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Jet interactions with magnetized clouds

Preliminary results from PIC code and large-scale hydrodynamic simulations for AGN jets

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Abstract. When astrophysical jets interact with the ambient medium through which they propagate, they lose energy and entrain (and accelerate) that medium. Recent observations of such interactions, including time-lapsed "movies" of both AGN and microquasar jets, can be used to inform models of the jet-ambient-medium interactions. In this paper, we discuss some aspects of these jets, including the mechanisms of their propagation, their constitution, and the non-linear character of their energy loss via plasma processes. We also present for the first time PIC code simulations to show momentum transfer via caviton formation as a result of plasma processes. An illustration of the microphysics of the interaction of a proton-electron beam with an ambient magnetic field is also presented.

Key words. jets, active galaxies, jets, blazars, intracluster medium, non-linear dynamics, plasma astrophysics

1. Introduction

Accretion onto a massive black hole can provide such large amounts of energy to power the jets in astrophysical sources. Wu et al. (2002); Bower et al., (1995); and Beall et al. (2003) have noted that the energy production rate based 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.

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The luminosity available from accretion at the Schwarzschild radius is, therefore, $L = \eta 4.5x10^{20} dm/dt$ in ergs s^{-1}, where dm/dt is in gms s^{-1}, or $L = \eta 3x10^{46} dM_o/dt$ in ergs s^{-1}, where dM_0/dt is in solar masses per year. If the source has a luminosity of 10^{44} ergs s^{-1}, and $\eta \sim 0.1$, we infer an accretion rate of $3x10^{-2} M_0 yr^{-1}$.

If the jet persists for at least a time, τ_{jet}, of order the light travel time along its length, then $\tau_{jet} \sim 3x10^5$ years for a 100 kpc jet. This yields a total kinetic energy release of at least $9x10^{57}$ ergs over the 'lifetime" of a large scale jet. A Mpc-scale jet traveling at 0.1c would suggest an energy of $9x10^{59}$ ergs.

2. Modeling the jet interaction with the ambient medium

Analyses based on hydrodynamic simulations have 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 microscopical 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. a plasma). 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.

For this analysis, 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. Kundt (1987, 2001) also discusses the propagation of electron-positron jets.

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) generated as a result of the various instabilities produced as the jet penetrates the ambient medium.

The principal plasma waves can be characterized as follows: the two stream instability waves, W_1, interact directly with the ambient medium, and are "predated" (principally) by the oscillating two stream instability waves, W_2, and the ion-acoustic waves, W_S. To reiterate, these waves are generated by instabilities produced by the jet-ambient medium interactions. The waves generated in the plasma by the jet produce regions of high electric field strength and relatively low density, the so-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 when formed is of order 10's of Debye lengths, where a Debye length, $\lambda_D = 7.43x10^2 \sqrt{T/n_p}$ 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 very stiff, coupled differential equations (see, e.g., Beall et al. 2006), which simulate 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, and Beall (2002, 2005). The coupling of these instability mechanisms is expressed in the model through a set of rate equations. These equations are discussed in some detail by Rose et al. (1984, 1987), and Beall (1990).

The solutions to the wave population equations give a normalized wave energy. This wave energy density is then used to estimate 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 (see Beall et al. 2006, 2009 for a detailed discussion).

Beall et al., (2006) illustrates two possible solutions for the system of coupled differential equations that model the jet-ambient medium interaction: 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.

In order to benchmark the wave-population code, we use that code to calculate the propagation length of an electron-positron jet as described above. Specifically, 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 $\Gamma_1 \leq (\sqrt{3}/2\gamma)(n_b/2n_p)^{1/3}\omega_p$, 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). $dE_{plasma}/dx = -(1/n_b v_b)(d\alpha\epsilon_1/dt)$, can be obtained by determining the change in γ of a factor of 2 with the integration $\int d\gamma = -\int[d(\alpha\epsilon_1)/dt]/(v_b n_b m' c^2)$ as shown in Rose et al., 1978 and Beall 1990, where m' is the mass of the beam particle. Thus, $L_p = ((1/2)\gamma c n_b m c^2)/(d\alpha\epsilon_1/dt)\ cm$ 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 $< d(\alpha\epsilon_1)/dt >= n_p kT < W > (\Gamma_1/\omega_p)\omega_p\ ergs\ cm^{-3}s^{-1}$, 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 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.

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 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 1 shows the wave levels as calculated dynamically from our solution to the wave population code as compared to the PIC-code simulation. The plasma density for this simulation is $n_p = 1cm^{-3}$, the plasma temperature is $T_c = 10^4$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, where the plasma period, $\omega_p = 5.64x10^4 \sqrt{n_p}$.

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).

3. PIC code simulations showing momentum transfer to the ambient medium from beam-generated plasma waves

As part of our research into the micro-physics of the interaction of jets with an ambient medium, we have begun to investigate in some detail the transfer of momentum from the jet.

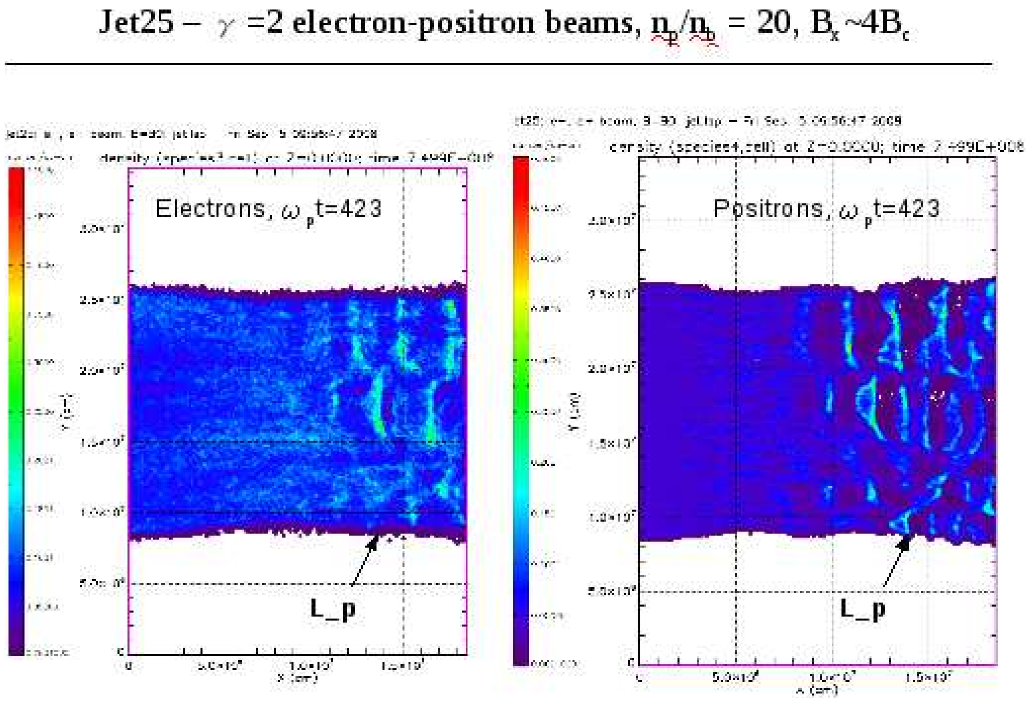

Fig. 1. This figure shows a recent PIC simulation of a jet-ambient-medium with the propagation length for the wave population code marked, and for $\gamma = 2$, $n_p/n_b = 20$, and $B_x \sim 4B_c$. As can be seen, the propagation length, L_p, calculated in Beall et al., 2005, is in agreement with the station along the axis of the jet where the plasma waves have developed significantly.

Understanding how such a transfer is accomplished is essential to understanding the manner in which the ambient medium (for example, from interstellar clouds) is accelerated and eventually entrained into the large-scale astrophysical jet.

We intend a further analysis of the PIC code simulations presented here in order to study several issues related to caviton dynamics, including momentum transfer from the cavitons to the background thermal plasma, and energetic electron and proton acceleration.

As a further continuation of this research, we plan to develop a multi-scale code which uses the energy deposition rates and momentum transfer rates from the PIC (Particle-In-Cell) and wave-population models as source terms for the highly parallelized hydrodynamic code currently running on the NRL Cray XD-1.

We use a PIC code simulation to model caviton formation and momentum transfer. This simulation is a one-dimensional (1-D) simulation with a length, $L = 6x10^6$ cm, using periodic boundaries. In the simulation, L is greater than the maximum two-stream unstable wavelength, the ratio of plasma to beam densities $= n_{pe}/n_{be} = 20$, $n_p = 1cm - 3$, the beam velocity, $v_b = 0.866$c, and the grid resolution $0.2x\lambda_D$, the Debye-length, in order to resolve the caviton structures. It is an understatement of considerable magnitude to say that this calculation is computationally intensive.

This result shows clearly the acceleration of the ambient medium via plasma processes in the interaction of an astrophysical jet with the ambient medium. It is the first such result that explicitly demonstrates momentum transfer from a consideration of the micro-physics of the interaction. We intend to use these re-

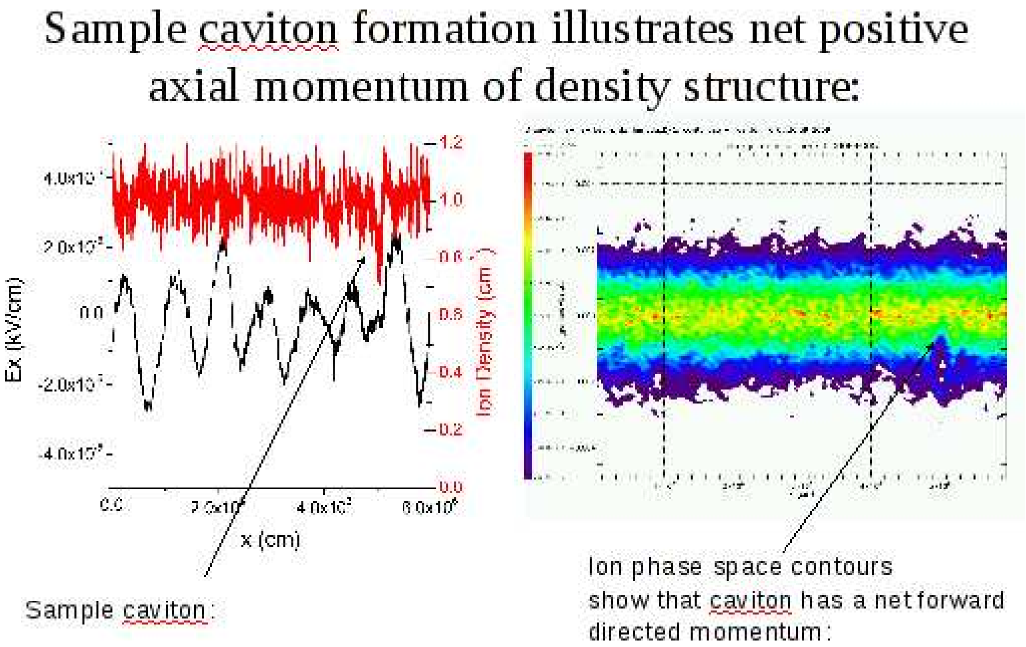

Fig. 2. PIC code simulation which for the first time specifically identifies one of the cavitons formed by a jet-ambient medium interaction. The left panel shows the electric field intensity (in kV/cm) along the x-axis. The right panel plots the velocity distribution of ions in the ambient medium vertically as a function of velocity, and as a function of position along the jet axis horizontally. Note the white region at roughly $5x10^7$ cm indicates a deficiency in the density of the ambient medium about a zero velocity. This indicates that the caviton at the same place in the jet has given the ambient medium a positive velocity at that location in the jet.

sults to aid us in benchmarking an analytical calculation of the momentum transfer so that we can incorporate the plasma processes as a source term for the hydrodynamic code we have ported to the NRL Cray XD-1.

4. PIC code modeling of the interaction of a plasmoid with a fixed magnetic field

It is possible (using PIC code simulations on available computing platforms) to investigate how jets might interact with magnetized clouds. Figure 3 shows a frame from a "movie" made from a PIC code simulation for a related problem of an electron-proton plasmoid interacting with a fixed magnetic field. P. The particular frame shown in the figure demonstrated the significant penetration of the magnetic field my the plasma, and shows that the interaction actually accelerated some of the plasmoid's particles.

We are considering the possibility of additional simulations of this sort as a means of modeling cross-field injection of jets into the magnetic fields of interstellar clouds. But even at first gloss, it is apparent that the plasmoid can interpenetrate the even a strong magnetic field, and that the interaction, in the center of momentum frame of the system of a jet and an interstellar cloud, can accelerate the cloud. We believe that the outcome of such interactions will be a magnetic field in the interstellar cloud co-aligned with the jet.

It is not too much to say that simulations of such interactions using PIC codes is computationally intensive.

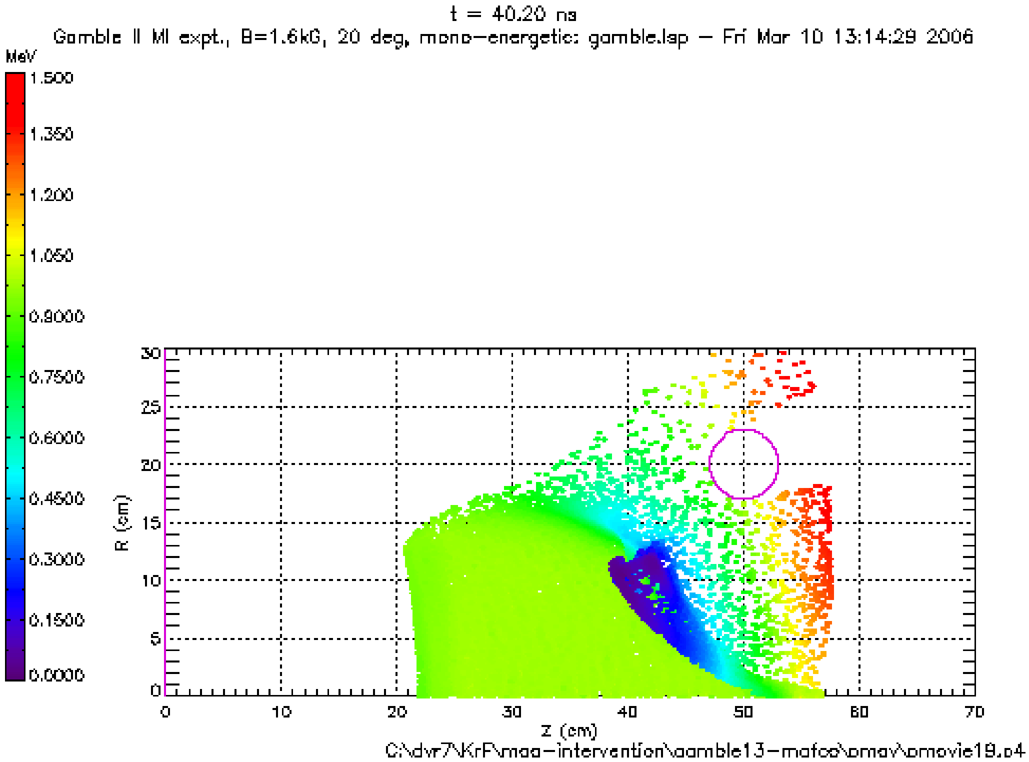

Fig. 3. Illustration of the capabilities of a PIC code simulation to model the interaction of an electron-proton plasmoid with a fixed magnetic field. The simulation shows the penetration of the magnetic field by the plasmoid. Magnetic fields "anchored" in an interstellar cloud are thus likely to entrain and accelerate the cloud as they penetrate the magnetic field and force it into an orientation aligned with the jet.

5. Hydrodynamic modeling of supersonic jet in a Seyfert galaxy

As part of our project to incorporate the plasma effects into a multi-scale code, we have begun modeling the interaction of a supersonic jet (for example, a Seyfert galaxy jet), using a highly parallelized version of the VH-1 code (see Figure 4).

The code has been ported to the NRL Cray XD-1 as part of a collaboration with Curtis Saxton and Kinwah Wu at the Mullard Space Sciences Laboratory, in order to model the interaction of a Seyfert jet with the interstellar medium. We have begun initial runs at various resolutions up to a 3-dimensional simulation of 1024^3 cells. This simulation will involve a calculation of more than $10x10^9$ floating point numbers for each time ste.

6. Concluding remarks

Plasma effects can have observational consequences. Beall (1990) has noted that plasma processes can slow the jets rapidly, and Beall and Bednarek (1999) have shown that these effects can truncate the low-energy portion of the γ-rays spectrum (see Figure 3). In the interests of brevity, we do not go into the (reasonable) assumptions for the calculation. Please see Beall and Bednarek (1999) for a detailed discussion. A similar effect will occur for neutrinos and could also reduce the expected neutrino flux from AGN. The presence of plasma processes in jets can also greatly enhance line species by generating high-energy tails on the Maxwell-Boltzmann distribution of the ambi-

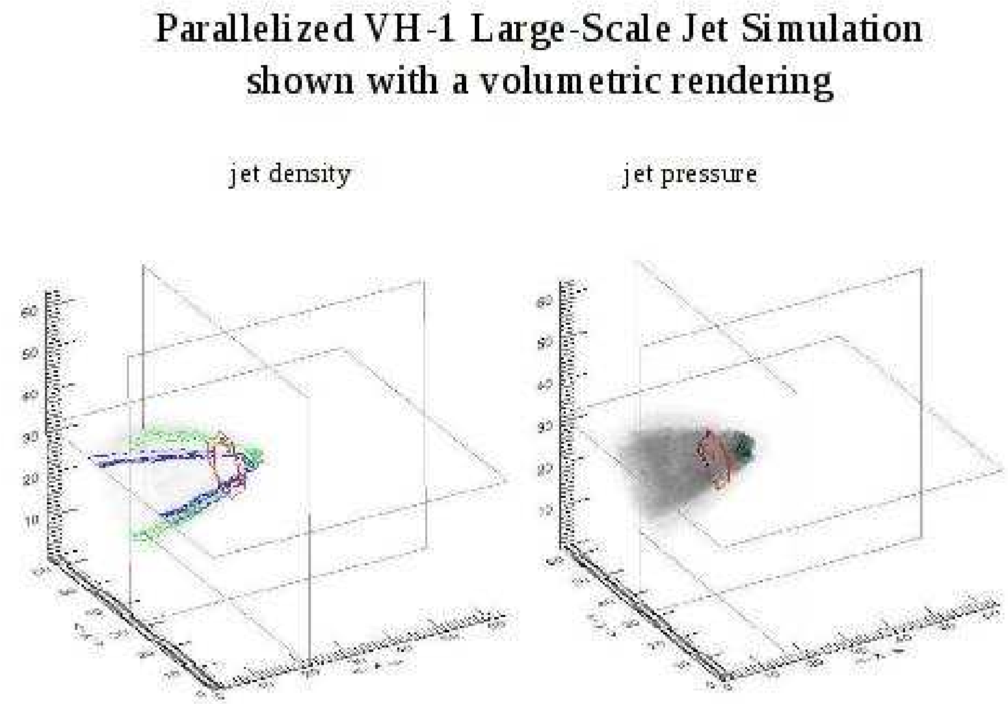

Fig. 4. Volumetric rendering of the density and pressure of the initial stages of jet in a Seyfert galaxy, using the highly-parallized version of the VH-1 code (in collaboration with Curtis Saxton and Kinwah Wu). The images show only the outermost shell of the ambient medium as it expands into the surrounding ISM. The actual jet structure is buried in the core of this volume.

ent medium, thus abrogating the assumption of thermal equilibrium. Beall, Guillory, and Rose (1999) have also calculated the greatly enhanced line emission for certain species in the presence of a relativistic jet due to plasma processes.

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 references, 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 $P_b = dE/dt = \gamma mc^2 n_b v_b \pi r_b^2$, where γ is the ratio of total energy to rest mass energy, mc^2 is the rest mass energy of the beam particles, v_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, and 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, 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 develop 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 electron energies in 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 $E_{het} \sim 30 - 100$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 (see Beall et al. 2006, and Beall, Guillory, and Rose 1999 for a detailed discussion).

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 10s to 100s of Kpc, despite plasma processes being dominant 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 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 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. The recent results from the Auger Collaboration (Letessier-Salvon 2009) suggest an extremely energetic hadronic component as a consequence of these jets.

7. DISCUSSION

SERGIO COLAFRANCESCO: What is the efficiency of the formation of the cavitons on the jet?

JIM BEALL: The cavitons are ubiquitous during the jet interaction. They are continually formed (being generated from different wave length plasma waves), phase mix (because the plasma is a dispersive medium), and then collapse. The process of collapse is likely to be much like waves breaking on a shore, so they are likely to transfer significant momentum to the ambient medium. But we need to model this quantitatively to be certain of how much momentum is transferred.

DMITRI BISIKALO: What happens with the magnetic field in the cloud during its interaction with the jet?

JIM BEALL: It's clear from the movie of our simulation (which was done for another project, by the way) that the interaction is incredibly violent. It is plausible that the jet transfers momentum to the magnetic field, and tends to force the transverse magnetic fields to co-align themselves with the longitudinal axis of the jet. This general picture seems right to me, but the details are very difficult to model.

SERGIO COLAFRANCESCO: What is the effect of magnetic reconnection on the formation of the cavitons in the jet?

JIM BEALL: The cavitons are of order centimeters in size, so they will form without interference from the magnetic fields. However, other instabilities are affected by the magnetic field. For example, a longitudinal magnetic field, like the ones inferred from polarization measurements, tends to suppress a filamentation instability that causes the jet to thread into many more, smaller-diameter jets which will then can recombine. This process does not affect estimations of the energy deposition rate or the propagation length of the jet.

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