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Hydrodynamic Simulations of Astrophysical Jets

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As part of an ongoing project, we have undertaken fully three-dimensional (3-D) simulations of astrophysical jets, using both a highly parallelized version of the VH-1 Hydrodynamics Code in the hydrodynamics (HD) regime (Colella and Woodward 1984, and Saxton *et al.* 2005); and in the hydrodynamic, relativistic hydrodynamic (RHD), and relativistic, magnetohydrodynamic (RMHD) regimes with the PLUTO code (Mignone *et al.* 2007). We also continue our investigation using particle-in-cell simulations to benchmark a wave-population model of the two-stream instability and associated plasma instabilities in order to determine the energy deposition and momentum transfer rates for these modes of jet-ambient medium interactions. It is important to note that "simple" HD, RHD, and RMHD simulations are unable to show the real effects of these essentially microscopic (at least in terms of the scales of the simulations) processes. Thus, these effects are being considered for use in a multi-scale code that incorporates energy deposition rate and momentum transfer from strong plasma turbulence generated by the interaction of the astrophysical jet with the ambient medium through which it propagates.

In this work, we show some elements of the modeling of these jets for a fully 3-D simulation of relativistic jets using the PLUTO code in the RHD regime for jets with a bulk relativistic velocity $\beta = 0.80c$.

Keywords: jets, active galaxies, blazars, intracluster medium, non-linear dynamics, plasma astrophysics, computational fluid dynamics

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1. Introduction

Recent, high-resolution (VLBA) observations of astrophysical jets (see, e.g., Lister *et al.* 2009) reveal complex structures apparently caused by ejecta from the central engine. We suppose that these ejecta are produced by quasi-periodic processes in an accretion disk. The ejected material then interacts with surrounding interstellar material in the Broad-Line Region (BLR) and Narrow-Line Region (NRL) clouds, and with ejecta from prior episodes of activity. A particularly interesting example of these complex interactions is shown by the galactic microquasar, Sco X-1 (Fomalhaut, Geldzahler, and Bradshaw, 2001).

Such observations can be used to inform models of the jet-ambient-medium interactions. Based on an analysis of these data, we posit that a significant part of the observed phenomena come from the interaction of the ejecta with prior ejecta as well as interstellar material.

2. Scales of Jet Interactions with the Ambient Medium

Large-scale hydrodynamic simulations can be used to illuminate a number of interesting consequences of the jet's interaction with the ambient medium through which it propagate. 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 2012).

We note, however, that hydrodynamic (HD), magneto-hydrodynamic (MHD) and (RMHD) simulations neglect important species of physics: the microscopic interactions that occur because of the effects of particle-particle interactions and the interactions of particles with the collective effects that accompany a fully or partially ionized ambient medium (i.e. a plasma). This is a similar problem to that presented by the estimation of viscosity in the hydrodynamic simulations.

While the physical processes (including plasma processes) in the ambient medium can be modeled in small regions by Particle-in-Cell (PIC) codes for some parameter ranges, simulations of the larger astrophysical jet structure with such PIC codes are not possible with current or foreseeable computer systems. For this reason, we have modeled these plasma processes in the astrophysical regime by means of a system of coupled differential equations which give the wave populations 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 scales of these interactions is small compared to most hydrodynamic simulations, and their time scales are typically very fast compared to the overall evolution time of the hydrodynamical simulations.

2.1 Energy Loss, Energy Deposition Rate, and Momentum Transfer from Plasma Processes

The system of equations used to determine the normalized wave energy densities is very stiff. Scott *et al.* (1980) estimated the equilibrium solution of this system of equations for heating of clusters of galaxies, and Rose *et al.* (1984) and Beall (1990) showed dynamical solutions that confirmed the stability of the equilibrium solutions. 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. These solutions can yield an energy deposition rate (dE/dt), an energy deposition length (dE/dx), and ultimately, a momentum transfer rate $(dp/dt) \sim (1/v_b) * (dE/dt)$ that can be used to estimate the effects of plasma processes on the hydrodynamic evolution of the jet.

For this part of the analysis, we suppose that a portion of the jet is composed relativistic particles 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, 1999) also discusses the propagation of electron-positron jets.

Beall *et al.* (2006) illustrate two possible solutions for the system of coupled differential equations that model this mode of 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.

The average energy deposition rate, $< d(\alpha\varepsilon_1)/dt >$, of the jet energy into the ambient medium via plasma processes can be calculated as

$$< d(\alpha\varepsilon_1)/dt >= n_p kT < W > (\Gamma_1/\omega_p)\omega_p \quad \text{ergs-cm}^{-3}\text{s}^{-1}, \tag{2.1}$$

where 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 α is a factor that corrects for the simultaneous transfer of resonant wave energy into nonresonant and ion-acoustic waves. The energy loss scale length, $dE_{plasma}/dx = -(1/n_b v_b)(d\alpha\varepsilon_1/dt)$, can be obtained by determining the change in γ of a factor of 2 with the integration $\int d\gamma = -\int [d(\alpha\varepsilon_1)/dt] dl/(v_b n_b m^{'} c^2)$ as shown in Rose *et al.* (1978) and Beall (1990), where $m^{'}$ is the mass of the beam particle. Thus, $L_p(\text{cm}) = ((1/2)\gamma c n_b m c^2)/(d\alpha\varepsilon_1/dt)$ is the characteristic propagation length for collisionless losses for an electron or electron-positron jet, where $d\alpha\varepsilon_1/dt$ 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 *et al.* (1999), Rose *et al.* (2002), and Beall *et al.* (2010) have compared the results of a PIC code simulations 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. At the same time, these papers demonstrate that the ambient medium is heated and partially entrained into the jet. The 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).

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, and expect to present these results shortly. In order to proceed to a more detailed analysis of the issue of momentum

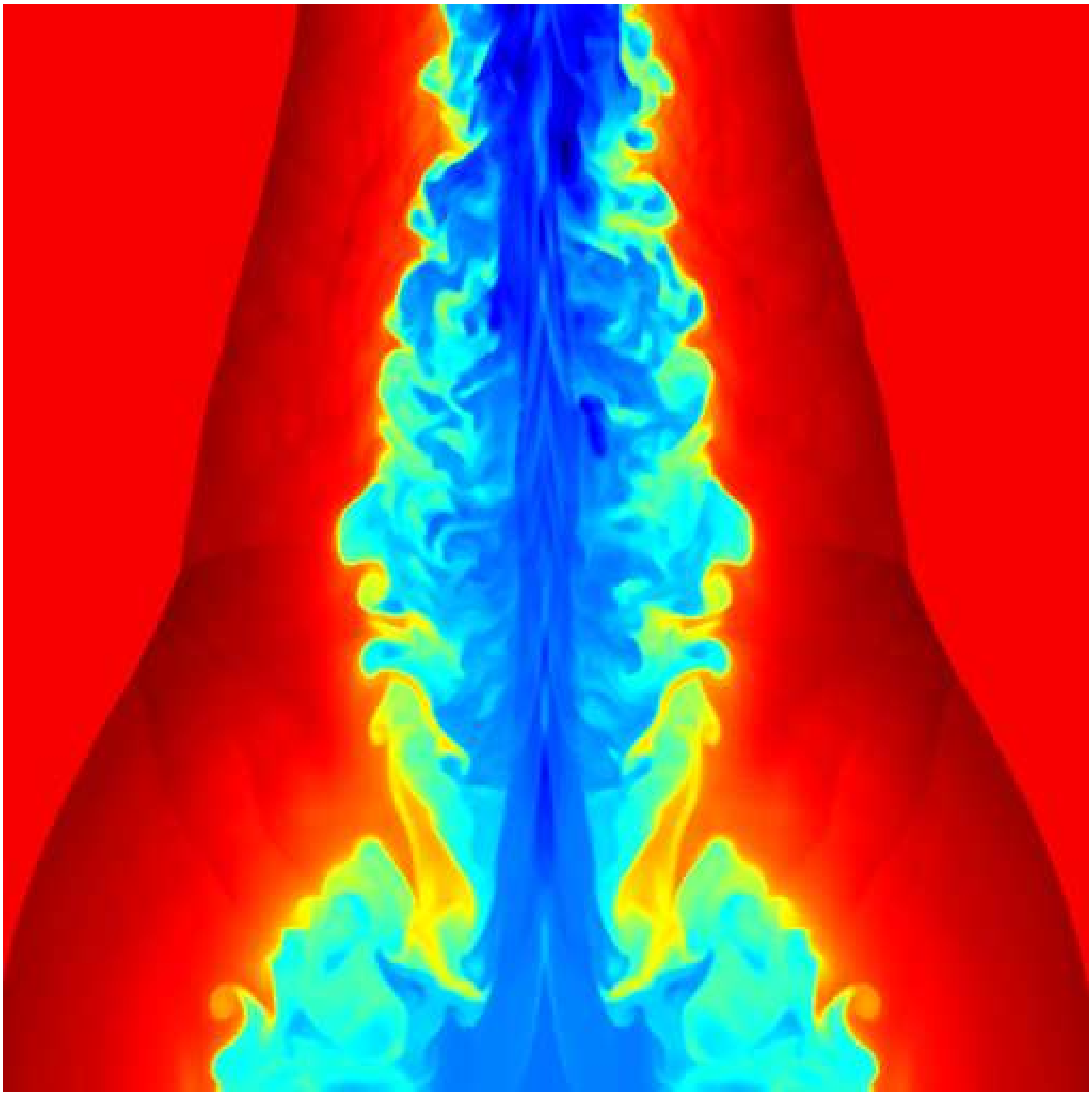

Figure 1: 3D simulation of an astrophysical jet gas density structures seen in an x-z cross-section with a bulk velocity of $v = 0.80c$. We have performed simulations with 1024^3 grid cells (512^3 cells are utilized in this image). Note the well developed Rayleigh-Taylor instabilities at the jet-ambient medium boundary. The simulation size is $\sim$5 kpc on a side and we show the structure after 2×10^3 time steps. In this simulation, the jet-to-ambient medium density ratio is 1/100 and the ratio of jet input pressure to ambient medium pressure is 5×10^{-3}

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.

2.2 Results of Hydrodynamical Calculations

Figure 1 shows an x-z cut of a fully 3-D simulation of a relativistic jet in the hydrodynamic (RHD) regime. The figure shows jet gas density structures seen in the x-z cross-section, a bulk velocity of $v = 0.998c$. We have performed simulations with 1024^3 grid cells (512^3 cells are utilized in this image). Note the well developed Rayleigh-Taylor instabilities at the jet-ambient medium boundary.

The simulation in Figure 1 was done using our modification of the PLUTO code (Mignone *et al.* 2007) on the NRL SGI Altix machine, ICEBERG . We are continuing to explore the parameter space of these jets by varying the bulk jet velocity, γ, and other jet parameters. We have used the 512^3 simulation in this representation The simulation was done using our modification of the PLUTO code (Mignone *et al.* 2007) on the Naval Research Laboratory SGI Altix machine, ICEBERG.

The cell simulation size is $\sim$5 kpc on a side and we show the structure after $\sim 2 \times 10^3$ time steps. In this simulation, the jet-to-ambient medium density ratio is 1/100 and the ratio of jet input pressure to ambient medium pressure is 5×10^{-3}.

Figure 2 shows a PIC code simulation of the effects of the “microscopic" two-stream (and related) processes on the Maxwell-Boltzmann distribution of the ambient medium through which the the relativistic jet passes. The production of a high-energy tail on the thermal distribution of the gas is manifest over just a few thousand plasma cycles. Such processes can produce orders-of-magnitude changes in the emitted line-spectrum of the gas. In the simulation shown, the ration of the densities, $n_b/n_p = 10^{-2}$.

shows the temperature structure for an x-z cut of an astrophysical jet with $v = 0.5c$ using the PLUTO code with the same parameters as the jet in Figure 1. We are continuing to explore the parameter space of these jets by varying the bulk jet velocity, γ, and other jet parameters. We have used the 512^3 simulation in this representation.

We are continuing to explore the parameter space for the jet simulations by varying the density of the jet and the ambient medium, the jet velocity, and the relative hydrostatic pressure and the pressure of the ambient medium. For a sufficient overburden of material in the ambient medium and a low-velocity jet, it is possible to demonstrate that the jet-propagation can be thwarted. This effect might explain the relatively truncated jets associated with Seyfert galaxies.

3. Concluding Remarks

The effects of collective and particle processes, including 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),

A similar effect will occur for particle-particle productions of neutrinos, pions, and (perhaps) neutrons (Atoyan and Dermer 2003). This could also reduce the expected neutrino flux from AGN.

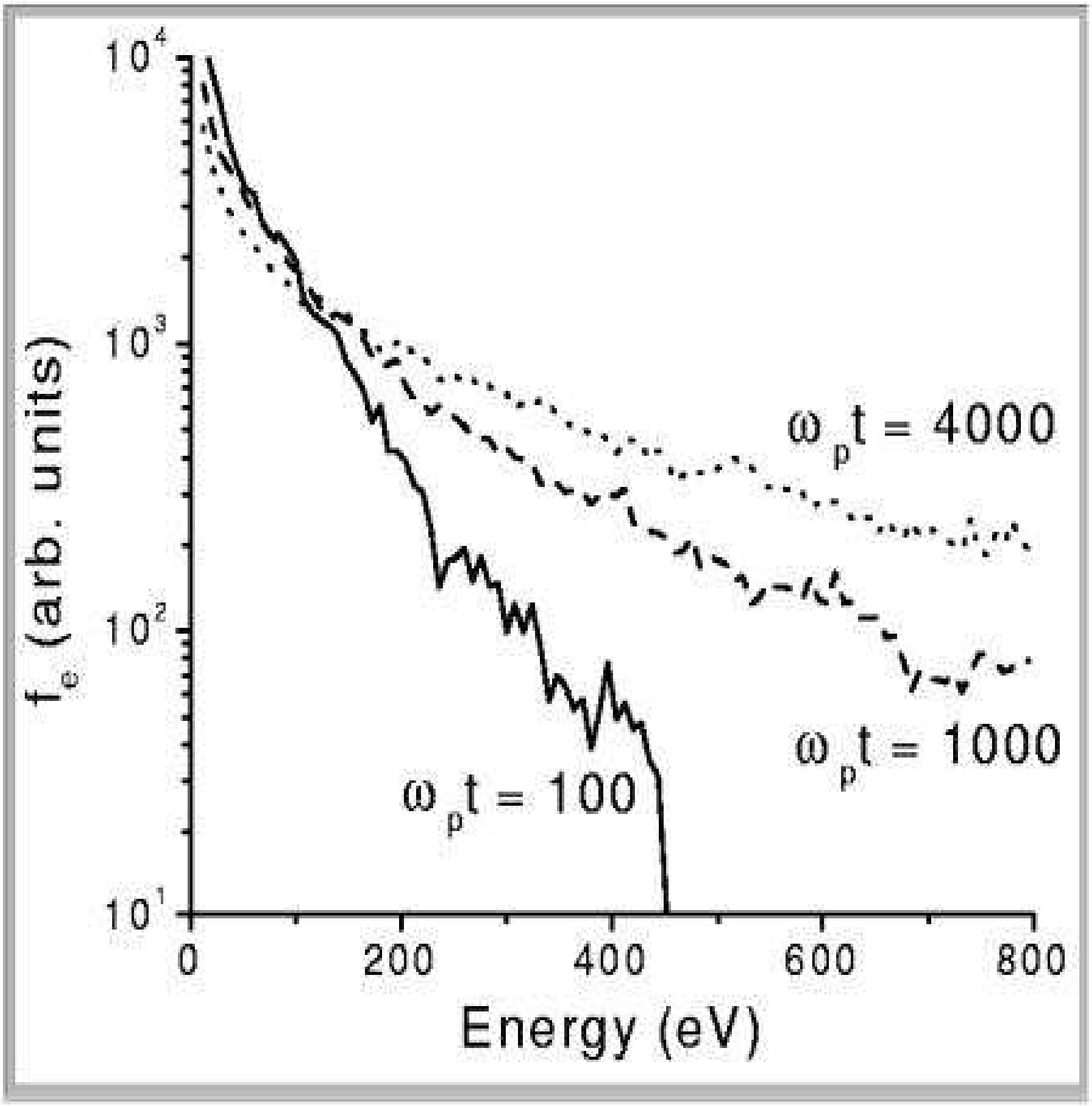

Figure 2: This figure shows a PIC code simulation of the effects of the “microscopic" two-stream (and related) processes on the Maxwell-Boltzmann distribution of the ambient medium through which the the relativistic jet passes. The production of a high-energy tail on the thermal distribution of the gas is manifest over just a few thousand plasma cycles. Such processes can produce orders-of-magnitude changes in the emitted line-spectrum of the gas. In the simulation shown, the ration of the densities, $n_b/n_p = 10^{-2}$.

The presence of plasma processes in jets can also greatly enhance line radiation 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 (Rose *et al.* 2005), 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).

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DISCUSSION

Dimitri Bisikalo: Two questions: 1. Did you consider any rotation of the jet in your simulations? 2. How did you define the temperature for th ematter with the suprathermal tail?

JIM BEALL: In answer to the first question, we have not yet considered rotation of the jet in our simulations. But this is an excellent suggestion, especially given the large-scale structure of the jets, which could be the result of precession.

As to the second question, for the Particle-in-Cell (PIC) simulations, the high-energy tails arise naturally from the electron-positron interactions in the ambient medium. For the wave-population model we use to estimate propagation length due to plasma process losses, we use a two-temperature estimate of Landau Damping, one with roughly $T = 10^4 K$, and the other, high temperature component with a fractional component of $T = 10^5 K$. The higher temperature component is some smaller fraction of the overall ambient medium temperature.

WOLDGANG KUNDT: The simulations you have shown are all trans-relativistic. Do you plan to do extremely relativistic simulations?

JIM BEALL: The highest Lorentz factor we have simulated thus far is 0.998c, which we have not shown in this talk. We began by benchmarking the PLUTO code to the VH-1 code, which is non-relativistic, out of an abundance of caution. I promise to show some more relativistic results in future talks.