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Hydrodynamic Simulations of Astrophysical Jets

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We present recent results of our three-dimensional (3-D) simulations of astrophysical jets. These efforts use the the PLUTO code (Mignone *et al. 2007*) run in a highly parallel environment for the hydrodynamic, magneto-hydrodynamic (MHD), relativistic hydrodynamic (RHD), and relativistic, magnetohydrodynamic (RMHD) simulations. In this recent work, we focus on RMHD simulations. 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 the jet-ambient medium interactions. As noted previoiusly, we believe that "simple" HD, MHD, RHD, and RMHD simulations are unable to show the real effects of very small scale plasma 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 (Beall, *2010*). In this work, we show some results from the modeling of these jets for a fully 3-D Cartesian simulation of relativistic jets using the PLUTO code in the RMHD regime.

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

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1. Introduction

High-resolution (VLBA) observations of astrophysical jets (see, e.g., Lister *et al.* 2009) and Beall (2015) for reviews) reveal complex structures in the cores of AGNs and microquasars apparently caused by ejecta from the central engine. The temporal and spatial structures of the jets at both microquasar and quasar scales (i.e., from milliparsecs to kiloparsecs), suggest that the effects might be produced by quasi-periodic processes in accretion disks. The ejected material then interacts with the surrounding interstellar material in the source region, that is, the Broad-Line Region (BLR) and Narrow-Line Region (NLR) 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 propagates. 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 believe, however, that hydrodynamic (HD), magneto-hydrodynamic (MHD) and (RMHD) simulations neglect important aspects 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 hydrodynamic simulations.

Though 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 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 regime.

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 $(dp/dt) \sim (1/v_b) * (dE/dt)$, where v_b is the beam velocity. This dp/dt 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 of 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 $< d(\alpha\varepsilon_1)/dt >= n_p kT < W > (\Gamma_1/\omega_p)\omega_p$ ergs-cm^{-3}s^{-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,

$L_p(\mathrm{cm}) = ((1/2)\gamma c n_b m c^2)/(d\alpha\varepsilon_1/dt)$

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 (Rose *et al.* 1984, Beall 1990). We can therefore model the energy deposition rate (dE/dt), the energy loss per unit length (dE/dx), and ultimately the momentum loss per unit length (dp/dx) due to plasma processes, and can add these as an external force term in the PLUTO code.

Beall et al.(2015) show a late-time appearance of a fully three-dimensional simulation of an astrophysical jet gas density structure seen in an x-z cross-section with a bulk velocity of $v = 0.80c$. In that work, they showed a simulation with 1024^3 grid cells The simulation demonstrated well-developed Rayleigh-Taylor instabilities at the jet-ambient medium boundary. The simulation size presented was $\sim$ 64kpc on a side and showed the structures developed after 2×10^3 time steps (roughly 10^4 years). In that 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} The simulation we present here is also 1024^3 grid cells, but with a fully relativistic magneto-hydrodynamic simulation. The magnetic field in the jet has a poloidal/toroidal structure with both intensities of $1.0x10^1$ Gauss, $\gamma = 10$, and an ambient medium to jet density ration of $100/0.1$. As can be clearly seen, the simulation shows well-developed Rayleigh-Taylor instabilities and significant shock structures along the jet core. In this simulation, we have used a linear reconstruction and Hancock time stepping, as well as the “tvdlf" solver.

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.

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 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 magneto-hydrodynamic (RMHD) regime. The figure shows jet gas density structures seen in the x-z cross-section, a bulk velocity of $v = 0.998c$. Simulations with 1024^3 cells are utilized in this image. Note the well developed Rayleigh-Taylor instabilities at the jet-ambient medium boundary.

The simulation shown in Figures 1 and 2 was done using the PLUTO code (Mignone *et al.* 2007) with relatively fast choice of solvers, time steps, and reconstructions between cells, but with a very large simulation volume. The simulations are conducted using the Naval Research Laboratory's SGI Altix machine, POLAR. Our modifications to the graphical outputs provides x-z slices at certain time steps in order to produce a convenient graphical guide. We use these images as“quick look" guides to investigate the details of the simulations. In addition, in past simulationswe have used the "external force" option in the code to simulate a disk gravity attraction that would illustrate coupling of the jet source to the jet-entrained ambient material.

We are continuing to explore the parameter space of these jets by varying the bulk jet velocity, γ, and other jet parameters. Given certain simulation parameters, including 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 suppressed. This "frustrated jet" effect might explain the relatively truncated jets associated of jets with Seyfert galaxies. These effects have been discussed in some detail in Beall et al. (2015)

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 of Beall and Bednarek, 1999).

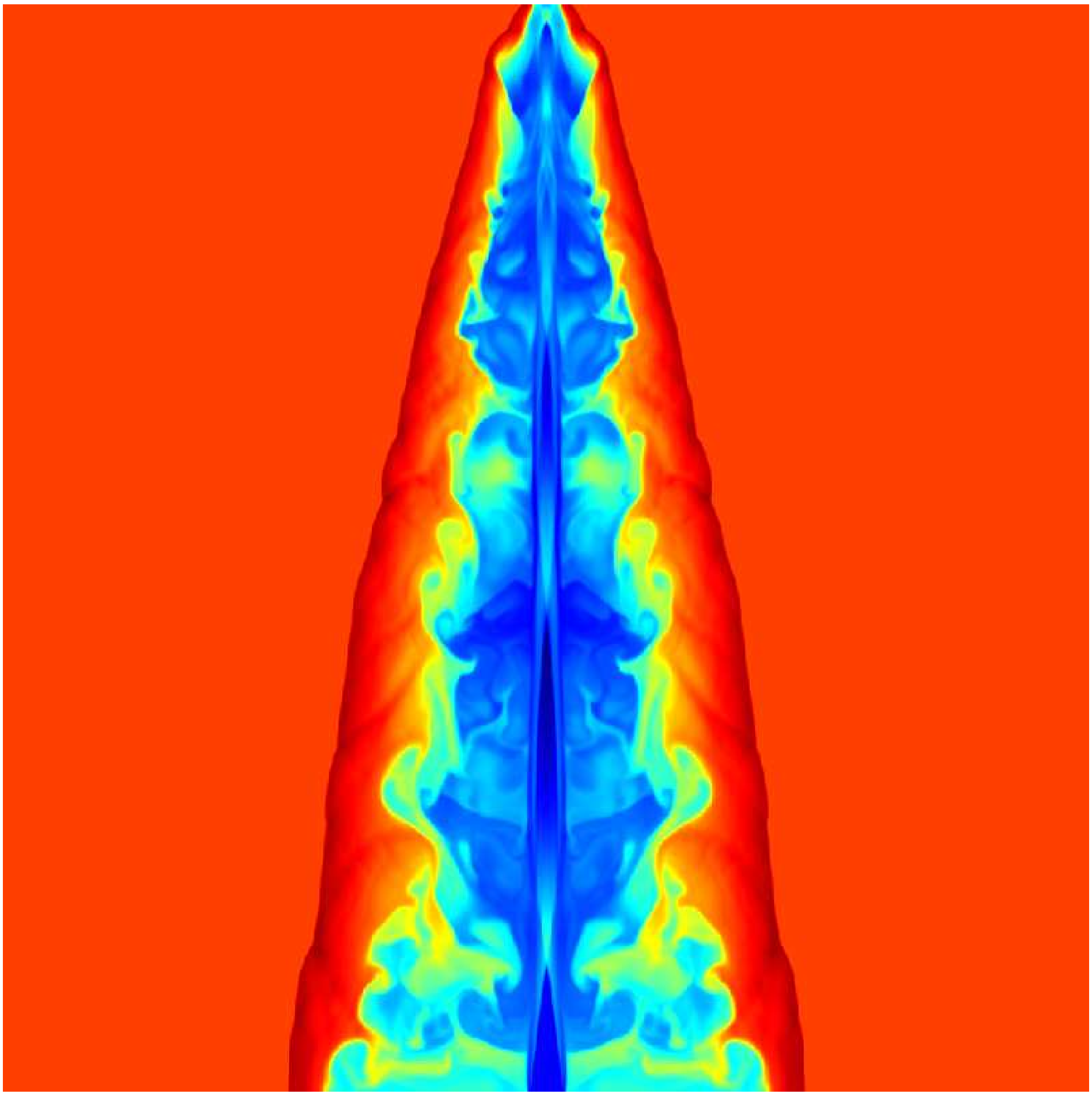

Figure 1: The image we present here shows the density structure of a fully relativistic, magneto-hydrodynamic simulation of the late-time evolution of an astrophysical jet, using 1024^3 grid cells. The magnetic field in the jet has a poloidal/toroidal structure with both intensities of $1.0x10^1$ Gauss, a ration of the jet energy vs. rest-mass, $\gamma = 10$, and an ambient medium to jet density ration of $100/0.1$. At this stage, the simulation shows well-developed Rayleigh-Taylor instabilities and significant shock structures along the jet core and where the jet interacts with the ambient medium. In this simulation, we have used a linear reconstruction and Hancock time stepping, as well as the "tvdlf" solver from the PLUTO code.

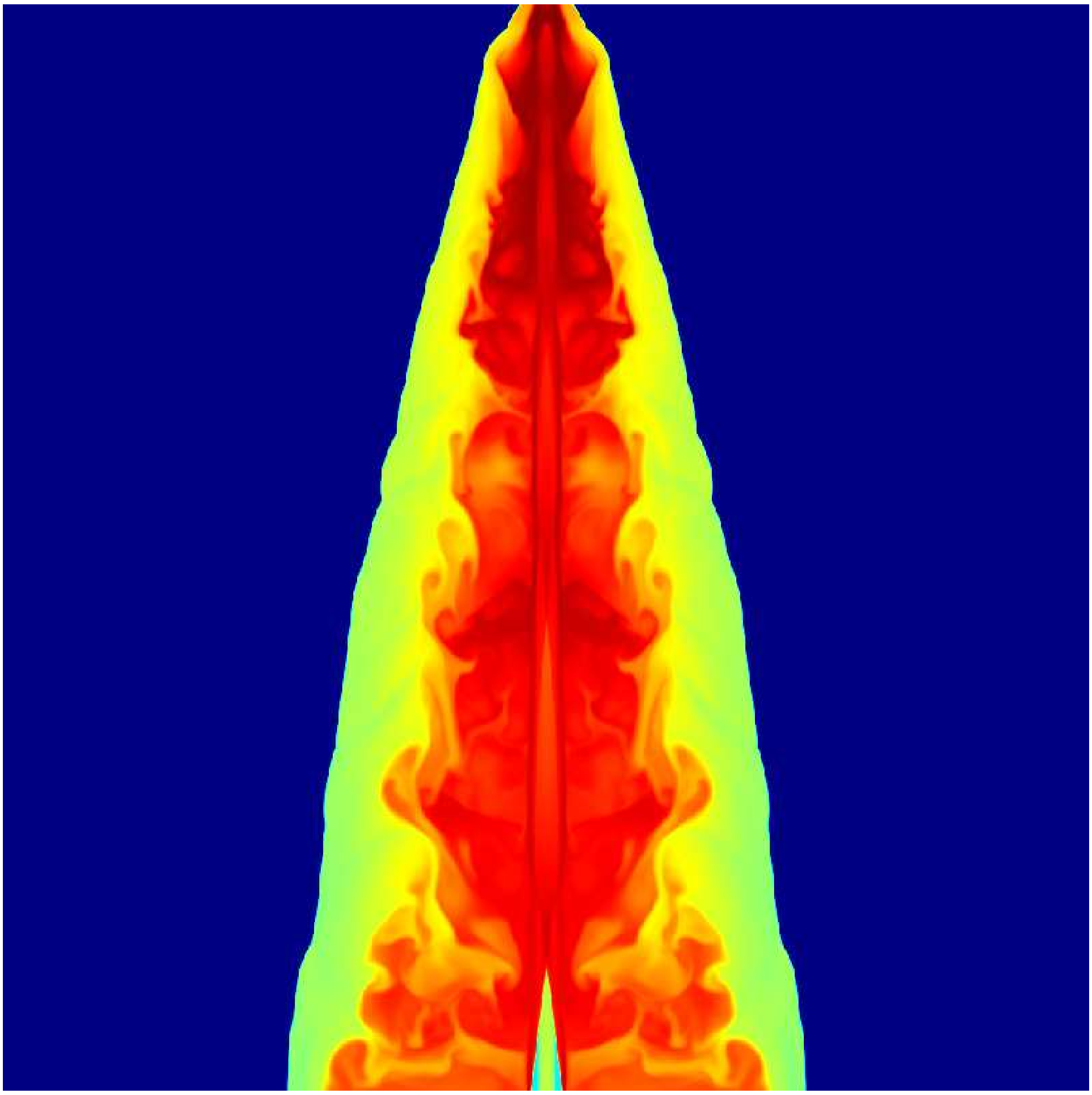

Figure 2: Figure 2 shows the temperature structure of the jet-ambient medium interaction region with the same parameters as Figure 1. The fully relativistic, magneto-hydrodynamic simulation uses 1024^3 grid cells. The magnetic field in the jet has a poloidal/toroidal structure with both intensities of $1.0x10^1$ Gauss, a ration of the jet energy vs. rest-mass, $\gamma = 10$, and an ambient medium to jet density ration of $100/0.1$.

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. The presence of plasma processes in jets can also greatly enhance line radiation 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

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