Acta Polytechnica **53**(Supplement):683–686, 2013
doi:10.14311/AP.2013.53.0683

MODELING JET INTERACTIONS WITH THE AMBIENT MEDIUM

J.H. Beall[a,b,c,*], J. Guillory[c], D.V. Rose[d], Michael T. Wolff[b]

[a] *St. John's College, Annapolis, MD*
[b] *Space Sciences Division, Naval Research Laboratory, Washington, DC*
[c] *College of Sciences, George Mason University, Fairfax, VA*
[d] *Voss Scientific, Albuquerque, NM*
[*] corresponding author: `beall@sjca.edu`

Abstract. Recent high-resolution (see, e.g., [13]) observations of astrophysical jets reveal complex structures apparently caused by ejecta from the central engine as the ejecta interact with the surrounding interstellar material. These observations include time-lapsed "movies" of both AGN and microquasars jets which also show that the jet phenomena are highly time-dependent. 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. In this view, astrophysical jets interact with the ambient medium through which they propagate, entraining and accelerating it. We show some elements of the modeling of these jets in this paper, including energy loss and heating via plasma processes, and large scale hydrodynamic and relativistic hydrodynamic simulations.

Keywords: jets, active galaxies, 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., [1, 10, 16, 23]. We present results for large scale hydrodynamic simulations and initial relativistic hydrodynamic simulations in this paper.

2. Modeling the jet interaction with the ambient medium

Hydrodynamic sumulations 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. a plasma).

While the physical processes (including plasma processes) in the ambient medium can be modeled in small regions by PIC (Particle-in-Cell) codes for some parameter ranges, simulations of the larger astrophysical jet structure with such a PIC code 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 [6, 8, 18, 19, 22].

The system of equations used to solve for the normalized wave energies is very stiff. 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 ($\mathrm{d}E/\mathrm{d}t$), an energy deposition length ($\mathrm{d}E/\mathrm{d}x$), and ultimately, a momentum transfer rate ($\mathrm{d}p/\mathrm{d}t$) 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 $\mathrm{e}^{\pm}$, 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 [8] notes. Kundt [11, 12] also discusses the propagation of electron–positron jets.

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-density fluctuations or 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, $\lambda_\mathrm{D} = 7.43 \times 10^2 \sqrt{T/n_\mathrm{p}}\,\mathrm{cm}$, 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}.

2.1. Energy loss, energy deposition rate, and momentum transfer

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., [7]), 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 [15]) 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 [20, 21]. 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. [18, 19], and Beall [8].

Beall et al. [7] illustrate 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 $\mathit{\Gamma}_1 \le (\sqrt{3}/2\gamma)(n_\mathrm{b}/2n_\mathrm{p})^{1/3}\omega_\mathrm{p}$, where γ is the Lorentz factor of the beam, n_b and n_p are the beam and cloud number densities, respectively, in units of cm^{-3} and ω_p is the plasma frequency, as described more fully in [18].

The average energy deposition rate, $\langle \mathrm{d}(\alpha\epsilon_1)/\mathrm{d}t \rangle$, of the jet energy into the ambient medium via plasma processes can be calculated as $\langle \mathrm{d}(\alpha\epsilon_1)/\mathrm{d}t \rangle = n_\mathrm{p} kT \langle W \rangle (\mathit{\Gamma}_1/\omega_\mathrm{p})\omega_\mathrm{p}\,\mathrm{erg\,cm^{-3}\,s^{-1}}$, where 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, $\mathit{\Gamma}_1$ 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, $\mathrm{d}E_\mathrm{plasma}/\mathrm{d}x = -(1/n_\mathrm{b}v_\mathrm{b})(\mathrm{d}\alpha\epsilon_1/\mathrm{d}t)$, can be obtained by determining the change in γ of a factor of 2 with the integration $\int \mathrm{d}\gamma = -\int [\mathrm{d}(\alpha\epsilon_1)/\mathrm{d}t]\mathrm{d}l/(v_\mathrm{b} n_\mathrm{b} m' c^2)$ as shown in [8, 17], where m' is the mass of the beam particle. Thus, $L_\mathrm{p} = ((1/2)\gamma c n_\mathrm{b} m c^2)/(\mathrm{d}\alpha\epsilon_1/\mathrm{d}t)\,\mathrm{cm}$ is the characteristic propagation length for collisionless losses for an electron or electron–positron jet, where $\mathrm{d}\alpha\epsilon_1/\mathrm{d}t$ 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 ($\mathrm{d}E/\mathrm{d}t$) and the energy loss per unit length ($\mathrm{d}E/\mathrm{d}x$), and ultimately the momentum loss per unit length ($\mathrm{d}p/\mathrm{d}x$) due to plasma processes.

Beall, Guillory, and Rose (2009) have compared the results of a 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 Fig. 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 are via plasma processes [8, 18].

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 and wave-population models as source terms for the highly parallelized hydrodynamic code currently running on the NRL SGI Altix machine.

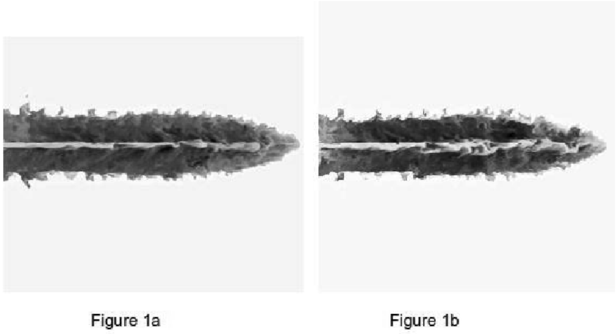

Figure 1a Figure 1b

Figure 1. 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 a jet with $v = 1.5 \times 10^9\,\mathrm{cm\,s^{-1}}$. The simulation length is approximately 64 kpc on the long axis.

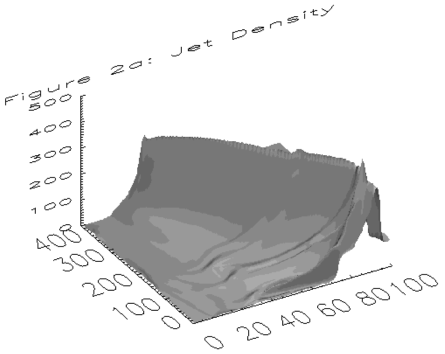

Figure 2. 2D simulation of an axially symmetric, relativistic hydrodynamic jet with $v/c = 0.995$, showing jet density (top) and axial velocity along the jet axis and radially (bottom) using the PLUTO code (Mignone et al. 2009)

Plasma effects can have observational consequences. Beall [8] has noted that plasma processes can slow the jets rapidly, and Beall and Bednarek [4] have shown that these effects can truncate the low-energy portion of the γ-ray spectrum (see their Fig. 3). In the interests of brevity, we do not go into the (reasonable) assumptions for these calculation. Please see [4] 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 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 $E_{\mathrm{het}} \sim 30 \div 100\,kT$, 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 [5, 7] 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., [7, 9, 20]). 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 PIC simulations we have used to benchmark the wave population codes appropriate for the astrophysical parameter range (see, e.g., [5, 21]).

3. 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 a jet with $v = 1.5 \times 10^9\,\mathrm{cm\,s^{-1}}$. 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 may feed the central engine in the AGN. In Fig. 2, we show the density and axial velocity plotted radially and along the jet axis for a 2D simulation of a relativistic jet using the PLUTO code [14]. We plan to develop a multi-scale code with the plasma processes as momentum and energy source terms for these codes.

Acknowledgements

HB and MTW gratefully acknowledge the support of the Office of Naval Research for this project. Thanks also to colleagues at various institutions for their continued interest and collaboration, including Kinwah Wu, Curtis Saxton, S. Schindler and W. Kapferer, and S. Colafrancesco.

References

[1] Basson, J.F., and Alexander, P., 2002, MNRAS, 339, 353

[2] Beall, J.H., et al. 1978: Ap.J., 219, 836

[3] Beall, J.H. and Rose, W.K. 1981: Ap.J., 238, 539

[4] Beall, J.H. and Bednarek, W. 1999: Ap.J., 510, 188

[5] Beall J.H., Guillory, J., & Rose, D.V., 1999, *Journal of the Italian Astronomical Society*, 70, 1235

[6] Beall J.H., Guillory, J., & Rose, D.V., 2003, C.J.A.A., Vol. 3, **Suppl.**, 137

[7] Beall J.H., Guillory, J., Rose, D.V., Schindler, S., Colafrancesco, S., 2006, C.J.A.A., Supplement 1, 6, 283

[8] Beall J.H., 1990, “Energy Loss Mechanisms for Fast Particles,” in *Physical Processes in Hot Cosmic Plasmas*, (Kluwer Academic Publishers: Dordrecht/Boston/London: W. Brinkmann, A.C. Fabian, and F. Giobannelli, eds.)

[9] Kaplan, S.A., & Tsytovich, V.N., 1973 *Plasma Astrophysics*, (Pergamon Press: Oxford, New York)

[10] Krause, M, & Camenzind, M., 2003, New Astron. Rev., proceedings of the conference in Bologna: “The Physics of Relativistic Jets in the CHANDRA and XMM Era”, Sep.,2002 Journal-ref: New Astron.Rev. 47 (2003) 573–576

[11] Kundt, W., 1987, In *Astrophysical Jets & Their Engines: Erice Lectures*, ed. W. Kundt (Reidel: Dordrecht. Netherlands)

[12] Kundt, W. 1999: in *Multifrequency Behaviour of High Energy Cosmic Sources*, F. Giovannelli & L. Sabau-Graziati (eds.), *Mem. S.A.It.* **70**, 1097

[13] Lister et al., 2009, AJ, 137, 3718

[14] Mignone et al., 2007, ApJS, 170, 228

[15] Oreskes, N., Shrader-Frechette, K., and Belitz, K., 1996, Science, 263, 641

[16] Perucho et al., 2012, MmSAI 83, 297

[17] Rose, D.V., 1997, PhD Dissertation, George Mason University, Fairfax, VA, USA

[18] Rose, W.K., Guillory, J., Beall, J.H., & Kainer, S., 1984, Ap.J., 280, 550

[19] Rose, W.K., Beall, J.H., Guillory, J., & Kainer, S., et al. 1987, Ap.J., 314, 95

[20] Rose, D.V., Guillory, J. & Beall, J.H., 2002, Physics of Plasmas, 9, 1000

[21] Rose, D.V., Guillory, J. & Beall, J.H., 2005, Physics of Plasmas, 12, 014501

[22] Scott, J.H., Holman, G.D., Ionson, and Papadopoulos, K., 1980, Ap.J., 239, 769

[23] Zanni, C., Murante, G., Bodo, G., Massaglia, S., Rossi, P., Ferrari, A., 2005, Astronomy and Astrophysics, 429

Discussion

Maria Diaz Trigo — Two questions: 1. Given that winds are slower than jets, do you expect that the interaction with the ambient medium, and therefore the energy deposition, is more efficient for winds? 2. At which temperatures is the ambient medium heated after the interaction with the jet?

Jim Beall — As to the first question, the winds being slower than the jet, I think they would tend to be less energetic, and therefore would tend to have a less dramatic effect on the ambient medium than do the jets. Regarding the temperatures the ambient medium can reach, PIC code simulations as well as analytical estimates indicate that the plasma processes can heat a 10^4 K ambient medium to 10^5 K using the plasma processes along.

Maurice van Putten — As you know, knotted structures are observationally quite generic. In your simulations in hydro, they do not form. In my simulations, with relativistic MHD (RMHD) in Ap.J., 467, L57 (1996), they form by dynamically significant magnetic field strengths. Adding “test” or “tracer” magnetic fields to hydro simulations does not seem to be a valid approximation.

Jim Beall — I agree that we need to move to MHD and RMHD simulations, and it is our plan of research to do this. But if you look closely at the structure of the jets in our simulations, you can see knotted structures along the jet’s longitudinal axis that are similar to those observed in the sky.