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Stability of Magnetized Spine-Sheath Relativistic Jets

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A new general relativistic magnetohydrodynamics (GRMHD) code “RAISHIN” used to simulate jet generation by non-rotating and rotating black holes with a geometrically thin Keplerian disk finds that the jet forms a spine-sheath (two-component) structure in the rotating black hole case. Spine-Sheath structure and strong magnetic fields significantly modify the Kelvin-Helmholtz (**KH**) velocity shear driven instability. The RAISHN code has been used to study the effects of strong magnetic fields and weakly relativistic shear motion, $c/2$, on the KH instability associated with a relativistic jet ($\gamma = 2.5$) spine-sheath interaction. In the simulations sound speeds up to $\sim c/\sqrt{3}$ and Alfvén wave speeds up to $\sim 0.56c$ are considered. Numerical simulation results are compared to theoretical predictions from a new normal mode analysis of the linearized RMHD equations. Increased stability of a weakly magnetized system resulting from $c/2$ sheath speeds and stabilization of a strongly magnetized system resulting from $c/2$ sheath speeds is found.

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1. Introduction

Relativistic jets have been observed in galaxies and quasars (AGNs)[20, 1], in black hole binary star systems (microquasars)[14], and are thought responsible for the gamma-ray bursts (GRBs)[13]. Proper motions observed in microquasar and AGN jets imply jet speeds from $\sim 0.9c$ up to $\sim 0.999c$.

Jets at the larger scales may be kinetically dominated and contain relatively weak magnetic fields, the possibility of much stronger magnetic fields certainly exists closer to the acceleration and collimation region. Recent GRMHD simulations of jet formation [12, 4, 7] indicate that highly collimated high speed jets driven by the magnetic fields threading the ergosphere may themselves reside with a broader wind or sheath outflow driven by the magnetic fields anchored in the accretion disk. This configuration might additionally be surrounded by a less collimated accretion disk wind from the hot corona [16].

Recent observations of QSO winds with speeds, $\sim 0.1-0.4c$, also indicate that a jet could reside in a high speed sheath [18]. Circumstantial evidence such as the requirement for large Lorentz factors suggested by the TeV BL Lacs when contrasted with much slower observed motions has been used to suggest the presence of a spine-sheath morphology [2]. A spine-sheath jet structure has also been proposed based on theoretical arguments [19, 8].

Previous relativistic hydrodynamic (RHD) simulation and theoretical work has shown the importance of spine-sheath structure to KH instability [5]. In this paper we investigate the stability properties of highly relativistic jet flows allowing for the effects of strong magnetic fields and relativistic flow in a sheath around the highly relativistic jet by 3D RMHD numerical simulations.

2. RMHD Spine-Sheath Simulations

In order to study the long-term stability of magnetized spine-sheath relativistic jets, we use the 3-dimensional GRMHD code "RAISHIN" with Cartesian coordinates in special relativity [15].

We consider the following initial conditions for the simulations: a "preexisting" jet is established across the computational domain of $6R_j \times 6R_j \times 60R_j$ with $60 \times 60 \times 600$ computational zones. The jet is in total pressure balance with a low-density magnetized sheath with $\rho_j/\rho_e = 2.0$, where ρ is the mass density in the proper frame. The jet speed is $v_j = 0.9165c$ and $\gamma \equiv (1-v^2)^{-1/2} = 2.5$. The initial magnetic field is assumed to be uniform and parallel to the jet flow. A precessional perturbation is applied at the inflow by imposing a transverse velocity with $v_\perp = 0.01v_j$. Here we show simulations with a precessional perturbation of angular frequency $\omega R_j/v_j = 0.93$. In order to investigate the effect of an external wind, we have performed simulations with no external wind ($v_e = 0.0c$) and a mildly relativistic external wind ($v_e = 0.5c$).

We have performed two sets of simulations. In the weakly magnetized (RHD) simulations, the Alfvén speed is much smaller than sound speed. In the strongly magnetized (RMHD) simulations, the Alfvén speed is about twice the sound speed.

Figure 1 shows the structure of a weakly and strongly magnetized jet (3D isovolume density image and transverse cut) without an external wind at $t = 60$. The precession at the jet inflow plane excites the Kelvin-Helmholtz (**KH**) instability. The initial perturbation propagates down the jet and grows as a helical structure.

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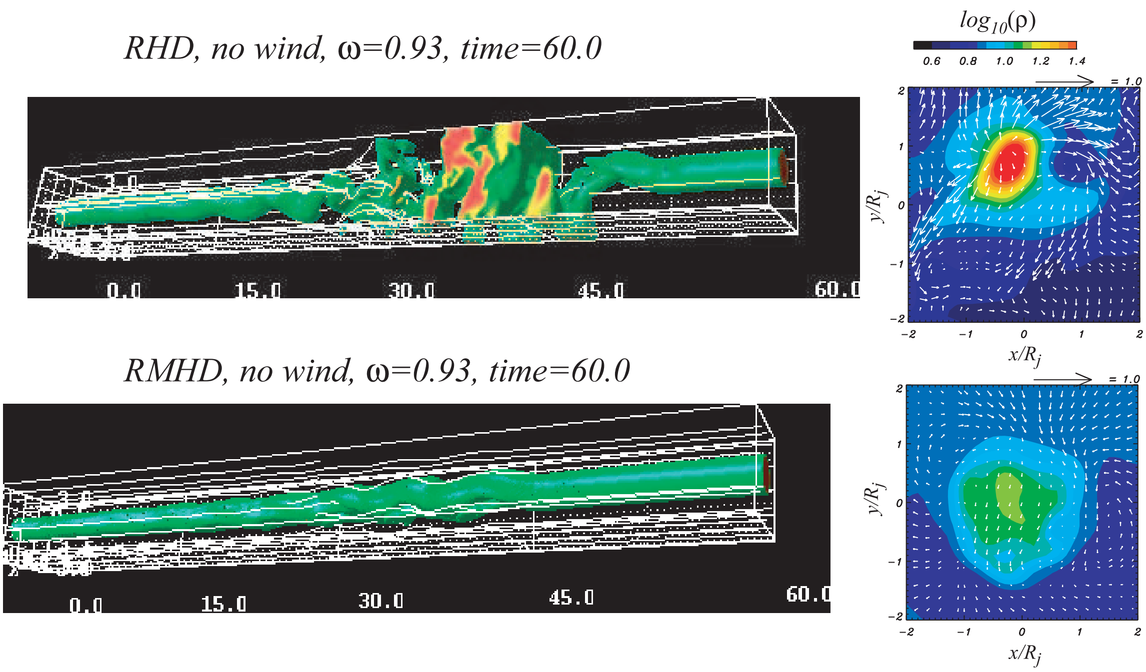

Figure 1: 3D isovolume density image (*left*) and transverse (*right*) cut ($z = 30R_j$) of the weakly magnetized (*upper*) and the strongly magnetized (*lower*) case without an external wind. The color scales show the logarithm of density. The white lines indicate magnetic field lines. The arrows depict transverse velocities.

In the weakly magnetized jet case, beyond $z = 40R_j$ the KH instability disrupts the jet structure strongly. The magnetic field is strongly distorted and becomes complicated. The transverse cut of the weakly magnetized jet case at $z = 30R_j$ shown in Figure 1, indicates strong interaction with the external medium at this distance. Transverse velocities show circular motions near the jet surface caused by the helically twisted jet.

In the strongly magnetized jet case, the helical KH mode grows but more slowly than in the weakly magnetized jet case and does not disrupt the jet inside $z \sim 40R_j$. A weakly twisted helical flow and magnetic field structure develops. The transverse slice at $z = 30R_j$ indicates weak interaction between the jet and the external medium at this distance.

To investigate simulation results more quantitatively, we take 1D cuts in the radial velocity through the computational box parallel to the z-axis at different radial distances along the transverse x-axis at $x/R_j = 0.2$, 0.5, and 0.8, as shown in Figure 2.

The weakly magnetized simulation results show velocity oscillation from the growing helical KH instability. The simulations are fully evolved to a non-linear phase. The external wind has reduced the growth of KH instability and has delayed the onset of the non-linear phase. The strongly magnetized simulation results without an external wind also show growing velocity oscillation (Figure 2c), albeit more slowly. The simulation is still evolving linearly and has not reached the non-linear phase. From the comparison with the weakly-magnetized cases, the stronger magnetic field reduces the growth rate of the helical KH instability. The strongly magnetized simulation result with an external wind reveals a damped oscillation. Therefore the external wind in the strongly magnetized case leads to damping of KH instability and stabilizes the jet.

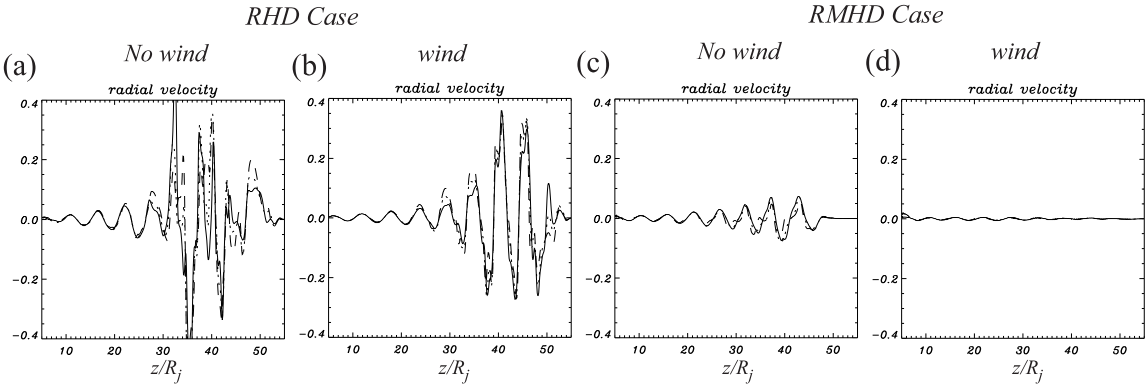

Figure 2: Radial velocity (v_x) along the one-dimensional cuts parallel to the jet axis located at $x/R_j = 0.2$ (solid line), 0.5 (dotted line) and 0.8 (dashed line) for the weakly (*a*, *b*) and strongly (*c*, *d*) magnetized cases without an external wind (*a*, *c*) and with an external wind (*b*, *d*).

3. Conclusion

Increased stability of the weakly-magnetized system with mildly relativistic sheath flow and stabilization of the strongly-magnetized system with mildly relativistic sheath flow is in agreement with theoretical results [6]. In the fluid limit the present results confirm earlier results obtained by Hardee & Hughes (2003) [5] who found that the development of sheath flow around a relativistic jet in their numerical simulations slowed the growth of KH instability.

The simulation results agree with theoretically predicted wavelengths and wave speeds, On the other hand, growth rates and spatial growth lengths obtained from the linearized equations or from the present relatively low resolution simulations only provide guidelines to the rate at which perturbations grow or damp.

Where flow and magnetic fields are parallel, current driven (**CD**) modes are stable [9, 10]. However, we expect magnetic fields to have a significant toroidal component. Provided radial gradients are not too large we expect the present results to remain approximately valid where $v_{j,e}$ and $B_{j,e}$ refer to poloidal velocity and magnetic field components.

In the helically twisted magnetic and flow field regime likely to be relevant to many astrophysical jets CD modes [11] and/or KH modes could be unstable. While both CD and KH instability produce helically twisted structure, the conditions for instability, the radial structure, the growth rate and the pattern motions are different. These differences may serve to identify the source of helical structure on relativistic jet flows and allow determination of jet properties near to the central engine.

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References

[1] A. Ferrari, *Modeling Extragalactic Jets*, *ARAA* **36** (539) 1998.

[2] G. Ghisellini, F. Tavecchio, & M. Chiaberge, *Structured jets in TeV BL Lac objects and radiogalaxies. Implications for the observed properties*, *A&A* **432** (401) 2005.

[3] G. Giovannini, *Observational Properties of Jets in Active Galactic Nuclei*, *Ap&SS* **293** (1) 2004.

[4] J.F. Hawley, & J.H. Krolik, *Magnetically Driven Jets in the Kerr Metric*, *ApJ* **641** (103) 2006.

[5] P.E. Hardee, & P.A. Hughes, *The Effect of External Winds on Relativistic Jets*, *ApJ* **583** (116) 2003.

[6] P.E. Hardee, *Stability Properties of Strongly Magnetized Spine-Sheath Relativistic Jets*, *ApJ* **664** (26) 2007.

[7] P. Hardee, Y. Mizuno, & K.-I. Nishikawa, *GRMHD/RMHD simulations & stability of magnetized spine-sheath relativistic jets*, *Ap & SS* **311** (281) 2007.

[8] G. Henri, & G. Pelletier, *Relativistic electron-positron beam formation in the framework of the two-flow model for active galactic nuclei*, *ApJL* **383** (L7) 1991.

[9] Y. N. Istomin, &V. I. Pariev, *Stability of a Relativistic Rotating Electron / Positron Jet*, *MNRAS* **267** (629) 1994.

[10] Y. N. Istomin, & V. I. Pariev, *Stability of a relativistic rotating electron-positron jet: non-axisymmetric perturbations*, *MNRAS* **281** (1) 1996.

[11] Y. E. Lyubarskii, *Kink instability of relativistic force-free jets*, *MNRAS* **308** (1006) 1999.

[12] J.C. McKinney, *General relativistic magnetohydrodynamic simulations of the jet formation and large-scale propagation from black hole accretion systems*, *MNRAS* **368** (1561) 2006.

[13] P. Mészáros, *Gamma-ray bursts*, *Rep. Prog. Phys.* **69** (2259) 2006.

[14] I.F. Mirabel, & L.F. Rodríguez, *Sources of Relativistic Jets in the Galaxy*, *ARAA* **37** (409) 1999.

[15] Y. Mizuno, P. Hardee, & K.-I. Nishikawa, *Three-dimensional Relativistic Magnetohydrodynamic Simulations of Magnetized Spine-Sheath Relativistic Jets*, *ApJ* **662** (835) 2007.

[16] K.-I. Nishikawa, G. Richardson, S. Koide, K. Shibata, T. Kudoh, P. Hardee, & G.J. Fishman, *A General Relativistic Magnetohydrodynamic Simulation of Jet Formation*, *ApJ* **625** (60) 2005.

[17] T. Piran, *The physics of gamma-ray bursts*, *Reviews of Modern Physics*, **76** (1143) 2005.

[18] K. Pounds, & K. Page, *Evidence for massive ionised outflows in (super-Eddington?) AGN*, *Nuc. Phys. B Proc. Sup.* **132** (107) 2004.

[19] H. Sol, G. Pelletier, & E. Assero, *Two-flow model for extragalactic radio jets*, *MNRAS* **237** (411) 1989.

[20] C.M. Urry, & P. Padovani, *Unified Schemes for Radio-Loud Active Galactic Nuclei*, *PASP* **107** (803) 1995.