THREE-DIMENSIONAL SIMULATIONS OF RELATIVISTIC PRECESSING JETS PROBING THE STRUCTURE OF SUPERLUMINAL SOURCES

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ABSTRACT

We present the results of a three-dimensional, relativistic, hydrodynamic simulation of a precessing jet into which a compact blob of matter is injected. A comparison of synthetic radio maps computed from the hydrodynamic model, taking into account the appropriate light-travel time delays, with those obtained from observations of actual superluminal sources shows that the variability of the jet emission is the result of a complex combination of phase motions, viewing angle selection effects, and nonlinear interactions between perturbations and the underlying jet and/or the external medium. These results question the hydrodynamic properties inferred from observed apparent motions and radio structures and reveal that shock-in-jet models may be overly simplistic.

Subject headings: galaxies: jets — hydrodynamics — radiation mechanisms: nonthermal

On-line material: color figures

1. INTRODUCTION

Numerical hydrodynamic simulations were initially used to study radio sources from their largest scales (Burns, Norman, & Clarke 1991) to the collimation and formation of their associated jets (Koide et al. 2002). Due to the relativistic nature of these sources, relativistic hydrodynamic simulations have become necessary for studying the superluminal sources present in the nuclei of active galaxies and in the microquasars of our Galaxy. Improving on previous idealized analytical calculations (Marscher & Gear 1985), these numerical methods are capable of studying the time-dependent nonlinear relativistic fluid dynamics, like for instance the formation and propagation of shocks (Martí, Müller, & Ibáñez 1994; Duncan & Hughes 1994; Koide, Nishikawa, & Mutel 1996; Falle & Komissarov 1996; Aloy et al. 1999a). The computation of the nonthermal emission from such hydrodynamic models provides the means for a direct comparison between observations and theory and is hence a significant step forward toward an understanding of the emission and structural variability of relativistic jets (Gómez et al. 1995, 1997; Komissarov & Falle 1997; Mioduszewski, Hughes, & Duncan 1997; Aloy et al. 1999b, 2000; Agudo et al. 2001).

Motivated by recent observations (e.g., Gómez et al. 2000; Tingay, Preston, & Jauncey 2001; Wehrle et al. 2001) revealing complex jet structure and dynamics suggestive of being the result of multidimensional nonlinear jet instabilities, we present a three-dimensional relativistic hydrodynamic and emission simulation of a precessing jet.

2. HYDRODYNAMIC MODEL

Our hydrodynamic code GENESIS (Aloy et al. 1999a) is based on high-resolution shock-capturing techniques that are best suited to describe ultrarelativistic flows with strong discontinuities. The code employs a method of lines to achieve third-order accuracy in both space (using a parabolic piecewise monotonic intercell reconstruction) and time (by means of a third-order total variation diminishing Runge-Kutta scheme). Guided by observational data, we simulate a jet composed of an ultrarelativistic plasma (with an adiabatic index of 4/3 and a specific energy of 50c2, c being the speed of light) in pressure equilibrium with an ambient atmosphere in which the jet propagates. The plasma is injected with a bulk Lorentz factor of 6 and is 104 times lighter than the environment. We enforce a twofold precession of the jet by imposing helical perturbations on the injection velocity with amplitudes \( \zeta_1 (\zeta_2) = 0.035 \) (0.005) and periodicities \( \tau_1 (\tau_2) = 400R/Rc (25R/Rc) \), where \( R \) is the beam radius (the definitions of \( \zeta_1, \zeta_2 \) and \( \tau_1, \tau_2 \) are the same as in Aloy et al. 1999b).

The first long-wavelength precession (\( \lambda_1 = 400R \)) causes a slight bending of the jet (within the computational domain of longitudinal size 90R), while the second precession, with a much shorter wavelength (\( \lambda_2 = 25R \)) and smaller amplitude than the first one, gives rise to a small helical modulation of the beam. Both structural characteristics are observed in many astrophysical sources (e.g., 3C 120; Gómez et al. 2000).

According to the recent observations of Marscher et al. (2002), radio components are generated by the injection into the jet of material coming from the inner accretion disk. Motivated by these observations, we perturb the jet by injecting a blob of relativistic particles through the jet inlet during 0.8R/c in the frame attached to the source (LAB-frame). The blob, initially a cylindrical region of thickness 0.8R, width 1.0R, is 4 times denser than the jet plasma but has the same velocity and internal energy per particle. As the injected perturbation travels downstream, it spreads asymmetrically along the beam and splits into two regions (Fig. 1) that have distinct observational signatures (§ 3). The fact that injected jet perturbations experience substantial evolution is general; i.e., it is not specific to the perturbation that we have chosen. Indeed, a similar hydrodynamic evolution should be expected for any perturbation that either does not match the shock jump conditions at its boundaries or propagates along a nonuniform beam. An idealized one-dimensional model of the perturbation allows us to explain the basic features of its evolution. The original state disappears after \( \approx 15R/c \) and displays a noticeable split after 30R/c and beyond in the LAB-frame (Fig. 2). In the three-dimensional simulation, the evolution of the perturbation is also affected by its interaction with the external medium and changing beam conditions down-
stream. The front region (A) of the original blob shows the largest Lorentz factor ($\geq 9$) and relatively small energy density, while the back region (B) possesses the largest energy density but the smallest Lorentz factor ($\approx 4.5$).

Initially the perturbation is ballistic as a consequence of its high relativistic density ($\approx 9.7$ times that of the external medium) and moves in a straight trajectory until it impacts on the bent walls of the beam, between times $20R_b/c$ and $40R_b/c$. This causes an increase of the internal energy density and a reduction of the Lorentz factor in the region of maximum shear (Figs. 3b and 3c). The heating is a consequence of the compression of the perturbation, which is enhanced by the presence of a standing shock in the beam (Fig. 3a). The interaction also leads to the formation of a conical-shaped bow shock that continues along...
We compute the synchrotron emission from the hydrodynamic model by assuming that the magnetic energy density is proportional to the particle energy density and that this proportionality remains constant throughout the whole computational domain (as in Gómez et al. 1995). We also assume that the magnetic field is dynamically negligible, and we account for the appropriate relativistic effects (including light-travel time delays as in Gómez et al. 1997) that are aimed to obtain synthetic radio maps (Fig. 4) that can be compared with observations of superluminal sources. In order to relate emission features in the observer’s frame (O-frame; Fig. 4) to their hydrodynamic counterparts, we provide a spacetime diagram (Fig. 5).

Figure 4 shows the appearance of a large region of increased emission, associated with the imposed perturbation, passing by several standing knots (S1, S2, and S3) that are caused by jet recollimation shocks. The large extension of this new emitting region is caused by the light-travel time delays between the front and the back of the perturbation, which stretch it by a factor of a rarefaction instead of a shock for impact angles smaller than $\sim 35^\circ$ (this is a genuine relativistic effect [Pons, Martí, & Müller 2000; Rezolla & Zanotti 2002]). After $\sim 55 R_b/c$, the perturbation is no longer ballistic and no longer covers the whole beam’s width.

3. EMISSION

with the perturbation, expanding at $\sim 0.2c$, which is seen in Figure 3a as a strong increase of the energy density emerging from the component and forming a small angle with the beam. In the bottom part of the component, the bow shock is weaker. The effect of the collision against the edge of the beam is relatively small because of the very small impact angle of $\sim 5^\circ$. A two-dimensional analytic modeling of the impact shows the generation of a rarefaction instead of a shock for impact angles smaller than $\sim 35^\circ$ (this is a genuine relativistic effect [Pons, Martí, & Müller 2000; Rezolla & Zanotti 2002]). After $\sim 55 R_b/c$, the perturbation is no longer ballistic and no longer covers the whole beam’s width.

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Go´mez, J. L., Martı´, J. M., Marscher, A. P., Iba´n˜ez, J. M., & Alberdi, A. 1997, L112 SIMULATIONS OF RELATIVISTIC PRECESSING JETS Vol. 585

radio maps, no observable knot is produced by region A because interactions between components and the external medium. Supporting the idea of a precessing jet in this source and of has been observed in the jet of 3C 120 (Go´mez et al. 2001), motions of the component’s emission peak. A similar behavior it passes through standing knots in the jet, leads to transverse interaction, together with the squeezing of the perturbation when a straight trajectory while the beam is helical. The resulting perturbation moves (during its ballistic epoch) along the maximum energy density in region B) varies with time position of the region of maximum interaction (corresponding to the shocks confining regions A and B have Lorentz factors of 7 and 4, respectively, which differ significantly from the estimated values. The proper motion of M is almost constant during the last four epochs and equals 1.7c, corresponding to a LAB-frame pattern Lorentz factor of 2.2, which is only slightly smaller than the Lorentz factor of the back shock of region B during these epochs (≈2.7; Fig. 5).

The internal brightness distribution of the superluminal component M also changes as a result of the interaction of the perturbation with the ambient medium and the jet. The azimuthal position of the region of maximum interaction (corresponding to the maximum energy density in region B) varies with time because the perturbation moves (during its ballistic epoch) along a straight trajectory while the beam is helical. The resulting interaction, together with the squeezing of the perturbation when it passes through standing knots in the jet, leads to transverse motions of the component’s emission peak. A similar behavior has been observed in the jet of 3C 120 (Gómez et al. 2001), supporting the idea of a precessing jet in this source and of interactions between components and the external medium.

While region B generates the most significant features in the radio maps, no observable knot is produced by region A because Lorentz factors are higher in this region and the radiation is thus beamed into a cone smaller than the viewing angle. A larger viewing angle would beam region A, and the resulting component would present a faster superluminal motion. Hence, the jet viewing angle may introduce a selection effect determining which parts of the perturbation appear as superluminal components (with different apparent speeds) in observed radio maps.

In contrast to M, the component H1 suddenly appears at some distance farther downstream in the jet (Fig. 4). This pop-up component (PUC) results from the nonlinear evolution of the secondary helical motion of the beam and hence does not correspond to any bulk fluid motion. Its apparent speed is 1.4c, which agrees with its LAB-frame pattern Lorentz factor of 2.0 (Fig. 5). PUCs occur when a relativistic perturbation (observable or not) causes enhanced beamed emission that suddenly becomes observable. In our model, the enhanced emission is produced by shock-heated matter at the edge of region A of the perturbation, and the beaming is produced by the relativistic flow speeds in that region. The pop-up effect arises when the emitting region moving along the helical beam turns toward the observer, and the edge of the beamed radiation suddenly crosses the line of sight. PUCs appear to have been observed in actual sources (PKS 0420–014; Zhou et al. 2000) and provide a good example of a coupling between phase (helical) and bulk (the fluid in region A) motions leading to the formation of new components.

4. CONCLUSIONS

Our simulation shows that the nonlinear hydrodynamic evolution of perturbations can determine the observed radio emission properties of superluminal sources and that the interpretation of observed radio maps is error-prone when naively associating single shocks to superluminal components. Indeed, if the radio components of actual sources are correctly represented by those studied in our model, most observable features should not be related to fluid bulk motions but instead should be related to a complex combination of bulk and phase motions, viewing angle selection effects, and nonlinear interactions between perturbations and the underlying jet and/or ambient medium. Further simulations spanning a wide range of the relevant parameters are underway.

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