A General Relativistic Magnetohydrodynamic Simulation of Outflow Formation around Rotating Black Hole

Shinji KOIDE*)

Faculty of Engineering, Toyama University, Toyama 930-8555, Japan

In the universe, several kinds of relativistic jets have been discovered, and it is believed they are formed by violent phenomena near black holes. Despite advancement of observations and black hole physics, their acceleration mechanisms are still mystery. Here we show that relativistic outflow is formed spontaneously by magnetic field near rapidly rotating black hole with numerical simulations. Previous simulations showed electromagnetic energy emission and non-relativistic outflow formation in the black hole magnetosphere, but actual relativistic outflows have not yet been obtained. Present simulation shows magnetic flux tubes oblique to the rotation axis across black hole horizon are twisted in the shape of screws and propel plasma around the black hole to relativistic regime.

§1. Introduction

In the universe, relativistic jets are observed from active galactic nuclei,[1] quasars,[2] objects called micro-quasars in our Galaxy,[3,4] and central objects of gamma-ray bursts (GRBs).[5] These relativistic jets are thought to be ejected due to violent phenomena around black holes. Among a number of theories of relativistic jet formation around the black hole, the magnetically-driven mechanism is most attractive and becomes noticeable because it can explain not only the acceleration of the jet but also its collimation and it explains some features of the recent observations.[6-8] However, the theory of the magnetically-driven relativistic jet formation lacks an important peace: the distinct, self-consistent solution without artificial assumption for plasma dynamics. In this report, we show a general relativistic MHD simulation result of the spontaneous formation of the relativistic outflow around the rapidly rotating black hole with the radial magnetic field whose field lines are oblique and widely open except for the rotation axis vicinity.

§2. General relativistic MHD simulation

To investigate the fundamental dynamics of the plasma and electromagnetic field around the Kerr black hole, we employ the general relativistic conservation laws of the particle number, momentum, and energy around the black hole.[9,10] We also use the general relativistic forms of Maxwell equations of the electromagnetic field around the Kerr black hole. In addition, we assume that the electric resistance is zero (ideal MHD condition). In this paper, we set the rotation parameter of the black hole, $a = 0.99995$, which means the black hole rotates almost maximally. To calculate the time evolution of the plasma and magnetic field around the black hole, we use a simplified total variation diminishing (TVD) difference scheme with

*) E-mail: koidesin@eng.toyama-u.ac.jp

3+1 formalism of the general relativistic MHD equations, in which spatial (three components) and time (one component) derivatives are separated completely.[10] As an initial condition of the magnetic field around the Kerr black hole, we set the magnetic field of the magnetically charged (monopole) rotating black hole. We write the strength of the initial magnetic field at $R = r \sin\theta = r_S$, $z = r\cos\theta = 0$ by B_0. Here, r_S is the Schwarzschild radius of the black hole and (r, θ, ϕ) is the Boyer-Lindquist coordinates. The plasma is assumed in the hydrostatic quasi-equilibrium, in which far from the horizon the plasma is hydrostatic and at the horizon, the plasma falls into the black hole with light speed. The initial angular momentum of the plasma is zero over the whole calculation region. In the case, the magnetic field energy is dominated compared with the thermal and rest mass energy of the plasma.

§3. Results

Figure 1 shows the magnetic field and the poloidal velocity of the plasma of a system of radial strong magnetic field, thin plasma, and rapidly rotating black hole at $t = 10.7\tau_S$ where $\tau_S = c/r_S$. It shows the increase in the azimuthal component of the magnetic field (B_ϕ). This is due to general relativistic effect around the Kerr black hole. The rotation of the black hole causes the rotation of the space around the black hole. This effect is called the *frame-dragging* effect. The frame-dragging effect forms a special region called ergosphere near the black hole, in which any material, energy, and information cannot propagate the opposite direction of the black hole rotation. In the ergosphere, the plasma hence rotates in the same direction of that of the Kerr black hole and never rotates against the direction. The magnetic field lines are tied to the rotating plasma (ideal MHD condition), therefore, the magnetic field lines are twisted azimuthally around the ergosphere and the azimuthal component of the magnetic field increases. The magnetic field lines are strongly twisted and the twist of the magnetic field line propagates outward as a torsional Alfven wave. The torsional Alfven wave is generated by essentially the same mechanism of the rotating disk in the non-relativistic cases.[11)−15)] In the present case, the plasma in the ergosphere plays the same role of the heavy disk of the non-relativistic cases. The magnetic force of the twisted magnetic flux tube blows off the plasma outward at $t = 10.7\tau_S$. The maximum velocity of the outflow is 0.86c at $t = 10.7\tau_S$ and the outflow is relativistic (Lorentz factor is $\gamma = 2.0$). Such

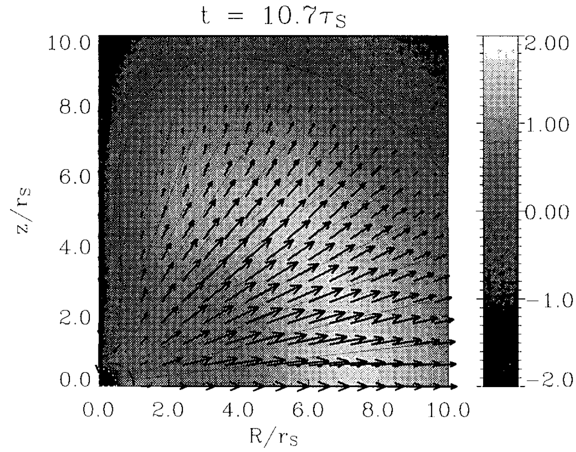

Fig. 1. The magnetic flux surface (lines), the plasma velocity (arrows), and $\log_{10}(B^2/\mu_0 c^2)$ (grey-scale) at $t = 10.7\tau_S$. The black quarter-circle at the origin indicates the event horizon of the black hole. The dotted lines show the inner boundary of the calculation region. The dashed lines show the boundary of the ergosphere.

distinct relativistic outflow has never been seen in the previous general relativistic MHD simulations.[9),10),16)-18)] Numerical results with other several sets of parameters show that such relativistic outflow from the Kerr black hole is formed only when the magnetic field is very strong ($B_0^2/\mu_0 \gg \rho c^2$) and the black hole rotates very rapidly ($a \sim 1$).

To demonstrate this result more intuitively, we show in three-dimensions the magnetospheric structure around the Kerr black hole at $t = 10.7\tau_S$ (Fig. 2). The tubes show the magnetic field lines and the arrows show the plasma velocity. All magnetic tubes cross the ergosphere and are twisted strongly azimuthally due to the frame dragging effect around the Kerr black hole. The magnetic flux tubes are shaped into propellers and the rapidly rotating propellers blow off the plasma because the plasma does not cross the magnetic flux tubes (ideal MHD condition). The magnetic propellers are supported by the magnetic pressure and tension. The strongly twisted magnetic field lines also increase the magnetic tension to pinch the outflow of the plasma. The relativistic outflow is formed outside of the ergosphere but it is not yet pinched strongly because of the short term of the present calculation.

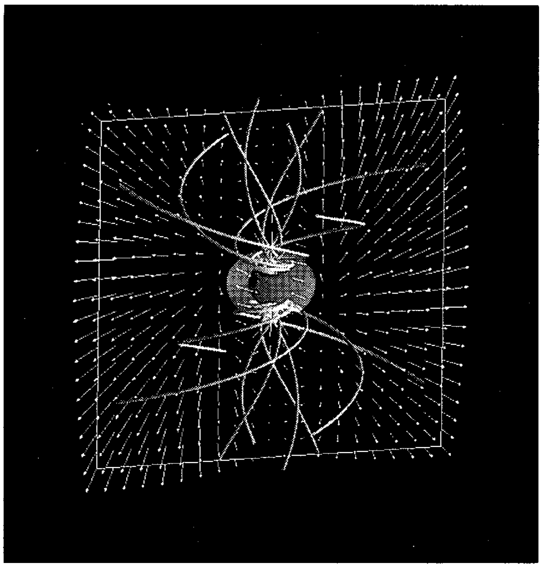

Fig. 2. Three-dimensional graphic of magnetic field lines and plasma flow around the Kerr black hole at $t = 10.7\tau_S$. The black sphere at the centre depicts the black hole horizon. The transparent, gray surface around the black hole is that of the ergosphere. The arrows show the plasma flow velocity. The tubes in the shape of propellers show the magnetic field lines.

The numerical simulation presented here clearly shows that when the magnetic flux tube, in which the magnetic energy dominates the rest mass energy and internal energy of the plasma, crosses the ergosphere of the rapidly rotating black hole, it rotates due to the frame dragging effect of the black hole like a propeller screw and propels the plasma outward near the black hole to the relativistic regime. This is the first distinct, self-consistent solution showing the possibility of the spontaneous relativistic outflow formation by the magnetic field around the rotating black hole. In the previous calculations with initially uniform, strong magnetic field, thin plasma around rapidly black hole, no outflow is found, while the strong energy is emitted from the ergosphere.[9),10)] This shows the importance of the magnetic configuration around the black hole for the relativistic jet formation.

Here we discuss the possible application of the presented process of the relativistic jet formation in the radial, strong magnetic field from the rapidly rotating black hole to the mechanism of the central engine of GRBs. Among many models of the relativistic jet from GRB engine, the model of the gravitational collapse of large star ($M > 10M_{\rm sun}$; $M_{\rm sun}$ is the mass of the sun) called collapsar or hypernova model seems to be the one of the most promising.[19),20)] It is plausible that the large star had strong magnetic field caused by the dynamo inside of the star. During the star collapse and the black hole formation, the plasma of the star falling into the black hole drags the magnetic field lines to the forming black hole. The most of the magnetic field lines may be swallowed by the black hole with the falled plasma. However, radial magnetic field lines parallel to the plasma flow velocity will remain. The present numerical simulations indicate that the relativistic outflow may be ejected directly from the ergosphere along the radial magnetic field lines when the magnetic field is strong enough to dominate the plasma around the black hole.

Acknowledgements

We thank Kazunari Shibata, Mika Koide, Takahiro Kudoh, and David. L. Meier for their crucial help for this study. We appreciate the support of the National Institute for Fusion Science in the use of its super-computers.

References

1) J. A. Biretta, W. B. Sparks and F. Macchetto, Astrophys. J. **520** (1999), 621.
2) T. J. Pearson and J. A. Zensus, *Superluminal Radio Sources*, ed. J. A. Zensus and T. J. Pearson (Cambridge Univ. Press, London, 1987), p. 1.
3) I. F. Mirabel and L. F. Rodriguez, Nature **371** (1994), 46.
4) S. J. Tingay et al., Nature **374** (1995), 141.
5) S. R. Kulkarni et al., Nature **398** (1999), 389.
6) W. Junor, J. A. Biretta and M. Livio, Nature **401** (1999), 891.
7) I. F. Mirabel and L. F. Rodriguez, Nature **392** (1998), 673.
8) P. Meszaros and M. J. Rees, Astrophys. J. **482** (1997), L29.
9) S. Koide, K. Shibata, T. Kudoh and D. L. Meier, Science **295** (2002), 1688.
10) S. Koide, Phy. Rev. D **67** (2003), 104010.
11) R. D. Blandford and D. Payne, Mon. Not. R. Astron. Soc. **199** (1982), 883.
12) Y. Uchida and K. Shibata, Publ. Astron. Soc. Jpn. **37** (1985), 515.
13) K. Shibata and Y. Uchida, Publ. Astron. Soc. Jpn. **38** (1986), 631.
14) R. Ouyed, R. E. Pudritz and J. M. Stone, Nature **385** (1997), 409.
15) D. L. Meier, S. Koide and Y. Uchida, Science **291** (2001), 84.
16) S. Koide, K. Shibata and T. Kudoh, Astrophys. J. **495** (1998), L63.
17) S. Koide, K. Shibata and T. Kudoh, Astrophys. J. **522** (1999), 727.
18) S. Koide, D. L. Meier, K. Shibata and T. Kudoh, Astrophys. J. **536** (2000), 668.
19) S. E. Woosley, Astrophys. J. **405** (1993), 273.
20) B. Paczynski, Astrophys. J. **494** (1998), L45.