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Non-Linear Wave Dynamics in the Jet-Ambient-Medium Interaction

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Abstract Jets from the central CD galaxy found within galaxy clusters can propagate to distances of $> 100\,$s of kiloparsecs, thereby interacting with the intracluster medium. X-ray data of the (intracluster) gas in galaxy clusters and their interpretations based on numerical modeling suggest 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, it is plausible that an additional heating mechanism for the ICM comes from astrophysical jets originating in the cores of radio galaxies. We discuss some aspects of these jets, including the mechanisms of their propagation and energy loss, their constitution, and the non-linear character of their energy loss processes.

Key words: jets — active galaxies — intracluster medium — non-linear dynamics

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 & Kahan 2003; Zanni et al. 2005; Basson & Alexander 2002 for discussions), along with older studies of ROSAT data (Bohringer et al. 1993). Several authors (Carilli, Perley & Harris 1994; Fabian et al. 2000; Fabian et al. 2002; Smith et al. 2002), have noted cavities or cocoons in the X-ray emitting gas that are coincident with extended radio jets (see, e.g., Beall et al. 2006 for a discussion). These extended radio structures arise from radio jets that originate from radio galaxies at the cores of the galaxy clusters (see e.g., McNamara et al. 2000). This has led a number of authors to speculate on the relation of cooling flows and intracluster cavaties to the large scale jets (see, e.g., Binney & Tabor 1995; Reynolds, Heinz & Begelman 2001; Quilis, Bower & Balogh 2001; Basson & Alexander 2002; Colafrancesco 2005).

The energy budget that can be provided by the central CD galaxy for cluster heating can be estimated in a number of ways. In considering the energetics of AGN, Beall & 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, $\int dE/dt * dt$ (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. More luminous sources can generate proportionally greater total amounts of energy.

The model of accretion onto a massive black hole can provide such large amounts of energy. Wu et al. (2001), Bower et al. (1995), and Beall et al. (2003) have noted that the energy production rate based

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on accretion is $dE/dt \sim \eta(1/2)(dm/dt)c^2$ 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 $L = \eta 3 \times 10^{46} dM_o/dt$ 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 traveling at $0.1c$ would produce 9×10^{59} erg.

2 MODELING THE JET INTERACTION WITH THE AMBIENT MEDIUM

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 & Alexander 2002; Zanni et al. 2005; Krause & 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). A detailed discussion of these effects can be found, variously, in 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.

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. The primary energy loss mechanism for the electron-positron jet is via plasma processes, as Beall (1990) notes.

While 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.

We therefore model these plasma processes for the astrophysical regime by means of a system of coupled, differential equations that represent the 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, $\lambda_{\rm D} = 7.43 \times 10^2 \sqrt{T/n_p}$ cm, T is the electron temperature in units of eV, and n_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.

The model for the plasma wave interactions is accomplished by a system of very stiff, coupled differential equations which model the principal elements of the plasma processes that draw energy out of the jet. As a test of the fealty of this method, we "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 & Beall (2002, 2005).

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)

$$\frac{\partial W_1}{\partial t} = \left[2\Gamma_1 W_1 H\left(\frac{\epsilon_w}{n_p T_e} - W_1\right)\right] - \left[2\Gamma^{\rm DO}(W_{\rm s})W_1 + 2\Gamma^{\rm OTS}(W_1)W_2 H(W_1 - k_1^2\lambda_{\rm D}^2)\right], \quad (1)$$

$$\frac{\partial W_2}{\partial t} = \left[2\Gamma^{\rm DO}(W_{\rm s})W_1 + 2\Gamma^{\rm OTS}(W_1)W_2 H(W_1 - k_1^2\lambda_{\rm D}^2)\right]$$

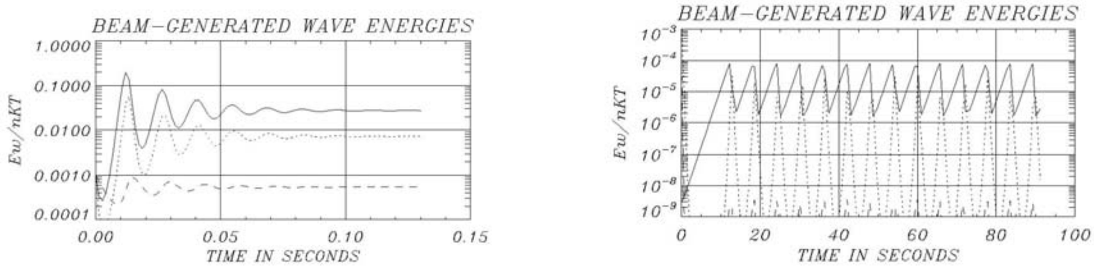

Fig. 1 This figure shows the dynamical solutions to the coupled system of equations that represent the plasma wave energies (Equations (1)–(4)). The top panel shows a typical damped oscillaton, while the bottom panel shows an oscillatory solution. Transitional, chaotic solutions are also possible for very high growth rates of the initial two-stream instability. The Landau damping rate for the two-temperature thermal distribution of the gas in the ambient medium is included in these solutions.

$$- \left[2\Gamma_L W_2 + 2\Gamma^{\mathrm{OTS}}(W_2) W_{\mathrm{s}} H \left(W_2 - \frac{4}{\omega_p}\Gamma_L \right) + \frac{W_2}{\tau_2} \right], \tag{2}$$

$$\frac{\partial W_{\mathrm{s}}}{\partial t} = \left[2\Gamma^{\mathrm{OTS}}(W_1) W_{\mathrm{s}} H(W_1 - k_1^2 \lambda_{\mathrm{D}}^2) + 2\Gamma^{\mathrm{OTS}}(W_2) W_{\mathrm{s}} H \left(W_2 - \frac{4}{\omega_p}\Gamma_L \right) \right]$$
$$- \left[2\Gamma^{\mathrm{DW}}(W_{\mathrm{s}}) W_{\mathrm{s}} + \frac{W_{\mathrm{s}}}{\tau_{\mathrm{s}}} \right]. \tag{3}$$

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 Equations (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}.

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 1 illustrates two possible solutions for the system of coupled differential equations shown in Equations (1)–(4): a damped oscillatory and an oscillatory solution. The Landau damping rate for the two-temperature thermal distribution of the ambient medium is used for these solutions. As noted in the figure caption, transitions toward chaotic solutions have been observed for very large growth rates for the two-stream instability.

It is of interest to compare the results of a Particle-In-Cell (PIC) code simulation of an electron-positron jet propagating through an ambient medium of an electron-proton plasma with the solutions obtained by the wave population model code. 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

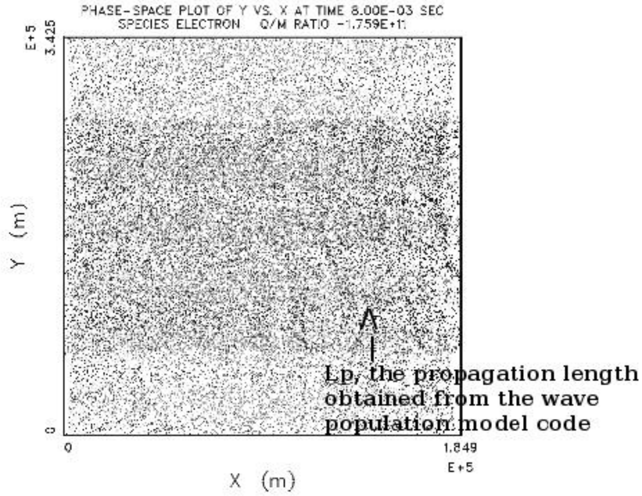

Fig. 2 This figure shows the PIC simulation of a jet-ambient-medium with the propagation length for the wave population code marked. As can be seen, the propagation length, L_{p}, is coincident with the position in the plasma where the plasma waves have developed significantly.

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.

Figure 2 shows the wave levels as calculated dynamically from our solution to the wave populating code as compared to the PIC-code simulation. The plasma density for this simulation is $n_{\mathrm{p}} = 1\,\mathrm{cm}^{-3}$, the plasma temperature is $T_c = 10^4\,\mathrm{K}$, 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 $10^6\,\mathrm{K}$. 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).

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 $\Gamma_1 = (\sqrt{3}/2\gamma)(n_{\mathrm{b}}/2n_{\mathrm{p}})^{1/3}\omega_{\mathrm{p}}$, where γ is the Lorentz factor of the beam, n_{b} and n_{p} are the beam and cloud number densities, respectively, and ω_{p} is the plasma frequency, as described more fully in Rose et al. (1984). $dE_{\mathrm{plasma}}/dx = -(1/n_{\mathrm{b}}v_{\mathrm{b}})(d\alpha\epsilon_1/dt)$, can be obtained by determining the change in γ of a factor of 2 with the integration $\int d\gamma = -\int [d(\alpha\epsilon_1)/dt]/(v_{\mathrm{b}}n_{\mathrm{b}}m^{'}c^2)$ as shown in Rose et al. (1978) and Beall (1990), where $m^{'}$ is the mass of the beam particle. Thus, $L_{\mathrm{p}} = ((1/2)\gamma c n_{\mathrm{b}} m c^2)/(d\alpha\epsilon_1/dt)\,\mathrm{cm}$ 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, $< d(\alpha\epsilon_1)/dt$, of the jet energy into the ambient medium via plasma processes can be calculated as $\langle d(\alpha\epsilon_1)/dt\rangle = n_{\mathrm{p}}kT < W > (\Gamma_1/\omega_{\mathrm{p}})\omega_{\mathrm{p}}\ \mathrm{erg\,cm^{-3}\,s^{-1}}$, ambient medium, k is Boltzmann's constant, T is the plasma temperature, $\langle W\rangle$ is the average (or equilibrium) normalized wave energy density obtained from the wave population code, Γ_1 is the initial growth rate of the two-stream instability, 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 & Bednarek (1999). A similar effect will occur for neutrinos and can also reduce the expected neutrino flux from AGN.

3 ANALYSIS OF THE 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 the preceding equations, 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 $P_{\rm b} = dE/dt = \gamma mc^2 n_{\rm b} v_{\rm b} \pi r_{\rm b}^2$, where γ is the ratio of total energy to rest mass energy, mc^2 is the rest mass energy of the beam particles, $v_{\rm b}$ is the beam velocity, and $r_{\rm b}^2$ 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 & Tsytovitch 1973; Rose, Guillory & Beall 2002; Beall et al. 2006). 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 & Rose 1999; Rose, Guillory & 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 develop in effect a two temperature distribution (see, e.g., Beall, Guillory & 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 such a high energy tail, with $E_{\rm het} \sim 30 - 100\,kT$, is confirmed by PIC-code simulations. Aside from altering the Landau damping rate, such a high-energy tail can greatly enhance line radiation over that expected for a thermal equilibrium calculation.

It is possible to make an order of magnitude estimate of the energy deposition scale length, $L_{\rm total}$, for an electron-proton jet using the analysis outlined in this paper. 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. For a cold beam with a beam radius, $r_{\rm b} = 3 \times 10^{19}$ cm, the temperature of the ambient medium, $T_c = 1 \times 10^4$ 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.

4 CONCLUDING REMARKS

Jets from active elliptical galaxies in the cores of clusters provide a significant source of energy that can contribute to the dynamics of the intracluster medium.

The dominant energy loss mechanism for the jets propagating outward from the AGN in the cluster core will be due to plasma processes for some significant portion of the jet's propagation length, and before the jet transitions to a hydronamic regime. Electron-hadron jets can apparently propagate to distances of 10 s to 100 s of kpc, despite plasma processes being 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 so produced will stabilize the jet.

The presence of hadrons in the jet will produce nuclear γ-rays and neutrinos as it interacts with the ambient medium (see Beall & 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 both the energy transport problem and their propagation length), then they probably also have a significant e^+/e^- component that will "fill in" to account for some of the observed radiation.

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 & 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; Frichter, Ralston & McKay 1996; Halzen 1998; Beall 2006).

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