Cosmological evolution and large scale structures of radio galaxies and quasars

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Abstract. The simple unification scheme of powerful radio galaxies and quasars, based entirely on the orientation dependent effects, has been confronted with the observed radio structures for 152 radio galaxies and 173 steep spectrum quasars. Contrary to the scheme’s prediction, the cosmological evolution of geometrical parameters describing the large scale structure of these two types of radio sources are different. Linear size, arm ratio asymmetry and bending are all together stronger evolving with epoch for radio galaxies. Moreover, linear size and bending are more closely correlated with radio luminosity for radio galaxies than for quasars. This supports the supposition that, even if these two AGN classes are intrinsically identical sets of objects in deep interior regions, their large scale structures reveal rather various host environmental conditions which can lead to various classes of objects.

Key words: cosmology – galaxies: radio – quasars – galaxies

1. Introduction

The large scale structures of extended quasars and radio galaxies can be used as a test for radio galaxy-quasar unification schemes. If both the mentioned categories of radio sources are intrinsically the same type of objects but only appear different to an observer due to the various viewing directions, according to the Barthel’s (1989) hypothesis, then their radio structures are expected to evolve with redshift in the same way. This suggestion was put forward by Gopal-Krishna and Kulkarni (1992) on the grounds of radio linear sizes attained by extended quasars and powerful radio galaxies. However, Chyży and Zięba (1993, hereafter CZ), came recently, on the base of 152 radio galaxies and 173 quasars, to a quite contrary view indicating differences not only in the cosmological evolution of radio galaxy and quasar linear sizes but also in their size dependence on radio luminosity. A conclusion supporting this point of view was also reported by Singal (1993b) who examined a large sample of 789 sources. Singal (1993a) also showed that observed relative numbers and linear sizes of radio galaxies and quasars from 3CR sample are inconsistent with unification even invoking a cosmic evolution in the opening angle of obscuring torus $\psi$. In recent work Gopal-Krishna et al. (1994) tried to bring into agreement Singal’s results with the unified scenario by incorporating a misalignment between the radio axis and the axis of the visibility cone defined by the optically-thick torus surrounding the nuclear region. However, their approach seems to be not convincing enough regarding the involvement of rather large misalignment angles without any discussion of their distribution.

In this paper we present further investigation of cosmic evolution of radio structures based upon the other geometrical parameters which describe the observed structures. Apart from the simplest linear size parameter $L$ it is possible to determine two independent parameters assessing the asymmetry of the structure: the arm lengths ratio $Q$, defined as the ratio of the distances of hot spots from the core; and the misalignment $M$, which measures the apparent bending, and is defined as the ratio of the displacement of the core from the source axis to the linear size (see also Fig. 1 in Zięba and Chyży 1991, hereafter ZC).

The asymmetry parameters $Q$ and $M$ can potentially be a powerful tool in the consistency test for the orientation based unification scheme as, according to it, their evolutionary patterns should be the same for radio galaxies and quasars. Contrary to the linear size, they are not sensitive to the simple homological rescaling of the whole structure and hence to the age or expansion velocity of the structure. In that case, possibly revealed differences in asymmetry evolution of radio galaxies and quasars might give evidence in favor of even deeper physical differences between these two AGN types of sources. We per-
formed such a quantitative comparison of radio galaxy and quasar apparent asymmetry, evaluating the dependence of the $Q$ and $M$ parameters on redshift $z$ and spectral radio luminosity $P$ at 1.4 GHz.

We also discussed the importance of projection effects using observed $Q$, $M$ and $L$ distributions for finding the best fits of the kinematical model, consistent with unification scenario, separately for radio galaxies and quasars. A similar orientation modeling of radio source properties was also presented by Lister et al. (1994). Another approach to the problem of asymmetry observed among extragalactic radio sources based on the detailed brightness distribution was recently published by Ryś (1994).

### 2. The samples

The observational base for our discussion comprises two samples which were described and used in our earlier papers (ZC, CZ). The radio galaxy sample contains 152 triple, edge-brightened FRII powerful objects (Fanaroff and Riley 1974), carefully selected from the GB/G2 complete sample (Machalski and Maslowski 1982) and the 3CR sample (Spinrad et al. 1985), based mainly on the compilation of Macklin (1981). The main contributions to the quasar sample, containing 173 objects, come from Barthel et al. list (1988), Hintsen et al. (1983), Miley and Hartsjijker (1978), 3CR sample (Spinrad et al. 1985) and GB/G2 sources (Machalski and Maslowski 1982). To avoid undesirable bias all possible subgalactic compact steep spectrum sources (linear size less than 10 kpc) had been extracted from the final sample.

Arm lengths ratio, misalignment and linear size were calculated from the positions of the hot spots and the central component, which are usually found in publications, or were estimated directly from maps. Radio flux densities at 1.4 GHz and 4.85 GHz were taken from White and Becker (1992) and Becker et al. (1991) catalogues respectively. Spectral indices and luminosities at 1.4 GHz and 4.85 GHz were taken from White or were estimated directly from maps. Radio flux densities at 1.4 GHz were derived from the positions of the hot spots and the central component, which are usually found in publications, or were estimated directly from maps. Radio flux densities at 1.4 GHz and 4.85 GHz were taken from White and Becker (1992) and Becker et al. (1991) catalogues respectively. Spectral indices and luminosities at 1.4 GHz in the emitted frame of the sources were derived from those data using an Einstein-de Sitter Universe ($q_0 = 0.5$) with a Hubble constant $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$. Table 1 and 2 (accessible in electronic form) list all selected radio galaxies and quasars along with redshift, luminosity, estimated geometrical parameters $Q$, $M$, $L$ and literature data. The radio galaxy sample spans the redshift range $0.03 \leq z \leq 1.8$ and the luminosity $10^{24.2} < P [\text{W Hz}^{-1}] < 10^{26.1}$ and the quasar sample spans respectively $0.1 < z < 2.7$ and $10^{25.1} < P [\text{W Hz}^{-1}] < 10^{28.3}$.

### 3. Results

In order to derive the evolutionary behavior of the asymmetry of radio structures we estimated the dependence of the median values of $Q$ and $M$ parameter on redshift and radio luminosity in the form: $\alpha (1+z)^n$ and $\alpha P^\beta$ respectively. As the coverage of the $P$-$z$ plane by our radio galaxies and quasars is not uniform the special method was applied to eliminate the influence of the observed redshift-luminosity correlation. This method follows Oort’s (1987) approach and was in detail described in our earlier paper (ZC). The first step consists in binning the data in broad regions in the $P$-$z$ diagram, so that for equal radio luminosity bins (0.6 and 0.45 for radio galaxies and quasars respectively), the number of sources in each two dimensional region $P$-$z$ was about 13($\pm$3). The observed median values calculated for the resulting regions are presented in Fig. 1.

![Fig. 1.](image)

The dependence of a median value of an asymmetry parameter on redshift was fitted in subsequent steps, simultaneously with rescaling the parameter to the chosen luminosity using the updated values of the $P^\beta$ relation found in the previous step. The best solutions we have found for the fitted $n$ and $\beta$ when this approach was used on our quasar and radio galaxy samples are listed in Table IV together with 95% confidence intervals and analogous values estimated for linear sizes. All numbers presented in Table IV were calculated in a uniform manner using $\log(Q,M,L)$-$\log P$ and $-\log(1+z)$ planes for rescaling of the source parameters to a fixed radio luminosity $P = 10^{26} \text{ W Hz}^{-1}$ and redshift $z = 0$. The radio galaxies were taken on the whole without dividing them into classes of weak and bright objects as we did before (ZC,CZ). As a consequence some numbers now obtained are slightly different from those published earlier indicating this way how rescaling procedure influences the results, however the obtained general picture is the same. The striking re-
The comparison of observed structures of radio galaxies and quasars can be also performed by another, distinct method. Having, for both analysed samples, the observed distributions of \( Q, M, \) and \( L \) we looked for the best parameters of the three-point kinematical model that can reproduce the observational data, and explored ranges of values, and the sensitivities of the results to them. According to the model, two plasmons, simultaneously and non-collinearly ejected from the core at two opposite sides, propagate through the external medium with constant but different velocities. The three-point representation of a radio source (the core plus two plasmons) is projected onto the sky, taking into account the Doppler effect, thus producing an observed structure for which the \( Q, M, L \) parameters can be computed. The detailed description of the model and the exact simulation procedure for achieving the model distribution of \( Q, M, \) and \( L \) was presented in our earlier paper (ZC). However, in order to make the procedure consistent with the unification scheme, the line of sight angle \( \psi \), measured from the radio axis, was chosen at random from the probability density \( P(\psi) \propto \sin(\psi) \) within the viewing angle interval \([18^\circ, 90^\circ]\) for quasars and \([\psi, 90^\circ]\) for radio galaxies (Fig. 3).  

As quasars in our sample are triple sources, larger than 10 kpc, we eliminated from simulation objects seen almost along the radio axis, inside the cone of \( 18^\circ \). This number follows from the comparison of quasars counts in our sample and the 3CR complete data set.

The procedure for searching the model parameters was used separately for different subsamples of radio galaxies and quasars constructed from our data set. We distinguished quasars and radio galaxies in two redshift intervals for which both types of objects are observed. The first spans a range \( 0.2 < z < 0.7 \) and the second \( 0.7 < z < 1.4 \) (in Fig. 3 they fill together the \( P-z \) space between plotted dividing lines). This division gives a reasonable numbers of objects and does not join rather different sources in one class (e.g. there is a deficiency of quasars in our neighbour and scarcity of far away triple radio galaxies). The model
The numbers in Table 2 indicate that:

1. it is difficult to find, at a significant level of the goodness of fit, the same model parameters for quasars and galaxies treated in accordance with the unified scheme
2. the large probabilities resulting from all the fitting procedures in the cases of the pure quasar and radio galaxy subsamples show that the rather different physical conditions, disclosed by the unlike model parameters, are responsible for the observed differences between quasars and radio galaxies.

4. Discussion

Extragalactic radio sources are observed as (elongated) structures being rather far from spherical symmetry, so knowledge of their orientation to our line of sight is an essential part of understanding their intrinsic structure and possible strong selection effects. Properly speaking, in the simple unified scheme proposed by Barthel (1989) the differences between quasars and radio galaxies are simply treated as a result of a strong orientation effect.

Recently, the selection approach to the radio galaxy-quasar problem was favoured by Gopal-Krishna and Kulkarni’s papers (Gopal-Krishna and Kulkarni 1992, Gopal-Krishna et al. 1994), which based on the observed radio sizes and number densities of extragalactic radio sources. However, in order to explain the dis-
crepancy in counts between radio galaxies and quasars reported by Singal (1993a), Gopal-Krishna et al. (1994) had to incorporate intrinsic misalignment between radio axis and visibility cone in a rather large range of angles (with a mean 30°). The significant role of misalignment effects, but related to overall bending of a radio structure, was already mentioned in our first paper (ZC) and recently underlined in the work of Lister et al. (1994) where orientation modelling of radio source properties was presented. Although in conclusions Lister et al. accepted to some extent orientation as a major parameter, they warned against their evidence as a proof that there are no intrinsic differences too. They supported the unification mainly on the base that the radio galaxy structure modelled with the parameters estimated from quasar data are consistent with observed radio galaxy morphology.

Unfortunately, they have not presented any statistical measure of this consistency. As it is indicated in our analysis, finding satisfactory fits of kinematical model with the same parameters for both radio galaxies and quasars is difficult, hence the intrinsic structure of extragalactic radio sources must play an important role in the distinction between these two classes of objects. Of course, the line of sight angle should be taken into account but rather as a sort of factor which influence the observed structures of physically different sources. In 1991 McCarthy et al. showed that the asymmetry of radio source structures must be physically related to the condition of the galaxy environment, namely the presence of thermal line-emitting gas. According to their study, the closer of the two lobes always lies on the side of high surface brightness optical line emission. Among nearby galaxies, there is also observed the correlation of asymmetry with radio luminosity (the objects which are less powerful are also more asymmetric and smaller in size, e.g. ZC) which most likely arises from the interaction of expanding structures with the surrounding medium. In that case, one possible interpretation of the results from the estimation of kinematical model and the comparison of evolutionary trends of \( Q, M, L \) parameters for quasar and radio galaxy structures is slightly different state of galactic environment as-

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**Fig. 2.** Estimated cosmological evolution for geometrical parameters \( Q, M, L \) of the radio galaxy \((\circ)\) and quasar \((\Delta)\) structures

**Fig. 3.** Estimated dependency of radio luminosity on geometrical parameters \( Q, M, L \) of the radio galaxy \((\circ)\) and quasar \((\Delta)\) structures
associated with these objects, even if their deep interiors are identical.

An example supporting this point of view is the comparison of linear sizes of nearby \((z < 0.7)\) radio sources. In our data sample of complete 3CR and GB/GB2 surveys, contrary to the unification scheme prediction, the linear sizes of radio galaxies (the median \(131^{+14}_{-16}\)) are less at 10\% of significance level in Student’s test than quasars sizes (with the median \(174^{+10}_{-51}\)). A similar tendency was spotted by Singal (1993b) in a large data set and interpreted as an evidence against the unified-scheme model. The higher linear sizes of nearby quasars cannot be attributed to their possible higher redshift in comparison to radio galaxies since if the cosmological evolution of linear sizes is homogeneous the nearby quasars sizes would be even underestimated.

One can be suspicious about this contradiction owing to broad line radio galaxies (BLRG) which are sometimes treated as close quasars. In our sample 6 such objects are known. Because their median size is \(187^{+40}_{-77}\) they are certainly not smaller than ordinary quasars and their exclusion from radio galaxies would even raise disagreement with the unification.

One should also keep in mind that the discrepancy with simple unification scenario is visible on higher statistical levels when wider redshift range and the appropriate trends are discussed, which Singal (1993a) reported and which can be seen from the numbers in Table 2 which were calculated for objects with all possible redshifts. That is probably one of the reasons why our results differ from those reported in Barthel (1989) and McCarthy et al. (1991) papers. Besides, due to the dependence of \(Q, M\) and \(L\) parameter not only on redshift but also on luminosity the appropriate radio structure analysis should be fully 3-dimensional, in \((L, Q \text{ or } L) - z - P\) space, as in Singal’s and our approach and contrary to the study in the two papers mentioned above.

The obtained results can also be interpreted in the framework of a subpopulation of radio galaxies which owing to different physical and morphological properties separate from other galaxies and should not be unified with quasars. Large linear sizes and small fraction of nearby quasars suggest that such contaminating group of radio galaxies should consist of objects with low radio power and small linear sizes. Among close radio sources, there is already known a group of low luminosity, small, edge-darkened (FRI) structures, with very weak emission lines and no detectable broad lines and featureless continuum - so called dull galaxies (Antonucci 1993). They are probably analogous to weak liners in a group of radio quiet sources and therefore cannot be unified by orientation effects with broad line objects. In our subsample we have only radio galaxies with FRII morphology but few low redshift ones have radio luminosity below the arbitrary FRI-II break at \(10^{25}\) W/Hz at 1.4 GHz. However, the performed additional estimation of \(P^2(1 + z)^n\) model for our radio galaxies but without those weakest objects \((P < 10^{25})\) has not revealed any statistical change in the description of linear sizes evolution, thus differences between radio galaxies and quasars certainly remain above the FRI-II break.

An interesting possibility is also to suppose that also some low power radio galaxies of FRI type are optically dull, so they do not possess the broad line region (BLR) and hence do not participate in the unification with quasars. In fact, such a hypothesis has been put forward (Antonucci 1994) to explain Singal (1993a) results but detailed dull object properties, redshift or luminosity ranges have not been specified yet. To test this hypothesis we performed the estimation of \(P^2(1 + z)^n\) model once again but without the weakest and intermediate power radio galaxies \((P < 10^{26},\) roughly corresponding to \(z < 0.5\)). This time the description of galaxy linear sizes was different. The model parameters were estimated at not satisfactory confidence level that may be attributed either to low density of objects in \(P - z\) space or to higher diversity of morphological properties of objects. In any case, the possibility of dull FRII galaxies cannot be excluded, and the reported modelling set up the redshift limit for the contaminating group of galaxies as large as about \(z \approx 0.5\). The existence of this separate class of objects is appealing not only because it accounts for the observed evolution of relative number and linear size of quasars and radio galaxies, which otherwise cannot be explained in the framework of simple unification scheme. Supposing the absent-BLR objects have also more asymmetric and bent structures than the other galaxies (that is in concordance with observed growing of the asymmetry with smaller structures) they would also explain an intrinsic asymmetry and bending for nearby radio galaxies higher than for quasars (see in Table 2 parameters \(\mu_{max}\) and \(k\) for the first redshift range). Further spectropolarimetric observations of the all nearby radio galaxies should reveal whether the subgroup of FRII
objects without BLR really exists and hence whether this supplementation of simple Barthel’s unification scheme is correct.

However, there is still a problem in this framework with high redshift radio galaxies, which nevertheless seem to be more intrinsically asymmetrical and bent than quasars (see Table 3). That contradiction cannot arise from possible higher luminosity of these radio galaxies in comparison with quasars as one might judge from Figure 1: if the correlation of asymmetry with luminosity for nearby galaxies still holds for the distant ones we can speculate that less powerful high-redshift radio galaxies would be even more asymmetrical and bent than those included in our data set.

5. Conclusions

The main results of this paper can be summarized as follows

1. The investigation of radio structures of quasars and radio galaxies shows that the cosmological evolution of geometrical properties of these two AGN types are different. As well as linear size, the arm asymmetry and bending evolve more strongly with epoch for radio galaxies and their dependence on radio luminosity is also stronger for radio galaxies than for quasars.

2. The performed estimation of kinematical model shows that finding the same set of model parameters which reproduce radio galaxy and quasar observed structures according to the simple unification scheme is not possible on high level of statistical significance. The much better fits are achieved when the structures of these two kinds of sources are modelled individually.

These findings seem to contradict the pure unification scenario based entirely on the viewing angle and may reveal a slightly different state of environmental conditions established during the evolution of these objects.

The other attractive possibility explaining the considered data is to admit the existence of subpopulation of moderate redshift FRII galaxies without BLR and with slightly smaller and more asymmetric structures than the remaining part of the observed radio galaxies.

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