General Relativistic Simulations of Jet Formation in Kerr Black Hole Magnetosphere

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Abstract

We report a two-dimensional numerical result of jet formation driven by magnetic field due to a current loop near a rapidly rotating black hole. It shows that the magnetic flux tube bridging the region between the ergosphere and the disk around the black hole is twisted rapidly due to the frame-dragging effect and expands explosively to form a jet.

Key words: relativistic jet, black hole, magnetic field, ergosphere, general relativistic MHD

1. Introduction

Superluminal motions, which indicate relativistic motions of emission regions and observational evidence of relativistic jets, were observed around the quasars and active galactic nuclei [1,2]. In our Galaxy, superluminal motions were observed around the binary systems called micro-quasars [3,4]. Recently, the observations of the afterglow of the long-duration gamma-ray bursts (GRBs) revealed that the long-duration GRBs also contain the relativistic jets [5]. It is believed that these relativistic jets are formed due to violent phenomena around black holes. However, the distinct mechanism of their formation has not been revealed yet. There are two primary but important questions with respect to the relativistic jet formation mechanism: how the outflow is accelerated to be relativistic, and how the relativistic outflow is collimated to be the jet. Many models were proposed to answer these questions. Among them, the models of magnetic mechanisms have become most promising, because they can explain the acceleration and the collimation of the jet all at once [6–10].

To investigate the magnetic mechanism around a black hole, We have performed the general relativistic magnetohydrodynamic (GRMHD) simulations to investigate the formation mechanism [11–17].

2. Results

We show a two-dimensional numerical result of jet formation driven by magnetic field due to a current loop near a rapidly rotating black hole whose rotation parameter is 0.99995 [17]. Here we assume the electric conductivity is infinity (ideal GRMHD). We set the current loop along the intersection of the equatorial plane and the surface of the ergosphere around the black hole initially. In such magnetic configuration, there are magnetic flux tubes which bridge the region between the ergosphere and the corotating disk. The magnetic flux tube, which we call 'magnetic bridge', is twisted rapidly by the plasma in the ergosphere due to the frame-dragging effect.

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The magnetic pressure of the magnetic flux tube increases and the strong magnetic pressure blows off the plasma near the ergosphere to form outflow (Fig. 1(a)). At t=40.02 τ_S, the outflow begins to be collimated by the magnetic tension of the magnetic flux tube. Here τ_S is the unit of time, $\tau_S = r_S/c$ (r_S is the Schwarzschild radius and c is light speed). Then, eventually, the jet is formed at t=110.8 τ_S (Fig. 1 (b)) where the maximum velocity of the jet is $0.46c$. That is, the magnetic bridges can not be stationary and expand explosively to form a jet. Around the disk surface, part of the magnetic surface is elongated horizontally. This separation of the outflow to the jet along the axis and the horizontal flow is also seen in the nonrelativistic MHD simulations due to the common feature of the magnetically-driven mechanism.

The parameter survey of the background pressure shows that the radius of the collimated jet depends on the gas pressure of the corona. That is, the higher background pressure makes the jet radius smaller. Similar results are also shown in the non-relativistic MHD simulations with pseudo-Newtonian potential [18]. This effect is also suggested by Lynden-Bell theoretically [19]. However, this does not mean the gas pressure collimates the jet. The gas pressure decelerates the jet and the pinch effect by the magnetic field becomes significant.

It is also noted that, in the bulk of the collimated jet, the magnetic island (plasmoid) is formed. However, because we use the ideal MHD condition (infinity electric conductivity; $\sigma \to \infty$) the magnetic reconnection never happens. Thus the formation of the magnetic island (plasmoid) is a numerical effect, while it suggests that such anti-parallel magnetic field configuration is realized naturally.

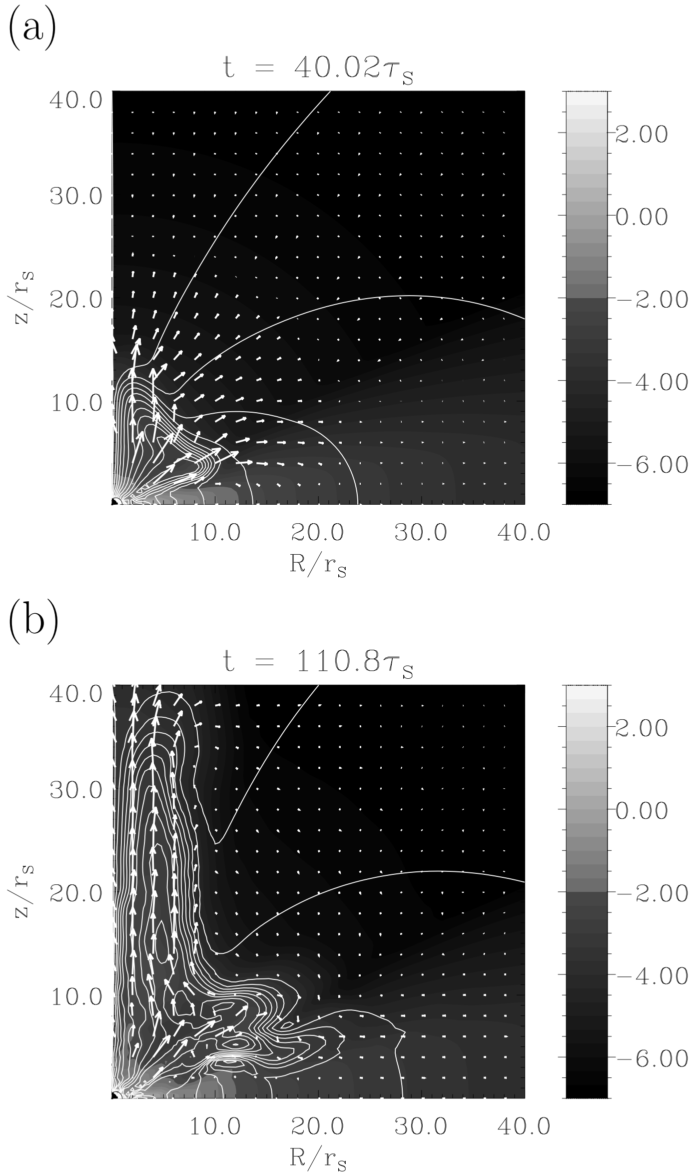

Fig. 1. Time evolution of the system of the current loop, equilibrium coronal plasma, the corotating disk, and the rapidly rotating black hole at the origin. The gray-scale portion shows the logarithm of the mass density of the plasma. The arrows show the poloidal component of the plasma velocity. The white lines show the magnetic flux surfaces.

3. Summary

In this paper, we presented the numerical results of the GRMHD simulations of the magnetic bridges between the ergosphere and the disk. Our results show the elemental processes of the jet formation caused by the magnetic bridges around the rapidly rotating black hole.

(i) The magnetic bridge between the ergosphere and the disk is twisted mainly by the plasma of the ergosphere.

(ii) The magnetic pressure in the magnetic bridge near the ergosphere increases rapidly and the magnetic force (pressure and tension) blows off the plasma near the ergosphere.

(iii) The outflow driven by the magnetic force is pinched by the magnetic tension and is collimated to be a jet.

(iv) The ambient gas pressure influences the jet collimation strongly. That is, higher gas pressure makes the jet radius smaller. This is explained by the deceleration of the outflow velocity by the gas pressure gradient.

In conclusion, the magnetic bridges between the ergosphere and the disk around the rapidly rotating black hole can not be steady, and they will be swallowed by the black hole or they will expand explosively to form the jet.

The numerical results also suggest that the magnetic bridges between the ergosphere and the disk expand vertically and anti-parallel magnetic field configuration is formed. In such magnetic configuration, the magnetic reconnection is expected to happen. The energy release by the magnetic reconnection will power the jet and heat the inner edge of the disk near the black hole. The magnetic reconnection of the magnetic bridges between the star and the disk was shown in the nonrelativistic resistive MHD simulations [18,20,21].

To investigate the magnetic reconnection near the black hole, we need to solve the GRMHD equations with the finite conductivity σ, which we call σGRMHD equations. The σGRMHD simulations whose method, tests, and applications were shown in the talk, are the forthcoming important topic.

Acknowledgements

One of authors (S.K.) thanks Mika Koide for her useful comments on this manuscript. The calculations in this study were performed by the supercomputers of National Institute for Fusion Science, Japan. This work was supported in part by the Scientific Research Fund of the Japanese Ministry of Education, Culture, Sports, Science, and Technology.

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