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Magnetohydrodynamic Production Of Highly Relativistic Jets

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Abstract

Recently, several groups around the world have begun to test theories of jet formation using magnetohydrodynamic (MHD) simulations (computer simulations of magnetized gas flow around black holes). While it is now generally accepted that jets, including relativistic ones, are accelerated and collimated by magnetized accretion disks, the Lorentz factors that have been achieved in these simulations still do not approach those suggested by Space VLBI observations. In this paper we discuss some of our recent simulations of MHD jet formation that indicate how highly relativistic outflows might be produced.

1 Introduction

Space VLBI studies of individual compact extragalactic radio sources indicate co-moving brightness temperatures of $3 - 5 \times 10^{12} K$ (Shen et al. 2000; Preston et al. 2000) and lower limits on some sources in the VSOP survey up to $10^{13} K$ or higher (Lovell et al. 2000). Assuming $\sim 10^{11} K$ for an intrinsic synchrotron source at rest, these results imply lower limits on the jet Lorentz factor of $8-12$ and 50, respectively, where $\Gamma_{min} \equiv (1 - V_{min}^2/c^2)^{-1/2} = 0.5\, T_{B,co-moving}/T_{B,intrinsic}$.

The leading model for producing and collimating relativistic jets is the magnetohydrodynamic (MHD) acceleration model, (e.g., Shibata 2000). While able to account for jet collimation, relativistic velocity, and magnetic fields, as well as fit in well with the black hole accretion model for active galactic nuclei (AGN), the MHD model has one potential problem. The terminal jet speeds obtained in numerical simulations are only of order the escape velocity at the foot point of the jet. This means that, even when the black hole is spinning rapidly, and the accretion disk inner edge reaches almost to the horizon, it is still very difficult to achieve jet Lorentz factors much above 3 — considerably slower than the speeds indicated by the observations.

In this paper we review some of the relevant properties of numerical simulations of MHD jet acceleration and discuss a physical process called the *magnetic switch* (Meier et al. 1997) which may aid in producing high Lorentz factor flow. That is, if the magnetic field anchored in a rotating Keplerian accretion disk threads a tenuous corona above the disk, then magnetic forces in that corona can significantly exceed gravitational forces, leading to very rapid acceleration and terminal jet speeds that depend on the properties of the rotating field and accelerated plasma, rather than the properties of the gravitational field. High Lorentz factors are potentially achievable in this case.

2 Review of Numerical Simulations of Jet Production by Magnetized Accretion Disks

Simulations of jet production by magnetized accretion disks falls into two general categories: a) steady-state and b) time-dependent. While the goal of all MHD acceleration studies is to understand the origin of jets, the immediate purpose of the steady-state simulations is to reproduce the results of the analytic and semi-analytic work — particularly those of Blandford & Payne (1982) — but without the restrictive assumption of self-similarity. The purpose of time-dependent simulations, on the other hand, is to study the initial transient effects associated with jet acceleration. As accretion and jet production are expected to be rather unsteady processes, such simulations provide some additional realism over the steady-state models.

2.1 Steady-State Simulations

We will use the results of Krasnopolsky et al. (1999) as an example, but there have been many other papers on the subject recently (e.g., Ustyugova et al. 1995; Ouyed et al. 1997). The cylindrically-symmetric computational region is a rectangular area, bounded on the left by the rotation axis, at the bottom by an accretion disk boundary condition, and at the top and right by "outflow" boundaries (see Figure 1). A poloidal (R, Z) magnetic field is anchored in the differentially-rotating disk and matter is injected from the lower boundary along the field lines at a speed slower than the escape speed. It is important to note that, while the axial field and velocity (B_Z and V_Z) and azimuthal velocity (V_ϕ) are fixed on the lower boundary, the radial components (B_R and V_R) and azimuthal field (B_ϕ) are allowed to change as the solution is

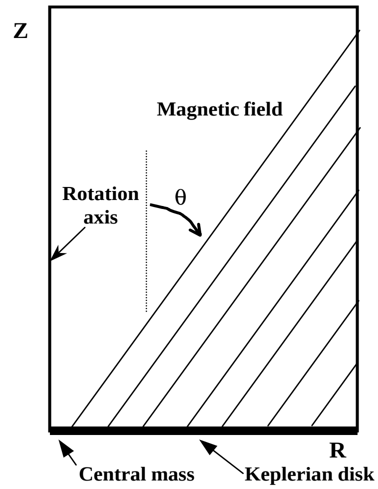

Figure 1: Initial conditions for steady-state simulations. Pseudo-relativistic simulations are similar, but have a hole in the disk center at $R = 6GM/c^2$.

obtained. The curvature and twist of the field lines is determined by the solution, and their slope and azimuthal pitch at the lower disk boundary are adjusted to be consistent with that solution. Note that the disk extends inward *all the way to the rotation axis*, requiring the gravitational potential of the central object to be smoothed at small radii to avoid a singularity. Typical results are shown in Figure 1 of Krasnopolsky et al. (1999), and they are indeed very similar to Blandford & Payne's (1982) semi-analytic results. The field lines must have a polar angle of $\theta > 30^\circ$ in order for magnetically-driven outflow to commence. However, well above the disk the field lines bend toward the axis, resulting in a magnetically-collimated wind or jet. The accelerating flow passes through a series of critical points, eventually reaching a terminal velocity of order the escape speed at the foot of the jet.

2.2 Time-Dependent Simulations

2.2.1 Fully General Relativistic Jet Production Near Rotating Black Holes

As the central engine is believed to be a rotating black hole, the full jet acceleration problem will involve MHD processes in curved spacetime near the horizon. Koide et al. (1999) have shown that, once a special relativistic MHD code has been developed, it is fairly straightforward to add the stationary Kerr geometry, allowing such processes to be studied.

Our fully relativistic simulations begin with a rather thick accretion disk, with inner edge at $R = 6\,GM/c^2 \equiv 6\,r_g$, threaded by a weak axial magnetic field (internal Alfven velocity of $V_A = 0.01c$). In addition to the disk, a freely-falling halo fills the remainder of the computational grid, which extends from $2.2\,r_g$ to $40\,r_g$ in spherical radius and from 0 to $\pi/2$ in polar angle. Five different scenarios were simulated in a series of papers: 1) non-rotating Schwarzschild black hole with a non-rotating (ADAF-like) disk; 2) non-rotating black hole with a rotating Keplerian disk; 3) rotating Kerr black hole with angular momentum parameter $j \equiv J/(GM^2/c) = 0.95$ and non-rotating disk; 4) rotating black hole with two kinds of Keplerian disk: co-rotating with the black hole and counter-rotating against the black hole's rotation. The simulations are followed for a fairly short period of time — on the order of $\sim 100\tau_g \equiv 100\,GM/c^3$.

In all cases except the co-rotating, Keplerian/Kerr case, the simulation reached the point when a significant portion of the disk had accreted into the hole, allowing the rotation of the disk or geometry and MHD processes to run their course. In the latter case, because co-rotating orbits at $6r_g$ are stable, and the field weak, the simulation evolved on a secular time scale and could not be run to completion because of cost and numerical problems. Work on this case is continuing.

As expected, in the Schwarzschild cases no significant MHD-driven outflow develops unless the disk is rotating; and the outflow velocity is of order the escape velocity from the last stable orbit of $6r_g$ $(0.4c)$.

In the Kerr cases, however, a powerful jet results *even when the disk is not rotating.* The main driver is the rotating geometry itself, rather than the rotation of the accretion disk. The disk falls rapidly into the ergospheric region ($R < 2r_g$), where the accreting matter must rotate with the black hole geometry. This rotation drives an MHD jet in a manner similar to the non-relativistic rotating disk simulations (see Shibata 2000). This process is closely-related to those discussed by Blandford & Znajek (1977), Punsly & Coroniti (1990), and Meier (1999). Our analysis shows that angular momentum, but not energy, is extracted from the hole. That is, while jet acceleration spins down the hole, more mass is gained by accretion itself than is expelled in jet energy. The highest jet speeds achieved so far in these simulations are of order the escape velocity from deep within the ergosphere ($\Gamma < 3$).

The counter-rotating disk case (Koide et al. 2000) behaves in a similar manner, since retrograde orbits are *unstable* at $R = 6r_g$. As the disk plunges rapidly into the ergosphere, the frame dragging actually reverses its spin, and a black-hole-rotation-driven MHD jet again ensues.

2.2.2 Pseudo-Relativistic Simulations of Black Hole Accretion Systems

While understanding the fully relativistic problem is the goal, the simulations described in the previous subsection have a few numerical drawbacks. Because the disk has a finite thickness, and because the simulations can handle only a modest density contrast across the grid, it is not possible to study the behavior of very tenuous coronae. Furthermore, because fully relativistic simulations must solve a nonlinear algebraic equation for the Lorentz factor in each cell at each time step, there is a possibility that one of these millions of solutions will diverge, bringing the entire simulation to a halt. This is a significant problem as the magnetic field becomes more dominant and the Lorentz factor higher.

To study the strong field situation in very tenuous coronae, and to follow the evolution to many thousands of τ_g, we have employed the simpler non-relativistic simulations — with an infinitely thin disk boundary condition — and interpreted them in a relativistic manner (Lind et al. 1994; Meier et al. 1997; Meier et al. 2000). That is, as long as the inertia of the magnetic field and internal energy are small ($c_{sound} < c$; $V_A < c$), the non-relativistic MHD equations have the same form as the relativistic ones if the velocity V is replaced with the proper velocity $U \equiv \Gamma V$. When U exceeds c (unity here), it can be identified with the Lorentz factor Γ. Thus, these pseudo-relativistic simulations account for the inertia of the kinetic energy, which will be important even for a cold gas.

The initial conditions for these simulations are very similar to those of the steady state ones in Figure 1, except that the disk is truncated interior to the last stable orbit, and B_R, V_R, and B_ϕ are all *fixed* on the lower boundary, as would be the case in an actual accretion disk. These conditions result in a new magnetic field structure during the simulation (Figure 2). The anchored field lines at the inner edge of the disk are bent inward, creating a substantial B_R in the corona, which is then wound up by the differential rotation into B_ϕ, expelling plasma upward and pinching it into a collimated jet. One such simulation is shown at late times (a time in gravitational units, $\tau_g = GM/c^3$, of 700)

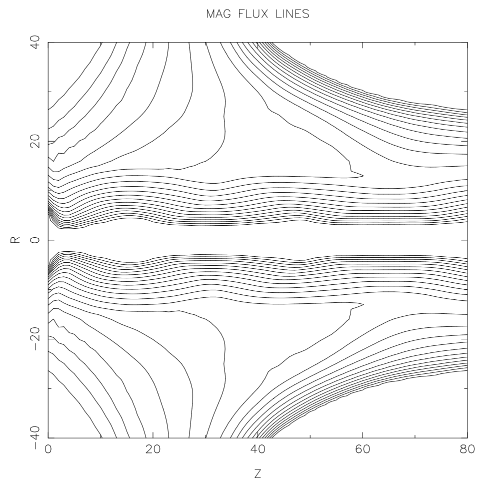

Figure 2: Field structure of the inner disk edge. Image is rotated 90°clockwise from Figure 1 and includes both negative and positive R regions. The black hole is at the origin and length units are in r_g.

in Color Figure 2. It bears a striking resemblance, in both morphology and magnetic field structure, to the observations of Moellenbrock et al. (2000). This highly-collimated inner jet appears to compete with the outer, loosely-collimated wind found in the steady state simulations: in the ~ 80 simulations we have run, we see either the inner jet or wind, but rarely both at the same time.

2.2.3 The Magnetic Switch

Because the field is anchored on the boundary, and because we have control over the density of the injected material, the pseudo-relativistic simulations can study the case where the field dominates the dynamics in a very tenuous corona. We have found that an important transition in the character of the outflow occurs when the MHD power input $L_{MHD} \equiv B^2_{corona} R^4_{corona} \Omega^2/4c$ (where R_{corona} is the size of the coronal region ejecting the jet and Ω its angular velocity) exceeds a critical value $L_{crit} \equiv E_{escape}/\tau_{free-fall} = 4\pi\rho_{corona}R^2_{corona}(GM/R_{corona})^{3/2}$ (Meier et al. 1997; Meier 1999). L_{crit} can be considered to be the MHD equivalent of the Eddington limit: for $L_{MHD} < L_{crit}$, gravity dominates, whereas magnetic forces dominate above the critical value. For $L_{MHD} > L_{crit}$, the jet is initially unbound an accelerates rapidly to a terminal velocity that depends only on the properties of the injected matter and rotating magnetic field ($\Gamma_{jet} = L_{MHD}/\dot{M}c^2$), not on the escape velocity from the black hole region. As a result, high Lorentz factors are possible when the mass loss rate $\dot{M}$ is low and the MHD power high. This appears to occur both in the case of the inner jet and the outer MHD wind. So far, our simulations have achieved Lorentz factors of $\Gamma_{jet} = 10 - 20$ and could potentially go much higher when we begin to take the magnetic inertia into account and explore the very large field regime.

To summarize, we find that the fastest and most powerful jets are produced when the central black hole rotates rapidly, the accreting material falls rapidly into the ergosphere, and the material accelerated in the jet is of very low density.

3 Discussion

These results suggest two possible scenarios for MHD production of highly relativistic jets in AGN. Both involve low density, advection-dominated flows (ADAFs). In the first case the entire disk is an ADAF, rapidly plunging into the ergosphere, and the jet is produced very near the black hole. Most of the outflow is at the escape velocity ($\Gamma < 3$), but high Lorentz factors can be achieved in very low density, magnetically-dominated "coronal holes". In the second scenario, the magnetic field is anchored in a thin, dense Keplerian disk, and only the corona is advection-dominated. Either an inner jet or outer wind is possible in this case. Again much of the outflow is at the local escape velocity, but high Lorentz factor flow can occur in very low density coronal holes.

The outer relativistic wind is a tempting model for M87, because the observations indicate a large opening angle in the jet collimation region (see Junor et al. 2000). However, such a structure also can be obtained, even in the inner jet case, if that jet is accelerated from a satellite black hole orbiting around the large $3 \times 10^9 M_{\odot}$ hole rather than from a large accretion disk around the central hole. As the period of such an orbiting satellite is ~ 10 years, if this model is viable, we should see variations in the 43 GHz structure of the M87 core over the next few years.

4 Conclusions

Magnetically-driven outflow from accretion disks around black holes appears to have two main components: a slowly-collimating wind from the disk surface and a highly-collimated jet from the disk inner edge.

Both types of outflow are subject to magnetic switching, with a critical MHD power analogous to the Eddington limit for radiative acceleration. When $L_{MHD} < L_{crit}$, gravity is important and $V_{jet} \sim V_{escape}$ ($\Gamma < 3$). When $L_{MHD} > L_{crit}$, gravity is unimportant and $\Gamma_{jet} \sim L_{MHD}/\dot{M}c^2$, allowing high Lorentz factors if the MHD power is high and mass loss is low. When the black hole rotates, the jet is accelerated from the frame-dragged matter inside the ergosphere. The strongest and fastest jets occur when the material plunges rapidly into the ergosphere, as in the case of an ADAF or when the disk counter-rotates with respect to the hole's rotation.

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