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THREE-DIMENSIONAL MAGNETOHYDRODYNAMIC SIMULATIONS OF RELATIVISTIC JETS INJECTED INTO AN OBLIQUE MAGNETIC FIELD

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ABSTRACT

We discuss the structure and relativistic kinematics that develop in three spatial dimensions when a moderately hot, supersonic jet propagates into a denser background medium and encounters resistance from an oblique magnetic field. Our simulations incorporate relativistic MHD in a four-dimensional spacetime and clearly show that (1) relatively weak, oblique fields (at 1/16 of the equipartition value) have only a negligible influence on the propagating jet and they are passively pushed away by the relativistically moving head; (2) oblique fields in equipartition with the ambient plasma provide more resistance and cause bending at the jet head but the magnitude of this deflection and the associated backflow are small compared to those identified by previous studies. The new results are understood as follows: Relativistic simulations have consistently shown that these jets are effectively heavy, and so they do not suffer substantial momentum losses and are not decelerated as efficiently as their nonrelativistic counterparts. In addition, the ambient magnetic field, however strong, can be pushed aside with relative ease by the beam, provided that the degrees of freedom associated with all three spatial dimensions are followed self-consistently during the simulations. The effect is analogous to pushing Japanese "noren" or vertical venetian blinds out of the way while the slats are allowed to bend in three-dimensional space rather than as a two-dimensional slab structure. Applied to relativistic extragalactic jets from blazars, the new results are encouraging, since superluminal outflows exhibit bending near their sources and their environments are profoundly magnetized—but observations do not provide support for irregular kinematics such as large-scale vortical motions and pronounced reverse flows near the points of origin.

Subject headings: galaxies: jets — methods: numerical — MHD — relativity

1. INTRODUCTION

VLBI observations of superluminal ejections from the centers of quasars and BL Lacertae objects (e.g., Gabuzda, Wardle, & Roberts 1989; Mutel et al. 1990; Cawthorne 1991; Gabuzda et al. 1992; Fejes, Porcas, & Akujor 1992; Hummel et al. 1992a, 1992b; Ghisellini et al. 1993; Conway & Davis 1994; Biretta, Zhou, & Owen 1995; Wardle & Aaron 1996) and VLA/VLBI observations of Galactic X-ray sources (e.g., Mirabel & Rodríguez 1994; Hjellming & Rupen 1995) have established that jet outflows commonly occur with speeds near the speed of light and that the outflowing material in extragalactic sources does not slow down to nonrelativistic speeds out to kiloparsec scales. The surrounding intergalactic and interstellar media in which these jets propagate are clearly magnetized and often show, even on very large scales, a well-organized magnetic field structure. Ordered magnetic fields of several microgauss have been observed on kiloparsec scales in the centers of some clusters of galaxies such as Coma and Hydra A (Kim et al. 1990; Crusius-Watzel et al. 1990; Taylor & Perley 1993). Even stronger magnetic fields are expected on smaller scales, in the close surroundings of active galactic nuclei, because of compression and amplification of any frozen-in magnetic fields (e.g., Soker & Sarazin 1990) carried by accretion flows that are infalling toward the "central engine." Regarding the stellar case, many jets emanating from young stellar objects (YSOs) are aligned with the local interstellar magnetic field (Reipurth 1989). Nonaligned stellar jets are also observed, but they could be related to the presence of a binary star system at the central source (B. Reipurth 1997, private communication). These results suggest that the interstellar magnetic field plays, at some level, a primary role to the dynamics of YSO jets, although binarity at the source could mask the magnetic influence (e.g., by changing the angular momentum vector of the accreted matter).

In the case of extragalactic jets, there are many unresolved problems concerning curvature effects and the observed distortions. One long-standing question is the peculiar morphology of wide-angle–tail radio galaxies that does not admit any direct explanation in terms of external or ram pressures, gravitational effects, motion of the host galaxy, collisions with intergalactic clouds, or electric current-carrying jets (Eilek et al. 1984; O'Donoghue, Owen, & Eilek 1990, 1993). Another puzzling enigma is the secondary peak found at about 90° in the distribution of misalignment angles between VLBI (parsec) jets and their extensions on kiloparsec scales (Pearson & Readhead 1988; Wehrle et

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al. 1992; Conway & Murphy 1993; Xu et al. 1994; Appl, Sol, & Vicente 1996). Other specific features observed in samples of distorted radio jets—such as the sharp bends observed in the three superluminal quasars 3C 216, 3C 309.1, and 3C 345—are also difficult to model without introducing too many free parameters in the fits.

In this paper we pursue the idea that relativistic jets can be deflected by an external magnetic field. The elemental process of this bending mechanism, which is the deflection of a relativistically propagating beam by a strong magnetic field embedded in the surrounding medium, has been previously studied in three spatial dimensions in the nonrelativistic domain (Koide et al. 1996b) and in a two-dimensional slab geometry using a relativistic magnetohydrodynamics (RMHD) computer code (Koide 1997). The computer code that we are currently using is an outgrowth of this two-dimensional RMHD code, but the algorithm follows the time evolution of plasma and magnetic field in all three spatial dimensions (see Koide, Nishikawa, & Mutel 1996a for details and tests of the numerical scheme). Allowing for both three-dimensional relativistic and three-dimensional magnetic effects is also what distinguishes this code from other codes that have been used by various researchers to study relativistic jets in two dimensions with or without magnetic fields (e.g., van Putten 1993, 1996; Duncan & Hughes 1994; Martí, Müller, & Ibáñez 1994; Martí et al. 1995, 1996, 1997; Koide, et al. 1996a; Komissarov & Falle 1996, 1997; Koide 1997).

Our simulations indicate that the results obtained previously for this problem do not carry over when the fully three-dimensional RMHD code is utilized to follow the interaction between a relativistic plasma beam and a strong, oblique, ambient magnetic field. We describe these new simulations below. In § 2 we discuss the influence of both three-dimensional and relativistic effects through comparisons to the corresponding three-dimensional nonrelativistic (Koide et al. 1996b, hereafter KSNM) and two-dimensional RMHD (Koide 1997) results. A summary of our conclusions is presented in § 3.

2. INITIAL CONDITIONS AND NUMERICAL RESULTS

The relevant initial conditions have also been described by Nishikawa et al. (1997), who studied relativistic jets injected along magnetic field lines (“parallel-injection” case). For the present “oblique-injection” simulations, we employ a Cartesian XYZ grid with 101 equally spaced zones in each direction. The computational box is a cube that occupies the region $0 \le X \le 20$, $-10 \le Y$, $Z \le 10$. This box is filled uniformly with fluid of rest mass density $\rho_a = 1$, pressure $P_a = 0.6$, and specific energy $\epsilon_a = 0.9$; a uniform magnetic field B is also embedded at an initial angle of 45° to the XY-plane. At times $t \ge 0$, jet material of rest mass density $\rho_j = 0.3$ ($\eta \equiv \rho_j/\rho_a = 0.3$) and specific energy $\epsilon_j = 3$ is injected in the X direction from an orifice at $X = 0$, $Y^2 + Z^2 \le 1$. The jet's proper pressure is initially equal to the thermal pressure of the ambient medium. No symmetry is assumed across any of the boundaries during evolution. In addition, fixed-inflow and radiative boundary conditions are implemented at the $X = 0$ surface and at all the other surfaces, respectively. Thus, the propagation of the jet can be followed only for a relatively brief period of time spanning ≤ 20 initial jet radii.

We express velocities in units of the sound speed v_s in the ambient medium [where $v_s = (\gamma P_a/\rho_a)^{1/2} \equiv 1$] and we measure time in units of τ_s, the transit time of a sound wave over unit distance. In addition, we choose an adiabatic index of $\gamma = 5/3$ for the fluid and an injection speed v_j that leads to a proper Mach number of $M_j \equiv v_j/v_s = 4$ and a Lorentz factor of $W_j = (1 - v_j^2/c^2)^{-1/2} = 4.56$ ($v_j/c = 0.9756$ for $c = 4.1v_s$).

Each simulation requires more than 1 Gbyte of dynamic memory and takes about 35 CPU hours on the power challenge of the National Center for Supercomputing Applications. We have so far carried out two comparative runs characterized by different strengths of the initial oblique magnetic field ($B_{X0} = B_0 \cos\theta$ and $B_{Z0} = B_0 \sin\theta$, with $\theta = 45°$): in run A, the energy density of the field, $B_0^2/2$, was equal to $\frac{5}{9}$ of the internal energy density, $\rho_a \epsilon_a$, of the ambient plasma (i.e., $B_0 = 1$ and Alfvén speed $v_A \equiv B_0 \rho_a^{-1/2} = v_s$); in run B, the energy density of the field was reduced by a factor of 16 (i.e., $B_0 = 0.25$ and $v_A = 0.25v_s$). In addition, the condition $B_{Z0} = 0$ was implemented at $X = 0$ to avoid numerical problems at the orifice.

Figures 1*a*, 1*b*, 1*c*, and 1*d* (Plate 1) show various MHD variables on the XZ-plane at $t = 8.0\tau_s$ for runs A and B, respectively. Panels (*a*) and (*c*) depict the rest mass density and the velocity, while (*b*) and (*d*) depict the thermal pressure and the magnetic field. The Mach disks are located at $X \approx 14.5$ (run A) and $X \approx 16.0$ (run B) because the average propagation speed of the head in run A ($v_h = 1.81v_s$) is reduced by the resisting magnetic field. The corresponding value in run B, $v_h = 2.00v_s$, is effectively the same as that obtained by Nishikawa et al. (1997) in the parallel-injection runs. This indicates that the weak oblique field in run B has a negligible influence on the kinematics of the jet. In run A, we have also measured the average head speed at $t = 7.0\tau_s$ for comparison to the corresponding two-dimensional run of Koide (1997). We have found that $v_h = 1.85v_s$, a value considerably larger than $v_h = 1.57v_s$ obtained in two dimensions. This comparison implies that the jet can propagate faster and easier in three dimensions by pushing the field lines out of the way and by slipping through the opening just as people do when they get through a Japanese “noren” or push vertical venetian blinds to the side.

In the strongly magnetized run A, the jet is deflected above the $Z = 0$ plane, but the bending is not as strong as in the corresponding two-dimensional RMHD run. As a result of bending and compression at the head, the high-pressure region is offset from the high-density region (Figs. 1*a* and 1*b*). This feature is not seen in the weakly magnetized run B (Figs. 1*c* and 1*d*), which proceeds just as the corresponding parallel-injection run (run B in Nishikawa et al. 1997). Furthermore, because the jet slips through the magnetic field, strong backflow and large-scale vortical motions do not develop in these runs. The shock “wings” seen in run B are consistent with those seen in the parallel-injection case. In run A, the limited flow away from the surface of the beam is asymmetric. A weak reverse flow develops on the lower section of the beam (Fig. 1*a*), where the field has been pushed down by the jet and the field lines are now parallel to the direction of propagation (Fig. 1*b*). The plasma is forced to follow field lines. Above the jet, the outflow is more substantial and more extended, which is illustrated as a bending process by Soker (1997). This material then develops a “forward” flow (at about 30°–45° to the XY-plane) and inflates the asymmetric cocoon seen in Figure 1*a* between the upper surface of the beam and the strongly distorted part of the bow shock. Finally, comparing run A to run B, we see that the transverse propagation of the bow shock is faster in run A, owing to the increased fast magnetosonic speed in the strongly magnetized ambient medium; and the width of the bow shock in run A is much larger because the stronger field resists more and creates a larger pileup of field lines.

For comparison to the corresponding three-dimensional nonrelativistic case with $\theta = 45°$, we refer to the results from cases D ($M_j = 4$) and E ($M_j = 7$) of KSNM. The most striking features of those runs were strong reversals of the field lines above the deflected jet and field cancellation on the surface of the beam by the generated current. Figure 1 shows that, although bent, the magnetic field in the RMHD runs does not at all suffer large-scale reversals above the jet. On the other hand, the field is canceled near the surface of the relativistic beam where localized reversals do occur on the interface between the jet plasma and the ambient medium, but this effect was also observed in the parallel-injection case; thus, localized field reversals cannot be used to characterize jets produced by oblique injection. Instead, special attention should be given to the electric currents that develop on the surfaces of the beams because their characteristics do change in the oblique-injection case, as will be discussed later.

One of the best ways to illustrate the interaction between the jet and the oblique magnetic field is to trace the magnetic field lines in three-dimensional space. This is shown in Figure 2 (Plate 1) for runs A (Fig. 2*a*) and B (Fig. 2*b*) at $t = 8.0\tau_s$. The observer is located in front and to the side of the approaching beam. The unperturbed magnetic field lines lie approximately on concentric elliptical cylinders with the innermost (eight) lines in green, the outermost (eight) lines in red, and the (eight) blue lines in between. The green lines are such that they threaded through the jet head near its head.

As shown in Figures 2*a* and 2*b*, in the plane at the center of the jet ($Y = 0$) the three most bent field lines that start from $(X, Z) = (14.0, 8.0)$ (red), (15.9, 7.0) (blue), (17.9, 6.0) (green) are strongly disturbed by the jet. These magnetic field lines are bent in a similar way as shown in Figure 2 by Soker (1997) (see also the arrows in Soker's Figs. 1*b* and 1*d*). These three field lines are piled up near the jet head where the magnetic field is intensified. The red and blue field lines are connected with the magnetic field in the jet. On the other hand, the green magnetic field lines are just bent without being connected with the jet.

It should be noted that shapes of these three field lines are different due to the different strength of the ambient magnetic field. For example, the red field line shown in Figure 2*a* is bent far from the jet due to the stronger piled-up magnetic field than in Figure 2*b*. In weak-field case (Fig. 2*b*), the red and blue lines are not only dragged along by the jet, but also bent back near the jet head in a kind of "hook." The field reversals are clearly recognized with these dragged field lines. Faraday rotation measurement can be attributed to the interaction of the jet with the oblique magnetic fields as suggested by Soker (1997).

As a summary, the following features are readily apparent.

1. Bending of the field lines due to the pressure at the location of the jet head.
2. The field lines that are dragged in both cases connect to the magnetic field lines near the center of the jets.
3. Field lines (green) near the jet are bent aside in both sides (Y direction) of the jet.

The distribution of electric current density $\boldsymbol{J} \equiv \nabla \times \boldsymbol{B}$ on the XZ (vertical) and XY (horizontal) planes is illustrated in Figure 3 (Plate 2). This complex distribution is generated from the interaction of the jet with the oblique magnetic field. As in the parallel-injection runs, currents generally flow on the bow shock and on the surface of the beam. The present runs reveal, however, several important differences that can be used to identify and recognize jet propagation into an oblique magnetic field.

1. The current on the bow shock is weak, not very extended spatially, and strongly asymmetric. This is because the field is mostly bent above and near the head of the jet.
2. As shown in Figures 3*a* and 3*b*, the strong currents behind the bow shock at $X \approx 15$ (dark blue) correspond to field lines that have been piled up and carried by the central regions of the jets. The enhanced magnetic field is recognized in the Mach disk as shown in Figures 1*b* and 1*d*. These currents are localized at $Y = 0$ and their distances from the weak currents on the front sides of the bow shocks (orange) are consistent with the thicknesses of the bow shocks seen in Figure 1.
3. In the upper section of the beam on the XZ-plane, field lines have been reversed and canceled as shown in Figures 1*b* and 1*d*. The resulting current loops are no longer circular and situated on YZ-planes. In order to show the noncircular current around the jet, Figure 4 (Plate 2) shows the flow lines of electric currents for run A in three-dimensional simulation space. In order to show the three-dimensional structure effectively, two view angles are chosen (*a*) from the front and side of the jet and (*b*) from straight ahead of the jet. The flow lines are traced from the three different jet locations ($X = 14$ [red], 12 [blue], 10 [green]) at the edge of the jet. For example, red flow lines start at equally spaced eight points at $X = 14$, and $Y^2 + Z^2 = 1$ near the jet head ($X = 15$). As shown in Figure 4, the current flow lines are tilted backward and are elongated in the $+Z$ direction. In addition, the loops are not round on the lower side of the jet, and the currents form a configuration that looks like a half-saddle (in particular with blue curves above the jet) rather than a collection of parallel circular loops.
4. In the lower section of the beam on the XZ-plane, field lines have also been dragged by the jet in a way that produces a second component of electric current that flows roughly on the surface of the beam (red and blue lines on the lower parts of Fig. 4). Consequently, all these asymmetries imposed on the magnetic field prevent the formation of well-organized, concentric, cylindrical currents such as those found in the parallel-injection case.

Comparing the currents in runs A and B (i.e., Figs. 3*a* and 3*c* to Figs. 3*b* and 3*d*), we see that their distributions are qualitatively similar. As expected, the currents in run B are weaker by factors of 2–3, owing to the lower strength of the magnetic field. In addition, the XY and XZ cross-sectional areas of each beam are obviously unequal, indicating that the jet is no longer circular. In particular for run A, the beams are wider on the XY-plane where they have to actively push the field lines to the side. On the XZ-plane, where the field provides bending, the lower part of the surface layers of the beam are pushed upward and the jet remains slender.

3. CONCLUSIONS

We have performed three-dimensional RMHD jet simulations in which the relativistic beam encounters an oblique ambient magnetic field. As in the parallel-injection case (Nishikawa et al. 1997), the present simulations show how important the inclusion of three-dimensional effects is to the resulting morphology and propagation characteristics. As was expected from previous nonrelativistic three-dimensional simulations (KSNM), the resisting field lines are deflected away by the head of the jet instead of being dragged downstream; the ambient medium and its magnetic field, which are compressed at the tip of the head, have only a small influence on the propagation of the jet. As a result, the beam can easily slip through the magnetic field (unlike in the two-dimensional slab case). Furthermore, because the jet is relativistic, the plasma does not suffer substantial momentum losses as observed in the three-dimensional nonrelativistic computations. Neither the three-dimensional relativistic effects nor the three-dimensional magnetic effects favor the development of irregular large-scale kinematics. Thus, if the ambient medium is weakly magnetized the jet propagates just as in the parallel-injection case. If the embedded field is in equipartition with the ambient plasma, then

1. The beam suffers a deflection, but the bending is not as strong as in the previously studied cases and the jet slows down very little—note, however, that bending may increase over longer timescales;
2. Flow away from the beam occurs mostly in the upper section, where the plasma follows the oblique field lines and moves forward (i.e., in the direction of deflection) without generating reverse vortices or backflowing wings on large scales;
3. The head speed is significantly larger than that in the two-dimensional slab case although its value is $\sim 10\%$ lower than that obtained in the parallel-injection case;
4. Electric currents flow predominantly on the surface of the beam, where they create complicated asymmetric patterns that include both partial circulation around the beam and partial flow along the direction of propagation of the jet.

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