Young radio galaxies and their environments

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Abstract

Many of the powerful radio galaxies observed at high redshift are very small, presumably because they are very young. A simple model, which treats the radio source as a bubble expanding into a radially stratified medium, is capable of explaining the main features of their size and luminosity evolution. In particular, the model predicts strong negative luminosity evolution with increasing size, thus accounting for the large number of short-lived small sources in flux-limited samples.

A variety of observational characteristics can be understood within the framework of the bubble model. I address three of these: 1) the number versus size statistics, which may provide a clue that jets in radio galaxies are intermittent, with “on–off” cycles lasting only $10^4 - 10^5$ yr; 2) the rarity of spectral steepening due to synchrotron cooling at frequencies of a few GHz, and its implications for source geometry and assumptions about equipartition; and 3) the prevalence of gigahertz-peaked spectra among small sources.

I argue that all of these phenomena are primarily the consequence of the youth and compactness of the radio source, and depend only weakly on environment. There is no need to postulate an ISM with properties any different from that of an ordinary nearby galaxy.

1 Introduction

Powerful double radio sources are observed to range in projected linear size ($LS$) from less than 100 pc to more than a megaparsec. They have been divided arbitrarily into a sequence of size categories, ranging from compact symmetric objects (CSOs, $LS < 500$ pc: Wilkinson et al. 1994), to medium symmetric
objects (MSOs, 500 pc < LS < 15 kpc: Fanti et al. 1995), to full-size FR II radio galaxies (LS > 15 kpc). The CSOs contain two important subcategories based on spectral classification, compact steep spectrum (CSS) sources (Fanti et al. 1990) and gigahertz-peaked spectrum (GPS) sources (O’Dea, Baum, & Stanghellini 1991). There is still some debate about whether the small sources are young versions of the large sources (see, e.g., O’Dea & Baum 1997). Alternative views propose that the small sources are short-lived or evolve into some other type of source (e.g., FR I radio galaxies) as they grow. In this paper I will adopt the view that all of these categories fit into a single evolutionary sequence, which I believe is the easiest hypothesis to reconcile with both observations and theory.

According to the evolutionary scenario, the small sources are plentiful not because their growth is stunted by interaction with an exceptionally dense interstellar medium (ISM), or because the average source is short-lived. Rather, the brevity of the compact phase is partly compensated by strong negative luminosity evolution (Readhead et al. 1996), which allows the smaller sources to be included in flux-limited surveys out to much larger distances. This luminosity evolution is expected on the basis of simple physical models (Begelman 1996).

To capture the main features of radio source evolution, it suffices to treat the cocoon as an adiabatic spherical bubble, filled with relativistic fluid. Real cocoons are elongated along the jet axis, but the “aspect ratio” (length/width) is seldom much larger than 3, presumably because the “dentist’s drill” effect (Scheuer 1982) spreads out the ram pressure of the jets over a large solid angle. The cocoon and shell of shocked ISM expand supersonically into the ambient medium at a speed $v \sim \left(\frac{p_c(t)}{\rho(r)}\right)^{1/2}$, where $p_c(t)$ is the cocoon pressure at time $t$ and $\rho(r)$ is the ambient density at the radius of the outer shock. The synchrotron emissivity comes mainly from within the cocoon, and is probably dominated by “lobe” regions near the ends of the jets, where the pressure is a few times the mean cocoon pressure (see section 3). Significant synchrotron emission may also come from the hotspots, instantaneous impact points of the jets, where the pressure can be much larger still.

A useful family of models can be derived by assuming a power-law distribution of ambient density, $\rho(r) \propto r^{-\delta}$. The internal structure of the cocoon is assumed to evolve self-similarly (Falle 1991; Begelman 1996; Kaiser & Alexander 1997), with a relativistic electron energy distribution of fixed slope and a fixed ratio of magnetic to relativistic particle energy density, $\epsilon_{\text{mag}}/\epsilon_{\text{rel}} \equiv \zeta \leq 1$. The latter parameterization serves to generalize the usual assumption of equipartition ($\zeta = 1$). We consider $\zeta < 1$ since synchrotron cooling is less efficient in this regime, a desirable feature for compact sources as we shall see in section 3.
Using this simple model, one can explain the observed number versus size relation \( N \propto (LS)^{0.4} \) (Fanti et al. 1995; Readhead et al. 1996), which seems to apply over limited ranges of \( LS \), if the density index \( \delta \) lies in the range 1.5–2 (Begelman 1996). The velocity of expansion is nearly constant and the radio power (at a fixed frequency) declines roughly as \((LS)^{-1/2}\). For ISM number density \( n(r) = n_0 R_{\text{kpc}}^{-2} \text{ cm}^{-3} \) (where \( R_{\text{kpc}} = r/1 \text{ kpc} \)) and jet power \( L_j = 10^{45} L_{45} \text{ erg s}^{-1} \), we obtain the following estimates of the cocoon pressure, expansion speed, and elapsed lifetime for a source that has expanded to radius \( r \):

\[
\begin{align*}
 p_c &= 6 \times 10^{-8} n_0^{1/3} L_{45}^{2/3} R_{\text{kpc}}^{-2} \text{ dyn cm}^{-3} \\
 v &= 2700 n_0^{-1/3} L_{45}^{1/3} \text{ km s}^{-1} \\
 t &= 0.4 n_0^{1/3} L_{45}^{-1/3} R_{\text{kpc}} \text{ Myr.}
\end{align*}
\]

The “bubble model” seems to provide a robust framework for understanding both the luminosity and size evolution of young radio galaxies. In this paper, I will show that it also readily accommodates the next level of observational detail. In section 2, I show that the “plateau” in the number–size relation, discovered by O’Dea & Baum (1997), can be interpreted as the consequence of intermittency, with the jets switching on and off on timescales of \( 10^4 \text{ to } 10^5 \text{ yr} \). In section 3 I analyze the synchrotron emissivities predicted by the bubble model. Spectral steepening at a few GHz, attributable to synchrotron cooling, is seldom observed. Given the high synchrotron efficiencies predicted by the bubble model for small sources, the scarcity of evidence for cooling suggests that most of the emission comes from lobe regions only briefly traversed by the radiating electrons. It may also indicate the presence of sub-equipartition magnetic fields. Finally, I examine the possible causes of gigahertz-peaked spectra in section 4. As an alternative to extant models invoking synchrotron self-absorption or free-free absorption by a screen, I propose a model in which the free-free absorption is produced by interstellar clouds that have been engulfed by the bubble, and whose surface layers are photoionized by UV radiation internal to the bubble. This model naturally predicts the inverse correlation between turnover frequency and source size, as well as the typical change in spectral index at the turnover, without any special assumptions about the ISM density.

Except where otherwise noted, all succeeding calculations are based on the \( \rho \propto R^{-2} \) model described in equations (1)–(3). The reader should keep in mind that the results presented may depend quantitatively on \( \delta \), although the qualitative dependence (for \( 1.5 \leq \delta \leq 2 \)) will be weak.
2 Do source counts imply intermittency?

A power-law relationship between number counts and size does not seem to continue uniformly across the entire range of source sizes. When O’Dea & Baum (1997) combined data on the two principal classes of CSOs—the gigahertz-peaked spectrum (GPS) and compact steep spectrum (CSS) sources—with data on 3CR classical doubles, they found the \((LS)^{0.4}\) behavior above 10 kpc, and perhaps some hint of a similar behavior at \(LS \lesssim 0.3\) kpc. But between 0.3 and 10 kpc, \(N\) is nearly independent of \(LS\). They suggested that GPS and CSS sources might be overabundant, relative to the extrapolation from larger sources, because they are short-lived and never evolve into large sources, because their growth is “frustrated” by an exceptionally dense ISM, or because they decline in luminosity more rapidly than predicted by the bubble model. Since an explanation in terms of environmental differences is not attractive due to the insensitivity of bubble evolution to ambient density, their interpretation would suggest that the GPS–CSS sources form a distinct class of objects.

However, Reynolds & Begelman (1997) showed that a “plateau” in the \(N – LS\) distribution could simply indicate that radio galaxies are intermittent. According to the bubble model, the cocoons of small sources are highly overpressured with respect to the ambient medium. They would therefore keep expanding supersonically long after the central source turned off. The radio emission, dominated by the regions near the hotspots, would fade quickly. Once the nucleus turned on again, the cocoon would partially repressurize, the radio flux would rise, but the emissivity would be lower than before due to the increased volume and lower pressure. If a large source of instantaneous power \(L_j\) had experienced many on–off cycles, its evolutionary state would be indistinguishable from that of a source that had been on all the time, but had a mean power of \((t_{on}/t_{off} + t_{on})L_j\). Reynolds & Begelman (1997) found that the factor \(~ 10\) difference between the actual GPS–CSS number counts and the extrapolation of 3CR number counts could imply that radio galaxies are “on” only about 30% of the time. (These calculations assumed \(\delta = 1.8\).) Ages corresponding to the source sizes bounding the plateau measure the typical durations of the “on” and “off” cycles. These are surprisingly short, of order 30,000 and 70,000 yr, respectively. The timescales are intriguingly close to the timescales of viscous accretion disk instabilities studied by Siemiginowska & Elvis (1997).

A prediction of the intermittency hypothesis is that there should be \(~ 3\) times as many radio galaxies in the “off” state as in the “on” state. These might be detectable in low-frequency, low-surface brightness radio surveys, since their spectra would tend to be steep and their emission diffuse. One might also
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search for X-ray emission from the shell of shocked ISM that surrounds the cocoon (Heinz, Reynolds, & Begelman 1997). Whereas the radio emissivity probes the instantaneous jet power, the X-ray emission is more indicative of the mean jet power averaged over the lifetime of the source. By comparing the radio and X-ray properties of Perseus A (NGC 1275), Heinz et al. (1997) deduced that Per A might currently be in an “off” state.

3 Synchrotron emissivity and radiative efficiency

Young, compact, and therefore high-pressured sources should radiate synchrotron emission much more efficiently than their larger descendants. Where the synchrotron cooling timescale of radio-emitting electrons is shorter than the expansion timescale (assumed to be of the same order as the timescale for injecting freshly accelerated electrons), the spectral index should steepen by $\Delta \alpha \approx 0.5$ over the value determined by the particle acceleration process. While compact steep spectrum (CSS) sources all have spectra steeper than 0.5, they are not often observed with $\alpha > 1$ at GHz frequencies, as would be expected if cooling were important.

The lack of spectral evidence for cooling places a significant constraint on the region that dominates the emission. If the observed synchrotron radiation came from the bulk of the cocoon, the bubble model would predict steepening above frequencies

$$\nu_{\text{cool}} \sim 3.5 \times 10^{-3} \zeta^{-3/2} n_0^{-7/6} L_{45}^{-1/3} R_{\text{kpc}} \text{GHz.}$$

The monochromatic radio power at 5 GHz is given by

$$P_5 \sim 3 \times 10^{28} \zeta^{3/4} n_0^{7/12} L_{45}^{7/6} R_{\text{kpc}}^{-1/2} \text{W Hz}^{-1}.$$  

Thus, for observed sources with a typical 5 GHz power $10^{27} P_{27}$ W Hz$^{-1}$, we predict that the spectrum should steepen above

$$\nu_{\text{cool}} \sim 9 P_{27}^{-2/7} \zeta^{-9/7} n_0^{-1} R_{\text{kpc}}^{6/7} \text{MHz.}$$

In other words, if the mean emissivity of the cocoons dominated the 5 GHz emission then all CSOs should have $\alpha \gtrsim 1$ unless $n_0 \zeta^{9/7} < 10^{-3}$. The latter exception involves such extreme conditions (low ambient densities and/or sub-equipartition magnetic fields) that it is unlikely to be satisfied.

This situation is ameliorated somewhat if the emission comes mainly from the overpressured lobes within the cocoon. The important effect is not the higher
emissivity in the lobes (the high emissivity in the cocoon is the cause of the rapid cooling problem), but rather the fact that the electrons spend a short time in the high-pressure region, compared to the age of the source. Suppose that the lobes occupy a fraction \( x \) of the cocoon’s volume and that the lobe pressure is \( y > 1 \) times the cocoon pressure. In order for the lobes to dominate the synchrotron flux (if \( \zeta \) has the same value throughout) we must have \( xy^{7/4} > 1 \).

If the relativistic electrons traverse the lobes at a speed \( v_l \sim 0.3c \), then the steepening occurs at

\[
\nu_{\text{cool}} \sim 70 \ x^{4/21} P_{27}^{-6/7} (v_l/0.3 \ c)^2 \zeta^{-6/7} R_{\text{kpc}}^{4/7} \text{ GHz. (7)}
\]

Note that equation (7) depends weakly on \( x \) and not at all on \( y \) or \( n_0 \). Although this result seems more consistent with observations than equation (6), it is sensitive to the highly uncertain value of \( v_l \), which may well be smaller than our optimistic fiducial value. If this analysis is correct, we might expect the spectra of most CSOs to steepen at frequencies \( \lesssim 100 \) GHz, and to find an inverse correlation between 5 GHz power and steepening frequency. If the spectra of the most powerful CSOs do not break at high frequency, it could indicate that the magnetic fields are below equipartition.

4 Absorption in gigahertz-peaked sources

It is not yet certain whether the spectral turnovers in GPS sources are caused by synchrotron self-absorption (O’Dea & Baum 1997), free-free absorption (Bicknell, Dopita, & O’Dea 1997), or some other mechanism (G. Bicknell 1997, private communication). Two features which should be explained by any successful model are the typical change in spectral index across the turnover, \( \Delta \alpha \sim 2 \pm 0.5 \), and the relationship between turnover frequency and source size, \( \nu_t \sim R_{\text{kpc}}^{-0.7} \) GHz (O’Dea & Baum 1997).

If the bulk of the cocoon dominated the emission, synchrotron self-absorption could be ruled out immediately as the main absorption mechanism. The brightness temperature at 5 GHz would then be \( T_{b,5} \sim 5 \times 10^6 \ P_{27} \ R_{\text{kpc}}^{-2} \) K, orders of magnitude below the energies of synchrotron emitting electrons. However, as we saw above, the emission is likely to be dominated by high-surface brightness compact regions within the cocoon. If we restrict the emission to the overpressured lobes, parameterized as above, the brightness temperature increases by a factor \( x^{-2/3} \). To reach the brightness temperature required for self-absorption at 5 GHz, \( T_{b,5} \sim 6 \times 10^{12} \ x^{1/7} P_{27}^{-1/7} \zeta^{-1/7} R_{\text{kpc}}^{3/7} \) K, the lobes would have to
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subtend an angle on the sky less than one percent that of the entire source, 
\( x^{1/3} \lesssim 0.003 P_{27}^{-8/17} c^{3/17} R_{\text{kpc}}^{-1} \). Note that the required size of the emitting region is completely independent of the pressure enhancement in the lobes (the factor \( y \)). Such a compact emitting region seems implausible, given what we know about the morphologies of large FR II radio galaxies; in any case, the prediction could be tested through VLBI observations.

Free-free absorption seems a more promising mechanism for shaping the spectral peaks of GPS sources. In modeling the absorption there is a choice of geometries, ranging from an external screen to a spray of absorbing clouds mingled with the synchrotron-emitting gas. Bicknell et al. (1997) have adopted the former approach, attributing the absorption to the shell of shocked ISM. In order to obtain the observed change of spectral slope across the GHz-peak, rather than an exponential cutoff, they argue for a particular power-law distribution of column densities covering the source. In order to obtain enough emission measure in the absorbing layer, the shock has to be able to cool in less than the expansion timescale of the cocoon. This, plus the requirement that the shock be autoionizing (i.e., that the cooling layer emit enough UV radiation to ionize the surrounding gas), forces one to demand a rather low shock speed (\( \lesssim 1000 \text{ km s}^{-1} \)) and high ambient density (10–100 cm\(^{-3}\)).

4.1 The “engulfed cloud” model

Constraints on the ambient conditions are relaxed considerably if the absorption is supplied by interstellar clouds engulfed by the cocoon. The “engulfed cloud” model has the advantage that it automatically yields \( \Delta \alpha \sim 2 \) across the spectral peak, due to the fact that the free-free opacity varies with frequency \( \propto \nu^{-2} \). An important difference between the Bicknell et al. model and the engulfed cloud model is the source of the ionizing radiation. Bicknell et al. rely on radiation from the narrow layer of cooling shocked gas to ionize the (much thicker) neighboring layers of gas that have already cooled. In the engulfed cloud model, a “skin” on the surface of each cloud is photoionized by a combination of synchrotron UV emission from the lobes (if relativistic electrons are accelerated to high enough energies in the hotspots) and radiation from the active nucleus. If clouds at \( 10^4 T_4 \text{ K} \) are in pressure equilibrium with the interior of the cocoon and are irradiated by \( 10^{45} L_{\text{UV,45}} \text{ erg s}^{-1} \) in diffuse UV luminosity, the neutral fraction in the ionized layer is given by \( n_H/n_e \sim 0.1 T_4^{-3/4} n_0 L_{\text{UV,45}}^{-1/2} R_{\text{kpc}}^{1/3} \) and is independent of \( R \). In the overpressured lobes, this ratio is increased by a factor of \( y^{1/2} \). Thus, for a wide range of reasonable parameters we can consider
the layer to be fully ionized. If the column density is sufficiently large that the clouds are ionization bounded, the emission measure of the photoionized gas saturates at

$$EM_{\text{max}} = \langle n_e^2 R \rangle_{\text{max}} \sim 3 \times 10^{24} T_4^{1/2} L_{UV,45} R_{\text{kpc}}^{-2} \text{cm}^{-5}$$

(8)

and the turnover frequency, which scales as $(EM)^{1/2}$, is given by

$$\nu_t \sim 0.6 T_4^{-0.4} L_{UV,45}^{1/2} R_{\text{kpc}}^{-1} \text{GHz.}$$

(9)

Given the crudeness of the assumptions that went into its derivation, equation (9) agrees remarkably well with the observational result $\nu_t \sim R_{\text{kpc}}^{-0.7}$ GHz obtained by O'Dea & Baum (1997).

It does not take much entrained matter to produce the observed absorption in the engulfed cloud model. The maximum filling factor of ionized gas is

$$f = \frac{EM_{\text{max}}}{n_e^2 R} \sim 5 \times 10^{-7} T_4^{5/2} L_{UV,45}^{2/3} n_0^{-2/3} R_{\text{kpc}}^2$$

(10)

corresponding to a mean density

$$\langle n_e \rangle = fn_e \sim 0.02 T_4^{3/2} L_{UV,45}^{2/3} n_0^{-1/3} \text{cm}^{-3}.$$  

(11)

This is smaller than the amount of cold matter likely to be present in the ambient ISM, and validates the assumption that the clouds are ionization bounded and that the emission measure is close to the maximum possible value. Indeed, the amount of ionized gas is far smaller than the mean density needed to confine the bubble as it passes through its GPS phase. This implies either that most of the matter within and around the bubble is neutral or that the ISM mass is dominated by the diffuse intercloud medium.

The small amount of matter required for GPS absorption is also reassuring from a hydrodynamical perspective. Simulations by Klein, McKee, & Colella (1994) suggest that cold clouds engulfed by a blast wave can be shredded in several times the "cloud-crushing" timescale. The latter is given by $\chi_{1/2} \equiv \langle \rho_{\text{cloud}} / \rho_{\text{ambient}} \rangle^{1/2}$ times the sound-crossing time across the cloud. If the shocked ISM shell has a thickness about 10% the radius of the bubble, and the cloud density in the ISM is $\chi_0 \sim 100$ times that of the intercloud medium, then clouds should be able to survive passage through the shocked shell if the cloud size satisfies $r_{\text{cl}} \gtrsim 0.01 \chi_0^{1/2} T_4^{1/2} L_{45}^{-1/3} n_0^{1/3} R_{\text{kpc}}$ pc, where we have taken the cloud destruction time to be 4 times the crushing time. Since the mean density of
the hot gas inside the bubble is likely to be more than 100 times lower than that of the shocked shell (Bicknell & Begelman 1996), clouds which survive the shell-crossing are likely to survive once inside the bubble. But it is not certain whether such large clouds will have enough covering factor to blanket the entire synchrotron source. This is where the modest mass requirements of the engulfed cloud model can work to our advantage, since there may be adequate opacity (with high covering factor) in the residual shredded clouds, even if the bulk of the swept-up cloud mass has been mixed into the low-density hot phase. We also note that the smaller swept-up clouds might never penetrate the cocoon, but rather join the outward motion of the ISM shell. The morphology of the line-emitting gas surrounding the M87 bubble suggests that much of this material has been excluded from the cocoon (Bicknell & Begelman 1996). Even if the clouds pile up on the outer surface of the cocoon, however, ionization by UV from inside the cocoon could still produce an absorbing layer with similar properties to those predicted by the engulfed cloud model, at the cost of sacrificing a natural explanation for $\Delta \alpha \sim 2$.

We conclude by noting that the engulfed cloud model, as well as the Bicknell et al. (1997) screen model, can easily account for the observed Faraday rotation measures in the range $10^3 - 10^4 \text{ rad m}^{-2}$. Since the depth to which one can “see” in the cloud model scales as $\nu^2$, the effective rotation measure scales similarly at frequencies below the turnover. This implies that the Faraday rotation angle (or dispersion) should be independent of frequency below the turnover, while displaying the normal $\nu^{-2}$ behavior at higher frequencies. If this effect could be detected observationally, it could be used to distinguish between the engulfed cloud model and screen models, since in the latter the Faraday rotation scales as $\nu^2$ on both sides of the turnover.

5 Conclusions

I have tried to show how readily the simple bubble model of young radio galaxies can accommodate a variety of observational details, with few additional assumptions. The existence of a “plateau” in the number versus size counts plotted by O'Dea & Baum (1997) need not imply physically distinct classes of source. Instead, it could constitute evidence for intermittency in the central engines of powerful radio galaxies (Reynolds & Begelman 1997). The lack of steepening attributable to synchrotron cooling at a few GHz is harder to explain, as small radio sources should be extremely efficient synchrotron emitters. An observable cooling signature can be avoided, at frequencies $\lesssim 100 \text{ GHz}$, if the emission is
dominated by electrons traversing the overpressured lobe regions of the cocoon, as indeed is the case in large FR II sources. Magnetic fields of sub-equipartition strength can also help.

There are several possible explanations for the spectral turnovers in GPS sources. Synchrotron self-absorption is the least viable, since it would require most of the emission to come from extremely tiny spots within the cocoon. Free-free absorption, on the other hand, is extremely promising, and may arise in a foreground screen and/or embedded clouds within the cocoon. To provide an alternative to the Bicknell et al. (1997) screen model, I proposed a simple model in which the absorption arises in interstellar clouds that have been engulfed by the cocoon. The compressed surface layers are kept photoionized by UV from the central engine and the relativistic cocoon plasma itself. The emission measure in the ionization bounded clouds saturates at a value that approximates the observed relationship between turnover frequency and source size, and the model naturally reproduces the typical change in spectral index across the turnover, $\Delta \alpha \sim 2$. I suggested a diagnostic, involving the Faraday rotation as a function of frequency near the turnover, that might help to distinguish between screen and embedded cloud models.

With the exception of the high densities required by the Bicknell et al. (1997) GPS model, none of the distinctive properties of young, compact radio galaxies discussed above require ambient conditions that are any different from those found in ordinary, nearby galaxies. Most of the relations I have derived depend weakly on the ambient ISM density, so we cannot use the properties of CSOs to argue that galaxies at high-$z$ had ISMs similar to those we find today. What we can conclude is that the distinctive properties of young radio galaxies reflect their relative youth much more sensitively than they reflect their environments.

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