Numerical Models of Jet Disruption in Cluster Cooling Flows

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Chris Loken, Jack Burns, Kurt Roettiger
Dept. of Astronomy, New Mexico State University
Las Cruces, NM 88003

Mike Norman
Dept. of Astronomy and National Center for Supercomputing Applications
University of Illinois, Urbana, IL 61801

Abstract

We present a coherent picture for the formation of the observed diverse radio morphological structures in dominant cluster galaxies based on the jet Mach number. Realistic, supersonic, steady-state cooling flow atmospheres are evolved numerically and then used as the ambient medium through which jets of various properties are propagated. Low Mach number jets effectively stagnate due to the ram pressure of the cooling flow atmosphere while medium Mach number jets become unstable and disrupt in the cooling flow to form amorphous structures. High Mach number jets manage to avoid disruption and are able to propagate through the cooling flow.

Introduction

X-ray observations have been used to infer the existence of cooling flows in a significant number of observed clusters (e.g. Jones and Forman 1984, Arnaud 1988). Burns (1990) found that $\approx 70\%$ of cDs with cooling inflows are radio-loud whereas $< 25\%$ of cDs in non-cooling flow rich clusters are radio-loud. Thus, cooling flow environs appear to be intimately linked with the existence of radio emission.

Many of the radio sources associated with dominant galaxies in cooling flow clusters are observed to have amorphous radio morphologies (Burns, 1990). Theses sources (e.g. 3C 317, Burns 1990) typically exhibit steep radio spectra, high rotation measures, small (50-100 kpc) diameters and small (< 1 kpc) or nonexistent jets. However, there are also good examples of extended, well-collimated jets in cooling flows - notably Cygnus A.

Since jet stability properties depend strongly on the internal jet Mach number, we propose that high Mach number jets manage to traverse cooling flows whereas their less powerful counterparts are disrupted and decollimated. In the latter case, the amorphous radio emission may then result from diffusion of the relativistic particles into the dense ICM or via a slow bulk flow of the poorly collimated radio plasma (Zhao 1990).

Cooling Flow Model

We have utilized ZEUS-3D, a sophisticated time-dependent hydrodynamics code (Clarke 1992, Stone and Norman 1992), to "relax" towards a steady-state cooling flow. We begin with an isothermal gas in hydrostatic equilibrium with the potential of a King model cluster and turn on radiative cooling. Mass drop-out is also included in these spherically-symmetric calculations.

Our "standard" cooling flow model assumes realistic cluster parameters with the gas initially in hydrostatic equilibrium at a temperature of 10^8 K. A steady-state cooling flow is established in a time just less than the initial cooling time of the central region with a sonic point at 0.73 kpc. The Mach number at the inner boundary (located at 0.4 kpc) is M=3 at this time.

Jet Stability

The cooling flow atmosphere derived above was used to initialize our 2-D hydrodynamical jet simulations performed with ZEUS-3D. Our geometry is the spherical coordinate analogue of the usual slab jet and allows us to investigate non-axisymmetric instability modes. These modes are excited by means of a small perturbation, with frequency near the resonant frequency (e.g. Hardee and Norman 1988), applied to the θ-component of the jet velocity at the inlet.

The simulations discussed here have an inner boundary at 0.5 kpc and outer boundary at 20.5 kpc. Across this range, the density of the cooling flow atmosphere decreases monotonically by a factor of 10 while the temperature increases by a factor of 13. The Mach number of the cooling flow is M=1.8 at the inner boundary, corresponding to an inflow velocity of 280 km/s, and decreases to M=0.02 at the outer boundary. The jet radius at the inner boundary is fixed to be 0.1 kpc with an opening angle of 1°.

In order for the jets to be able to propagate any significant distance through this particular atmosphere, we find that we need a relatively heavy ($\eta = 0.3$), overpressured ($K = 2$) jet. Mach numbers of 100, 25 and 6 were used in order to investigate the effect of jet Mach number upon the resultant morphology.

We scale the physical time as $t = t' r_j / M / c_a$ where r_j is the jet radius, M is the jet Mach number and c_a is the external soundspeed. Fig. 1 displays logarithmic density contours for the $M = 100, 25$ and 6 jets at $t' = 375, 375$ and 180, respectively. At this point the $M = 100$ jet is still propagating freely, the M=25 jet has begun flapping about and is hardly advancing and the M=6 jet has essentially been stagnant for half its lifetime. These results are in rough agreement with the linear stability analysis predictions of jet disruption occurring after $\sim (5 - 7) M r_j$ (e.g. Hardee and Norman, 1988).

Conclusions

We have begun to investigate the stability properties of radio jets propagating through realistic, cooling-flow atmospheres. We have demonstrated here that varying only the jet Mach number can result in a variety of possible radio morphologies. Low Mach number jets are not able to propagate through the cooling inflow resulting in compact structures; weak compact radio sources are commonly observed in association with dominant galaxies in clusters (Ball *et al.* 1992). Intermediate Mach number jets disrupt and can give rise to amorphous radio structures (e.g. 3C 317) whereas high Mach number jets can effectively blow through the cooling flow without being disrupted (e.g. Cygnus A).

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Fig. 1. Logarithmic density contours and velocity vectors for models with M=100, 25, and 6.