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Cosmic evolution of linear sizes and luminosity function of powerful radio galaxies: Is there a common cause?

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Abstract. For the population of active elliptical galaxies associated with powerful double radio sources, it is proposed that the empirically derived brightening of their radio luminosity function (RLF) and the statistical decrease in their linear size at higher redshifts (up to $z \sim 1$, or 2) could *both* arise if the hot gaseous halos seen to surround the ellipticals were denser at earlier epochs. The postulated density increase of the halo medium by about an order-of-magnitude between $z = 0$ and 1 would not just impart an extra stopping power needed to explain the smaller sizes of the double radio sources in the past but would, at the same time, enhance their efficiency for converting the beam power into radio emission by a factor which is quantitatively shown to be consistent with the empirically deduced evolution of the RLF up to $z \sim 1$. It seems thus possible to envision a *unified framework* for understanding the physical origin of these two well-known cosmological trends displayed by powerful radio galaxies. We also briefly explore a possible physical link between the two basic morphological classes of extragalactic radio sources, namely the powerful, edge-brightened and the weaker, edge-darkened double radio sources.

Key words: cosmology – galaxies: radio – galaxies: interstellar matter – galaxies: jets – radio sources: extended – X-rays: sources

1. Introduction

Recent years have witnessed an impressive progress in delineating the cosmic evolution of the radio source population, mainly on account of the increased degree of completeness attained in the distance estimates for samples of fainter radio sources (e.g. Dunlop & Peacock 1990, hereafter DP, and references therein). Combining such new data with previously-studied data sets, DP have recently shown that the radio luminosity functions (RLF) of both flat and steep spectrum radio sources evolve with redshift z, the evolution being positive up to $z \sim 2$ but, probably declining at higher redshifts. Further, out to $z \sim 1$, or even 2, the data seem consistent with pure luminosity evolution (also, Peacock 1990); between $z = 0$ and 1 the RLF shifts to about an order-of-magnitude higher radio luminosity. The origin of the evolution is, however, not clear.

Another interesting cosmological trend established during the past few years concerns the linear sizes of powerful radio sources whose extremities are usually marked by compact hot spots. For such edge-brightened double radio sources, associated with highly active elliptical galaxies, it has been demonstrated that at fixed radio luminosity, the median linear size $2D = l \propto (1+z)^{-3}$ (Kapahi 1987, 1989; Oort et al. 1987; Singal 1988; Swarup 1988). Further, most of these workers have found that at fixed z the median size, l, increases with monochromatic radio power, P, approximately as: $l \propto P^{0.3}$. Attempts to understand these phenomena have been made by considering the propagation of beams through the hot gaseous halos (Gopal-Krishna & Wiita 1987, 1988, hereafter GW87 and GW88; Gopal-Krishna et al. 1989; Wiita et al. 1990), as revealed by the X-ray imaging of many nearby massive ellipticals (Forman et al. 1985; Trinchieri & Fabbiano 1985; Canizares et al. 1987). In this context a cosmological evolution of the dense galactic halos has also been postulated (Swarup 1988; Barthel & Miley 1988). Such a notion might be a more realistic extension of the original scheme that attributed the linear-size evolution to an evolving uniform intergalactic medium with density being higher when the universe was less expanded (e.g. Miley 1971; De Young 1971; Wardle & Miley 1974).

In a quantitative development of the idea of evolving galactic halos, Subramanian & Swarup (1990) have recently estimated that a large increase in the halo gas density, by an order-of-magnitude between $z = 0$ and 0.5, would be required to explain the $l - z$ relation. In a related work, Gopal-Krishna & Wiita (1991, hereafter GW91) have drawn attention to the deficiency arising from the usual practice of comparing sources of similar radio luminosities (instead of similar beam powers, which is the real intrinsic quantity). We estimated that the efficiency of radio emission is a rather strong function of the ambient density. By incorporating this quantitatively into the model for beam propagation through a galactic halo (GW87), it was found that a relatively modest increase in the halo gas density (by a factor of ~ 3 by $z = 0.5$ and ~ 14 times by $z = 1$) would suffice to explain the observed linear-size evolution. In particular, it was found that a good part of the observed $l - z$ relation is probably an artefact of an increased efficiency of converting beam power into radio emission, resulting from a denser ambient halo medium at earlier epochs; the "intrinsic" size evolution (i.e., measured at fixed beam power, L_b) is considerably slower. The model also provided an excellent fit to the observed correlation, $l \propto P^{0.3}$, mentioned above. Further, the postulated modest increase in the halo gas density with z was shown to be in accord with the limit set by the soft X-ray background, since the estimated conribution from all massive ellipticals up to $z = 1$ would add up to just $\sim 1\%$ of the observed 2 keV background. Interestingly, such an inferred evolution of the halo gas density seems to be consistent with the recent studies of the optical nebulosities around quasars (Forbes et al. 1990; Heckman et al. 1991). In this communication we shall argue that the same physical approach invoking cosmologically evolving galactic halos and the concomitant rise in the radio efficiency can also quantitatively explain the redshift-dependence of the RLF of active elliptical galaxies. Thus, quite plausibly, a single underlying cause may be responsible for the cosmological evolution of both the RLF of powerful radio galaxies and of their linear sizes.

2. The model

We first present the essential outline of our analytical model, additional details of which are presented in GW91. The model considers the dynamics of a conical beam of relativistic plasma through a hot galactic halo whose density profile is a scaled-up version of the density distribution deduced for nearby ellipticals:

$$n(D, z) = \frac{n_0 \eta(z)}{[1 + (D/a)^2]^{\delta}}. \tag{1}$$

The X-ray observations have yielded $\delta \sim 0.75$, $a \sim 2\,\mathrm{kpc}$, $n_0 \sim 10^{-2} - 10^{-1}\,\mathrm{cm}^{-3}$ and a temperature $T_\mathrm{h} \sim 10^7\,\mathrm{K}$ as typical values for the halo parameters (Forman et al. 1985; Fabbiano & Trinchieri 1985; Canizares et al. 1987). $\eta(z)$ is the density-scaling factor characterising the postulated modest cosmological evolution of the halos, which is shown to explain the linear-size evolution data and is independently supported by the recent optical studies of the environments of distant active galaxies (Sect. 1). Lacking the X-ray images of distant galaxies, we make the neutral assumption that the halo parameters δ, a and T_h, as well as the density distribution profile do not change with z, at least up to a redshift of ~ 1, which is as far back as it seems currently reasonable to extrapolate this simple scheme of cosmologically evolving halos. At a time t, the head of a conical beam with an opening angle θ and kinetic power L_b would be at a separation D from the nucleus, given by

$$D(t) = [A\, t\, (L_\mathrm{b}/n_0 \eta)^{1/2}]^{1/(2-\delta)}, \tag{2}$$

with

$$A = (2-\delta)\, a^{-\delta} [4 K_1/(\pi \mu m_\mathrm{H} \theta^2 c)]^{1/2},$$

where K_1 is a constant of order unity, μm_H is the mean molecular mass and c is the speed of light (GW87). The best available estimates for the duration of intense nuclear activity, t_max, are $\sim 10^8\,\mathrm{yr}$, or somewhat smaller (Gopal-Krishna & Wiita 1989; Leahy et al. 1989; Efstathiou & Rees 1988). We assume this duration to remain unchanged over the relevant range of redshift ($z = 0 \rightarrow 1$).

Here it is important to recall an important property of powerful double radio sources, namely that the parts accounting for most of the radio luminosity typically coincide with the ends of the twin-beams and comprise only ~ 10–20% of the entire source extent and this fraction appears to remain unchanged with redshift, at least out to $z \sim 1$ (see, Kapahi 1978; Miley 1980). Thus, we adopt for the lobe diameter $2R \sim 0.15\,D$ and, hence, the time over which the currently bright portion of the lobe has been created by the advancing beam is $t_\mathrm{a} \sim 0.15\,(2-\delta)\,t$, from differentiating Eq. (2). Further, the part of the medium into which the relatively small, bright portion of the lobe is inflated can be reasonably approximated to have a uniform density, though a large density variation is expected over the entire extent of a typical radio source ($\sim 350\,\mathrm{kpc}$ for $z \sim 0.1$, taking $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, which will be assumed throughout this paper, GW87).

A first-order estimate of the radio-emitting efficiency can now be obtained employing the model for the energetic evolution of a synchrotron emitting uniform radio lobe, developed recently by Eilek & Shore (1989, hereafter ES). In this somewhat "idealized", yet the most detailed model available, it is assumed that the beam deposits into the lobe constant fractions of its energy, L_b, in the forms of relativistic electrons, ions, thermal particles and magnetic fields. Thus,

$$L_\mathrm{b} = F_\mathrm{e} + F_\mathrm{i} + F_\mathrm{th} + F_\mathrm{B}. \tag{3}$$

Further, assuming that the lobe expands into a uniform density external medium at a pressure much higher than the external pressure (both conditions being quite applicable to the present case), ES show that the radius of the lobe at an age t_a is,

$$R(t_\mathrm{a}) = a' \left[\frac{125 a' b (\Gamma - 1)}{189 \Gamma - 84} \frac{L_\mathrm{b}}{\varrho_\mathrm{a}}\right]^{1/5} t_\mathrm{a}^{3/5} \equiv a' C^{1/3} t_\mathrm{a}^{3/5}. \tag{4}$$

Here Γ is the adiabatic index of the lobe plasma, ϱ_a is the ambient density and a' and b are constants of the orders of 1 and 10, respectively, reflecting the geometry of the lobe.

Using Eqs. (14) and (15) of ES, the "bolometric" synchrotron efficiency arising mainly due to relativistic electrons can be shown to be

$$\varepsilon_\mathrm{bol}(t) = \frac{L_\mathrm{e}(t_\mathrm{a})}{L_\mathrm{b}} = \frac{\beta_1 e_\mathrm{eb}}{m_\mathrm{e}} \frac{B^2(t_\mathrm{a}) E_\mathrm{e}^2(t_\mathrm{a})}{L_\mathrm{b} F_\mathrm{e} t_\mathrm{a}}. \tag{5}$$

Here e_eb is the average energy of an electron emerging from the "working surface" at the beam's head, assumed to remain constant with time, E_e is the total energy in electrons, m_e is the rest mass of an electron, $\beta_1 = \sigma_\mathrm{T}/(4\pi c^3) \sin^2\chi$, taking σ_T to be the Thompson cross section and χ the electron pitch angle. Also, from Eqs. (23) and (25) of ES: $B^2(t) \propto (F_\mathrm{B}/C)\, t^{-4/5}$, and $E_\mathrm{e}(t) \propto F_\mathrm{e}\, t$ for times short compared with initial electron radiative lifetime $\tau_\mathrm{sy,\,b}$ (note that this condition is largely satisfied as seen from the lack of strong spectral gradients over the bright outer parts of the radio lobes, (GW 1991; Leahy et al. 1989). Using the above relations, we get from Eq. (5):

$$\varepsilon_\mathrm{bol}(t_\mathrm{a}) \propto L_\mathrm{b}^{2/5}\, t_\mathrm{a}^{1/5}\, \varrho_\mathrm{a}^{3/5}. \tag{6}$$

Now, the power emitted between frequencies ν_1 and ν_2 for a power-law distribution of electron energies such that the flux density $S_\nu \propto \nu^\alpha$ is given by ES Eq. (26),

$$L_\mathrm{R} = \varepsilon L_\mathrm{b} = \varepsilon_\mathrm{bol} \left[\frac{\nu_2^{1+\alpha} - \nu_1^{1+\alpha}}{\nu_\mathrm{m}^{1+\alpha} - \nu_0^{1+\alpha}}\right] L_\mathrm{b}, \tag{7}$$

where $\nu_\mathrm{m} \propto e_\mathrm{m}^2 B$ and $\nu_0 \propto e_0^2 B$, and e_m and e_0 are the upper and lower electron energy cutoffs, respectively. For typical spectral index $\alpha > -1$ the term inside brackets in Eq. (7) is dominated by $\nu_m^{-(1+\alpha)}$ and, as e_m can be shown to vary as $t^{-1/5}$ (see ES Appendix B), we find:

$$\begin{aligned}\varepsilon(t_\mathrm{a}) &\propto \varepsilon_\mathrm{bol}(t_\mathrm{a})\, [e_\mathrm{m}^2(t)\, B(t)]^{-(1+\alpha)} \\ &\propto \varepsilon_\mathrm{bol}(t_\mathrm{a})\, [t_\mathrm{a}^{4/5}\, \varrho_\mathrm{a}^{-3/10}\, L_\mathrm{b}^{3/10}\, F_\mathrm{B}^{-1/2}]^{(1+\alpha)}\end{aligned} \tag{8}$$

Substituting Eq. (6) into Eq. (8) and recalling that $F_\mathrm{B} \propto L_\mathrm{b}$, [see Eq. (12) of GW91]:

$$\varepsilon(t_\mathrm{a}) \propto t_\mathrm{a}^{(5+4\alpha)/5}\, \varrho_\mathrm{a}^{3(1-\alpha)/10}\, L_\mathrm{b}^{(1-\alpha)/5}. \tag{9}$$

For $D \gg a$, Eq. (1) implies $\varrho_\mathrm{a} \sim n_0 \eta(z) (D/a)^{-2\delta}$. Substituting the value of D from Eq. (2) and taking $t_\mathrm{a} \sim 0.15\,(2-\delta)\,t$ (see above):

$$\varrho_\mathrm{a} \propto \{n_0 \eta(z)\}^{2/2-\delta} \{L_\mathrm{b}\, t_\mathrm{a}^2\}^{\delta/\delta-2}. \tag{10}$$

Substituting Eq. (10) into Eq. (9), we finally get:

$$\varepsilon(t) \propto t^X \eta^Y L_b^Z, \tag{11}$$

where $X=(5+4\alpha)/5+3\delta \quad (1-\alpha)/5(\delta-2)$, $Y=3(1-\alpha)/5 \quad (2-\delta)$ and $Z=\{(1-\alpha)/10\}\ \{(5\delta-4)/(\delta-2)\}$.

Note that for typical values of $\delta\,(0.75)$ and $\alpha\,(-0.8)$, ε is barely sensitive to $t\,(\varepsilon \propto t^{-0.29})$ and even less to $L_b\,(\varepsilon \propto L_b^{0.036})$. Thus, making a reasonable assumption that the typical ages of powerful radio galaxies at $z=0$ and 1 are nearly the same, it follows from Eq. (11) that a roughly 15 times scaled-up halo density between $z=0$ and 1 [$\eta(1) \sim 15$] would yield ~ 10 times stronger radio source at $z=1$, as compared to a local radio source powered by an equally energetic beam.

3. Discussion and implications

Transforming the local radio luminosity function for extended radio sources associated with elliptical galaxies (DP) by applying the luminosity evolution according to Eq. (11) yields the RLF at a higher redshift, as predicted by the present model for the region of RLF above the break. The predicted RLF for $z=1$ is compared in Fig. 1 with that derived by DP empirically using complete samples of radio sources (Sect. 1). A good agreement is found for a halo density scaling factor $\eta\,(z=1) \sim 15$ which is very close to value $\eta\,(z=1)=14 \pm 3$ inferred *independently* from an application of this same model to the linear-size data on radio galaxies (GW91; Sect. 1). It may be noted that we have restricted the application of the model to the part of RLF above the break, since the lower luminosity regime of the RLF is mainly populated by edge-darkened sources (Fanaroff & Riley 1974) to which the model in its present form cannot be applied. But, qualitatively, even such weaker sources are expected to radiate more efficiently in a denser environment due to a better confinement; the effect is, though, harder to quantify. Thus, a positive luminosity evolution of the entire RLF with increasing redshift can be expected, consistent with the observationally inferred trend up to at least $z \sim 1$ (DP; Fig. 1).

The quantitative agreement between the values of η deduced from the modelling of the redshift dependences of linear-sizes and RLF of powerful double radio sources is indicative of a common underlying cause. This raises the possibility of unifying the physical understanding of these two important cosmological effects revealed by the studies of extragalactic radio sources during the past couple of decades. It is further encouraging that the halo density evolution inferred by us is fairly consistent with the recent optical observations of the filaments in the environments of quasars (Forbes et al. 1990; Heckman et al. 1991) and is also supported by the theoretical modelling of the ISM of elliptical galaxies (David et al. 1990). Since a denser galactic halo medium, besides boosting the radio efficiency, is also expected to enhance the optical line emissivity via a more effective confinement of the thermal filaments embedded within the halo, the observed correlation between the radio lobe emission and [O III] line luminosity for powerful radio galaxies (Rawlings et al. 1989; also Baum & Heckman 1989) can indeed be expected. Also, conceivably, the positive correlation found between the radio core and lobe emission (e.g. Rawlings et al. 1979; Giovannini et al. 1988) may have a similar physical connection. The other evidences for a denser circumgalactic medium and a stronger jet-halo interaction at higher redshifts include: (i) the optical detection of huge (~ 100 kpc) galaxy halos of ionised gas around high-z galaxies, and (ii) the observed alignment of such gaseous halos and of the optical/infrared galactic continua with the radio jets at higher redshifts (see Miley & Chambers 1990; McCarthy 1990).

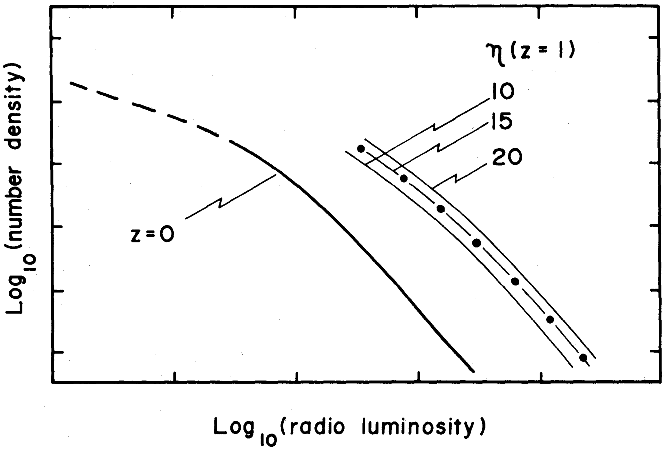

Fig. 1. The thick curve shows the local radio luminosity function (RLF) for steep-spectrum extragalactic radio sources, plotted on logarithmic scale in arbitrary units (DP). The broken curve extending to lower powers refers to the regime populated mostly by weaker, edge-darkened radio sources which fall outside the scope of the model presented here. The thin lines illustrate the luminosity evolution of the RLF; as predicted by our model for $z=1$ and the three indicated values of the halo density – scaling factor $\eta\,(z)$ [Eq. (11)]. The dots delineate the RLF at $z=1$, resulting from the empirical modelling of the radio-optical data on radio source samples (Fig. 7 of DP)

3.1. *The break in the RLF and the two morphological classes of radio sources*

Finally, we briefly discuss an important feature of the RLF, namely the "break", originally noted by Auriemma et al. (1977) (Fig. 1). A recent plot of the local RLF for early-type galaxies by Franceschini et al. (1988) shows a flattening i.e., the, so called, break, near a power $P^* \sim 10^{24}\,\mathrm{W\,Hz^{-1}}$ at ~ 2 GHz (see also GW88). Integrating over the radio band, taking $\alpha=-0.8$, and adopting a reasonable value for radio efficiency $\varepsilon \sim 0.1$ (GW91) the observed P^* translates to a beam power $L_b \sim 10^{42}\,\mathrm{erg\,s^{-1}}$. Differentiating Eq. (2), the velocity of the beam head would be:

$$V(t)=\frac{1}{(2-\delta)}\left\{A\left(\frac{L_b}{n_0\,\eta}\right)^{1/2}\right\}^{1/(2-\delta)} t^{(\delta-1)/(2-\delta)}, \tag{12}$$

where A is defined following Eq. (2). Substituting the observationally determined values of $\delta=0.75$, $a \sim 2$ kpc and taking $L_b=L_b^* \sim 10^{42}\,\mathrm{erg\,s^{-1}}$, Eq. (12) gives for $z \sim 0$ (i.e., $\eta=1$):

$$V\,(t=10^7\,\mathrm{yr}) \simeq 500\,\mathrm{km\,s^{-1}}$$

$$\cdot\left\{\frac{\theta}{10\,\mathrm{deg}}\right\}^{-0.8}\left\{\frac{n_0}{0.01\,\mathrm{cm^{-3}}}\right\}^{-0.4}\left\{\frac{t}{10^7\,\mathrm{yr}}\right\}^{-0.2},$$

where $\theta \sim 10°$ has been inferred from the maps of jets in the sources of intermediate radio power corresponding to the region of the "break" in RLF (e.g. Bridle 1986). $n_0 \sim 0.01\,\mathrm{cm^{-3}}$ is deduced from X-ray observations (Sect. 1).

From the above simple dynamical picture it is thus apparent that well before the end of the nuclear activity, which is expected to last for $\sim 10^8$ yr (GW91; Sect. 1), a point may be reached when, having propagated only ≈ 10 kpc from the nucleus, the beam has been decelerated to $V \sim 500\,\mathrm{km\,s^{-1}}$, i.e., close to the sound velocity in the halo [$c_s=(\gamma k T_h/\mu m_H)^{1/2} \sim 500\,\mathrm{km\,s^{-1}}$ for the halo temperature $T_h \sim 10^7$ K, adiabatic index $\gamma = 5/3$ and Boltzmann constant $k = 1.38\ 10^{-16}$ erg deg^{-1}]. The subsequent evolution of such "arrested" jets, in the absence of ram pressure confinement, would be marked by the absence of hot spots near their extremities and a rapid radio fading, leading to their reduced contribution to the RLF. As discussed by Gopal-Krishna & Wiita (1988, GW 88), a flattening of the RLF is expected to arise naturally in such a situation, even if no corresponding flattening is present in the distribution of intrinsic power, i.e., L_b. Moreover, the relativistic plasma delivered by such jets would slowly advance as a plume made of a quasi-continuous string of bubbles, rising buoyantly in the galactic halo, instead of advancing supersonically as a well confined flow (GW 88). Such a physical scenario could, thus, broadly explain *both* the origin of the break in the RLF and the preponderance of edge-darkened sources below the break, two well-known attributes of the extragalactic radio source population (Auriemma et al. 1977; Miley 1980).

Thus, although the treatment presented here is a grossly simplified version of a complex situation, a substantially more comprehensive analysis without resorting to many additional assumptions would only be possible after the energetics and dynamics of radio lobes has been understood in much greater detail. It is nonetheless encouraging that even the rather idealized approach attempted here is capable of quantitatively reproducing some of the most salient properties of extragalactic radio sources and their cosmological evolution up to fairly high redshifts.

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