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INTERMITTENT RADIO GALAXIES AND SOURCE STATISTICS

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ABSTRACT

We suggest that extragalactic radio sources are intermittent on timescales of $\sim 10^4$–10^5 yr. With the use of a simple spherical model of a cocoon/shock system, it is found that inactive sources fade rapidly in radio luminosity but that the shock in the ambient medium continues to expand supersonically, thereby keeping the whole source structure intact during the inactive phases. The fading of inactive sources, and the effect of the intermittency on the expansion velocity, can readily explain the observed overabundance of small radio sources. In particular, the plateau in the observed distribution of sizes found by O'Dea & Baum can be interpreted as being due to intermittency. The model predicts that very young sources will be particularly radio luminous, once the effects of absorption have been accounted for. Furthermore, it predicts the existence of a significant number of faint "coasting" sources. These might be detectable in deep, low-frequency radio maps or via the X-ray and optical emission-line properties of the shock front.

Subject headings: galaxies: active — galaxies: jets

1. INTRODUCTION

Recent radio surveys have identified numerous objects that are morphologically similar to Fanaroff-Riley II (FR II) radio galaxies but are appreciably smaller. Those sources that are less than 500 pc in extent are termed compact symmetric objects (CSOs; Wilkinson et al. 1994). This class also contains many gigahertz-peaked sources (GPSs), sources whose radio spectrum is seen to peak at gigahertz frequencies (O'Dea, Baum, & Stanghellini 1991). The spectral form of GPSs is thought to be due to either free-free absorption by an inhomogeneous foreground screen or synchrotron self-absorption in the source itself. Slightly larger sources, those in the range of 0.5–15 kpc, have been termed medium symmetric objects (MSOs) by Fanti et al. (1995). These various classes of small sources are found to constitute 10%–30% of all sources in a flux-limited sample.

It is tempting to consider an evolutionary picture in which CSOs evolve into full-size FR II radio galaxies, passing through the MSO stage. Since we would expect the sources to remain small for a relatively short period of time, there must be strong luminosity evolution for us to see so many small sources (Begelman 1996, hereafter B96; Readhead et al. 1996). B96 showed how this luminosity evolution could be understood in terms of a declining source pressure as the source evolves.

O'Dea & Baum (1997; hereafter OB97) have recently studied a combined sample of objects including CSOs, MSOs, and classical FR II radio galaxies. In particular, they examine the distribution of (projected) linear sizes. Using the B96 evolution model, and assuming physically realistic interstellar medium (ISM) density profiles, they find a clear overabundance of CSOs and MSOs as compared with classical FR II radio galaxies. This is seen as a plateau in the size distribution of their sample of sources between $\sim$100 pc and $\sim$10 kpc. They suggest that either (1) a large fraction of the small sources are transient or frustrated and never evolve into large sources or (2) the luminosity evolution is much stronger than that predicted by B96, possibly because of a decline in the efficiency of conversion of jet kinetic energy into radio power.

In this Letter, we suggest that radio sources are intermittent and that the source statistics examined by OB97 can be understood in the context of a simple evolutionary picture if this intermittency is taken into account. In § 2, we develop a simple model of radio source evolution including intermittency. Theoretical source statistics are calculated in § 3. Section 4 discusses predictions of this scenario. Our conclusions are summarized in § 5.

2. THE COUPLED COCOON/SHOCKED-SHELL MODEL

2.1. *The Basic Model*

Adopting the standard evolutionary picture (Scheuer 1974; Begelman & Cioffi 1989), we assume that the radio jets are enveloped in, and feed, a cocoon of relativistic material that is overpressured with respect to the ambient medium (which may be the ISM of the host galaxy or the intracluster medium [ICM] of the host cluster). This overpressure drives a strong shock into the ambient medium and forms a shell of shocked ISM/ICM surrounding the relativistic cocoon. The expansion velocity of this shell is determined by the ram pressure of the ambient material entering the shock. The cocoon material and the shocked ISM/ICM shell are separated by a contact discontinuity.

While it is clear that the large-scale structures of radio sources show elongation along the jet axis, one rarely observes large axial ratios. For example, low-frequency (327 MHz) radio maps of the powerful FR II source Cygnus A (Carilli, Perley, & Harris 1994) reveal a radio-emitting cocoon with an axial ratio of $\sim$3, even though its jets are observed to be collimated to within a few degrees. A similar situation is found for the smaller CSOs and MSOs. Thus, for the purposes of our simple model, we shall assume that the cocoon and bow shock are spherical. We will denote the radius of the cocoon as r_c and the radius of the bow shock as r_s ($r_s > r_c$). We also denote by V_c and V_s the volume of the cocoon and shocked shell, respectively.

We make several further assumptions. First, we assume that at any given instant the pressure in the shock (of both the

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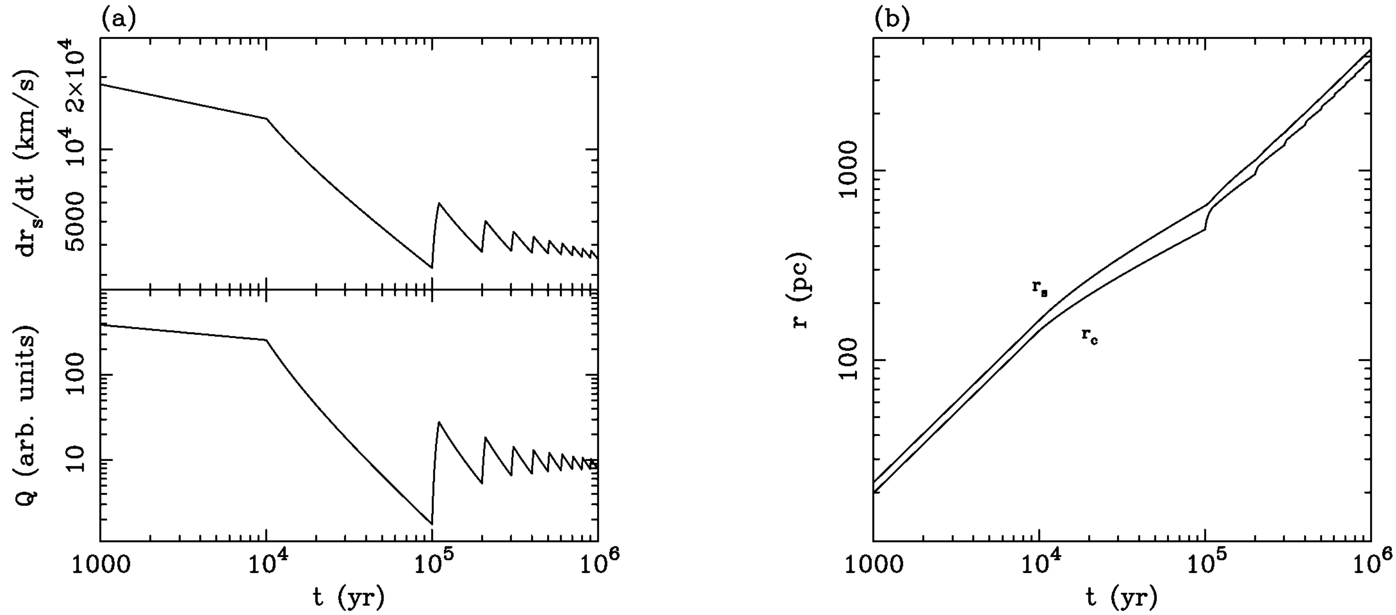

FIG. 1.—Properties of a periodically intermittent source (see § 2.2 for source parameters). (*a*) Velocity of the shock in the ambient medium (*top panel*) and the radio luminosity of the cocoon (*bottom panel*). (*b*) Evolution of the cocoon radius (*bottom curve*) and shock radius (*top curve*).

cocoon and the shocked ISM/ICM shell) is spatially uniform with a value $p(t)$. See Kaiser & Alexander (1997) for an explicit justification of this assumption. Second, we suppose that only a small fraction of the total kinetic luminosity of the source, $L_j(t)$, is radiated. The rest of this energy is assumed to be fed into the cocoon and thus drive the expansion of the cocoon/shocked-shell system. Third, the ambient (undisturbed) medium is assumed to have a density distribution of the form $\rho(r) = \rho_0(r/a)^{-\alpha}$, where r is the distance from the center of the radio source.

Given these assumptions, the conservation of energy can be applied to the cocoon and shocked shell to give

$$(\gamma_c - 1)^{-1}(V_c\dot{p} + \gamma_c p \dot{V}_c) = L_j(t) \tag{1}$$

and

$$(\gamma_s - 1)^{-1}(V_s\dot{p} + \gamma_s p \dot{V}_s) = \frac{1}{2}\,4\pi r_s^2\rho(r_s)\dot{r}_s^3, \tag{2}$$

where γ_c and γ_s are the ratio of specific heat capacities in the cocoon and shocked shell, respectively, and the dot denotes differentiation with respect to time. We close the system of equations with the ram-pressure condition, $p = \rho(r_s)\dot{r}_s^2$. This condition will be valid provided that the expansion of the shocked shell remains highly supersonic with respect to the ambient medium. If the ambient medium is identified with the hot component of the ISM/ICM, its sound speed will be $c_s \sim$ 1000 km s^{-1}. Thus, the expansion of the source will be highly supersonic provided that $\dot{r}_s \gtrsim$ a few $\times$ 1000 km s^{-1}. Once the expansion of the source ceases to be supersonic, the cocoon/shocked-shell structure will disrupt and dissipate.

In order to relate this model to radio observations, we need a prescription relating the radio luminosity, Q, to the physical parameters of the model. To do this, we assume that the radio emission is dominated by the synchrotron radiation of the relativistic electrons in the cocoon. If we further suppose that the magnetic field is in equipartition with the relativistic electrons, standard minimum pressure arguments give $Q \propto p^{7/4}V_c$.

2.2. *Evolution of a Periodically Intermittent Source*

We now apply the above model to the case of a periodically bursting source. For concreteness, we shall consider an initially small source that undergoes 10,000 yr long bursts that recur every 100,000 yr. We take the jet power to be $L_j = 10^{46}$ ergs s^{-1} during the bursts and negligibly small at other times. The cocoon is assumed to be dominated by relativistic material (i.e., $\gamma_c = \frac{4}{3}$), and we take a nonrelativistic equation of state for the shocked ISM/ICM shell (i.e., $\gamma_s = \frac{5}{3}$). Finally, the following physically reasonable parameters are taken to characterize the density profile of the ambient medium: $\rho_0 = 1.7 \times 10^{-25}$ g cm^{-3}, a = 500 pc, and α = 1.5. The qualitative behavior described below is insensitive to reasonable departures from these canonical parameter values.

Figure 1 shows the results of a numerical integration of equations (1) and (2). During the initial burst of activity ($t <$ 10,000 yr), the source expands self-similarly; i.e., the cocoon radius is a constant multiple of the shock radius. This is the evolutionary phase that has been previously examined by Falle (1991), B96, and Kaiser & Alexander (1997). As found in previous works, $r_s \propto t^{3/(5-\alpha)}$. By assumption, the power source switches off at t = 10,000 yr, and the cocoon/shocked-shell system enters a "coasting" phase akin to Taylor-Sedov expansion. It must be stressed that the expansion during this coasting phase is still pressure driven, as opposed to being driven by the momentum of the shocked shell. Despite the increased deceleration of the shocked shell, it still remains highly supersonic for the entire period of this coasting phase (i.e., until t = 100,000 yr). However, because of the drop in source pressure, the radio luminosity of the cocoon will fall rapidly once the power source has turned off. Thus, even though the basic source structure remains intact, a coasting source will be significantly fainter than an active source. It is also interesting to note that

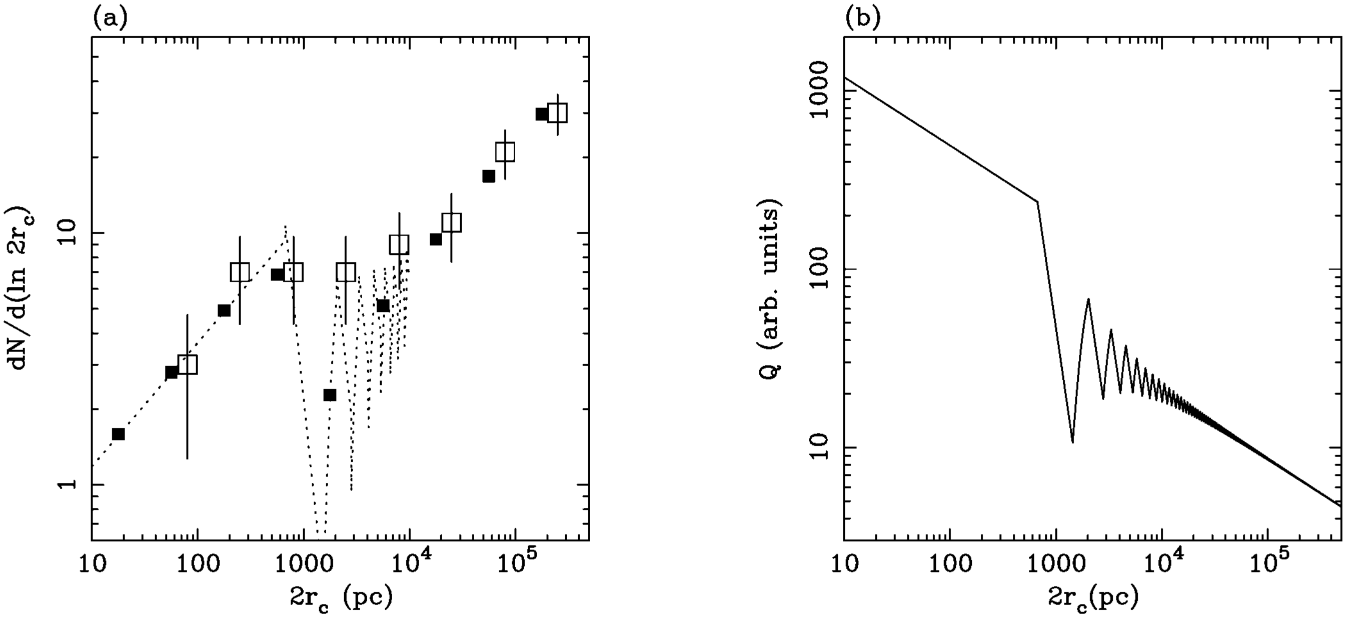

FIG. 2.—(*a*) Theoretical and observed size distributions. The dotted line shows the fine-grained (i.e., unbinned) theoretical model, which, for clarity, has not been displayed beyond 10 kpc. The filled squares show the binned theoretical distribution using bins of size 0.5 log $(2r_c)$. The data from Fig. 10 of OB97 (with 1 σ errors) are shown as open squares. (*b*) Radio luminosity as a function of r_c for these same (theoretical) intermittent sources.

the source evolution is no longer self-similar in the coasting phase.

The onset of the second burst of activity induces a rapid increase in pressure, leading to a subsequent increase in both the source expansion rate and cocoon radio luminosity. Note that during the (brief) period in which the contact discontinuity is accelerating (i.e., $\ddot{r}_c > 0$), this interface will be subject to Rayleigh-Taylor instabilities that will tend to mix material from the shocked shell with the relativistic cocoon material. This mixing will produce time dependence in the effective value of γ_c, thereby affecting the detailed evolution of the cocoon. The implications of this mixing will be addressed in future work.

After many bursts (or, more precisely, when the recurrence timescale is short compared with the expansion timescale), the intermittent nature of the source will be unimportant in determining its evolution. It will behave as a constantly fed source with jet power fL_j, where f is the fraction of time that the source is on with power L_j. The reestablishment of an approximately self-similar expansion in our numerical experiment reflects this fact.

3. SOURCE STATISTICS

Suppose that we have a single population of evolving radio sources. Further, suppose we form a flux-limited sample of these sources. With the assumption of a Euclidean universe, the number of sources in the luminosity range $Q \rightarrow Q + dQ$ is $dN \propto \phi(Q)Q^{3/2}dQ$, where $\phi(Q)dQ$ is the volume density of sources in that luminosity range. Since $\phi(Q)dQ$ is proportional to the time that a given source spends in this luminosity range, we have

$$\phi(Q) \propto \dot{Q}^{-1} = \left(\dot{r}_c \frac{dQ}{dr_c}\right)^{-1}, \qquad (3)$$

which implies that

$$\frac{dN}{dr_c} \propto Q^{3/2}\dot{r}_c^{-1}. \qquad (4)$$

The evolutionary model of § 2 allows us to determine the functions $Q(r_c)$ and $\dot{r}_c(r_c)$. Thus, equation (4) is an explicit expression for dN/dr_c as a function of r_c. We have chosen to examine the distribution of r_c, since it is the cocoon radius that will be identified observationally as the half-size of the radio source.

Figure 2*a* shows a comparison of the observed size distribution of OB97 with our theoretical size distribution for a single population of periodically intermittent sources. To facilitate this comparison, we have binned the theoretical size distribution using bins of 0.5 log $(2r_c)$. In order to match the distribution of OB97, we set $\alpha = 1.8$ (determined by the slope of the distribution at large sizes) and assume a burst duration of 30,000 yr. All other parameters have the values of § 2.2.

The intermittency of the sources allows the qualitative features of the OB97 size distribution to be reproduced. In particular, there is a plateau in the size distribution resulting from sources that are still undergoing their first few bursts of activity. If the break in the OB97 distribution at small sizes ($\lesssim$100 pc) is real, this could be identified as being due to sources that are still undergoing their first burst of activity. In this idealized case of a single evolving population, there is fine structure in the size distribution corresponding to the distinct cycles of activity. In practice, the stochastic nature of the parameters in any real source population will wash out this fine structure. In particular, the disagreement between our model and the data at ~2 kpc can be resolved if we consider realistic source populations. Note that we have not included the largest size bin of the OB97 distribution since this is probably affected by the complete turning off of old sources.

Figure 2*b* shows the radio luminosity Q as a function of the total source size $2r_c$. This is to be compared with Figure 9 of OB97. An important feature of Figure 2*b* is the dramatic decline in radio luminosity between the first burst and all subsequent bursts. In other words, if one were to assume a constantly fed source and extrapolate from large sources to small sources, then one would substantially underestimate the small source luminosity.

4. DISCUSSION

There are two immediate predictions of the intermittency model. First, Figure 2*b* suggests that statistically complete samples of GPSs and small CSOs will show them to be very much more radio luminous than suggested by extrapolation of MSO/FR II properties. With the assumption that the (optically thin) radio luminosity depends on cocoon pressure in some way, this prediction should hold for any physically reasonable prescription relating p, V_c, and the radio luminosity, Q. It must be noted, however, that there are observational complications involved in testing this prediction. As well as being comparatively rare, these small sources are often absorbed at typical radio frequencies. This may be due to free-free absorption in an inhomogeneous foreground screen or synchrotron self-absorption in the source itself. This absorption must be corrected for before comparisons of the type discussed above can be made.

A second prediction is that there should be a large number of medium-sized objects (a few hundred to a few thousand parsecs across) that are in a coasting phase and have faded below the flux limits of current radio surveys. There are several methods that could be employed to search for such sources. Deep, low-frequency radio maps might reveal the coasting cocoons of such sources. Alternatively, we might hope to observe the ISM/ICM shock either through X-ray signatures (using the high spatial resolution of *AXAF*) or via the Hα emission that it surely excites (see, e.g., Bicknell & Begelman 1996).

5. CONCLUSIONS

We have explored the implications of radio source intermittency on source statistics. To do this, we have developed a simple model for the evolution of a cocoon/shocked-shell system that is expanding supersonically into an ambient medium that possesses a power-law density profile. The cocoon is assumed to be fed energy at a rate $L_j(t)$. This model is integrated numerically for the case of a periodic source that has active phases (with constant L_j) separated by inactive, or coasting, phases in which $L_j = 0$. During the first few periods of inactivity, the radio luminosity will fade rapidly. However, these young sources can maintain highly supersonic expansion during their coasting phases and, hence, will remain intact throughout the inactive periods. Once a source has grown large enough so that the expansion timescale is longer than the recurrence timescale, the intermittency will not affect its subsequent evolution. The fading of small, inactive sources and the effect of intermittency on the expansion velocity of the sources produce a double break in the size distribution. This can be readily identified with the plateau found in the size distribution of OB97.

There are two clear predictions of this model. First, one could search for the faint, inactive sources. These sources might reveal themselves in deep, low-frequency radio surveys. Alternatively, they could be detectable via the X-ray signatures or Hα emission accompanying the coasting ISM/ICM shock front. Second, statistically complete radio samples of small sources (~100 pc and smaller), once corrected for absorption effects, should show these sources to be very over luminous as compared with an extrapolation from larger sources. Since this is essentially reflecting the high pressure of these small sources, this prediction should be independent of the precise form of the radio emissivity.

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