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Large scale modeling of astrophysical jets

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Abstract. Astrophysical jets interact with the ambient medium through which they propagate, entraining and accelerating the ambient medium through which they propagate. 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. Some comments on the development of a multi-scale code are also included.

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

1. Introduction

Large scale hydrodynamic simulations of the interaction of astrophysical jets with the ambient medium through which they propagate can be used to illuminate a number of interesting consequences of the jets' presence. These include acceleration and entrainment of the ambient medium, the effects of shock structures on star formation rates, and other effects originating from ram pressure and turbulence generated by the jet (see, e.g., Basson and Alexander, 2002; Zanni et al. 2005; and Krause and Camenzind 2003; Perucho, 2011). We will present some results of large scale hydrodynamic simulations later in this paper.

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).

While the physical processes (including plasma processes) in the ambient medium can be modeled by PIC (Particle-in-Cell) codes for some parameter ranges, applications of the PIC code to astrophysics are not possible with current or foreseeable computer systems. We therefore model these plasma processes in the astrophysical regime by means of a system of coupled differential equations which give the wave generated by the interaction of the astrophysical jet with the ambient medium through which it propagates.

A detailed discussion of these efforts 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 system of equations used to solve for the normalized wave energies is very stiff.

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Solving the system of equations yields a time-dependent set of normalized wave energies (i.e., the ratio of the wave energy divided by the thermal energy of the plasma) that are generated as a result of jets interaction with the ambient medium. As we will show, these solutions can yield an energy deposition rate (dE/dt), an energy deposition length (dE/dx), and ultimately, a momentum transfer rate (dp/dt) that can be used to estimate the effects of plasma processes on the hydrodynamic evolution of the jet.

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.

2. The wave population model

The principal plasma waves generated by the jet-ambient-medium interaction 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. The waves produced 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).

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).

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.

The energy loss scale length, $dE_{plasma}/dx = -(1/n_b v_b)(d\alpha\epsilon_1/dt)$, 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.

We can therefore model the energy deposition rate (dE/dt) and the energy loss per unit length (dE/dx), and ultimately the momentum loss per unit length (dp/dx) due to plasma processes.

Beall, Guillory, and Rose (2009) have compared 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, and have found good agreement between the two results (see Figure 1 from that paper). At the same time, that paper demonstrates that the ambient medium is heated and entrained into the jet. That analysis also shows that a relativistic, low-density jet can interpenetrate an ambient gas or plasma.

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. Strong plasma turbulence: momentum transfer due to beam-generated plasma waves

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

In order to proceed to a more detailed analysis of the issue of momentum transfer, we have used modern PIC code simulations to study the dynamics of caviton formation, and have confirmed the work of Robinson and Newman (1990) in terms of the cavitons formation, evolution, and collapse.

We are in the process of developing 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 SGI Altix machine.

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 their 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 ambient medium, thus abrogating the assumption of thermal equilibrium.

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

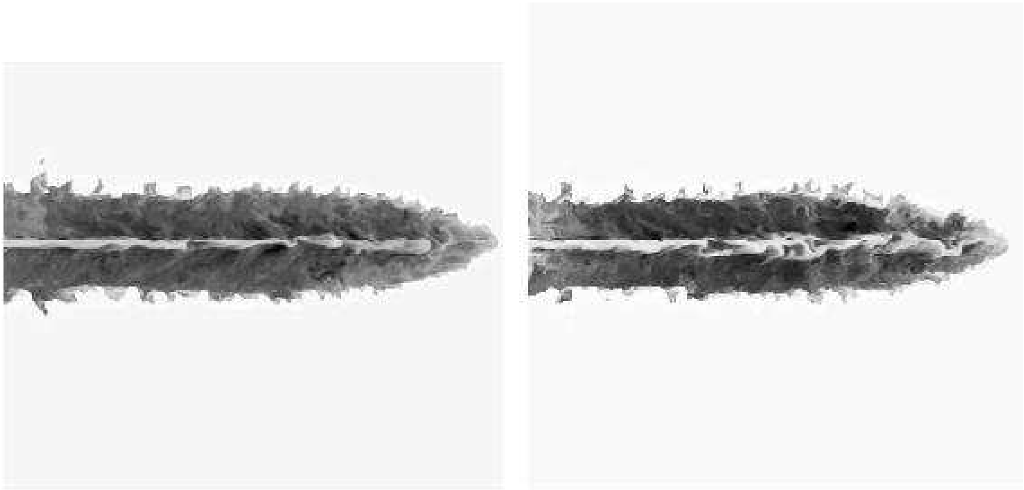

Figure 1a Figure 1b

Fig. 1. Jet simulation using a highly-parallelized version of the VH-1 hydrodynamics code. The figure shows the x-z cross-section (Figure 1a) and the y-z cross-section (Figure 1b) for a fully 3-dimensional hydrodynamic simulation of jet with $v = 1.5x10^9 cm/sec$. The simulation length is approximately 64 kpc on the long axis.

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).

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).

4. Large scale hydrodynamic simulations

As an example of the large scale hydrodynamic simulations we are conducting, we show a jet simulation in the x-z cross-section (Figure 1a) and the y-z cross-section for a 3-dimensional hydrodynamic simulation of jet with $v = 1.5x10^9 cm/sec$. The simulation length is approximately 64 kpc on the long axis. The simulation shows the detailed structure of the shocks generated by the jet as well as the Kelvin-Helmholtz instabilities of the jet itself, which generate additional shock structures. These shocks produce Jeans-length structures which will ultimately collapse to form stars that in turn feed the central engine in the AGN.

A volumetric rendering of the same jet-ambient-medium interaction is shown in Figure 3.

It is this code (a highly-parallelized version of the VH-1 code) that we intend to adapt for the multi-scale code effort.

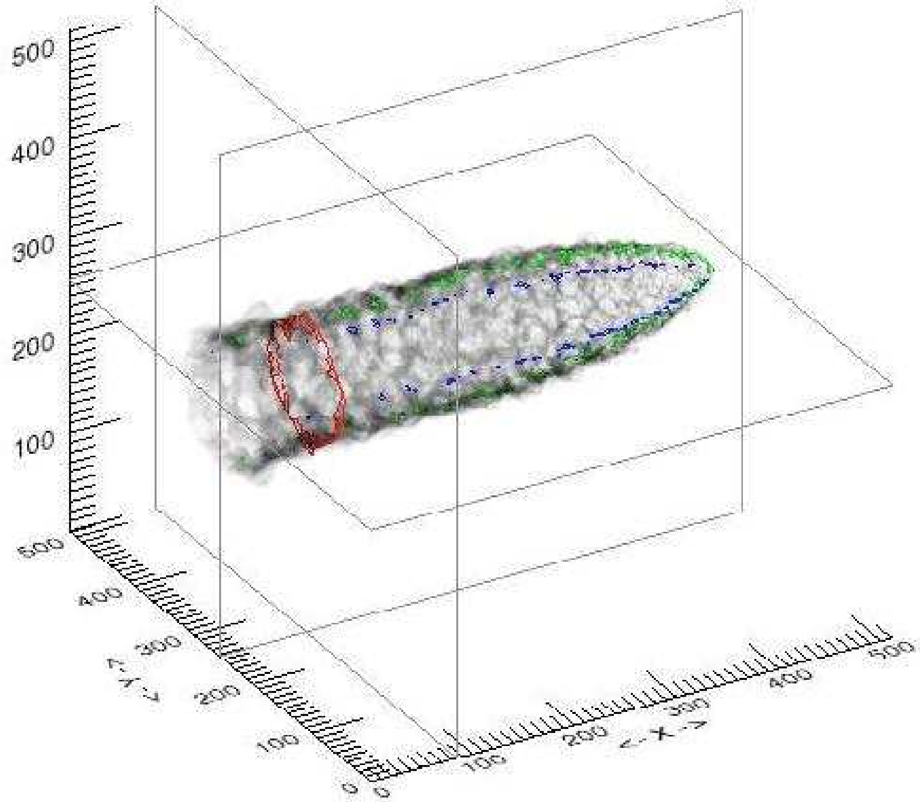

Fig. 2. Volumetric rendering of the jet simulation shown in cross-section in Figure 1.

5. Discussion

MANEL PERUCHO Is there any critical density under which these instabilities do not develop?

JIM BEALL For a low density jet interacting with a higher density medium, the instabilities grow as the ratio of the beam density, n_b, to the ambient medium density, n_p, to the 1/3 power. If the jet is significantly heated, the instabilities grow as n_b/n_p to the first power. The instabilities also grow inversely with the beam $\gamma = E/mc^2$, so a highly relativistic beam tends to propagate for longer distances. If the beam is more dense than the ambient medium, then hydrodynamic effects would also contriubute to the jet-ambient-medium interaction.

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