The Particle Content of Extragalactic Jets

David S. De Young

NOAO, Tucson, AZ 85719

ABSTRACT

Recent radio and x-ray data from radio sources in galaxy clusters are used to place constraints on the particle content and kinematics of jets that supply these radio sources. These data show that the $pdV$ work required to inflate the radio lobes in the ICM exceeds all other estimates of the amount of energy needed to supply the observed radio emission. If the required jet energy density has an isotropic pressure, then in almost all cases the jets cannot be confined by the external pressure of the ICM. This problem can be resolved with jets dominated by a cold and relatively dense proton population, but even here the accompanying energy density in electrons alone can cause jet decollimation in many cases. Calculation of particle interactions in a cold proton jet shows the electron-proton energy transfer times to be very long. Electron-positron jets, unless highly beamed and with an unusual energy distribution, cannot solve the decollimation problem. A viable alternative may be "Poynting Flux" dominated jets with a very low particle content.

Subject headings: radio galaxies, jets, galaxy clusters

1. Introduction and Motivation

Although collimated bipolar outflows from active galactic nuclei have been studied for over forty years, many fundamental characteristics of these outflows are still poorly known or completely unknown. Among these are the outflow speed, the energy flux of the outflow, and the nature and composition of the outflowing material (e.g., De Young 2002). In particular, the particle content and the total energy flux of the outflows, both key parameters to characterizing the nature of the "central engine" that creates them, are poorly known. Radio observations require only the presence of a relativistic electron population and an accompanying magnetic field to produce the observed synchrotron radiation. There is presumably another charged particle species carried outward with the electrons and field that provides charge neutrality, but its nature has remained generally obscure and observationally inaccessible. Hence indirect arguments have been put forward to support various possibilities, such as positrons, protons, and possibly other more exotic species (e.g., Ghisellini et al. 1993; Celotti & Fabian 1993; Reynolds et al. 1996). Because the energy flux carried by this positively charged population has had no clear empirical constraints, its value has been usually set by assumption or by past practice.

However, during the last few years a combination of x-ray and radio data has emerged that provides for the first time some unambiguous measurements of the characteristics of extragalactic jets. These observations are of extended radio sources that reside in rich clusters of galaxies, and the data reveal the presence of cavities in the intracluster medium (ICM) that are coincident with the extended lobes of radio emission associated with an active galaxy within the cluster. (e.g., Böhringer et al. 1993; Fabian et al. 2000, 2003a, 2003b; McNamara et al. 2000, 2001; David et al. 2001; Nulsen et al. 2002; Birzan et al. 2004; Blanton et al. 2004; Kempner et al. 2004). The inference drawn from these data is that the cavities in the ICM have been inflated by the expanding radio lobes; in some cases the extended radio emitting regions show evidence of ongoing injection of energy from jets emanating from the nucleus, while in other cases the cavities are associated with relic radio lobes. In many cases there is evidence suggesting that the lobes are currently expanding very
slowly, if at all, into the ICM, and that the radio "bubbles" may be rising buoyantly through the intracluster medium. Many ideas have been put forward in interpreting the data or in modeling the dynamics of these objects (e.g., Quilis et al. 2001; Brighenti & Mathews 2002; Brüggen 2003; De Young 2003). Hydrodynamic simulations of the rise of buoyant bubbles have been carried out in two and three dimensions (e.g., Churazov et al. 2001; Brüggen et al. 2002; Brüggen & Kaiser 2002; Reynolds et al. 2002), and more realistic MHD simulations have also been performed (Brüggen & Kaiser 2001; Robinson et al. 2004; Jones & De Young 2005).

An essential aspect of these observations relevant to the content of extragalactic jets is that the pdV work required to form the cavity in the ICM can be directly measured, since the density and temperature of the ICM are known. Hence for the first time an unambiguous measure of the minimum total energy injected into the expanding radio sources can be made, and the consequences of this remarkable calorimetry in understanding the nature of the radio sources themselves is the subject of this paper. Section 2 derives some constraints that can be placed on the energetic and dynamics of jets which come directly from the pdV values derived from observations. Section 3 considers some consequences of the results of Section 2 in terms of the content of outflowing jets, and Section 4 discusses particle interactions within jets. Section 5 provides some additional overall conclusions and consequences of this work.

2. Observational Constraints

In this section observational data are used in conjunction with a minimal set of additional assumptions to determine constraints that can be placed on the content of extragalactic jets. The x-ray data and the radio morphology data permit a direct determination of the pdV work needed to inflate the cavity in the ICM, with no additional assumptions (e.g., McNamara et al. 2001; Birzan et al. 2004). The radio flux, source distance and spectral index provide a measure of the radio luminosity. With just these numbers some interesting comparisons can be made. For example, if the value of pdV is a measure of the energy injected to date into the ICM by the active nucleus, how does this compare with the energy needed to power the radio source at its current luminosity over some radiative or dynamical lifetime? Is there enough pdV energy to do this? Is there an excess of energy, and if so, what form has it taken? (The total energy injected is of course more than the value given by pdV, since there is some internal energy present in the material that has inflated the bubble.) How do these numbers compare to the usual "equipartition" energies for the radio source? If more energy is needed to perform the pdV work than is required to account for the radio emission, how is this energy transported from the nuclear regions into the radio lobes? Does consideration of this energy transport place any constraints on the form the energy takes; i.e., upon the content of the extragalactic jets? It is this last question that is the focus here.

2.1. Total Energies

The first step in providing some answers to these questions is to estimate the total energy $E_e$ needed in relativistic electrons to produce the radio emission that is seen at the present time. At least this much energy must be produced in the nucleus and carried outward by the jets, and it can then be compared to the pdV energy measured by completely different means. For an observed power law radio flux distribution of the form $S(\nu) \propto \nu^{-\alpha}$, with $\alpha$ positive, the underlying relativistic electron energy distribution per unit volume is of the form $n(E,r)dE = KE^{-\alpha}dE$, where $\alpha = (p-1)/2$. Here the electron distribution has been assumed homogeneous and isotropic, so that $K$ is not a function of position $r$ within the emitting region. The total energy in electrons that is needed is then just $E_e = \int n(E,r)EdEdr = KV \int E^{-\alpha+1}dE$, and the problem is then to determine the value of the coefficient $K$ in the electron energy distribution. This is done by first writing the intensity of synchrotron radiation $I_\nu$ emitted along a line of sight. This expression, which contains $K$, is then integrated over the emitting volume to obtain a value for the total radio flux $S_\nu$. For a power law flux distribution of the above form, $S_\nu$ is related to an observed flux $S_\nu$ at some frequency $\nu_o$ by $S_\nu = S_\nu(\nu/\nu_o)^{-\alpha}$, and this expression is then solved for $K$ and the result inserted into the equation for $E_e$. The derivations of $I_\nu$, $S_\nu$, and $E_e$ are well known (e.g., Ginzburg &
Syrovatskii 1959; De Young 2002), but care needs to be exercised in integrating over the frequency spectrum of the individual electrons and in integrating over the pitch angle distribution of the electrons (e.g., Korchak 1957; Trubnikov 1958; Syrovatskii 1959). Combining the derivations in these references gives, in CGS units,

\[
E_e = \frac{1.48 \times 10^{12}}{a(p)} D^2 B^{-3/2} \times \frac{S_o \nu_p^4}{1/2 - \alpha} (\nu_U^{(1/2-\alpha)} - \nu_L^{(1/2-\alpha)}),
\]

(1)

where \(D\) is the distance to the source and \(\nu_L\) and \(\nu_U\) are the lower and upper frequency limits. The function \(a(p)\) contains the coefficients resulting from integration over electron pitch angles and over the emitted radiation of individual electrons. The values of \(a(p)\) range from 0.28 to 0.07 as \(p\) varies from 1 to 4, so this variation of \(a(p)\) can have meaningful consequences. A more approximate treatment that does not integrate over the pitch angle distribution or the emission spectrum of individual electrons eliminates \(a(p)\), and the coefficient becomes a constant approximately equal to \(4 \pi \times 10^{12}\) in the same cgs units (Lang 1980, Fabian et al. 2002).

In order to proceed further the magnetic field in Eq. 1 must be specified, and there are no independent observational constraints available to determine the mean value of \(B\). A common practice is to assume rough energy equipartition between the magnetic and particle energies in a radio lobe, since this minimizes the total energy required. This total lobe energy is \(E_{tot} = E_p + E_B\), where \(E_p\) is the energy of all particles present (the "plasma"), and \(E_B\) is the total magnetic field energy. The energy in electrons (Eq. 1) can be written as \(fB^{-3/2}\), and it is usually assumed that the additional energy in the charge neutralizing species (and any others) can be written as some multiple \(\kappa\) of \(E_e\), so that \(E_p = (1 + \kappa)E_e\). For a field that is homogeneous and isotropic on scales comparable to the source size, \(E_B = V(B^2/8\pi)\), where \(V\) is the source volume and \(B\) is some appropriate average value of the magnetic field. In addition a filling factor \(\phi\) for the "relativistic plasma" in the lobe can be introduced into \(E_B\) (e.g., Fabian et al. 2002; Dunn & Fabian 2004; Dunn et al. 2005), but in view of the unknown nature of the interstitial material, it is not clear that firm new constraints on the jet content will be obtained from values of \(\phi \neq 1\). Differentiation of \(E_{tot}\) with respect to \(B\) and finding the extremum value gives the standard equipartition result:

\[
B_{eq} = \left[\frac{8\pi (1 + \kappa)}{V} f^{2/7}\right]^{1/2}
\]

(2)

It seems unlikely that the magnetic field will exceed this equipartition value, since in that case the magnetic field will control the dynamics of the radio source evolution, and models of magnetically dominated jets have not yet been shown to be stable over long periods of time and over distances of tens to hundreds of jet radii (e.g., Begelman 1998; Li 2002; Hsu & Bellan 2002). (This applies to MHD models and does not include "Poynting Flux" models (e.g. Lovelace et al. 2002).) The field strengths could be well below the equipartition value, and this has been argued to be the case for several cluster radio sources (e.g., Fabian et al. 2002; Dunn & Fabian 2004). Of course, as the magnetic field strength decreases below equipartition, the required electron energy rapidly rises, as can be seen in Eq. 1. However, the electron energy cannot rise without limit, as will be discussed in Section 2.4, and so this sets lower limits to the departure from equipartition of \(E_e\). Another issue is equipartition with respect to the entire particle population or with respect to the relativistic electrons only. This is relevant if the charge neutralizing species that is co-located with the electrons carries significantly more energy per particle than the electrons. In this case the magnetic field could be in near equipartition with the electrons and yet be well below equipartition with the particle population in general. If this is so, then the magnetic field is given by \(B_{eq}\) with \(\kappa = 0\), and this value can then be used in Eq. 1 to determine a value for the total electron energy.

There has previously been no observational motivation for choosing a value for the energy contained in the positively charged particle species. While it may be true that "a typical value used in the literature is \(k = 100\)" (Fabian et al. 2002) this value arises from consideration of cosmic rays in our own Galaxy (Burbidge 1956, 1959) and has no relation to extragalactic radio sources. If the positively charged species is positrons, then it is likely that they will be in energy equipartition with the relativistic electrons. while if this species is pro-
tons, then there is no a priori value that is more likely than any other.

2.2. Timescales

A second step is to estimate the time during which the $pdV$ energy is injected into the ICM in order to obtain the total energy fluxes required to be transported by the collimated outflows. This timescale is not known, since the ages of the extended radio sources are not known. However, limits can be placed on the duration of the injection process. One limit is the electron radiative lifetime, unless reacceleration is the major source of electron energy at the present epoch.\(^1\) Absent significant reacceleration, the outflow has occurred over a time less than the radiative lifetime of the electrons, and a relativistic electron radiating at a frequency $\nu$ loses one half its energy in a time given by (e.g., De Young 2002)

$$t_{1/2} = \frac{9m_e^3c^5}{4e^4} \left( \frac{3e}{4\pi m_e c} \right)^{1/2} B^{-3/2} \nu^{-1/2}, \quad (3)$$

or, $t_{1/2} = 5.2 \times 10^7 B_{-5}^{-3/2} \nu_9^{-1/2}$ yr. Here $B_{-5}$ is the average magnetic field strength in units of $10^{-5}$ G, and $\nu_9$ is the frequency of the synchrotron radiation in GHz.

A second time scale comes from estimates of dynamical processes involved in these objects, and a time that has been frequently used in this connection is the buoyant rise time of the source, assuming sources form buoyant bubbles in the ICM. Given that assumption, buoyant rise times can be estimated from approximate buoyant speeds (e.g., Churazov et al. 2001), where the time calculated is that for the radio emitting cavity to rise buoyantly from the location of the active nucleus to its presently observed position. These lifetimes are also upper limits, for it is very unlikely that the buoyant phase actually begins at the position of the central energy source. A more accurate buoyant lifetime would be the time required for the cavity to rise from the termination radius of the outflowing jet (which is not known) to the present position of the bubble. The buoyant rise time obtained from the estimated buoyant velocity given by Churazov et al. (2001) is $t_{buoy} = D/v_b \sim D/[2gV_b/C_D A_b]^{1/2}$, where $D$ is the distance of the bubble from the parent nucleus, $A_b$ is the bubble cross section, $V_b$ its volume, $g$ the (average) gravitational acceleration, and $C_D$ is an estimated drag coefficient.

2.3. Energy Fluxes

Given the total energy requirements from both the $pdV$ energy and the total energy in electrons required to power the observed synchrotron radiation, the above timescales allow an estimate of lower limits to the energy flux carried by the jets. Since the magnetic field dependence of the total electron energy is the same as that for the radiative lifetime (Eqs. 1 and 3), the energy flux required to produce the observed synchrotron emission during a radiative lifetime, $E_c/t_{rad}$, is independent of the assumed value for the magnetic field. Although this estimate of the energy flux is free from assumptions of magnetic field strength, a comparison needs to be made with the energy flux needed to supply the $pdV$ work, which may not be independent of $B$. This latter energy flux can be found once an outflow time is chosen, and logical choices are both the radiative and buoyant timescales. Use of a radiative timescale requires an assumption about magnetic field strengths, and the above discussion about equipartition fields suggests that use of a field value that is in equipartition with the electron energy density alone can provide an interesting limiting case, given other arguments that suggest that the field is at or below overall equipartition (Fabian et al. 2002, Dunn & Fabian 2004).

Once these energy fluxes are in hand, parameters that characterize the collimated outflow itself can be used to arrive at the final set of constraints. The two jet parameters that are needed are the jet radius and the bulk flow speed of material within the jet. These, when combined with the total energy flux required, give the energy density $\epsilon_j$ within the jet, since the total energy flux is just $dE_j/dt = \epsilon_j v_j A_j$, where $v_j$ is the bulk flow speed in the jet, and $A_j$ is the jet cross section. For radio sources and relics in clusters of galaxies the pressure in the ICM through which the jet travels is known, and this external pressure

\(^1\) Though there is indirect evidence for reacceleration in the lobes of some large sources from spectral index maps and particle transit time arguments (e.g., Mack et al. 1998), the spectral index data are not unambiguous (Blundell & Rawlings 2000; Treichel et al. 2001) and the phenomenon is not generally seen in small FR-I sources such as the ones in this sample.
can be compared with the range of internal energy densities $\epsilon_j$ interior to the jet. This comparison assumes that the internal energy density results in an isotropic comoving pressure, such as that from a relativistic electron population with random velocities. Internal energy densities in excess of the external values of $nkT$ mean that that particular jet cannot be confined by the ICM. For these cases either the internal energy density must be lowered by some means, or the internal energy in the jet must not create an associated isotropic pressure, or an alternate confinement mechanism must be invoked. The most obvious candidate for alternate confinement is some form of magnetic confinement, but as mentioned previously, these mechanisms require very special initial conditions, very strong anisotropic magnetic fields, and they are often unstable. Since magnetic confinement has not yet been shown to be effective over tens of kiloparsecs or for times of order $10^8$ years, and because specific models with specialized geometry are needed to address any particular confinement picture, this alternative will not be considered further here.

2.4. Inferences from Data

The general relations derived above are applied to a subset of radio bubbles and relic radio sources for which radio and x-ray luminosities and geometries are known. The source sample is taken from the sample of objects discussed by Birzan et al. (2004). These authors tabulate, for a sample of 17 sources, radio and x-ray data, lobe geometries, $pdV$ values, buoyant rise times and other derived properties for each component of the sources in the sample. The sample used here is taken from this single source in order to ensure a uniform treatment in the derivation of radio lobe volumes, buoyant rise times and values of $pdV$. The objective is to consider clear examples of radio source configurations that have been inflated in the ICM, with well defined boundaries, to enable the use of buoyant timescales in calculating energy fluxes and in comparing various possible implications for the content of the collimated outflows. Hence the non-cluster objects HCG 62 and M84 listed by Birzan et al. are not included here. In addition the clearly "non-bubble" sources Cyg A and M87 are also excluded. Added to this list is the very luminous radio bubble source MS0735 at a redshift of 0.22 reported by McNamara et al. (2005). The final list of objects used is, in order of decreasing luminosity, MS0735, Hydra A, A2597, MKW 3S, A2052, A133, A4059, A2199, Perseus, RBS797, A1795, A478, 2A0335, and A262. In each case the associated galaxy cluster name has been used, consistent with the notation of Birzan et al. (2004).

For each of these sources, or for each component of a source if the source is listed by Birzan et al. as having two components, the following quantities were calculated: (1) The distance, using $H_0 = 75$ km/sec/Mpc; (2) the volume of each component, using the major and minor axis data of Birzan et al. and assuming each component is an oblate spheroid; (3) the equipartition value of the magnetic field, using Eq. 2 for equipartition with the electron population only; (4) the energy in the electrons required to produce the radio luminosity reported by Birzan et al., using Equations 1 and 2 (for the source MS0735 the radio luminosity was calculated using a spectral index of $\alpha = 2.5$ ( McNamara 2005)). All calculations were carried out using a low frequency cutoff of 10 MHz (the same cutoff used by Birzan et al. (2004)) and also of 3 MHz to test the sensitivity of the results to $\nu_L$; (5) the radiative lifetime $t_{rad}$ against synchrotron losses at a frequency of 1 GHz; (6) the radio luminosity of each component as determined by the ratio of its volume to the total volume times the total radio luminosity; (7) the total energy of each component required to radiate at the observed luminosity for a time $t_{rad}$ in order to compare with the $pdV$ energy; (8) the total energy required for each component to radiate at its luminosity for the buoyant risetime $t_{buoy}$ given by Birzan et al.; (9) the ratios of the energies (4), (7) and (8) to the $pdV$ energy of that component given by Birzan et al.; (10) the maximum total energy flux required for each component to supply the $pdV$ energy in a time $t_{rad}$ and in a time $t_{buoy}$; (11) the total energy density $\epsilon_j$ in a jet required by (10) for a given jet radius and bulk flow speed (from $dE_j/dt$) for each component; (12) the value of $nkT$ in the ambient ICM surrounding the jet. This ambient value is found by use of a power law fit to the radial dependence of ICM pressure and then determining the value of $nkT$ in the ambient ICM at a distance one half that of the distance from the nucleus of the parent galaxy to the center of the radio lobe. This distance should approximate well the condi-
tions that surround the jet which feeds the radio lobe. The values of $nkT$ at the radio lobe are taken from the results of Birzan et al. (2004). The power law fit used is $p(r) = p_0(r/r_0)^{-0.6}$, which fits well the data reported by McNamara et al. (2005) for MS0735 as well as the data reported for Perseus by Fabian et al. (2006).

### 2.4.1. Total Energies

The first comparison to make is one between the known $pdV$ energy required to inflate the radio lobes and the other estimates of the energy present in each radio source component. These other energy estimates are the calculated radio luminosity $L_{\text{R}}$ times the radiative lifetime using the equipartition magnetic field discussed above, the radio luminosity times the estimated buoyant rise-time, and the minimum (equipartition) energy in electrons required to produce the observed radio luminosity. The total minimum equipartition energy present is of course at least twice this last value when the magnetic field is included, and it may be more if the charge neutralizing species carry a significant amount of energy. But the issue here is a comparison of $pdV$ with estimates of the energy needed to produce the observed radio emission. The $pdV$ energy is an observed minimum; there must be at least this much energy carried out to each radio component.

![Figure 1](image_url)

Fig. 1.— Distribution of the ratio $(pdV/E_i)$ for each component of the radio sources in the sample. Values of $pdV$ are taken from Birzan et al. (2004), and $E_i$ are the values of $L_{\text{R} \text{rad}}$, $L_{\text{R} \text{buoy}}$ and $E_{\text{min}}$ as described in the text.

Figure 1 shows the distribution of the logarithm of $(pdV/E_i)$, where $E_i$ is each of the three other energies listed above, for each radio component of the sample used here. Hence each two component source contributes six entries to Fig. 1. Two things are immediately evident from this figure. First, in every case the minimum total energy required to account for the $pdV$ work exceeds all other energy estimates. Second, the excess in $pdV$ energy over the other estimates is often very large, from factors of ten to factors of several hundred. Thus this result is insensitive to uncertainties in the data introduced by measurement errors in the lobe geometries or low frequency cutoffs in the synchrotron spectrum, since these will introduce uncertainties of factors of two or less. The essential conclusion from this comparison is that the energy present in the radio lobes required to account for the $pdV$ work is by far the dominant energy measure for all these radio sources, and possibly for all radio sources as well. And again, the $pdV$ energy is an observed quantity, not an estimate based upon any assumptions about equipartition, source lifetimes, or source dynamics.

### 2.4.2. Jet Energetics

What are the implications of this dominant $pdV$ energy for the jets that supply this energy to the lobes? Using the $pdV$ values, the required energy flux in the jet and an accompanying energy density in the jet can be found, as described in steps (10) and (11) above. Calculation of an energy density requires specification of an average jet cross sectional area $(\pi r_j^2)$ and a mean value of the speed $v_j$ with which material is advected outward by the jet. Nominal values chosen here are $v_j = 0.1c$ and $r_j = 0.1$ kpc. The value of of $v_j$ was chosen because these objects are more similar to FR-I objects than to FR-II sources, and hence the mean jet speeds are likely to be non-relativistic or even subsonic or transonic. In addition, in those cases where jet structures are seen in the radio data, they are often distorted, which further suggests

---

2 The values of $pdV/E$ for the powerful source MS0735 lie near the upper end of the distribution in Figure 1, and this is also true for the energy density distributions discussed in Section 2.4.2 and Section 3. Although MS0735 is an exceptional source in this sample, it may be more representative of FR-II objects and the most luminous FR-I sources; hence it is of particular interest because of this.
non-relativistic speeds. For completeness the calculations were also carried out with $v_j = 0.5c$, but it seems that a mean value of $v_j$ this large is unlikely.

The value of $r_j$ chosen is comparable to or larger than many values of $r_j$ for highly resolved jets such as that in M87 (Sparks et al. 1996). For most of the radio bubble sources in this sample the resolution of the radio observations is not high enough to resolve the jet structures that carry energy to the lobes. Hence values for small scale jets such as M87 may be the most appropriate here. An extreme upper limit would be to use an average jet diameter of 1 kpc, which is applicable as an upper limit to very large scale (~ 100 kpc) jets such as Cygnus A (e.g., Swain, Bridle & Baum 1996). Values of jet energy density $\epsilon_j$ for this limiting value of jet diameter were also calculated. Hence the nominal values of $v_j = 0.1c$ and $r_j = 0.1kpc$ are near the middle to upper end of the range of values applicable to these objects (with the possible exception of MS0735), and this choice will then result in values of the jet energy density that are near the lower end of their possible range.

The resulting values for $\epsilon_j$ can then be compared to the values of $nkT$ for the ambient ICM surrounding the jets, as described in steps (11) and (12) in the previous section. Figure 2 shows the distribution of $\epsilon_j$ derived from the $pdV$ requirements divided by the values of $nkT$ in the ambient ICM around each jet. For $r_j = 0.1kpc$ and $v_j = 0.1c$, Figure 2 shows that almost all (96%) jets with an internal energy density required to supply the observed $pdV$ energy to their associated lobe cannot be confined by the external medium. This result is independent of the form taken by the energy being transported by the jet and only requires that the $\epsilon_j$ produce pressure via a standard equation of state.

Thus, unless some specific external magnetic confinement model is employed in almost every cluster radio source, the jet energy densities required would result in decollimation and destruction of the jet. The resulting outflow would be more like an isotropic wind and would not produce the typical double lobed radio structure seen here and in essentially all extended radio sources. Increasing the mean jet advection speed to $0.5c$ for all jets decreases the value of $\epsilon_j$, but in most cases the jet energy densities still cannot be confined. In this case 90% of the jets could not exist if they were to supply the required energy to their respective lobes. Increasing the jet diameter to 1 kpc lowers the internal energy more dramatically, but even in this case almost two-thirds (65%) of the jets would not be confined. It is important to recall that the $pdV$ values are minimum energy requirements because the enthalpy in the lobes is larger than this, and in addition $t_{rad}$ and $t_{buoy}$ are upper limits to the actual outflow times.

3. Implications for Jet Content

The results of Section 2.4.2 show that measurements of the $pdV$ work needed to create the radio "bubble" sources in the sample used here imply that the jets supplying the energy will be decollimated in almost all cases as long as the energy density in the jet has an associated pressure given by a conventional equation of state. One obvious solution to this problem is to include in the content of the jet a component that carries energy but does not contribute significantly to the internal pressure of the jet. A leading candidate for this component is a population of "cold" protons as the charge neutralizing species.

A cold proton population moving at the advection speed of the jet can carry energy as directed kinetic energy $m_p v_j^2$ per particle, and this energy...
can be significantly greater than the energy per particle carried by the relativistic electrons. If the relativistic electron population has a power law energy distribution of the form \( N(E)dE = KE^{-p}dE = K\gamma^{-p}d\gamma \), where \( \gamma \) is the Lorentz factor of the electrons, then the average value of \( \gamma \) is just

\[
\bar{\gamma} = \frac{\int N(\gamma)\gamma d\gamma}{\int N(\gamma)d\gamma} = \frac{\int \gamma^{1-p}d\gamma}{\int \gamma^{-p}d\gamma}.
\]

For \( p > 2 \), \( \bar{\gamma} = \left( \frac{p-1}{p} \right) \gamma_{min} \) (using \( \gamma_{max} >> \gamma_{min} \)), and for a radio flux of the form \( S_\nu \propto \nu^{-\alpha} \), \( p = 2\alpha + 1 \), hence values of \( p \geq 2 \), corresponding to \( \alpha \geq 0.5 \), are most likely here. The value of \( \gamma_{min} \) is not known, though estimates can be obtained via inverse Compton scattering models of x-ray emitting jets (e.g., Celotti et al. 2001). Conservative estimates of \( \gamma_{min} \) in the range of 1 - 10, together with \( \gamma_{max} \) values of \( 10^3 - 10^4 \), all suggest that \( \bar{\gamma} \sim 10 \) is a number with wide applicability. In any case \( \bar{\gamma} \) is very unlikely to be near \( 10^3 \), and hence the cold protons carry much more energy in the jet than the electron population. The interaction of these protons with the relativistic electrons in the jet will be considered in Section 4.

For the sample of sources here one can equate the required energy in \( pdV \) work to an energy flux carried by cold protons in the jet, \( \dot{E}_p = \pi n_p m_p v_j^2 r_j^2 \), times the outflow lifetime. This then gives the number density of cold protons in the jet needed to provide the required energy. The jet proton number densities required for each of the radio sources used here fall between 0.2 and \( 3 \times 10^{-6} \) cm\(^{-3} \), with a concentration between 0.02 and \( x \times 10^{-4} \) cm\(^{-3} \), using energy fluxes delivered over the electron radiative lifetimes or over the buoyant risetimes and with \( v_j = 0.1c \) and \( r_j = 0.1 \) kpc. For the much higher average jet speed of \( v_j = 0.5c \), the values of \( n_p \) will be reduced by a factor of 125. The directed flux of protons can be thermalized through one or more termination shocks that occur at the end of the jet when it encounters either the surrounding ICM and begins to form the radio lobes or when it encounters a similar shock due to the internal back pressure in the already growing lobe.

The simplest cold proton flux model assumes that the relativistic electrons are also advected outward at \( v_j \) along with a dynamically unimportant magnetic field and that the electron momentum distribution is isotropic in a co-moving frame. Setting the electron number density \( n_e \) equal to the derived proton number density \( n_p \) and assigning an average \( \bar{\gamma} \) to each electron then allows calculation of the electron energy density \( \epsilon_e \) within the jet and also the total electron energy flux \( \dot{E}_e \) into the lobe. A first test is to see if the values of \( \dot{E}_e \) are equal to or greater than the radio luminosity \( L_R \) associated with a given lobe. The calculated values of \( \dot{E}_e/L_R \) here for \( v_j = 0.1c \) and \( r_j = 0.1 \) kpc are greater than one for all but 3 out of 52 source components, so in general this requirement is satisfied. A second test is to compare values of \( \epsilon_e \) and the values of \( nkT \) in the ICM surrounding the jets. With an average value of \( \bar{\gamma} = 10 \), jet parameters of \( v_j = 0.1c \) and \( r_j = 0.1 \) kpc give values of \( \epsilon_e = n_e \bar{\gamma} m_e c^2 \) that are greater than the ambient values of \( nkT \) for almost all radio components (48/52), resulting in jet destruction in those cases. The distribution of \( \epsilon_e/nkT \) in this case is shown in Figure 3. (In principle there is a contradiction between the value of \( \bar{\gamma} = 10 \) and a value of \( \nu_L \sim 10^8 \) Hz used earlier, but only if \( \nu_L \) reflects a true cutoff in the radio emission, which is unlikely. Raising \( \bar{\gamma} \) to correspond to \( \nu_L \) means \( \bar{\gamma} \sim 10^2 \), which makes the confinement problem even more severe.) If the average jet speed is increased to \( v_j = 0.5c \), the required values of \( n_p = n_e \) decrease by a factor of 125, as does \( \epsilon_e = n_e \bar{\gamma} m_e c^2 \). In this case jet confinement and collimation can be maintained for about 80% of the objects. Increasing the jet diameter to 1 kpc will ensure confinement in almost all cases.

However, high speed flow all along the jet creates a further complication if the electrons flowing in the jet are the sole supply of energy that powers the observed synchrotron radiation. For mean values of \( v_j = 0.1c \), the energy flux in electrons emerging from the jet is comparable to or greater than the integrated radio luminosity of the associated lobe in nearly every case, as described above. Since the net proton energy flux \( \dot{E}_p = \pi r_j^2 n_p m_p v_j^2 \) is fixed by the \( pdV \) requirement in a given lobe, and since \( n_e = n_p \), increasing the flow speed to \( 0.5c \) to avoid decollimation reduces the jet electron energy density \( \epsilon_e = n_e \bar{\gamma} m_e c^2 \) at a fixed \( \bar{\gamma} \) by \( (\Delta v_j)^2 \), while the flux of particles from the jet into the lobe increases only by \( \Delta v_j \). As a result, the net electron energy flux \( \dot{E}_e = \pi r_j^2 \epsilon_e v_j \) into the lobe is reduced, and in the case of \( v_j = 0.5c \), the
electron energy flux $\dot{E}_e$ is equal to or greater than the radio luminosity of the associated lobe in only 46% of the lobes in this sample. Thus high values of $v_j$ may require some mechanism to augment the energy of the relativistic electron population, possibly via conversion of some fraction of the proton energy flux.

Hence an important conclusion about cold proton dominated jets is that such jets can provide the very large energy fluxes needed to explain the values of $pdV$ energy observed in the ICM cavities, but if the accompanying relativistic power law distribution of electron energy is isotropic in the frame comoving with the jet, then unrealistically large values of the jet average flow speeds are needed to avoid jet decollimation. In addition, such high flow speeds in turn reduce the net electron energy flux into the lobes to a level that cannot support the observed radio luminosities in roughly two-thirds of the sources in the sample. These results may indicate the need for more complex internal structures in particle dominated jet models beyond the simple structures tested here, such as conversion of some fraction of the proton energy to the relativistic electron population or use of a "cold but relativistic" electron beam. It is not clear how this latter option could be maintained against streaming instabilities or how it would produce the synchrotron radiation seen in jets. The problems are generally most extreme for large and luminous sources such as the one seen in MS0735 (and possibly all FR-II objects as well).

A further indication of the possible need for complexity in particle dominated jet flows comes from a minimalist electron energy flow model that is independent of all the above restrictions imposed by $pdV$ energy requirements. Without reference to total energy fluxes, possible proton populations, etc., an electron energy flux required to produce the observed radio emission alone can be constructed from the ratio of the electron energy $E_e$ divided by the radiative lifetime $t_{\text{rad}}$ of the same electrons (cf. Sect 2.3). This ratio is independent of the magnetic field strength and is thus not dependent on any assumptions about equipartition magnetic fields. From Eqs. 1 and 3,

$$\dot{E}_{e,\text{min}} = \frac{E_e}{t_{\text{rad}}} = \frac{8\pi}{27a(p)}D^2
$$

$$\nu \left(\frac{1}{2} - \frac{\alpha}{2}\right) \left(\frac{L}{L_c^{(1/2-\alpha)}} - \nu_L^{(1/2-\alpha)}\right).$$

This ratio gives a minimum value for the electron energy density $\epsilon_{e,\text{min}}$ in the jet for a given value of $v_j$ and $r_j$. Values of $\epsilon_{e,\text{min}}$ can be found for each radio component and compared again to the ambient pressure in the ICM that surrounds the jet. The distribution of these ratios shows that the internal energy density from this minimum electron energy flow at $v_j = 0.1c$ and $r_j = 0.1$ kpc still exceeds the ambient pressure for many objects (58%). Increasing the flow speed to 0.5c and jet diameter to 1 kpc essentially removes this problem, but only for extremum values of jet flow speed and size, given the overall geometry of these small radio sources. This exercise again suggests that a simple particle dominated jet picture may encounter difficulties even in the absence of the increased energy requirements imposed by the $pdV$ measurements. In principle a "beamed" population of very cold relativistic particles, in addition to a heavy cold particle flux, could, if stable, satisfy all the constraints on energy supply and collimation. A beamed electron-positron jet would be less successful in solving this problem unless the average $\gamma$ of the electrons (and positrons) is of order 1000, which in turn places strong constraints on either the spectral index $\alpha$ or the value of the low energy cutoff $\gamma_{\text{min}}$ of the particle energy distribution.
4. Internal Dynamics of Electron-Proton Jets

A question that has not generally been addressed in particle dominated jet models is that of the interactions among particle species present in the jet. Of particular relevance here are the particle interactions in a "cold proton - hot electron" jet that can provide the required $pdV$ energy and the radio luminosity as described in Section 3. The basic question is whether or not the relativistic electrons can transfer a significant amount of their energy to the comoving cold protons during their time of residence in the jet. This is an issue of general interest in jets with multiple particle populations at different temperatures; in this case if there is a significant energy transfer then not only may the electrons be unable to power the observed radio luminosity without reacceleration, but there may in addition be important changes in the power law form of the electron energy distribution. Also, if the cold proton population is "warmed" in any significant manner then the interactions among protons, electrons and magnetic field become more complex, and the possibility of significant thermalization of the proton population may arise, resulting in potential decollimation and destruction of the jet.

Thus the problem is to calculate the collision rate and resulting energy equipartition time between relativistic electrons and cold protons. A similar problem involving the interaction between very high temperature "thermal" electrons and cooler protons has been treated by Gould (1981, 1982). The problem here is somewhat different in that it involves the interaction between a power law distribution of electron energies. However, the approach here uses the method developed by Gould as a starting point. The first step is to calculate the energy loss of a relativistic electron population against electron-proton collisions; from this an energy loss time $[(1/E)dE/dt]^{-1}$ can be found and compared to the estimated lifetimes of the radio source obtained from $t_{rad}$ or $t_{buoy}$. The treatment in this section neglects the presence of a magnetic field. Though electron wortoradii are small compared to the radio source dimensions, electron trajectories at high energies can still be treated as single particle paths moving in a stationary background of cold protons.

A good approximation in the co-moving jet frame is to consider the target protons as stationary, since their temperature is very low. In this case the energy loss rate of an incident relativistic electron is just $\Delta E_e/\Delta t = n_p \int \Delta E_p v_e da$, where $\Delta E_p$ is the energy transferred to the proton, $v_e$ is the electron speed, and $da$ is the differential scattering cross section. This interaction is basically that of relativistic Coulomb scattering with quantum mechanical corrections, and integration of the above equation for $\Delta E_e/\Delta t$ gives, in the Born approximation (Gould 1981),

$$\frac{\Delta E_e}{\Delta t} = -\frac{4\pi e^4}{m_e c} n_p [\ln(2E_e/\hbar \omega_p) - 1/2].$$

The above equation has set $\beta_e \approx 1$, and the $\omega_p$ term arises from very small angle, low energy transfer scattering that can be represented by a single plasma oscillation. Since here the relativistic electrons have a non-thermal energy distribution, $\omega_p^2 \approx 4\pi n_e e^2 / \gamma_m e$, where $\gamma_m e \ll m_p$, $n_e$ is averaged over electron energy, and $\gamma_e$ is the average value of the Lorentz factor for a power law energy distribution. Charge neutrality in the jet requires $n_e = n_p$, and Eq. 8 then allows an evaluation of the electron energy loss time, $t_{e-p} = [1/E_e (dE_e/dt)]^{-1}$. Evaluating the coefficients gives

$$t_{e-p} = \frac{1.9 \times 10^8 \gamma_e/n_p}{37.5 + \ln(\gamma_e/(n_e/\gamma_e))^{1/2}}.$$

where the units are years.

Average number densities in the proton dominated jets here range from about $0.01$ to $10^{-6}$, with an average near $10^{-3}$. Hence it is clear from Equation 7 that the high energy electrons responsible for the radio emission ($\gamma_e > 10^3$) do not lose any significant energy to the proton population over the source lifetime. For spectral indices of $\alpha = 0.5$ or greater, most of the electrons have values of $\gamma_e$ near $\gamma_{min}$, but even with $\gamma_e \approx 10$ and $n_p \sim 0.1$ the electron-proton loss times are well in excess of the upper end of the distributions of source lifetimes, which lie at values of $t_{buoy} \sim 10^8$ yr. Thus in general there is a negligible transfer of energy within the jet from a relativistic electron population with a power law energy distribution to a cold proton population. Hence the "cold proton - hot electron" model for particle dominated
jets can maintain the two distinct populations over the transit time for particles in the jet.

Though not directly related to cold proton dominated jets, another possible energy transfer process that has not been treated previously in extragalactic radio jets is the loss of energy due to electron-electron collisions from the high energy end of a power law electron energy distribution to the much more numerous population of low energy electrons near the low energy end of the distribution. If this interaction is significant, it could have a very large effect on the evolution of the radio luminosity of extended radio sources. Again following Gould (1981), for an isotropic distribution of electrons the loss rate of particle 1 against a lower energy population of particles of energy $E_2$, where $n(E_2) = K E_2^p$, gives upon integration

$$-\frac{1}{\gamma_1} \frac{d\gamma_1}{dt} = 2\pi r_e^2 cn_e \frac{p-1}{p} [\ln(\gamma_1/\gamma_L) - 1/p - 0.82],$$

(8)

where $\gamma_1$ is the Lorentz factor of the high energy electron, $\gamma_L$ is the low energy end of the electron energy distribution, and $r_e$ is again the classical electron radius. The condition $\gamma_H \gg \gamma_L$ has been used in deriving Eq. 8. Values of the electron energy transfer time $t_{e-e} = [1/\gamma_1(d\gamma_1/dt)]^{-1}$ can then be found. Evaluating the coefficients in Eq. 10 then gives

$$t_{e-e} = 6.76 \times 10^{13} n_e^{-1} \frac{p}{p-1} [\ln(\gamma_1/\gamma_L) - 1/p - 0.82]^{-1}$$

in cgs units. For $p \approx 3$, $\gamma_1 \geq 10^5$, and $\gamma_L \approx 10$, this reduces to

$$t_{e-e} \simeq 2 \times 10^6 n_e^{-1} \text{yr.}$$

(9)

For the proton dominated jets with $n_e = n_p$, the values of $n_e$ in the present sample are less than $10^{-2}$ in almost all (85%) of the cases for $v_j = 0.1c$ and $r_j = 0.1kpc$, and the maximum value of $n_e$ in this case is $1.45 \times 10^{-2}$. For larger values of $v_j$ and $r_j$, $n_e$ will be much smaller. Thus it is clear that for almost all values derived for $n_e$, the transfer of energy from the high energy electrons to the more numerous low energy population is negligible over the estimated lifetimes of the radio sources.

5. Summary and Conclusions

5.1. Summary

Examination of data from recent radio and x-ray observations of radio sources in clusters of galaxies shows that the energy required to inflate the radio lobes against the ambient pressure of the ICM exceeds all other (and less certain) estimates of the energy present in the radio lobes. Supply of this $pdV$ energy to the radio lobes places a stringent lower limit on the energy flux that must be supplied by the jet over any given time, since the enthalpy of the material residing in the lobe exceeds this $pdV$ value. Specification of a jet radius $r_j$ and a mean flow speed $v_j$ allows a determination of the energy density (in an unspecified form) that must be present in the jet, and it was shown in Section 3 that this energy density $\epsilon_j$ almost always exceeds the known ambient pressure of the ICM surrounding the jet. Hence such jets cannot be pressure confined, and either some other confining mechanism such as magnetic confinement must be employed, or else the energy density in the jets must not have a significant associated pressure. We conclude that the most natural way to do this is to use a charge neutralizing population of "cold" protons that are advected outward with the mean jet flow. For a given jet radius and mean jet flow speed, the energy flux in protons required to provide the $pdV$ energy over either a radiative or a buoyant lifetime then fixes the particle number density ($n_p = n_e$) in the jet. This then specifies the mean jet kinematics.

Although cold proton dominated jets can solve the required energy flux problem, the accompanying relativistic electron population can still pose difficulties. The derived proton number density $n_p$ gives the electron density $n_e$, and the jet parameters plus the radio source luminosity and radiative or buoyant lifetimes then give the electron energy density $\epsilon_e$ in the jet. The results of Section 3 show that in many cases this lower value of $\epsilon$ ($\epsilon_e < \epsilon_p$) also exceeds the values of the ambient pressure unless large (and possibly unrealistic) values of $v_j$ and $r_j$ are used, and thus jet destruction will occur. Section 3 also showed that even the minimum energy present in the jet can cause jet destruction in a significant number of cases. Another conclusion from Section 3 is that electron-positron jets will have great difficulty in meeting the overall en-
nergy transport requirements unless extremely cold and extremely relativistic ($\gamma \geq 1000$) energy distributions are used.

In Section 4 the interaction among particle species in particle dominated jets was calculated, and it was shown that in almost all cases the cold proton-relativistic electron energy exchanges are so small that negligible energy transfer between these two populations will occur over the source lifetime. In addition, energy transfer between the high and low energy ends of a power law electron energy distribution present in a jet was calculated. In this case it was also found that this energy transfer has no significant effect over the lifetimes of the radio sources considered here.

5.2. Conclusions

Cold proton particle dominated jets can transport the required energy to the radio lobes. But the results of Section 3 suggest that the accompanying electron energy density in radio jets may cause decollimation unless some form of magnetic confinement is used. In the absence of this, some version of electron streaming that reduces the transverse pressure may be needed, but it is not clear how to construct such distributions in a natural way in the first place, nor is it clear how then to produce the synchrotron radiation seen in jets or how to protect this streaming population against instabilities with rapid growth rates.

A major unresolved issue is that of the creation and acceleration of the cold proton population. Entrainment of a (relatively) cold ISM through the mixing layer on the surface of the jet may work, especially since Section 4 showed there is little interaction between the hot electrons and cold protons. However, this entrained ISM is charge neutral, and so the charge neutralizing species in the original jet has still to be specified. Moreover, the initial jet must still carry all the energy (in some form) needed to supply the $pdV$ energy in the lobes; transfer of this energy to a cold entrained proton population only adds the need for an additional process to take place in the jet. Electron-positron jets cannot solve this problem unless they are cold and highly beamed, as discussed in Section 3. Thus once again the solution to the problem is pushed back to the largely unknown physical processes occurring in the immediate neighborhood of the central black hole. All of these problems may be more serious for the general population of FR-II objects; they have very large lobe energies and thus large $pdV$ values, and they usually have very highly collimated jets that extend over very long distances.

An alternate solution that may address these issues is the class of “Poynting Flux” models of collimated energy transport which have a nearly negligible particle content and are dominated by an intense and highly collimated electromagnetic flux (e.g., Romanova et al. 1997; Ustyugova et al. 2000; Lovelace et al. 2002; Lovelace & Romanova 2003). These models are still under development, and it is not clear at this time if they can provide stable, long term collimated outflows over long distances that can reproduce the radio morphology of both lobes and jets. In particular, major difficulties may be encountered in reproducing the morphologies of the most common FR-I class of objects. However, the results shown here may serve to motivate additional development of these models as well as encourage possible refinement and modification of particle dominated jet models.

Thanks are due to Tom Jones and Brian McNamara for valuable comments and to a referee for very useful suggestions.

REFERENCES

Begelman, M. ApJ, 493, 291
Birzan, L., Rafferty, D.A., McNamara, B.R., Wise, M.W., & Nulsen, P.E.J. 2004, ApJ, 607, 800
Blanton, E.L., Sarazin, C.L., McNamara, B.R., & Clarke, T.E. 2004, ApJ, 612, 817
Böhringer, H., Voges, W., Fabian, A.C., edge, A.C., & Neumann, D.M. 1993, MNRAS, 264, L25
Blundell, K.M., & Rawlings, S. 2000, AJ, 119, 1111
Brighenti, F., & Mathews, W.G. 2002, ApJ, 573, 639
Brüggen, M. 2003, ApJ, 592, 839
Brüggen, M., & Kaiser, C.R. 2001, MNRAS, 325, 676
Romanova, M.M., Ustyugova, G.V., Koldoba, A.V., Chechetkin, V.M., Lovelace, R.V.E. 1997, ApJ, 482, 708

Syrovatskii, S.I. 1959, Sov Astron-AJ, 3, 22

Treichel, K., Rudnick, L., Hardcastle, M., & Leahy, J.P. 2001, ApJ, 501, 691

Trubnikov, B.A. 1958, Sov. Phys-Doklady, 3, 136

Ustyugova, G.V., Lovelace, R.V.E., Romanova, M.M., Li, H., & Colgate, S.A. 2000, ApJ, 541, 21

This 2-column preprint was prepared with the AAS LaTeX macros v5.2.