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The expansion and cosmological evolution of powerful radio sources

Gopal-Krishna *Tata Institute of Fundamental Research, PO Box 1234, Indian Institute of Science Campus, Bangalore 560 012, India*

Paul J. Wiita *Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303, USA*

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Summary. A simple analytical model is formulated to study beam dynamics in powerful extragalactic radio sources. Two phases are considered for the beam propagation: first through the gaseous halo of the parent galaxy and then through a much hotter intergalactic medium (IGM). These two media are conceived to be pressure-matched at their interface, which is expected to move closer to the parent galaxy with increasing redshift, owing to a steeply rising IGM pressure. We argue that the advance of the beam can be ignored quantitatively (notwithstanding a continuing nuclear activity) once its rate has become subsonic relative to the ambient medium.

For the input parameters to the model, we adopt from the literature typical values for a powerful radio source, its associated X-ray emitting halo, and the IGM, and show that the model can explain in a fairly natural way the observed linear sizes of the sources at small redshifts and also their cosmological evolution. The possible relevance of the model to the reported prevalence of subgalactic-sized sources at very high redshifts ($z \gtrsim 2$) is also discussed.

1 Introduction

At least up to moderate redshifts ($z \lesssim 1$), most powerful radio sources ($P_{1.4\,\mathrm{GHz}} \gtrsim 10^{25}\,\mathrm{W\,Hz^{-1}}$) are found to consist of a pair of radio lobes straddling a massive elliptical galaxy or quasar. As noted by Fanaroff & Riley (1974), bright spots of radio emission are found near the extremities of the lobes and it is now commonly accepted that these hotspots are energized by narrow jets emanating from the nucleus of the central galaxy (Bridle & Perley 1984). The separation between the pair of hotspots defines the overall linear size of the radio galaxy which, for nearby sources ($z \sim 0.1$), has a median value of about 350 kpc for an assumed Hubble constant of $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (e.g. Kapahi 1985; Gopal-Krishna *et al.* 1986; Kapahi 1986). Also from recent studies, it has been established that the median linear size for samples of similar radio luminosities decreases with cosmological redshift z, roughly as $(1+z)^{-\sigma}$ where $\sigma=1-2$ (Kapahi 1985, 1986; Eales 1985; Gopal-Krishna *et al.* 1986).

From recent X-ray observations, there is a strong indication that hot gaseous haloes or coronae are associated with most massive early-type galaxies including those lying near the periphery of the Virgo cluster and relatively isolated large elliptical galaxies (Forman, Jones & Tucker 1985: hereafter FJT). Further, a re-analysis of the 5–200 keV X-ray background emission favours the hypothesis that a hot intergalactic medium (IGM) with a present density of $\sim 7\times10^{-7}\,\mathrm{cm}^{-3}$ and temperature between 10–25 keV pervades the Universe (Guilbert & Fabian 1986). In this paper we show that both the median linear size at the present epoch and its cosmological evolution can be understood in terms of a simple but reasonable model for jet propagation through the corona and IGM.

2 The gas distribution

2.1 THE X-RAY HALOES

Extensive haloes around giant elliptical galaxies like M87 and NGC 1275 have been studied by Fabian, Nulsen & Canizares (1984) and Sarazin (1986) among others. Large cooling inflows, perhaps leading to thermal instabilities and star formation, have been inferred, although this conclusion is controversial (Stewart *et al.* 1984; Fabian *et al.* 1985; Bertschinger & Meiksin 1986; Miller 1986). Powerful radio sources nevertheless usually avoid regions of high galactic density (Longair & Seldner 1979), and it is radio sources of this type that we are concerned with here. The weaker X-ray emission from ellipticals near cluster peripheries and from relatively isolated galaxies has meant that they have not been so well mapped. Nonetheless, recent analyses of the *Einstein* Imaging Proportional Counter data for 55 optically bright early-type galaxies has shown that they typically possess haloes emitting between 10^{39} and $10^{42}\,\mathrm{erg\,s^{-1}}$ (Stanger & Schwarz 1986; Long & van Speybroeck 1983; Nulsen, Stewart & Fabian 1984; FJT). X-ray surface brightness profiles could be deprojected for 13 of the galaxies in that sample, yielding good fits to electron density models of the type $n(r)\propto[1+(r/a)^2]^{-3\beta/2}$ where the core radius, a, ranged from ~1.5 to ~6 kpc and β was 0.5 ± 0.1 (FJT). The maximum radius to which X-ray emission could be detected ranged from 15 to 110 kpc (i.e. ~30 core radii). FJT argue that the gas distributions are essentially hydrostatic, since all the profiles are close to $r^{-1.5}$ and not to r^{-2}, which would be characteristic of an outflowing gas (wind). Further, infall models demand extremely high galaxy masses (FJT). The available data are consistent with approximately isothermal haloes whose characteristic temperatures are between 0.8 and 3 keV. Allowance for moderate positive temperature gradients (cooling inflows) would not significantly affect either FJTs or this paper's conclusions. Note that all these galaxies in the *Einstein* sample belong to nearby space ($z<0.1$) and no X-ray maps are available for distant galaxies.

For our purposes we assume that the haloes themselves have not evolved much since $z\sim1$, and in particular that their pressure distribution has not changed significantly over that period. This implies that we are assuming that the galactic masses have remained practically constant so the amount of gas at a given temperature that can be bound has remained the same. This supposition is conservative with respect to our argument on linear size evolution (Section 4) in that, if galaxies have grown in that period, even smaller haloes would have been present in the past.

Further, we assume that, at least over this period, the supernova (SN) rate, and therefore the dominant heat input to the gas, has stayed the same. This assumption is reasonable for the best understood case, our Galaxy (e.g. Twarog 1980), but is uncertain for radio galaxies where some evidence for bluer colours, and presumably enhanced star formation, at $z\sim1$ has been reported (Lilly, Longair & Allington-Smith 1985). This uncertainty in the heating history is unfortunate for it could act either way: if the enhancement in the SN rate was relatively small, the corona would have been hotter and somewhat larger in the past, but if the earlier SN rate was sufficiently high, the gas would have been expelled as a wind, leaving the galaxy essentially stripped of a corona (Mathews & Baker 1971).

Our final key assumption is that an heat conduction from the IGM to the halo has not been significant in determining the temperature and extent of the halo. Although Bertschinger & Meiksin (1986) have shown that, in the absence of a tangled magnetic field, conduction should be important, we adopt the common viewpoint that the presence of even a minute magnetic field provides adequate insulation (e.g. Stewart *et al.* 1984). It is important to realize that the above assumptions on the nature of galactic haloes at earlier times could be significantly relaxed and the main point of our argument would not be much affected (Section 4).

2.2 THE INTERGALACTIC MEDIUM (IGM)

Evidence for the existence of a hot IGM has been frequently discussed (e.g. Cowsik & Kobetich 1972; Field & Perrenod 1977; Fabian & Kembhavi 1982). A recent analysis by Guilbert & Fabian (1986) shows that point X-ray sources are not likely to be the major contributors to the X-ray background. Their analysis of the possible IGM incorporates relativistic corrections to the gas emissivity and thermodynamics as well as Compton scattering of the microwave background, and leads to densities lower than those found by some previous workers; this model requires a major injection of heat at a redshift between 3 and 6 and yields current IGM densities of $6-9\times10^{-7}\,\mathrm{cm}^{-3}$, and satisfactory fits to the X-ray background from 5–200 keV are obtained with current temperatures between 11 and 25 keV. These values correspond to baryon densities of 0.22–0.32 of the closure density and are therefore nominally inconsistent with the observed deuterium abundance, although clumping of the IGM or the possibility of post-cosmological nucleosynthesis of deuterium (Ramadurai & Rees 1985) could obviate this difficulty. An advantage of this picture is that the Compton-scattered high-energy tail can produce a significant fraction of the 100-μm infrared background (Rowan-Robinson 1985). Here, we assume the validity of this description of the IGM and use the standard relations: $\varrho_{\mathrm{IGM}}(z)=\varrho^*_{\mathrm{IGM}}(0)(1+z)^3$ and $T_{\mathrm{IGM}}(z)=T^*_{\mathrm{IGM}}(0)(1+z)^2$, so that the pressure $P_{\mathrm{IGM}}(z)=P_{\mathrm{IGM}}(z=0)(1+z)^5$.

Within the above framework the size of the halo, R_{h}, decreases with increasing redshift, since the halo pressure is approximately constant while the IGM pressure rises steeply. At the current epoch, we find $R_{\mathrm{h}}\simeq170$ kpc (Section 3), balancing $P_{\mathrm{IGM}}(0)$ against the pressure distribution in the halo.

3 The beam dynamics

A few analytic models for the propagation of beams have been discussed by Scheuer (1974) for the case of a uniform ambient medium. A modification was subsequently suggested by Baldwin (1982) to account for beam propagation inside an extended halo of hot gas associated with the parent galaxy, with a power-law decrease in density with radius. Here we present a slightly refined beam propagation model, taking into account (i) the more recent determinations of gas density profiles around massive and relatively isolated early-type galaxies (FJT), which are believed to produce typical powerful radio sources (*cf.* Longair & Seldner 1979); and (ii) the beam propagation in a two-component medium comprised of a gaseous halo bound to the parent galaxy (medium 1) and the surrounding (hotter) IGM of uniform density (medium 2). The two-component model seems warranted since, at small redshifts ($z\sim0.1$), the halo–IGM interface is expected to occur at a distance $D\sim125$ kpc from the galactic nucleus (see below) and the beams of a majority of classical double sources at such redshifts should then have already penetrated beyond the interface, considering that the observed median overall size for $z=0.1-0.2$ is around 350 kpc (Kapahi 1985; Gopal-Krishna *et al.* 1986). The parameters adopted for the two components are:

(i) Medium 1: following FJT, we adopt for the halo a nearly uniform temperature of 1 keV and a gas density varying with radial distance D as

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

Here the central density $n_0 \simeq 10^{-2}\,\mathrm{cm}^{-3}$, the core radius $a \simeq 2$ kpc, and $\delta \simeq 0.75$ (Section 2.1). In order to simplify the presentation we use $\delta \equiv (3/2)\beta$ in the rest of the paper. Note that the assumption of isothermality and the adopted density distribution follow directly from the best deconvolution of the X-ray data reported in FJT (the density distribution is insensitive to the relatively small variations in temperature allowed by the data – see FJT, pp. 116–117).

(ii) Medium 2: following an intermediate model of Guilbert & Fabian (1986) we adopt for the IGM a temperature of $18(1+z)^2$ keV and a density of $7\times10^{-7}(1+z)^3\,\mathrm{cm}^{-3}$ (Section 2.2).

At $z=0.15$, the pressure balance between the two components is thus expected to occur at $\sim$107 kpc from the galactic nucleus and this distance of the interface, R_h, is expected to vary as $R_\mathrm{h} \propto (1+z)^{-5/(2\delta)}$ out to redshifts for which the halo parameters themselves do not evolve [assuming $R_\mathrm{h}(z) \gg a$; see Section 2.1].

For $D \leq R_\mathrm{h}$ (i.e. Medium 1), we shall assume the beam to propagate with a constant opening angle, θ, as in model A of Scheuer (1974). Note, however, that for our purposes we do not need to assume constancy of internal energy density in the cavity so that the high predicted brightness of the lobes that worried Scheuer need not be of concern here. As discussed in the Appendix, such a behaviour is found to be consistent with the numerically simulated propagation of supersonic jets through a typical galaxy halo (Siah & Wiita 1986; Wiita & Siah 1986). Thus, from ram-pressure balance:

$$n(D)\left(\frac{dD}{dt}\right)^2=\frac{4K_1Q}{\pi m_\mathrm{H}\theta^2 D^2 c}. \tag{2}$$

Here Q is the beam power (assumed to be constant), m_H is the mass of a hydrogen atom, c is the speed of light and K_1 is a constant with a value between 1 and 2 (Scheuer 1974). Further, the jet speed is assumed to be close to the speed of light. Now, substituting from equation (1) and approximating $(D/a)^2 \gg 1$, we find

$$D^{(1-\delta)}\frac{dD}{dt}=a^{-\delta}\left(\frac{4K_1Q}{\pi m_\mathrm{H}\theta^2 c n_0}\right)^{1/2} \equiv A. \tag{3}$$

Integrating (3) and substituting $V=V_*$ at $D=D_*$ gives (for $D \leq R_\mathrm{h}$):

$$A=V_* D_*^{(1-\delta)}, \tag{4}$$

$$V(D)=V_*\left(\frac{D_*}{D}\right)^{(1-\delta)}, \tag{5}$$

$$D(t)=[(2-\delta)\,V_* D_*^{(1-\delta)} t]^{1/(2-\delta)}. \tag{6}$$

Here V_* is the head velocity, taken to be $0.03\,c$ at a distance $D_*=10$ kpc from the galactic nucleus. Since V is a very slow function of D (equation 5), the choice of D_* is not critical.

The adopted value of V_* corresponds to an average head velocity V_av of $\sim 0.027\,c$ over $D=50$ kpc (equation 5). This is consistent with the ages of medium-sized classical double sources, as estimated from studies of radio spectral gradients across them, particularly after making an allowance for a substantial backflow speed of the relativistic plasma escaping from the heads (Burch 1977; Alexander, Brown & Scott 1984; Myers & Spangler 1985; Spinks, Rees & Duffett-Smith 1986). Firm upper limits of $\sim 0.2\,c$ to $V_{\rm av}$ are obtained from the general structural symmetry observed in most double sources (Longair & Riley 1979; Banhatti 1980; Katgert-Merkelijn, Lari & Padrielli 1980). Considering a variety of effects, Baryshev (1983) found an upper limit to the average head velocity of $\sim 0.03\,c$ for powerful sources, a claim supported by the recent work of Fokker (1986).

At $D = R_{\rm h}(z)$ the beam enters a medium an order-of-magnitude less dense but pressure-matched (the hot IGM). The influence of such a transition on the beam is much less clear and does not seem to have been discussed in the literature, even though many extended double sources are likely to have experienced the transition as noted above. Here we present an idealized, analytic treatment for the beam propagation over this regime, considering the following two cases which should broadly represent the two extreme situations for the source expansion.

3.1 MODEL A

Here a continuity of the beam opening angle, θ, is envisaged across the interface ($D = R_{\rm h}$). The order-of-magnitude decrease in the ambient density upon crossing the interface would then be able to produce sufficient ram-pressure only if the beam head velocity increased abruptly at $D = R_{\rm h}$ followed by a gradual slow down to approach the $V \propto D^{-1}$ law expected for a uniformly dense medium. Quantitatively

$$n_{\rm IGM}\left(\frac{dD}{dt}\right)^2 = \frac{4K_1 Q}{\pi m_{\rm H}\theta^2 D^2 c}, \qquad \text{for } D \geq R_{\rm h}. \tag{7}$$

Integrating this equation and setting the constant of integration C_1 by demanding that the time $t_{\rm h}$ corresponding to $D = R_{\rm h}$ is the same as that derived from equation (6) for the regime $D \leq R_{\rm h}$, we obtain

$$V(D) = a^\delta V_* D_*^{(1-\delta)} D^{-1}\left[\frac{n_0}{n^*_{\rm IGM}}(1+z)^{-3}\right]^{1/2}, \tag{8}$$

$$D(t) = 2^{1/2}\left\{C_1 + a^\delta V_* D_*^{(1-\delta)}\left[\frac{n_0}{n^*_{\rm IGM}}(1+z)^{-3}\right]^{1/2} t\right\}^{1/2}, \tag{9}$$

where

$$C_1 = \frac{R_{\rm h}^2(z)}{2} - R_{\rm h}^{(2-\delta)}(z)\, a^\delta (2-\delta)^{-1}\left[\frac{n_0}{n^*_{\rm IGM}}(1+z)^{-3}\right]^{1/2}, \qquad \text{for } D > R_{\rm h}.$$

3.2 MODEL B

Here equation (7) is integrated by imposing an additional condition, namely that the velocity across the halo–IGM interface remains continuous and therefore matched to the value given by equation (5) for $D = R_{\rm h}$. This entails an abrupt flaring of the beam at the interface to an opening angle $\theta_{\rm IGM}$ such that

$$\theta_{\rm IGM} = \theta\left[\frac{a}{R_{\rm h}(z)}\right]^\delta \left[\frac{n_0}{n^*_{\rm IGM}}(1+z)^{-3}\right]^{1/2}. \tag{10}$$

This corresponds to

$$V(D)=V_* D_*^{(1-\delta)} D^{-1} R_{\rm h}^{\delta}(z) \tag{11}$$

and

$$D(t)=2^{1/2}\left[V_* D_*^{(1-\delta)} R_{\rm h}^{\delta}(z)\ t+R_{\rm h}^2(z)\left(\frac{1}{2}-\frac{1}{2-\delta}\right)\right]^{1/2} \tag{12}$$

for $D>R_{\rm h}(z)$.

Before proceeding further, it may be pertinent to stress that, since both Model A and Model B represent a discontinuity in either the head velocity or in beamwidth at the halo–IGM interface, they only represent two extreme possibilities. But the reality probably lies closer to Model B, since the detailed maps of the jets available for a few nearby radio galaxies, namely NGC 315 (Willis *et al.* 1981) and NGC 6251 (Perley, Bridle & Willis 1984) have revealed a rapid flaring occurring at a distance of about 100–200 kpc from the nucleus, which could well be coincident with the interface. After the flaring, both jets seem to propagate out to hundreds of kiloparsecs, widening almost linearly with distance. Although we are unaware of any explicit numerical hydrodynamical simulations of this situation, the likelihood of a substantial flaring is indirectly supported by several analyses (Smith 1982; Sumi & Smarr 1984; Bicknell 1986; Norman 1986). In a real situation, the evolution of the jets could also be affected by internal dissipation such as shocks, although the numerical simulations of Norman, Smarr & Winkler (1984) indicate that the jets typically survive such internal (reflection) shocks without any great change in opening angle. This is consistent with the observational results mentioned above.

4 Results and discussion

For both models A and B we list in Table 1 the values of age t and head velocity βc at different distances from the galactic nucleus, computed using equations (5) and (6) for $D\leq R_{\rm h}$ and equations (8)–(12) for $D>R_{\rm h}$. The computations were made for redshifts of 0, 0.15 and 1. As discussed earlier, the values adopted for the input parameters are $\delta=0.75$, $a=2$ kpc, $n_0=10^{-2}\,{\rm cm}^{-3}$, $V_*=0.03\,c$, $D_*=10$ kpc, $n_{\rm IGM}(z)=n_{\rm IGM}^*(1+z)^3=7\times10^{-7}(1+z)^3\,{\rm cm}^{-3}$ and $R_{\rm h}(z)=171\,{\rm kpc}(1+z)^{-5/(2\delta)}$. Based on the available data, these can be considered as being representative of an average powerful radio source. The time dependence of D is also shown graphically in Fig. 1 for $z=0.15$ and $z=1.0$.

Note that the symbols X mark the stages ($t=t_{\rm max}$, $D=D_{\rm max}$) at which the computed head speeds $c\beta$ have fallen to the ambient sound speed (in the IGM) which is given by

$$c_{\rm IGM}^{\rm s}=c\beta_{\rm s}=\left(\frac{\gamma kT}{\mu m_{\rm H}}\right)^{1/2}=1.57\times10^4(1+z)\sqrt{T_{\rm IGM}^*}. \tag{13}$$

Here we take $\gamma=5/3$ and the mean molecular weight $\mu=0.56$. The present value of IGM temperature is taken to be $T_{\rm IGM}^*=18$ keV. The proposed virtual halt of source expansion at $D=D_{\rm max}$ corresponding to $t=t_{\rm max}$, despite any continuing nuclear activity, seems well justified because the subsequent motion of the head would be subsonic, leading to its rapid lateral expansion in the absence of the confining ram-pressure. This should cause a drastic reduction in both velocity and luminosity of the head, thus effectively limiting further growth of the source both in size and radio output. This suggested *growth freeze* is supported by numerical experiments illustrating the rapid disruption and effective termination of jets on becoming subsonic (Wiita 1978; Smith *et al.* 1983; Norman 1986). The stoppage of source expansion after an age $t_{\rm max}$, despite a possible continuation of the nuclear activity, forms an important aspect of the model

Table 1. Computed dynamical parameters.

$z = 0$, $R_h = 171$ Kpc, $\beta_s = 7.59(-3)$					$z = 0.15$, $R_h = 107$ Kpc, $\beta_s = 8.72(-3)$					$z = 1$, $R_h = 17$ Kpc, $\beta_s = 1.52(-2)$				
	Model A		Model B			Model A		Model B			Model A		Model B	
D(Kpc)	t(yr)	β	t(yr)	β	D(Kpc)	t(yr)	β	t(yr)	β	D(Kpc)	t(yr)	β	t(yr)	β
10	8.70(5)	3.00(-2)	8.70(5)	3.00(-2)	10	8.70(5)	3.00(-2)	8.70(5)	3.00(-2)	5	3.66(5)	3.57(-2)	3.66(5)	3.57(-2)
50	6.50(6)	2.01(-2)	6.50(6)	2.01(-2)	50	6.50(6)	2.01(-2)	6.50(6)	2.01(-2)	10	8.70(5)	3.00(-2)	8.70(5)	3.00(-2)
100	1.55(7)	1.69(-2)	1.55(7)	1.69(-2)	100	1.55(7)	1.69(-2)	1.55(7)	1.69(-2)	17	1.69(6)	2.63(-2)	1.69(6)	2.63(-2)
150	2.57(7)	1.52(-2)	2.57(7)	1.52(-2)	107	1.68(7)	1.66(-2)	1.68(7)	1.66(-2)	20	1.74(6)	1.90(-1)	2.09(6)	2.23(-2)
171	3.03(7)	1.48(-2)	3.03(7)	1.48(-2)	125	1.76(7)	6.95(-2)	2.07(7)	1.42(-2)	25	1.83(6)	1.52(-1)	2.92(6)	1.79(-2)
200	3.19(7)	5.36(-2)	3.72(7)	1.26(-2)	150	1.89(7)	5.80(-2)	2.70(7)	1.18(-2)	30	1.95(6)	1.26(-1)	3.92(6)	1.49(-2)
250	3.53(7)	4.29(-2)	5.18(7)	1.01(-2)	175	2.04(7)	4.97(-2)	3.45(7)	1.01(-2)	50	2.64(6)	7.58(-2)	9.77(6)	8.93(-3)
300	3.95(7)	3.58(-2)	6.95(7)	8.41(-3)	200	2.22(7)	4.35(-2)	4.31(7)	8.87(-3)	100	5.87(6)	3.79(-2)	3.72(7)	4.47(-3)
500	6.38(7)	2.15(-2)	1.73(8)	5.05(-3)	300	3.16(7)	2.90(-2)	8.90(7)	5.92(-3)	250	2.85(7)	1.52(-2)	2.29(8)	1.79(-3)
1000	1.78(8)	1.07(-2)	6.58(8)	2.52(-3)	500	6.16(7)	1.74(-2)	2.36(8)	3.55(-3)	350	5.43(7)	1.08(-2)	4.48(8)	1.28(-3)
2000	6.34(8)	5.36(-3)	2.60(9)	1.26(-3)	1000	2.02(8)	8.69(-3)	9.25(8)	1.78(-3)	500	1.09(8)	7.58(-3)	9.14(8)	8.94(-4)

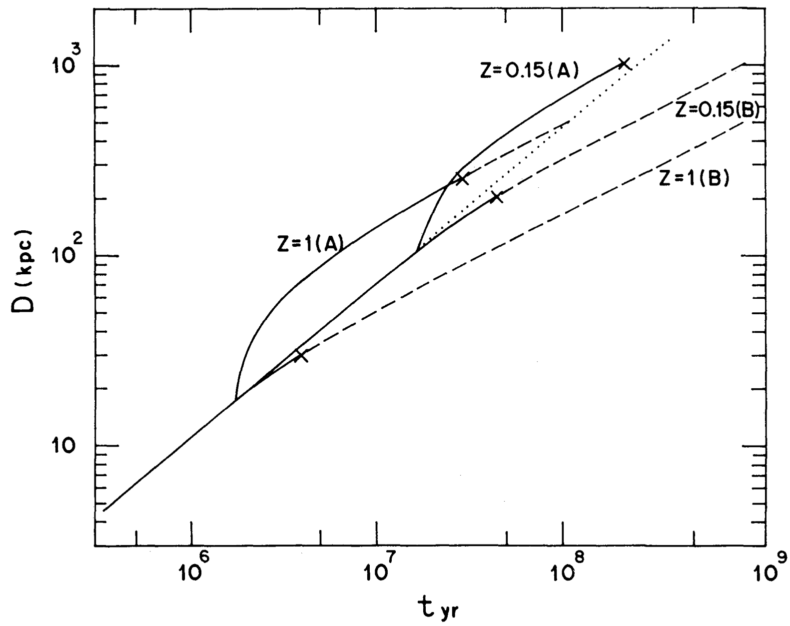

Figure 1. Distance of the head of a radio source from the nucleus as a function of time. The labels on the curves identify the resdshift ($z=0.15$ or 1.0) and Model (A or B). The X marks denote when the head velocity becomes subsonic with respect to the IGM, and the dashed continuation illustrates the putative evolution if the head were to remain confined. The dotted extension shows the evolution if the galactic halo density profile were to extend to 1 Mpc.

presented here. Clearly, if the nuclear activity persists much beyond t_{max}, most of the observed edge-brightened doubles would have approached a limiting 'maximum size' (D_{max}), assuming that they all had identical initial conditions. For the duration of nuclear activity in powerful radio sources a statistical estimate of $t_N \sim 10^7 - 10^8$ yr is commonly accepted (e.g. De Young 1977; Begelman, Blandford & Rees 1980), although in weaker radio sources the nuclear activity may last much longer (e.g. Cordey 1986). For the powerful radio sources being considered here, we shall thus regard 10^8 yr as a typical duration of nuclear activity. As seen from Fig. 1, $t_N \approx t_{max}$ for either Model A or Model B for $z=0.15$, which is a representative redshift for the 'local' samples of powerful radio sources. For this redshift, Model A would then predict a typical overall size of 0.9 Mpc corresponding to the median age of $t_N/2$. For $z=1$, $t_N > t_{max}$, and the overall size (determined by t_{max}) would be ~ 0.5 Mpc. Both these values are much greater than the median linear sizes of powerful radio sources which are found to be ~ 0.35 Mpc ($z \sim 0.15$) and $\lesssim 0.1$ Mpc ($z=1$) (Kapahi 1985, 1986; Gopal-Krishna *et al.* 1986). These observed values are, on the other hand, in much better agreement with the predictions of Model B, according to which the typical overall size of a powerful radio source is expected to be about 400 kpc at $z=0.15$ and ~ 60 kpc at $z=1$. Note that this model was also considered to be physically more plausible, in view of its consistency with the observed rapid flaring of jets some 100–200 kpc away from the nucleus (Section 3). These predictions for $z=0.15$ and $z=1$ imply an index of $\sigma \simeq 3$ for an evolutionary form $(1+z)^{-\sigma}$. The recently claimed estimates of n lie in the range 1 to 2 (Kapahi 1985; Eales 1985), although a recent analysis by Kapahi (personal communication) is consistent with a value somewhat steeper than 2. Moreover, because of the posited hot IGM, our picture requires $\Omega \geq 0.22$, implying that the published estimates of σ for $\Omega=0$ are on the low side. Therefore we feel that there is no significant discrepancy between the predictions of our Model B and the observations. Oort *et al.* (1986) have, in fact, recently suggested that σ may be close to 3.

The discussion hitherto pertained to an average member of the class of powerful radio sources. But since our model also constrains the maximum size of such a source, it should be further possible to test the model against the observed largest double sources at different redshifts. Now, the largest known double source 3C 236 has a size of 5.6 Mpc and is associated with a galaxy of $z=0.1$ (Willis, Strom & Wilson 1974). The corresponding largest size for $z=1$ is found to be only $\sim$500 kpc (e.g. Hintzen, Ulvestad & Owen 1983), i.e. about 11 times smaller than the local value (note that although the size given by Hintzen *et al.* refers to quasars it should be applicable to radio galaxies as well; *cf.* Kapahi 1986, and personal communication). From Fig. 1, the values of maximum attainable total linear size predicted by Model B for our typical source with expansion limit set by T_{max} are $\sim$650 kpc and 60 kpc, respectively, for $z=0$ and $z=1$. The ratio of these two predicted values for the largest sizes is again similar to the value deduced above from the observations. Thus, the Model B also gives a fairly good account of the size evolution of the largest double sources, without the need to deviate from the simple premise that right up to $z\simeq1$, at least, the difference between the initial conditions producing a typical source and a giant source remains such that their sizes differ by the same factor of about 8.

Extrapolation of these ideas to redshifts much beyond $z=1$ is highly speculative at present, given the lack of any observational clues about galaxy evolution and hence about the nature of the galaxy haloes. On the neutral assumption that the gas pressure in the galaxy haloes at $z\sim2$ was not much different from that found for nearby galaxies, the condition of pressure balance would demand that the halo–IGM interface occurs at a radius of just a few kiloparsecs. Likewise the predicted value for D_{max} would also be subgalactic. Thus, if the initial conditions for the expansion of a typical powerful radio source at $z\sim2$ were similar to those applicable to their nearby counterparts, it is to be expected that a majority of the sources at $z=2$ should not have been able to expand beyond the confines of their parent galaxies. Qualitatively, this is in agreement with some recent findings which point towards a preponderance of powerful radio sources with sizes smaller than $\sim$10 kpc at $z\gtrsim2$ (e.g. Barthel 1986). Thus, at such high redshifts, the radio sources would be typically confined within the interstellar medium of the parent galaxy. The tremendous discharge of momentum flux by the twin beams into such small volumes would then cause a substantial heating of the ISM (Lonsdale & Barthel 1985) leading to bulk flows of the gas. This might be responsible for the distorted radio structures often seen among the high-redshift quasars (e.g. Barthel 1986).

Our neglect of the possible heating of the halo gas through any one of several mechanisms (Lonsdale & Barthel 1985; Miller 1986; Bertschinger & Meiksin 1986) would appear to imply a lesser degree of linear-size evolution, in that only the increase in IGM density, and not temperature, in crossing the halo–IGM interface would be available for causing a shrinking of R_h with z. However, partial evaporation of the halo should ensue under these circumstances, thereby providing an alternative way of shrinking R_h. Although quantitative calculations of these effects should be carried out, they are beyond the scope of this paper, and in any event, we do not believe that they would strongly alter our conclusions.

Other possible explanations of the size evolution have involved an increased energy density of the microwave background at earlier epochs, leading to a more rapid inverse Compton quenching of the relativistic electrons in the beams (Rees & Setti 1968; Scheuer 1977), or a relation between source power and size which evolves with cosmological time. But, as discussed by Eales (1985), these proposals seem to be inadequate when confronted with the current observational data. A simple model, related to our picture, where the cosmic evolution of the IGM density seems to imply $D\propto(1+z)^{-3/2}$ has also been discussed (Eales 1985; Kapahi 1985), although this is probably also too simplistic, for the assumption of a constant rate for the advance of the beams is unlikely in most gas distributions, particularly in view of the fact that all well-resolved jets show a tendency to widen while propagating outward.

To summarize, Model B proposed here, despite its simple analytical approach, seems to be able to account successfully for the cosmological evolution as well as the actual linear sizes of powerful radio sources. For a numerical evaluation of the model, we have assigned to the various input parameters values plausible for an average powerful radio source. While many refinements to the present approach are desirable, one of the most rewarding possibilities would be to extend the numerical simulation experiments for beam propagation to a two-component ambient medium of the type considered here. On the observational front, a detection of physically smaller gaseous haloes around distant ellipticals would greatly strengthen the basis of our model. Such measurements should be practical with the AXAF telescope.

5 Conclusions

We have investigated a simple model for the propagation of a radio beam through a galactic gaseous halo and then across its pressure-matched interface with the intergalactic medium. If the beams flare as they pass through this strong density and temperature gradient, as both observations and numerical experiments seem to indicate, then we can explain the median size of powerful radio sources observed at the present epoch. According to this model, the effective growth of a source will stop, regardless of continuing nuclear activity, when the velocity of the head becomes subsonic with respect to the IGM. Such a model is found to give a good account of the cosmological evolution of linear size of both typical and giant radio sources out to $z \simeq 1$. A speculative, but natural, extension of this picture could explain the observed prevalence of subgalactic-sized sources at $z \simeq 2$. Our model predicts that the X-ray haloes of relatively isolated elliptical galaxies were smaller at higher redshifts.

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Appendix: Concordance of analytic and numerical propagation models

Although the assumption that the slowing down of the jet is governed by ram pressure (equation 2), so that $D \propto t^{1/(2-\delta)}$ (equation 6) while the jet is flowing through a medium whose density varies as $r^{-2\delta}$, is certainly an oversimplification, it can be supported by numerical experiments. Wiita & Siah (1986) and Siah & Wiita (1986) have investigated the formation and propagation of jets in essentially power-law atmospheres, although they allowed for flattening of the confining cloud as well as partial evacuation along the rotational axis and some effects of magnetic fields (Siah & Wiita 1986). Their programme essentially follows the boundary between the jet fluid (assumed to have a relativistic equation of state) and the external medium, and is not a full (magneto-) hydrodynamical code; nevertheless, earlier versions demonstrated important effects which were essentially confirmed by more complex two-dimensional codes (see Siah & Wiita 1983), so that the results of these computations concerning such basic points as expansion versus time and variation in opening angle are probably close to the mark.

We have analysed the distance versus time behaviour of several published and unpublished runs with $\delta=0.75$, 1.0 and 1.3, ignoring case with unrealistically deep dimples along the axes or significant magnetic fields. For essentially every run satisfying these conditions a good power-law fit can be obtained once the beam has gone beyond a couple of scale heights: with $D \propto t^s$, s is constant to $\sim \pm 0.06$. Because of variations in cloud flattening, angular momentum distributions and magnetic field configuration, the value of s did vary from run to run for a given δ, but these variations were not large. Averaging the numerical runs we find: for $\delta=0.75$, $s=0.888 \pm 0.034$ [versus $1/(2-\delta)=0.800$]; $\delta=1.0$, $s=1.090 \pm 0.063$ (1.000); $\delta=1.3$, $s=1.360 \pm 0.143$ (1.429). The agreement between the simple theory and the numerical models is clearly good in this regard.

Our assumption that $\theta=$constant, at least while propagating through a region of constant δ, is also well verified by these numerical models. Although most of them produced nominal opening angles of $\sim 12-15°$, rather than the observed values of $\sim 1°-3°$, these nominal values are certainly overestimates (Wiita & Siah 1986). The key point is that $\theta_e/\theta_* = 1.09 \pm 0.25$, where θ_e is the nominal angle at the termination of a run and θ_* is the opening angle at a fixed time early in the numerical experiment, so that while some jets open up a bit more and others get somewhat narrower, the changes are usually quite small and a constant opening angle is a good approximation.