Simulations of Nonthermal Electron Transport in Multidimensional Flows: Application to Radio Galaxies

T.W. Jones\textsuperscript{a,1}, I.L. Tregillis\textsuperscript{a,2} & Dongsu Ryu\textsuperscript{b,3}

\textsuperscript{a}School of Physics and Astronomy, University of Minnesota, 116 Church St. S.E., Minneapolis, MN 55455
\textsuperscript{b}Department of Astronomy and Space Science, Chungnam National University, Daejeon, 305-764, Korea

Abstract

We have developed an economical, effective numerical scheme for cosmic-ray transport suitable for treatment of electrons up to a few hundreds of GeV in multidimensional simulations of radio galaxies. The method follows the electron population in sufficient detail to allow computation of synthetic radio and X-ray observations of the simulated sources, including spectral properties (see the companion paper by Tregillis et al. 1999). The cosmic-ray particle simulations can follow the effects of shock acceleration, second-order Fermi acceleration as well as radiative and adiabatic energy losses. We have applied this scheme to 2-D and 3-D MHD simulations of jet-driven flows and have begun to explore links between dynamics and the properties of high energy electron populations in radio lobes. The key initial discovery is the great importance to the high energy particle population of the very unsteady and inhomogeneous flows, especially near the end of the jet. Because of this, in particular, our simulations show that a large fraction of the particle population flowing from the jet into the cocoon never passes through strong shocks. The shock strengths encountered are not simply predicted by 1-D models, and are quite varied. Consequently, the emergent electron spectra are highly heterogeneous. Rates of synchrotron aging in “hot-spots” seem similarly to be very uneven, enhancing complexity in the spectral properties of electrons as they emerge into the lobes and making more difficult the task of comparing dynamical and radiative ages.

\textsuperscript{1} E-mail: twj@astro.spa.umn.edu
\textsuperscript{2} E-mail: tregilli@msi.umn.edu
\textsuperscript{3} E-mail: ryu@canopus.chungnam.ac.kr
1 Introduction

The jet-based, dynamical paradigm for radio galaxies now seems secure, but our understanding of the basic physics remains primitive. A key barrier has been our limited ability to fill the enormous gap between complex plasma flows thought to drive the phenomenon and the emissions that reveal them. The emissions come from particles very far from thermodynamic equilibrium, so that their energy distributions depend on local microphysics and their histories. Further, the posited plasma flows are strongly driven systems, so they are also mostly far from any stable dynamical equilibria. Among other things this leads to very unsteady flows. These characteristics make numerical simulations a necessity to push beyond the simplest characterizations of the phenomena and to verify even simple analytical calculations based on equilibrium assumptions.

The past decade has seen a revolution in our ability to carry out sophisticated multidimensional gasdynamical simulations, including magnetic fields (e.g., Clarke et al. 1989; Lind et al. 1989; Kössl et al. 1990; Nishikawa et al. 1998). The diffusive shock acceleration paradigm for particle energization, which is relatively robust in relating bulk dynamics and particle spectra, seems to offer an attractive way past ignorance of some microphysical details. Despite these advances, modeling the relevant particle microphysics adequately in simulations has remained illusive. These difficulties come from both severe technical constraints on simulations and ignorance of some of the most important physical parameters. Now we have initiated a program that takes a significant technical step forward, and which we hope will help resolve some of the key physical ambiguities. In multi-dimensional MHD flow simulations we follow the nonthermal electron population in some detail, allowing us to compute for the first time meaningful model emissions. This paper describes some initial results as they apply to the properties of the nonthermal electrons. A companion paper (Tregillis et al. 1999) describes application of our methods to synthetic radio and X-ray observations and what they seem to be telling us about interpretation of observations in terms of physical source parameters. A report of initial 2-D simulations, plus additional references are given in Jones et al. 1999. The 3-D results shown here are preliminary. A full report is in preparation.

2 Background

Our flow dynamics is treated with a second-order accurate, conservative, “TVD” ideal MHD code described in Ryu & Jones 1995; Ryu et al. 1995; Ryu et al. 1998. It maintains the divergence free condition to the magnetic
field to machine accuracy using an upwinded constrained transport scheme as described in Ryu et al. 1998. For energetic particle transport we use the conventional “convection diffusion equation” for the momentum distribution function, $f$, (e.g., Skilling 1975) which follows spatial and momentum diffusion as well as spatial and momentum advection of the particles. The last of these corresponds to energy losses and gains from, for example, adiabatic expansion and synchrotron aging.

However, high computational costs prohibit solving this equation through standard finite difference methods in complex flows expected in radio galaxies. To circumvent this we use a conservative finite volume approach in the momentum coordinate, taking advantage of the broad spectral character expected for $f(p)$. Particle fluxes across momentum bin boundaries are estimated by representing $f(p)$ as $f(p) \propto p^{-q(p)}$, where $q(p)$ varies in a regular way. Numerically we use the integrated number of electrons within each bin and the slope, $q$, within each bin. Thus, we can follow electron spectral evolution in smooth flows for all the effects mentioned above with a modest number of momentum bins. Typically we have used 8 bins to cover energies up to a few hundred GeV for electrons. We have shown that this approach produces solutions in good agreement with more conventional methods, including diffusive acceleration at shocks and synchrotron energy losses. However, in the flows being studied, diffusive acceleration of electrons to GeV energies at shocks is effectively instantaneous within a dynamical time step. Because of that direct simulation of this physics would be prohibitively expensive. We can, however, also circumvent this difficulty if we assume the analytic, steady, test particle form for the electron distribution just behind shocks. Ignoring for this discussion some details, that spectrum will be a power law with an index, $q = \frac{3r}{r-1}$, where $r$ is the shock compression ratio.

Together these features give us a powerful tool for numerical simulations of such complex phenomena as radio galaxies (Jones et al. 1999; Jun & Jones 1999). Our method is complementary to that recently described by Micono et al. 1999. Those authors followed the convection-diffusion equation in detail outside of shocks using conventional methods, but were constrained by the numerical limitations we describe to follow a very limited number of Lagrangian volume elements within the flow. That approach does not allow one to make synthetic observations of the simulated flows, whereas ours does.

3 Discussion

Our initial radio galaxy explorations with this new tool have focussed on improved understanding of the ways that complex jet flow dynamics influence the spectral properties of electrons. For this purpose we carried out 2-D axisym-
metric and fully 3-D MHD simulations of light, pressure-balanced, supersonic jets carrying weak, but “active”, magnetic fields, which are helical inside the jet and axial in the uniform ambient medium. So far we have followed the dynamics until the jets propagate \( \sim 40 \) – 50 jet radii, considering cases where the magnetic fields are strong enough to cause significant synchrotron aging and cases where it is too weak for this to matter. We have considered cases in which the relativistic electrons are injected naturally as part of diffusive acceleration physics at shocks and cases where only an electron population introduced with the jet flow is represented. For the latter cases, we assume this population comes onto the grid with a power law spectrum, \( q = 4.4 \), corresponding to a synchrotron spectral index, \( \alpha = \frac{q-3}{2} = 0.7 \). In all cases the spectra evolve appropriately within the flows in response to shock acceleration, synchrotron aging and adiabatic effects.

Fig. 1 illustrates some of the important common properties in our simulations. This case is a 3-D, Mach 8 (internal Mach number), light, MHD jet \((\rho_j/\rho_a = 10^{-2}, \beta = p_b/p_g \approx 10^2\), where \(\beta\) refers to the magnetic field on the jet axis\),
which was slowly precessed on a 5 degree cone at the origin. The center of
the jet origin is marked in the figure by the small green boxes. This numerical
experiment was carried out on a 576 × 192 × 192 grid. The inflowing jet had
a top hat velocity profile with a thin transition sheath around it. The core
radius spanned 15 zones.

This flow is not at all steady, since the jet terminus tends to “whip” around,
sometimes forming “splatter spots” (Williams & Gull 1985) and then pinch-
ing off and redirecting itself. Here we show properties at a moment when the
flow is relatively simple. The left panel reveals through volume rendering of
$\nabla \cdot \mathbf{u}$ the locations of shocks in the jet and its back-flow. The strongest shocks
appear blue, while relatively weaker shocks are red. The right panel shows
the spatial distribution of the spectral index of $\sim 10 \text{ GeV}$ electrons at the
same time. Synchrotron aging is negligible in this case, so we are seeing in
the electron spectra only effects from shock acceleration and advective mix-
ing. Shock-modified spectra flatter than the “injected spectrum” are shown
in color, with the relatively flatter (steeper) spectra being blue (red). The
injected spectral index, $q = 4.4$, is rendered in white. Given the absence of
synchrotron aging, all spectra are at least as flat as that entering at the jet or-
igin. For this simulation there were no additional electrons injected at shocks;
that is, the entire relativistic electron population entered with the jet. In this
case those electrons constitute a fraction $10^{-4}$ of the total number of electrons.
The remainder are thermal. Since the jet speed is assumed to be 0.1 c, ther-
mal electrons in the jet have energies $\sim 70 \text{ keV}$. Only flow regions filled with
plasma originating in the jet are shown in the figure. So, for example, the bow
shock preceding the jet is not visible in the left panel, since it occurs in the
ambient medium.

These images illustrate dramatically that shock structures in jet driven flows
are very complex, and also show our consequent key finding that the spectral
properties of electrons emerging into the cocoon are extremely heterogeneous.
Comparison of the images shows us why this finding makes sense. First, let
us locate the jet flow itself. Near its base the jet can be followed through
its conical internal shocks. The terminus of the jet occurs at the far upper
left in a small, strong shock. It turns out that only the central core of the
jet actually exits through that terminal shock. Much of the plasma emerging
from the jet has passed through only weak shocks before it is redirected into
the cocoon. Consequently, shocks inside and at the end of the jet have had a
relatively small influence on the spectra of electrons entering the cocoon. Note
next that most of the rather complex “shock web” near the jet head involves
cocoon flow, in fact. Remarkably, the strongest shocks are often in the cocoon,
rather than the jet. They appear to be generated by the non-axial motions of
the jet head.

The distribution of electron spectra in the adjacent image does not map in an
obvious way onto the shock distribution. Some insight into this complication comes from noting the apparent “streams” in the particle spectra, which are especially apparent near the jet terminus. The streams highlight flows downstream of localized, strong shocks. This feature emphasizes that the shocks are themselves very complex, and also that we are seeing a blend of many different flow histories. The relative importance of shocks inside the cocoon compared to the jet can be recognized by understanding the origin of a relatively flat spectral region visible in the figure roughly 2.5 cm to 4.5 cm from the end of the jet towards the origin (green box). There, \( q \approx 4.3 \), so it shows yellow in the image. Examination of flow streaklines shows that this plasma all passed through a small shock visible in the shock image (with a yellow color) about 2.5 cm from the end of the jet, but physically in the cocoon, not the jet itself. These results emphasizing the complexity of the evolution of particle spectra in jet head regions support and augment our earlier findings from 2-D axisymmetric simulations (Jones et al. 1999).

An analogous finding from the 2-D study was that magnetic field structures are highly inhomogeneous (“intermittent”), especially in the head region. Thus, synchrotron emissivity and associated aging rates are very inhomogeneous. That behavior seems even stronger in our initial examination of a 3-D run that was similar to the one shown in Fig. 1, except that the magnetic field was strong enough to produce significant aging on the time scales simulated. Observational properties of these flows are described in the companion paper by Tregillis et al. 1999.

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**Q: D. Harris** Great code, but deductions about particle vs B field distributions may be misleading, because you still have MHD, where basic fluid controls where and how much e & B occur/get carried. Is it not true that in real jets the dynamics may be controlled by the relativistic particles and B field?

**A: T. Jones** Magnetic fields are fully dynamically coupled in our simulations. In fact, although we described the magnetic fields as “weak” because the nominal ratio of gas to magnetic pressure in the jet is large, we find that there are numerous places in the cocoon where magnetic, Maxwell stresses are significant. They are properly accounted for. The relativistic particles represent a high energy tail to the bulk population, so their dynamics accurately reflects the total. We have restricted their energy content so that it does not dominate in order that the overall flows may be treated non-relativistically. The relativistic particles are handled correctly in the context of the nonrelativistic bulk flow. Eventually we will want to do simulations like these with fully relativistic MHD codes. That step is some distance off, even if we accept the good progress being made on relativistic fluid codes. Treatment of particle acceleration at relativistic shocks is much more subtle than at nonrelativistic shocks, so it is not obvious how we will make that step for complex problems. Here we have assumed that the shocks are not relativistic and not superluminal.