Numerical Simulations of Bent, Disrupted Radio Jets

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Abstract

We present preliminary results from three-dimensional hydrodynamical simulations designed to investigate the physics of jet bending and disruption. The specific scenario considered here involves a mildly supersonic jet crossing a contact discontinuity at the interface between the interstellar medium (ISM) and the intercluster medium (ICM) and then encountering a cross-wind in the ICM. The resultant morphologies show many of the features observed in radio sources including jet flaring, bending and extended tails.

Introduction

WATs are generally the most luminous radio sources found in nearby rich clusters. Their morphological structure typically consists of two narrow, linear jets extending from the galaxy core for a distance of 10 - 50 kpc which symmetrically and suddenly transform into diffuse, edge-darkened tails up to a Mpc in length. The prototypical example is 3C 465 (e.g. Eilek *et al.* 1984) in A2634 but there is substantial variation in WAT morphologies (see e.g. O'Donoghue *et al.* 1990). Narrow-Angle Tailed (NAT) radio sources, such as 3C 83.1B in NGC 1265 (e.g. O'Dea and Owen, 1986), also exhibit bent jets. Clearly it is important to understand the processes involved in bending and disrupting jets but the inherent 3-D nature of the problem has severely limited numerical simulations until very recently.

Norman, Burns and Sulkanen (1988) carried out 2-D simulations which demonstrated that a jet could disrupt and flare upon passing through an external shock. Further 3-D investigation of this scenario was carried out by Balsara and Norman (1992) who passed a helically perturbed jet through an oblique shock in an effort to duplicate WAT behaviour. The same authors modelled the bending of narrow-angle tailed (NAT) radio sources in 3-D by propagating a jet through a cross-wind (with symmetry through the midplane of the jet enforced).

Jet Model

The atmosphere through which we propagate our jets consists of two uniform, static media separated by a contact discontinuity (a jump in density and temperature but not in pressure). A cross-wind blows parallel to the interface in the ICM (second medium). The jet travels first through the ISM and then encounters the ISM/ICM interface (oriented perpendicular to the jet axis). ZEUS-3D, a sophisticated Eulerian, finite-difference MHD code developed at NCSA was used for all our simulations (Clarke 1992, Stone and Norman 1992).

The simulation is completely characterized by 6 dimensionless numbers: the ratio of jet-to-ISM densities (η), the ratio of jet-to-ISM pressures (K), the internal Mach number of the jet ($M_j \equiv v_j/c_j$ where v_j is the jet velocity and c_j is the speed of sound in the jet), the ratio of ICM-to-ISM temperatures (ΔT), the Mach number of the wind ($M_w \equiv v_w/c_{icm}$ where v_w is the wind velocity and c_{icm} is the speed of sound in the ICM, $c_{icm} = \sqrt{\Delta T}\, c_{ism}$), and the distance from the jet origin to the ISM/ICM interface (X_{int}, in units of jet radii). We work in dimensionless units with distances given in terms of jet radii (r_j) and the ISM density and sound-speed both set to unity.

The time evolution of one of our simulations is shown with logarithmic contours and velocity vectors in a slice through the symmetry plane of the jet in Fig. 1. The region shown is $60r_j \times 50r_j$ in size, spanned by 180×101 zones, and the jet radius is resolved laterally by 6 zones. A symmetry plane is assumed to reduce CPU time. Parameters are: $\eta = 0.02$, $K = 1.5$, $M_j = 3$, $\Delta T = 10$, $M_w = 0.5$, and $X_{int} = 10r_j$.

The cross-wind blows upwards in Fig. 1 and the resultant shear distorts the jet cocoon and drags it downstream of the jet. The wind sweeps away the cocoon on the upstream side of the jet, leaving it effectively naked. The jet is strongly bent at the contact discontinuity yet the flow remains continuous. In terms of jet radii, the radius of curvature of the jet is expected to be given by the ratio of the jet and crosswind ram pressures. For our model we get the expected radius of curvature to be $KM_j{}^2/M_w{}^2 = 54$ jet radii which is in rough agreement with the results of the simulation.

Fully three-dimensional simulations (no assumed symmetry plane) with a helical perturbation applied to the jet in order to break all symmetries have also been performed and yield similar results.

Conclusions

Our 3-D simulations reproduce many of the features seen in WATs and NATs including jet bending, flaring and the extended tails. We are currently investigating the results of projecting the fully 3-D model onto the sky in order to help identify features seen in radio maps.

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Figure 1: Logarithmic density contours and velocity vectors for the 3-D simulation described in the text at scaled times t=3.5, 7.5 and 11.5. The crosswind velocity vectors are barely visible as they are so much smaller than the jet velocity.