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Energetics of Jet Interactions with the Intracluster Medium

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Abstract An interpretation of X-ray observations of the (intracluster) gas in galaxy clusters, when combined with significant numerical work in simulating cluster formation, suggests that an additional heating mechanism is required to explain the dynamics and temperature profile in the intracluster medium (ICM). In addition to shock heating, star formation, and supernovae, a likely candidate for a heating mechanism for the ICM comes from the jets of material originating in the cores of active radio galaxies, themselves located in the cores of clusters. These large-scale jets propagate outward from the core of the galaxy into the intracluster medium. In this paper, we discuss the origin and energetics of these jets, the mechanisms of their propagation and energy loss, their constitution, and the likely consequences of their interactions with the intracluster medium in clusters of galaxies.

Key words: jets: active galaxies: intracluster medium:

1 INTRODUCTION

The intracluster gas in clusters of galaxies is observed in X-rays, with considerable recent data coming from *CHANDRA* and *XMM* (see, e.g., Paerels and Kahan 2003, Zanni et al. 2005, and Basson and Alexander 2002 for discussions), along with older studies of ROSAT data (Bohringer et al. 1993).

Several authors (Carilli, Perley and Harris 1994, Fabian et al. 2000, Fabian et al. 2002, and Smith et al. 2002), have noted cavities or cocoons in the X-ray emitting gas that seem coincident with extended radio structures (Figure 1). These extended radio structures arise from radio jets that appear to originate from radio galaxies at the cores of the galaxy clusters (see e.g., McNamara et al. 2000) and has led a number of authors to speculate on the relation of cooling flows to the large scale jets (see, e.g., Binney and Tabor 1995; Reynolds, Heinz and Begelman 2001; Quilis, Bower and Balogh 2001; and Basson and Alexander 2002, and Colafrancesco 2005).

The energy budget of the cluster becomes an interesting question. In considering the energetics of AGN, Beall and Rose (1981) showed that the non-thermal activity in the core of Centaurus A can, when integrated over time, provide the energy estimated to be in Cen A's giant radio lobes. That is, $\int dE/dt \times dt$ (in the core) $= E_{\rm tot}$ in radio lobes. The total energy for relativistic electrons producing the synchrotron radiation in the giant radio lobes of Centaurus A is $\sim 10^{60}$ erg.

Accretion onto a massive black hole can provide such large amounts of energy. Wu et al. (2002); Bower et al. (1995); and Beall et al. (2003) have noted that the energy deposition rate based on accretion $dE/dt \sim (GM(dm/dt))/r$, where M is the mass of the compact object, G is the gravitational constant,

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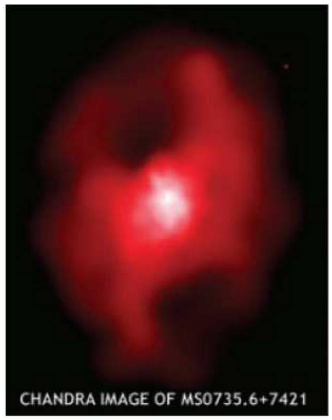

Fig. 1 *CHANDRA* image of cluster "holes" in MS0735 +7421 that could have been formed by jets (Courtesy of the *CHANDRA* picture galaxy, NASA/CXC/Ohio U./B.McNamara., but see Weiskopff, 2005 for a discussion).

dm/dt is the accretion rate, and r is the radius at which the energy is released. The escape velocity, v, is related to the mass of the attracting body by $(1/2)mv^2 \sim GMm/r$, and and for a compact object, $v \sim c$, i.e., the speed of light. Therefore, $dE/dt \sim \eta(1/2)\,(dm/dt)c^2$ where η is an efficiency factor usually taken to be $\sim 10\%$, and c is the speed of light. We note that the efficiency for nuclear reactions is $\sim 1\%$, which makes conventional stellar processes an unlikely energy source for AGN.

The luminosity available from accretion at the Schwarzschild radius is, therefore, $L = \eta 4.5 \times 10^{20}\ dm/dt$ in erg s^{-1}, where dm/dt is in gms s^{-1}, or $L = \eta 3 \times 10^{46}\ dM_0/dt$ in erg s^{-1}, where dM_0/dt is in solar masses per year. If the source has a luminosity of 10^{44} erg s^{-1}, and $\eta \sim 0.1$, we infer an accretion rate of 3 $\times 10^{-2} M_0$ yr^{-1}. If the jet persists for at least a time, $\tau_{\rm jet}$, of order the light travel time along its length, then $\tau_{\rm jet} \sim 3 \times 10^5$ years for a 100 kpc jet. This yields a total kinetic energy release of at least 9×10^{57} erg over the "lifetime" of a large scale jet. A Mpc-scale jet travelling at 0.1c would produce 9×10^{59} erg.

Inoue and Sasaki (2001) have noted the apparent need for additional heating sources besides heating from infall, supernovae, and star formation, and have presented calculations of shock heating by the bow shocks of such large scale jets. Zanni et al. (2005) note, however, that we lack a "coherent" and physically well-based model for the coupling of this energy with the ICM.

2 MODELING THE JET INTERACTION WITH THE AMBIENT MEDIUM

The question of how the jet of material propagating through an ambient medium interacts with that medium can acquire more specificity in the following manner. First, what mechanisms work to deposit energy in the ambient medium as the jet propagates through it, and how does the jet maintain its coherence as it propagates such remarkable distances? One ought also to ask what the jet is made of and whether or not there are different modes of interaction with the ambient medium through which it propagates.

Credible analysis based on hydrodynamic simulations has demonstrated a number of interesting effects originating from ram pressure and the consequent, turbulent acceleration of the ambient medium (see, e.g., Basson and Alexander, 2002; Zanni et al. 2005; and Krause and Camenzind 2003). However, these hydrodynamic approaches neglect an important species of physics: the microscopic interactions that occur because of the effects of particles on one another and of particles with the collective effects that accompany a fully or partially ionized ambient medium (i.e. plasmas). For a detailed discussion of these effects, see, e.g., Scott et al. 1980, Rose et al. 1984, Rose et al. 1987, Beall 1990, and Beall et al. 2003. The principal processes are outlined here.

For the purposes of specificity, we posit a relativistic jet of either $e^{\pm}$, $p - e^{-}$, or more generally, a charge-neutral, hadron-e^{-} jet, with a significantly lower density than the ambient medium.

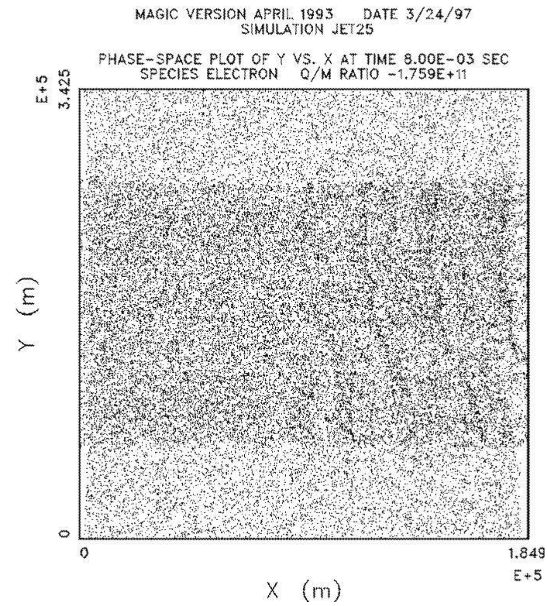

Fig. 2 Particle-In-Cell (PIC) code simulation of an electron-positron jet propagating through an ambient medium of an electron plasma. Note the development of the density perturbations to the right half of the propagation region. Results from the Rose (1997) PIC code simulation show clearly the beginning development of the two-stream instability in both the electron and the positron components of the relativistic beam. The length scale at which the jet begins to develop these significant effects is of order $L_{\rm p} \sim 0.9 \times 10^7$ cm. Note that the plot in the figure has units of meters.

The primary energy loss mechanism for the electron-positron jet is via plasma processes, as Beall (1990) notes. These plasma processes can be expressed in terms of their normalized wave energy densities (i.e., the ratio of the wave energy divided by the thermal energy of the plasma. The principal plasma waves are: the two stream instability waves, W_1; the oscillating two stream instability waves, W_2; and $W_{\rm S}$, the ion-acoustic waves. These waves are generated by instabilities driven by the jet. The waves in the plasma produce regions of high electric field strength and relatively low density, called cavitons (after solitons or solitary waves) which propagate like wave packets.

These cavitons mix, collapse, and reform, depositing energy into the ambient medium, transferring momentum to it, and entraining (i.e., dragging along and mixing) the ambient medium within the jet. The typical caviton size while formed is of order 10's of Debye lengths, where a Debye length, $\lambda_{\rm D} = 7.43 \times 10^2 \sqrt{T/n_{\rm p}}$ cm, where T is the electron temperature in units of eV, and $n_{\rm p}$ is the number density of the ambient medium in units of cm^{-3}. In order to determine the energy deposition rate, the momentum transfer rate, and heating, we model the plasma interaction as a system of coupled differential equations.

While the the physical processes in the plasma can be modeled by PIC (Particle-in-Cell) codes for some parameter ranges, astrophysical applications of the PIC code are not possible with current or foreseeable computer systems.

However, the plasma wave interactions can also be represented by a system of coupled differential equations which model the principal elements of the plasma processes that draw energy out of the jet. We therefore "benchmark" (see Oreskes et al. 1994) the wave population code by using the PIC code in regions of the parameter space where running the PIC code simulation is practicable. We then use the wave population code for regions of more direct astrophysical interest. A more detailed discussion of the comparisons between the PIC-code simulations and the wave-population model can be found in Rose, Guillory and Beall (2002, 2005).

We now consider a Particle-In-Cell (PIC) code simulation of an electron-positron jet propagating through an ambient medium of an electron-proton plasma. A small magnetic field is applied along the jet's longitudinal axis to suppress a filamentation instability, but this does not affect the propagation length, L_{p}, which is our principal concern here. L_{p} is the distance over which the plasma instabilities reduce the beam gamma by a factor of two. At the same time, the ambient medium is heated and entrained into the jet.

We believe that this configuration is a reasonable end point for the initial interaction of the relativistic jet with the interstellar medium, given the pressure exerted on the ambient medium with an oblique or transverse magnetic field. These simulations show that a relativistic, low-density jet can interpenetrate an ambient gas or plasma.

The coupling of these instability mechanisms is expressed in the model through a set of rate equations. These equations, with the right-hand-sides grouped as "source" and "sink" terms, are (Rose et al. 1984, 1987; Beall 1990)

$$\frac{\partial W_1}{\partial t} = \left[2\Gamma_1 W_1 H\left(\frac{\epsilon_{\mathrm{w}}}{n_{\mathrm{p}}T_{\mathrm{e}}} - W_1\right)\right] - \left[2\Gamma^{\mathrm{DO}}(W_{\mathrm{s}})W_1 + 2\Gamma^{\mathrm{OTS}}(W_1)W_2 H(W_1 - k_1^2\lambda_{\mathrm{D}}^2)\right], \tag{1}$$

$$\begin{aligned}\frac{\partial W_2}{\partial t} &= \left[2\Gamma^{\mathrm{DO}}(W_{\mathrm{s}})W_1 + 2\Gamma^{\mathrm{OTS}}(W_1)W_2 H(W_1 - k_1^2\lambda_{\mathrm{D}}^2)\right] \\ &- \left[2\Gamma_{\mathrm{L}} W_2 + 2\Gamma^{\mathrm{OTS}}(W_2)W_{\mathrm{s}} H\left(W_2 - \frac{4}{\omega_{\mathrm{p}}}\Gamma_{\mathrm{L}}\right) + \frac{W_2}{\tau_2}\right],\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{\partial W_{\mathrm{s}}}{\partial t} = &\left[2\Gamma^{\mathrm{OTS}}(W_1)W_{\mathrm{s}} H(W_1 - k_1^2\lambda_{\mathrm{D}}^2) + 2\Gamma^{\mathrm{OTS}}(W_2)W_{\mathrm{s}} H\left(W_2 - \frac{4}{\omega_{\mathrm{p}}}\Gamma_{\mathrm{L}}\right)\right] \\ &- \left[2\Gamma^{\mathrm{DW}}(W_{\mathrm{s}})W_{\mathrm{s}} + \frac{W_{\mathrm{s}}}{\tau_{\mathrm{s}}}\right].\end{aligned} \tag{3}$$

The function H is defined as,

$$H(a-b) = \frac{1}{2}\left\{1 + \tanh\left[K\left(1 - \frac{b}{a}\right)\right]\right\}, \tag{4}$$

where K is a constant, nominally set to 30. This function is a smoothed version of the Heaviside unit step function and is used to provide a smooth transition at the onset and saturation of the various growth rate terms. The terms of the rate equations are defined in Rose et al. (1984) and Beall (1990).

The terms W_2/τ_2 and $W_{\mathrm{s}}/\tau_{\mathrm{s}}$ in Eqs. (2) and (3) can be used to account for wave energy that is transported outside of the beam because of geometric effects. Thus τ_2 and τ_{s} can be used to model the propagation of secondary waves and ion-density waves out of the system (e.g. transversely out of the beam channel). For the calculations presented in this work and for astrophysical applications, these convective loss terms are considered negligible. However, Rose et al. (1984) give simple models for τ_2 and τ_{s}.

It is possible to gain some intuition about the behavior of such a system by imagining other physical systems described by predator-prey population models. For this purpose, we contemplate a population consisting of grass, rabbits, and foxes. Clearly, depending on the growth rate of each element, and of how rapidly it engages in predation on its food source, solutions to the equations can exhibit cyclic behavior or stable population levels.

The solutions to the wave population equations give a normalized wave energy. This wave energy density is then used to determine the energy deposition rate of the jet into the ambient medium, the propagation length of the jet, the heating of the plasma, and the momentum transfer rate from the jet to the plasma.

Figure 4 shows the wave levels as calculated dynamically from our solution to the wave populating code. The plasma density for this simulation is $n_{\mathrm{p}} = 1$ cm^{-3}, the plasma temperature is $T_{\mathrm{c}} = 10^4$ K, the ratio of the beam density to the plasma density, $R = 10^{-4}$, and the plasma has a hot electron tail (produced by the jet) with a temperature of 10^6 K. The vertical axis is the normalized wave energy density, and the horizontal axis is time, expressed in units of plasma periods (i.e,. $\omega_{\mathrm{p}} = 5.64 \times 10^4 \sqrt{n_{\mathrm{p}}}$).

Initially, and for a significant fraction of its propagation length, the principal energy loss mechanisms for such a jet interacting with the ambient medium is via plasma processes (Rose et al. 1984, Beall 1990).

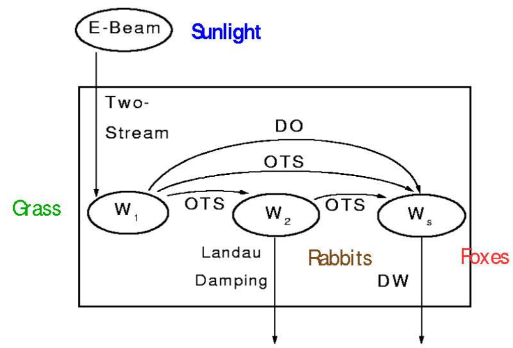

Fig. 3 This figure outlines the relationships between the elements of the system of coupled differential equations used to model the jet-plasma interaction.

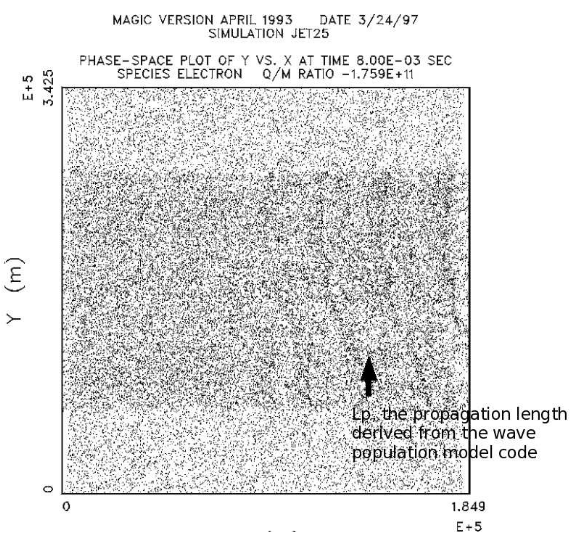

Fig. 4 This figure shows the PIC simulation of a jet-ambient-medium for the same parameters associated with Figure X, but with the propagation length for the wave population code marked. As can be seen, the propagation length, $L_{\rm p}$, is coincident with the position in the plasma where the plasma waves have developed significantly.

3 COLLISIONLESS (PLASMA) LOSSES

As discussed earlier, in order to calculate the propagation length of the electron-proton jet described above, we model the interaction of the relativistic jet with the ambient medium through which it propagates by means of a set of coupled, differential equations which describe the growth, saturation, and decay of the three wave modes likely to be produced by the jet-medium interaction. First, two-stream instability produces a plasma wave, W_1, called the resonant wave, which grows initially at a rate $\Gamma_1 = (\sqrt{3}/2\gamma)(n_{\rm b}/2n_{\rm p})^{1/3}\omega_{\rm p}$, where γ is the Lorentz factor of the beam, $n_{\rm b}$ and $n_{\rm p}$ are the beam and cloud number densities, respectively, and $\omega_{\rm p}$ is the plasma frequency, as described more fully in Rose et al. (1984).

$$dE_{\rm plasma}/dx = -(1/n_{\rm b}v_{\rm b})(d\alpha\epsilon_1/dt), \tag{5}$$

can be obtained by determining the change in γ of a factor of 2 with the integration

$$\int d\gamma = -\int [d(\alpha\epsilon_1)/dt]/(v_\mathrm{b} n_\mathrm{b} m^{'} c^2) \tag{6}$$

as shown in Rose et al., 1978 and Beall 1990, where $m^{'}$ is the mass of the beam particle. Thus,

$$L_\mathrm{p} = ((1/2)\gamma c n_\mathrm{b} m c^2)/(d\alpha\epsilon_1/dt)\ \mathrm{cm} \tag{7}$$

is the characteristic propagation length for collisionless losses for an electron or electron-positron jet, where $d\alpha\epsilon_1/dt$ is the normalized energy deposition rate (in units of thermal energy) from the plasma waves into the ambient plasma. In many astrophysical cases, this is the dominant energy loss mechanism.

The average energy deposition rate, $\langle d(\alpha\epsilon_1)/dt\rangle$, of the jet energy into the ambient medium via plasma processes can be calculated as

$$\langle d(\alpha\epsilon_1)/dt\rangle = n_\mathrm{p} kT \langle W\rangle \omega_\mathrm{p}\ \mathrm{erg\ cm^{-3}\ s^{-1}}, \tag{8}$$

where n_p is number density in units of cm^{-3} of the ambient medium, k is Boltzmann's constant, T is the plasma temperature, ⟨W⟩ is the average (or or equilibrium) normalized wave energy density obtained from the wave population code, and ω_p is the plasma frequency.

Plasma effects can also have observational consequences. Beall (1990) has noted that plasma processes can slow the jets rapidly, thus truncating the low-energy portion of the γ-rays spectrum. This calculation was carried out in some detail by Beall and Bednarek (1999). A similar effect will occur for neutrinos and can also reduce the expected neutrino flux from AGN.

4 JET INTERACTION WITH THE INTRACLUSTER MEDIUM

The hypothesis of jets from AGN interacting with the intracluster medium via collisionless (plasma) processes requires that the jets overcome collisional and collisionless losses and propagate to significant distances into the intracluster medium. This in turn allows us to constrain the jet parameters as the jet emerges from the elliptical AGN. In general, the jets must have values of γ, the ratio of the total particle energy over the particle rest mass, that are at least rather relativistic over a significant fraction of their propagation length.

An analysis of the energy loss due to plasma processes, taken from Equations (7) and (8), and the computer simulations that determine $(d\alpha\epsilon_1/dt)$, the average wave energy deposition into the ambient medium per unit time, yields some useful bounds for possible energy deposition rates due to plasma processes.

We can further constrain the jet parameters by expressing the kinetic luminosity of the jet as

$$P_\mathrm{b} = dE/dt = \gamma m c^2 n_\mathrm{b} v_\mathrm{b} \pi r_\mathrm{b}^2, \tag{9}$$

where γ is the ratio of total energy to rest mass energy, mc^2 is the rest mass energy of the beam particles, v_b is the beam velocity, and r_b^2 is the beam radius.

If the beam is significantly heated by the jet-cloud interaction, the beam will expand transversely as it propagates, and will therefore have a finite opening angle. These "warm beams" result in different growth rates for the plasma instabilities, and therefore produce somewhat different propagation lengths (see, e.g., Kaplan and Tsytovitch 1973, Rose, Guillory and Beall 2002). A "cold beam" is assumed to have little spread in momentum. The likely scenario is that the beam starts out as a cold beam and evolves into a warm beam as it propagates through the ambient medium. This scenario is clearly illustrated by the Particle-In-Cell (PIC) simulations we have used to benchmark the wave population codes appropriate for the astrophysical parameter range (see, e.g., Beall, Guillory and Rose 1999, and Rose, Guillory and Beall 2005).

Assuming that the ambient medium is also significantly heated by the jet (at some late times in the history of the interaction), the ambient medium will have in effect a two temperature distribution (see, e.g., Beall, Guillory and Rose 1999). The effect of the jet-cloud interaction is to produce a high-energy tail on the thermal distribution of the cloud. This high-energy tail critically alters the Landau damping rate of waves in the plasma.

An analytical calculation of the boost in energy of the electrons in the ambient medium to produce a high energy tail with $E_{\rm het} \sim 30 - 100kT$ is confirmed by PIC-code simulations. As noted earlier, this can greatly enhance line radiation over that expected for a thermal equilibrium calculation.

We now make a rough estimate of the energy deposition scale length, $L_{\rm total}$, for an electron-proton jet. The propagation scale length, $L_{\rm p}$, used in our calculations, is the distance over which the beam γ decreases by a factor of 2. This relates to $L_{\rm total}$ in the following manner. For a beam with a γ of 10^3, for example, we may estimate the energy deposition length to be $10^3/2 \sim 500 \times L_{\rm p}$ (i.e., of order 500 scale lengths). The reader should note that this is an order of magnitude estimate, since $L_{\rm p}$ depends on γ. The proper estimation of the energy deposition lento requires a multi-scale code effort, wherein the wave-population code is coupled to a hydrodynamic code. This work is planned by the authors.

For a cold beam with a beam radius, $r_{\rm b} = 3 \times 10^{19}$ cm, the temperature of the ambient medium, $T_{\rm c} = 1 \times 10^4$ K, a high-energy tail temperature, $T_{\rm h} = 1 \times 10^5$ K, a hot tail fraction, $f_{\rm h} = 0.10$, $n_{\rm b} = 0.001$, and $n_{\rm p} = 0.01$ (number density in units of cm^{-3}), and for $\gamma = 100$, the energy deposition rate, $dE/dt = 3.6 \times 10^{-15}$ erg cm^{-3} s^{-1}, and the propagation length for an electron-proton jet, $L_{\rm pe} = 9 \times 10^{20}$ cm. (i.e., ~ 300 pc). The energy deposition length for the jet, $L_{\rm total}$, will be $50 \times L_{\rm pe} = 9 \times 10^{20}$ cm, or $L_{\rm total} = 4.5 \times 10^{22}$ cm, or 15 kpc.

For $\gamma = 1000$, $L_{\rm p} \sim 3$ kpc, the distance over which the jet loses energy by a factor of two. The jet has roughly ~ 500 scale lengths for $\gamma \sim 10^3$, and, therefore, the total energy deposition scale length is $L_{\rm total} = 1500$ kpc.

For the same parameters but with $n_{\rm p} = 0.1$ and $\gamma = 100$, $dE/dt = 2.4 \times 10^{-15}$ erg cm^{-3} s^{-1} and $L_{\rm pe} = 7 \times 10^{19}$ cm (i.e., ~ 20 pc). The total energy deposition length, $L_{\rm total} \sim 1$ kpc. For $\gamma = 1000$, $L_{\rm p}$ is roughly 200 pc, yielding a total energy deposition length, $L_{\rm total}$, of order 100 kpc. Therefore, these jets can propagate significant distances before they are slowed to supersonic velocities and begin their motion in a hydrodynamic regime.

5 CONCLUDING REMARKS

Plasma processes dominate over other energy loss mechanisms in most cases.

In an electron-proton (or electron-hadron) jet, the electrons lose energy to plasma processes more rapidly than do the protons. The jet protons therefore drag the electrons. This produces a current along the jet in the jet's rest frame. A magnetic field will be generated that could stabilize the jet. This bears further investigation, since it might answer the question of how the jets maintain their coherence for such long distances.

If the jets have a hadronic component, the presence of hadrons in the jet will produce nuclear γ-rays and neutrinos as it interacts with the ambient medium (see Beall and Bednarek, 1999 for a discussion). The plasma instabilities modify the emitted γ-ray spectrum significantly.

If jets are hadronic (a scenario that would help with the energy transport problem), then they probably also have a significant e^+/e^- component that will "fill in" to account for some of the observed radiation. Furthermore, the detection of neutrinos from jet sources would directly suggest an hadronic component at relativistic (i.e. early) stages of jet formation. Such an hypothesis is consistent with Eichler's (1979) suggestion of using neutrinos as a probe of AGN.

Waxman and Bahcall (1998) have estimated the neutrino flux from AGN based on the assumption of isotropy of neutrino emission. A fully anisotropic calculation of the neutrino flux from a jet-cloud scenario will be of considerable interest. In this regard, neutrino instruments are coming online (see, e.g., Gaisser, Halzen & Stanev 1995, and Frichter, Ralston & McKay 1996, and Halzen 1998, and Beall 2005).

Jets from active elliptical galaxies in the cores of clusters can provide a significant source of energy that may contribute to the dynamics of the intracluster medium. This source of energetics bears further study in our efforts to understand the dynamics of clusters.

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DISCUSSION

Wolfgang Kundt: Comment: If you want to avoid in-situ acceleration - as I do - and if you want to transport electrons with lorentz factors $\leq 10^7$ out to distances of Mpc, I think youo have to tansport them through pure vacuum channels rammed clean by earlier generations fo charges. Your estimates of wave excitation in a plasma should be useful for the interaction of the beams with their channel walls.

Jim Beall As you know, I think the jets are very likely to have an hadronic component, and that the completely evacuated channel seems an idealization to me. I recognize, of course, that the scenario you posit can be applicable in at least some portions of the intracluster medium, and that the distribution of matter can be very non-uniform.

Anatoli Iyudin: What kind of magnetic field was assumed in your simulation of the jet propagation in the intracluster medium?

Jim Beall In the PIC code simulations, we used a small magnetic field sufficient to supress the filamentation instability in order to show the development of the two-stream instability and benchmark the propagation length calculation. We are assuming that the magnetic field is co-linear (or eventually so) in the wave population code analysis. A roughly co-linear magnetic field will not materially affect the propagation length calculations we develop using the wave population code.

Giuseppina Fabbiano Can your calculation explain the energy deposition in the ICM that “stops” the cooling flows?

Jim Beall I think the energetics will work out. The jets can provide an amount of energy that will be significant to the dynamics of the ICM. But we’re not quite to the point of confirming this by coupling the wave population code as an energy and momentum source to a hydrodynamic code. It is our intention to do this multi-scale code work and confirm my opinion about the energetics.