX1 3RH.
2 Mount Stromlo Observatory, The Australian National University, P.O. Private Bag, Weston Creek, ACT, Australia 2611.

Abstract

A new method of deriving the cosmological evolution of radio AGN is described which is based on the premise of unified models for quasars and radio galaxies.

The ‘starburst vs monster’ debate takes place on several levels, for example the relation between starburst and AGN nuclear activity[1] and between background contributions[2]. The original version of the Madau diagram [3] led several authors in early 1997 to note the similarity between the cosmic histories of AGN and star formation rate [4, 5]. The Madau diagram has evolved [6], as has our view of how to determine space densities of AGN [7, 8]. Here we briefly set out this new view of the cosmic history of radio AGN, a history which must be correctly described if the relation between AGN and star-formation activity is to be understood.

Previous analyses assumed two radio-AGN populations (e.g. [9]) based on radio spectrum: ‘flat-spectrum’ (core-dominated, and predominantly quasars) and ‘steep-spectrum’ (extended emission, double structures, and predominantly radio galaxies). In view of unification models which posit that radio quasars and BL Lac objects are end-on versions of radio galaxies, such a dichotomy makes no sense; and the derivations of space densities have dubious interpretation.

1 The paradigm

Two anisotropic effects give rise to the unified view of quasars and radio galaxies [10, 11]: relativistically-beamed twin jets feed the double lobes of powerful radio sources [12], and the black-hole/accretion disk system is shrouded in a dusty torus whose axis is aligned with the radio axis [13]. A radio galaxy with double lobes is seen when the system is viewed side-on. As lines-of-sight approach the axis, the torus opening reveals the light of the nuclear black-hole/accretion-disk system which comes to dominate the galaxy light to produce a quasi-stellar object. When lines-of-sight coincide closely with the axis, Doppler enhancement of the relativistically-approaching radio jet leads to its compact flat-spectrum radio emission dominating the extended emission. Such ‘core-dominated’ quasars show superluminal motions in the jet structures as revealed by repeated VLBI observations (e.g. [14]).

Recognition of these two mechanisms has given rise to the two current paradigms of radio-source unification, based on FRI and FRII radio galaxies [15] as the two parent populations. The FRI radio galaxies show the two regions of highest surface brightness in radio emission.
along the jets feeding the double radio lobes; they are generally less powerful than the FRIIs, and do not show strong optical/UV emission lines. The core-dominated counterparts are BL Lac objects [16, 17]. The powerful FRII galaxies show the brightest regions at the extremities of the double lobes and have strong emission lines; their projected counterparts are steep-spectrum quasars (at angles to the line-of-sight permitting a view of the nucleus), and core-dominated quasars when the line-of-sight coincides closely with the radio axis.

The first step in our analysis (described in detail in [7, 8]) is to estimate space densities as a function of epoch for the two isotropically-radiating parent populations, the FRI and FRII radio galaxies. As these objects dominate low-frequency radio surveys, we use counts from the 3C and 6C (151 MHz) surveys and the 3CRR luminosity distribution ([18] and R. Laing, private communication; see Figure 1) to derive space densities following the procedure of Wall et al. [19]. A parametric representation of luminosity-dependent density evolution (Figure 1) is chosen to mimic the evolution found by Shaver et al. [20], and we determine the best-fit parameters through a downhill simplex minimization process.

![Figure 1: Luminosity distributions for the 26 FRI (cross-hatched) and the 137 FRII (hatched) radio sources in 3CRR. Right: Space density enhancements for the FRII parent population determined from optimized model parameters over the range of log(P_{151 MHz}) shown.](image)

The second step was to ‘beam’ these parent populations to determine the contribution they make to the beamed flat-spectrum populations found in higher-frequency (ν ≥ 1 GHz) surveys. We adopt the simplest possible beaming models, characterised for each of the two populations by two parameters, a Lorentz factor describing the speed of ejection and the ratio of the (rest-frame) fraction of beamed core emission to total emission. Using Monte Carlo runs randomly-orienting the parent sources, source-count predictions together with the proportion of beamed objects involved can be made at all frequencies. We use the minimization procedure to determine the beaming parameters providing the best prediction of the source counts at 5 GHz (Figure 2).

2 Results and discussion

For the parent populations, the new analysis of space densities now based on their completely-defined luminosity distributions finds three essential features. (1) Powerful evolution is required for the FRII population; in our parametric representation of evolution as exp(Mτ) with τ as look-back-time, M_{max} = 10.9 for the most radio-luminous FRII galaxies. (2) This density enhancement peaks at z_{c}/2 and tapers off to a redshift cutoff z_{c} (Figure 3). We obtain z_{c} = 5.6;
Figure 2: Left: the 5-GHz source count in relative differential form. The solid line shows the fit from optimization of the space density description and beaming parameters. Populations 1 and 3 represent FRII galaxies, populations 2 and 4 the relativistically-beamed quasars and BL Lacs from these parents; population 5 the FRI parent population; and population 6 the BL Lac objects, the beamed products from these. Line 7 represents the starburst-galaxy population which comes to dominate counts below 1 mJy. Right: the proportions of these same populations making up the total count at all flux levels. Note the rapid increase of starburst objects below 1 mJy.

The fit with this value is superior to the fit with no redshift cutoff at the 99.9% level of significance. (3) The FRI population shows little or no evolution ($M \approx 0$), in agreement with the relative uniformity of space density found for BL Lac objects ([21] and references therein).

As for the beaming models, we find an optimum value of Lorentz factor $\gamma = 8.5$ for the radio quasars which are the beamed products of the FRII parents; the BL Lac objects which are the beamed products of the FRI parents show $\gamma = 15.0$. These values are not dissimilar from those determined from VLBI observations of superluminal sources [22].

The analysis accounts for major features of the source statistics from a population definition which is physically meaningful. The increasingly broad ‘evolution bump’ in the source counts as survey frequency is raised comes about naturally through the increasing intrusion of beamed (flat-spectrum) objects. Despite the simplicity of assumptions, the limited data defining the luminosity distribution and the small number of parameters, the data are well described, as shown in Figure 2. Other tests are successful [8], including source-count prediction at different frequencies and the proportion of compact objects and broad-line objects as a function of flux density.

The success of the model demonstrates that essentially all radio AGN detected in sky surveys above 1 mJy may be encompassed by the unification hypothesis: quasars and BL Lac objects are double-lobed radio galaxies seen end-on. At smaller flux densities, the population of AGN declines and is replaced by the emergent population of starburst galaxies (Figure 2).

There are deficiencies. The model over-predicts counts at faint levels; better estimates of the local luminosity function and of the starburst-galaxy evolution (e.g. [23]) should be incorporated. Moreover it is now known that the redshift cutoff found for core-dominated objects [20] is a function of radio luminosity; the cutoff moves to lower redshifts as radio luminosity decreases [24]. At the highest radio luminosities the space density profile with redshift resembles the behaviour of the star-formation rate with epoch as determined by Steidel et al. [1]. The sim-
plastic ‘opera house’ models of figure require modification accordingly. Finally VLBA/VLBI surveys of core-dominated quasars show that there is a range in jet speed with median values lower than those found here. How these are related to the ‘apparent’ jet speeds found here requires further consideration. Such modifications are unlikely to destroy the basic tenet of the analysis, that essentially all AGN found in radio surveys above 1 mJy can be described by unified (orientation-dependent) schemes. The modifications will refine the definition of the AGN space-density profile, and at such time the implications for associations between the AGN phenomena and starburst activity may emerge with greater clarity.

References

[1] Terlevich E., Diaz A. & Terlevich R.J., 1990, *MNRAS* 242, 271
[2] Heckman T., 1999, (Ringberg Conference) astro-ph/9903047
[3] Madau P., Ferguson H.C., Dickinson M.E., Giavalisco M., Steidel C.C. & Fruchter A., 1996, *MNRAS* 283, 1388
[4] Wall J.V., 1998, in *Observational Cosmology with the New Radio Surveys* p.129, eds Bremer M.N. et al., Kluwer Academic Publishers
[5] Boyle B.J. & Terlevich R.J., 1998, *MNRAS* 293, L49
[6] Steidel C.C., Adelberger K.L., Giavalisco M., Dickinson M. & Pettini M., 1999, *ApJ*, in press
[7] Wall J.V. & Jackson C.A., 1997, *MNRAS* 290, L17
[8] Jackson C.A. & Wall J.V., 1999, *MNRAS* 304, 160
[9] Dunlop J.S. & Peacock J.A., 1990, *MNRAS* 247, 19
[10] Scheuer P.A.G., 1987, in *Superluminal Radio Sources* p.104, eds Zensus J.A. & Pearson T.J., Cambridge University Press
[11] Barthel P.D., 1989, *Astrophys. J.* 336, 606
[12] Blandford R. & Rees M.J., 1978, in *Pittsburgh Conference on BL Lac Objects* p.328, eds Wolfe A.M. et al., University of Pittsburgh
[13] Antonucci R., 1993, *ARA&A* 31, 473
[14] Pearson T.J. & Zensus J.A., 1987, in *Superluminal Radio Sources* p.1, eds Zensus J.A. & Pearson T.J., Cambridge University Press
[15] Fanaroff B. & Riley J.R., 1974, *MNRAS* 167, 31P
[16] Browne I.W.A., 1983, *MNRAS* 204, L23
[17] Morris S.L., Stocke J.T., Gioia I.M., Schild R.E., Wolter A., Maccacaro T. & Della Ceca R., 1991, *Astrophys. J.* 380, 49
[18] Laing R.A., Riley J.M. & Longair M.S., 1983, *MNRAS* 204, 151
[19] Wall J.V., Pearson T.J. & Longair M.S., 1980, *MNRAS* 193, 683
[20] Shaver P.A., Wall J.V., Kellermann K.I., Jackson C.A. & Hawkins M.R.S., 1996, *Nature* 384, 439
[21] Cavaliere A. & Malquori D., 1999, *Astrophys. J.* 516, L9
[22] Vermeulen R.C., 1995, in *Quasars and AGN: High Resolution Imaging* p.11385, eds Cohen M.H. & Kellermann K.I., Publ. Nat. Acad. Sci.
[23] Haarsma D.B., Partridge R.B., Waddington I. & Windhorst R.A., 1999, in *Proceedings of the 19th Texas Symposium*, in press, astro-ph/9904036
[24] Jackson C.A., 1997, PhD Thesis, University of Cambridge
[25] Kellermann K.I., Vermeulen R.C., Zensus J.A. & Cohen M.H., 1999, in *Proc 4th JIVE Symposium*, in press, eds Garett M.A. et al., New Astronomy Reviews, Elsevier Science