General Relativistic Simulations of Jet Formation by a Rapidly Rotating Black Hole

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Abstract. We have performed general relativistic magnetohydrodynamic simulations of jet formation in accretion disks around rapidly rotating black holes. Here we compare the case where the disk rotates in the same sense as the black hole with the opposite, counter-rotating, case.

Radio observations of active galactic nuclei and “microquasars” in our Galaxy (Mirabel & Rodriguez 1994) have revealed compelling evidence of existence of relativistic jets. It is believed that the cores of these objects contain a rapidly rotating black hole and that magnetic phenomena occurring near the hole produce the relativistic jets (Blandford & Znajek 1977; Blandford & Payne 1982; Shibata & Uchida 1986; Kudoh & Shibata 1997). To simulate jet formation in the magnetosphere of a black hole, we have newly developed a Kerr general relativistic magnetohydrodynamic (KGRMHD) code (Koide et. al. 1998; Koide et. al. 1999; Koide et. al. 2000). We report here on the numerical results of our jet formation simulations.

Our study is based on the general relativistic conservation laws of mass, momentum, and energy in conducting fluids and on Maxwell equations. We use the Kerr metric with spin parameter $a = 0.95$, which describes the space-time around the nearly maximally rotating black hole. We employ the simplified total variation diminishing (TVD) method to integrate the partial differential equations. For the initial conditions, we assume a transonic free fall corona and relativistic Keplerian disk with a uniform magnetic field.
Figure 1 shows the simulation results when the accretion disk is rotating counter to the black hole rotation at a time $t = 47\tau_S$. Here $\tau_S$ is the unit of time, $\tau_S = r_S/c$, where $r_S$ is Schwarzschild radius and $c$ is speed of light. The disk falls toward the black hole rapidly because no stable orbit exists for $R < 4.5\tau_S$, allowing part of the magnetized disk to enter the ergosphere ($R < \tau_S$) quickly. The jet has two layers: the plasma beta of the head and skin of the jet is high and the magnetic field azimuthal component $B_\phi$ is negative, while that of the root and the center of the jet is low and $B_\phi$ is positive. The high beta jet is a gas pressure driven jet produced by a shock that develops in the disk, while the low beta jet is a magnetically-driven jet caused by the strong magnetic field and rapid field rotation due to frame dragging near and inside the ergosphere. This acceleration mechanism is thought to be identical to the Blandford-Znajek mechanism (Blandford & Znajek 1977). At $t = 47\tau_S$, the jet of the counter-rotating disk case is accelerated mainly by the electromagnetic force; in contrast, in the case of a co-rotating disk, the jet is due to gas pressure alone (in other words, no low beta jet is formed at this time).

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References

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Figure 1. The plasma beta (gray-scale) and the azimuthal component of the magnetic field $B_\phi$ (contour) of the counter-rotating disk case at $t = 47r_\text{s}$. The solid lines show contours of positive $B_\phi$ and the dashed lines negative $B_\phi$. The arrows indicate velocity vectors, and the black fan-shaped region at the origin shows the horizon of the Kerr black hole. The dashed line near the horizon is the inner boundary of the calculation region.