Part 3

Theoretical Considerations

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Extraction of Black Hole Rotational Energy by a Magnetic Field

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Abstract. We have developed a numerical method for general relativistic magnetohydrodynamic simulations in Kerr space-time. The method is applied to the basic astrophysical problem of the Kerr black hole activity in the large-scale strong magnetic field. The numerical result shows that the magnetic field extracts the rotational energy of the black hole with negative energy-at-infinity and the torsional Alfven wave is induced from the ergosphere.

1. Introduction

Relativistic jets have been observed by superluminal motion not only from the quasars and active galactic nuclei (AGNs) (Biretta, Sparks, & Macchetto 1999). but also from the binary systems in our Galaxy such as GRS1915+105 (Mirabel & Rodriguez 1994). Recently the biggest explosion in the universe, gamma-ray bursts are suggested to contain the extremely high Lorentz factor jets (Kulkarni 1999). It is believed that such highly relativistic jets are formed around the extremely rapidly rotating black hole (Kerr black hole). Especially, the interaction between the Kerr black hole and the strong magnetized plasma is one of the most promising model for the relativistic jet central engines. Among the violent phenomena due to the interaction, the magnetic extraction of the rotational energy of the black hole is one of the most powerful process. This is also regarded as a fundamental physical problem of the activity of the astrophysical black hole.

Blandford and Znajek presented the force-free, static solution of the electromagnetic field around the Kerr black hole (Blandford & Znajek 1977). The solution shows the electromagnetic energy is radiated from the black hole horizon directly. The power is so large if the magnetic field is strong enough that it is applicable to the astrophysical jet engine. When we consider the dynamic process of the magnetic extraction of the rotational energy of the Kerr black hole, the direct energy radiation from the black hole should be understood from the view point of the original meaning of the horizon: any material, energy, and information can not pass through the horizon outward.

We have developed the general relativistic MHD (GRMHD) simulation code (Koide, Shibata, & Kudoh 1998, 1999; Koide et al. 2000, 2001; Koide 2002). To investigate the dynamic process of the electromagnetic extraction of the rotational energy of the Kerr black hole within the causality, we applied the

GRMHD code to a simulation of a rather simple system of the strong magnetic field, thin plasma, and Kerr black hole (Koide et al 2002).

2. Numerical Result

To understand the basic physics of rotational energy extraction from a black hole with finite magnetic field, we have investigated a somewhat simpler system using the GRMHD numerical calculations (Koide et al. 2002). Initially the system consists of a Kerr black hole with a uniform magnetic field, uniform plasma, and no accretion disk. We set the rotational parameter of the Kerr black hole, $a = 0.99995$, which corresponds to a nearly maximally rotating black hole. Around the hole, we initialize the plasma to a uniform mass density, ρ_0 and low pressure, $p_0 = 0.06\rho_0 c^2$. The initial momentum of the plasma is zero everywhere, and the initial magnetic field is uniform (Wald 1974) with the magnetic field strength, $B_0 = 33.3\sqrt{\rho_0 c^2}$. This is the magnetic-field-dominated case, with the Alfven velocity, $v_A = 0.985c$ close to the speed of light. We assume axisymmetry with respect to the z-axis and reflection symmetry with respect to the equatorial plane. We perform simulations in the region $0.51 r_S \le r \le 20 r_S$ and $0.01 \le \theta \le \pi/2$, where r_S is the Schwarzschild radius.

Figure 1 shows the time evolution of the system where $\tau_S = r_S/c$ is the unit of time. The azimuthal component of the magnetic field has begun to increase due to the azimuthal twisting of the magnetic field lines. In the ergosphere, the plasma rotates the same direction of the black hole rotation due to the frame dragging effect in any case. The magnetic field lines then are twisted azimuthally in the direction of the black hole rotation by the rotation of the plasma in the ergosphere. The twist of the magnetic field lines propagates outward along the magnetic field lines against the infalling plasma flow as a torsional Alfven wave (Fig. 1).

We show the energy transport of the system of the strong magnetic field, thin plasma, and Kerr black hole (Fig. 2). The total energy flux density, $\mathbf{S}_{\rm tot}$ shows that the net energy flows out along the magnetic field from the ergosphere. We found the net power from the ergosphere is $L_{\rm tot} = 0.186 B_0^2 r_S^2 c/\mu_0$. This energy flux is so large, that the total energy-at-infinity density, e^∞ reduces quickly and eventually becomes negative in ergosphere at $t = 6.53\tau_S$. When the net negative energy-at-infinity is swallowed by the black hole, the total energy (mass) of the black hole decreases. So the ultimate result of the generation of an outward Alfven wave is the magnetic extraction of rotational energy of the Kerr black hole. The negative energy-at-infinity also appears in Penrose process to extract the rotational energy of the black hole within the causality (Penrose 1969). Then we call the extraction mechanism of rotation energy of the black hole the 'magnetohydrodynamic (MHD) Penrose process'. The energy flux from the ergosphere is dominated by the electromagnetic component (Fig. 2, right panel). The electromagnetic energy flux is transported by the torsional Alfven wave and the negative energy-at-infinity is responsible to the plasma. The power of the Alfven wave from the ergosphere is $L_{\rm EM} = 0.259 B_0^2 r_S^2 c/\rho_0$. The electromagnetic power of the Blandford-Znajek mechanism is estimated by $L_{\rm BZ} = (\pi/16)(a^2 c/v_A) B_0^2 r_S^2 c/\mu_0 \sim 0.2 B_0^2 r_S^2 c/\mu 0$ (Blandford & Znajek 1977), which is almost the same as the value we obtained from our numerical simulation.

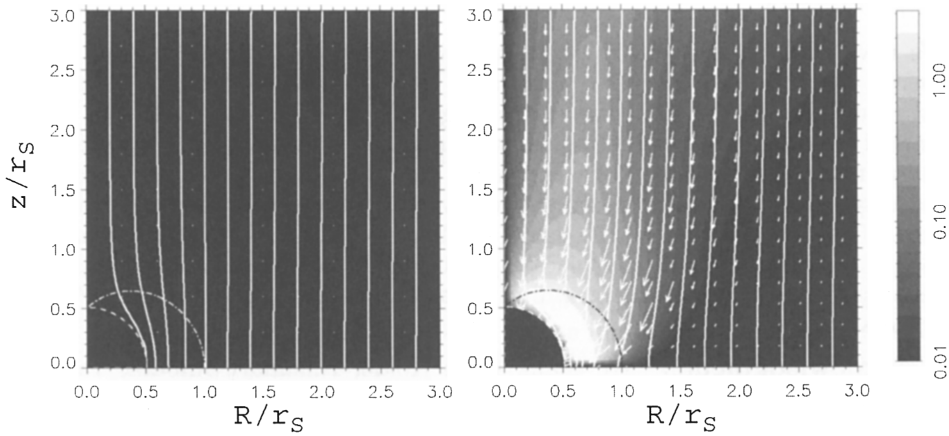

Figure 1. Time evolution of a simple system of a large-scale strong magnetic field, thin plasma, and a Kerr black hole at $t = 0$ (left panel) and $t = 6.53\tau_S$ (right panel). The gray-scale shows the value of $-B_\phi/B_0$. The arrows show the poloidal velocity of the plasma. Solid lines are magnetic field lines (surfaces). The black quarter-circle at the origin indicates the event horizon of the black hole. The dotted line shows the inner boundary of the calculation region at $r = 0.505 r_S$. The chain lines show the boundary of the ergosphere.

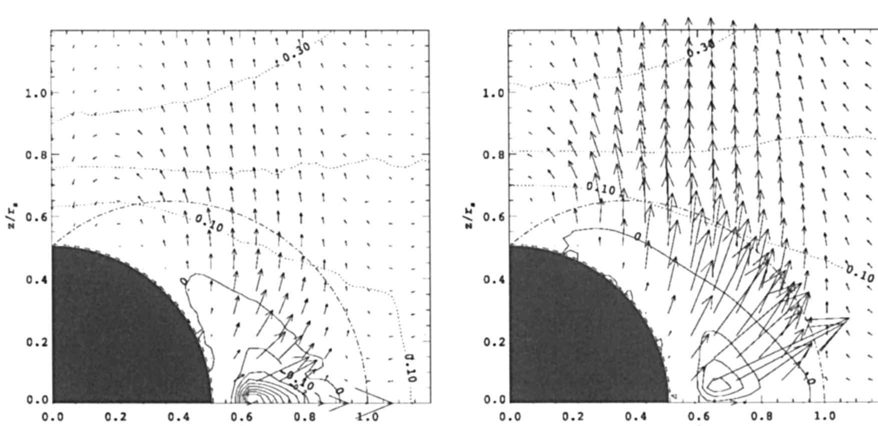

Figure 2. The total (left panel) and electromagnetic (right panel) energy transport at $t = 6.53\tau_S$. The dotted lines show the positive value of energy-at-infinity, $e^\infty_{\rm tot}$, $e^\infty_{\rm EM}$ and the solid lines show the non-positive (zero or negative) value. The arrows show the energy flux density, $\mathbf{S}_{\rm tot}$, $\mathbf{S}_{\rm EM}$. The black region indicates the inside of the black hole horizon. The dashed line is the boundary of the calculation region near the horizon. The chain line shows the boundary of the ergosphere.

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3. Summary

We have applied the GRMHD code to investigate the basic mechanism of the energy extraction of the Kerr black hole by the magnetic field. The numerical result shows that the rotational energy of the Kerr black hole can be extracted by the strong magnetic field with negative energy-at-infinity within the causality at the horizon. The extracted energy is transported outward from the ergosphere as the torsional Alfven wave. The electromagnetic power of the Alfven wave is almost the same as that of Blandford-Znajek mechanism: $L_{\rm EM} = (\pi/16)(a^2 c/v_{\rm A})B_0^2 r_{\rm S}^2 c/\mu_0$. We call this mechanism MHD Penrose process because the negative energy-at-infinity plays an essential role just like Penrose process.

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