S9-3 Numerical Simulations of Plasmas in Black Hole Magnetosphere
ブラックホール磁気圏のプラズマの数値実験

Shinji Koide
小出 眞路
Faculty of Engineering, Toyama University , 3190 Gofuku, Toyama 930-8555, Japan
富山大学工学部電気電子システム工学科，〒930-8555　富山市五福３１９０

Relativistic jets from several kinds of objects in the universe have been found. It is believed that they are all formed by violent phenomena near the black holes. However, the distinct mechanism of the jet formation has not yet been shown. Here we show the possibility of the relativistic jet formation by the interaction between the plasma and the magnetic field near the rapidly rotating black hole numerically.

1. Introduction

In the universe, relativistic jets are observed in active galactic nuclei (including quasars and BL Lactae objects), microquasars in our galaxy, and central objects of gamma-ray bursts [1]. In spite of the drastic difference of the scale and the Lorentz factor of these kinds of jets, it is believed that these relativistic jets are formed by the extreme phenomena around the black hole at the center of the objects. The definite mechanism of the jet has not yet been shown. There are two problems with respect to the jet formation, i.e. the acceleration and collimation of the gas/plasma. The magnetic mechanism is becoming most promising because it can explain both of the problems at once. To investigate the magnetic mechanism, we have performed numerical simulations of general relativistic magnetohydrodynamics (GRMHD). We showed that jet is ejected from the rotating disk around the black hole with the global, vertical magnetic field [2]. However, the maximum speed of the jet is (0.3-0.5)c, where c is light speed, which is sub-relativistic. Recently, we reported the relativistic outflow formation by the radial magnetic field from the ergosphere around the very rapidly rotating black hole [3]. In the ergosphere any material, information, or energy must rotate in the same direction as the black hole due to the frame-dragging effect of the rotating black hole. The relativistic outflow is powered by the frame-dragging effect through the magnetic field. However, the relativistic outflow is not collimated so we haven't found any relativistic jet yet. There are two important, various elements in the simulation setting. One is the initial conditions of the plasma and the other is the magnetic field configuration around the black hole. According to the previous calculations, we think the magnetic field configuration is more important for the relativistic jet formation around the black hole. We have already used the uniform and radial magnetic field configurations around the black hole. The next simple configuration is dipole magnetic field. However, the black hole can not have dipole magnetic field because of the causality at the black hole horizon, i.e. the electric current inside of the black hole horizon never influence to the magnetic field outside of the horizon. Therefore, we use the magnetic field caused by the electric current loop located on the equatorial plane around the rotating black hole for this study.

2. Numerical Methods

We have performed GRMHD simulations of plasmas around black holes [2-6]. The calculations are based on the general relativistic conservation laws of particle number, momentum, and energy of plasma and magnetic field and Maxwell equations. We assume the electric resistivity is zero. We also assume Kerr space-time around black hole. Here we use the rotation parameter of the black hole, a=0.99995, that means the black hole rotates almost maximally. We solve the equations with the 3+1 formalism numerically by simplified TVD scheme which was developed by S. F. Davis [7]. We set the quasi-equilibrium state of the plasma initially, where the plasma is in hydrostatic equilibrium far from the black hole horizon, and the plasma falls into the black hole smoothly near the horizon. The initial magnetic field is calculated by the vector potential of the current loop as shown in Figure 1 (solid lines: magnetic field lines). The current loop locates at $r=3r_S$, where r_S is Schwarzschid radius. The black region at the origin shows the inside of the black hole horizon ($r \leq 0.505 r_S$). The broken- line shows the surface of the ergosphere. The mass density near the current loop center is larger than the uniform density of the surrounding plasma (Fig. 1, gray-scale). Initially, the plasma near the current loop center rotates with

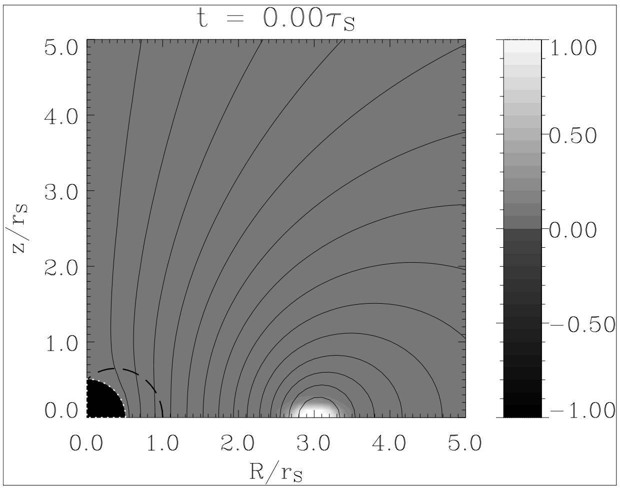

Fig. 1. The initial condition of the mass density (gray-scale) and the magnetic field (solid lines) of the GRMHD simulation around Kerr black hole (a=0.99995). The center of the electric current loop locates at R=3r_S, z=0.

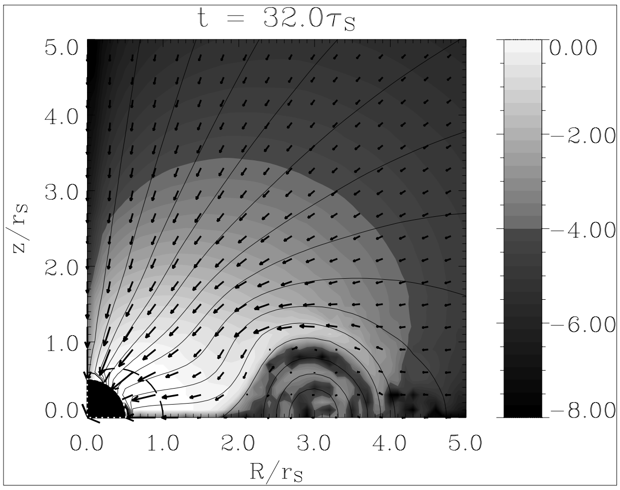

Fig. 2. The state of the plasma and the magnetic field at t=32τ_S. The solid lines show the magnetic field lines and the arrows show the plasma velocity. The gray-scale shows the value of $B_\phi^2 / \rho c^2$.

the Kepler velocity (circular orbit rotation velocity) and the momentum of the plasma is zero except for the region. It is noted that the system has axi-symmetry and the symmetry with respect to equatorial plane.

3. A Test Result

We show a test result of the GRMHD simulations of the plasma of the black hole magnetosphere with the magnetic field by the electric current loop here. Figure 2 shows the state of the plasma and magnetic field at t=32τ_S, where τ_S =r_S/c. The plasma falls into the black hole except for the region of the closed magnetic tube around the current loop. In the closed magnetic tube, the plasma almost stops against the strong gravity of the black hole. The gray-scale which indicates $B_\phi^2 / \rho c^2$ (B_ϕ and ρ is the azimuthal component of the magnetic field and the mass density of the plasma, respectively) of Fig. 2 shows that the azimuthal component of the magnetic field lines across the ergosphere are twisted due to the frame-dragging effect of the rapidly rotating black hole. The twist of the magnetic field lines propagates along the magnetic field lines against the plasma falling. If we can perform longer term simulation than present one, the twist of the field lines may spread and become very strong. It is expected that the magnetic pressure of the strongly twisted magnetic flux tube blows off the plasma and the relativistic jet is formed. The explosion of the closed magnetic flux tube will produce the anti-parallel magnetic field configuration. Then the magnetic reconnection will happen and the additional fast jet may be formed. This mechanism of the jet formation is already proposed using the non-relativistic numerical simulation with respect to the fast (but non-relativistic) jets from the protosteller objects [8]. The essence of these models are very similar to the unified model of solar flare [9].

Acknowledgments

We thank Kazunari Shibata, Takahiro Kudoh, and David L. Meier for their important, essential contributions to this study.

References

[1] D. L. Meier, S. Koide, and Y. Uchida: Science **291** (2001) 84.

[2] S. Koide, D. L. Meier, K. Shibata, and T. Kudoh: Astrophys. J. **563** (2000) 668.

[3] S. Koide: Astrophys. J. Letters **606** (2004) L45.

[4] S. Koide, K. Shibata, T. Kudoh, and D. L. Meier: Science **295** (2002) 1688.

[5] S. Koide: Phys. Rev. D **67** (2003) 104010.

[6] S. Koide, K. Shibata, and T. Kudoh: Butsuri **58** (2003) 743 [in Japanese].

[7] S. Koide, K. Shibata, and T. Kudoh: Astrophys. J. **522** (1999) 727.

[8] M. R. Hayashi, K. Shibata, and R. Matsumoto: Astrophys. J. **468** (1996) L37.

[9] K. Shibata: Astrophys. Sp. Sci. **264** (1999) 129.