BLACK HOLE AURORA POWERED BY A ROTATING BLACK HOLE

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ABSTRACT

We present a model for high-energy emission sources generated by a standing magneto-hydrodynamical (MHD) shock in a black hole magnetosphere. The black hole magnetosphere would be constructed around a black hole with an accretion disk, where a global magnetic field could be originated by currents in the accretion disk and its corona. Such a black hole magnetosphere may be considered as a model for the central engine of active galactic nuclei, some compact X-ray sources, and gamma-ray bursts. The energy sources of the emission from the magnetosphere are the gravitational and electromagnetic energies of magnetized accreting matters and the rotational energy of a rotating black hole. When the MHD shock generates in MHD accretion flows onto the black hole, the plasma’s kinetic energy and the black hole’s rotational energy can convert to radiative energy. In this Letter, we demonstrate the huge energy output at the shock front by showing negative energy postshock accreting MHD flows for a rapidly rotating black hole. This means that the extracted energy from the black hole can convert to the radiative energy at the MHD shock front. When an axisymmetric shock front is formed, we expect a ring-shaped region with very hot plasma near the black hole; this would look like an “aurora.” The high-energy radiation generated from there would carry to us the information for the curved spacetime due to the strong gravity.

Key words: accretion, accretion disks – black hole physics – magnetohydrodynamics (MHD) – relativistic processes – shock waves

Online-only material: color figures

1. INTRODUCTION

A number of observations provide evidence for super-massive black holes in galactic centers or stellar-mass black hole in galaxies (e.g., Miyoshi et al. 1995; Ghez et al. 1998, 2005; Genzel et al. 2000; Schödel et al. 2003; Bender et al. 2005; Eisenhauer et al. 2005). Several observations show high-energy phenomena around black hole candidates where some amount of energy in accretion flows is released. In this Letter, to understand the high-energy phenomena near the black hole and the nature of the curved spacetime due to the hole’s strong gravity, we consider inward magnetohydrodynamical (MHD) flows in the magnetosphere of a black hole, which is considered as the transit region from an accretion disk to the event horizon. The global magnetic field in the magnetosphere could be generated by currents streaming in the disk and its corona around the black hole.

The structure of a steady and axisymmetric black hole magnetosphere with a thin disk has been discussed by Tomimatsu & Takahashi (2001) as a vacuum magnetosphere, by Uzdensky (2005) as a force-free magnetosphere, and by Camenzind (1987) and Nitta et al. (1991) as an MHD magnetosphere. These models show the disk–black hole connecting magnetic field lines, as shown in Figure 1(a). The loop-like-shaped magnetic field is generated around the disk’s inner-edge region. Some magnetic field lines connect to the event horizon. Due to the plasma inertia effect, the magnetic field lines are forced to direct toward the event horizon, and then nearly radial flows would be reasonable at least near the event horizon. Such a configuration of the loop-like magnetic field lines indicates the interaction between the black hole and the disk surface (or corona) located at several times the inner-edge radius of the thin disk. Along these loop-like magnetic field lines, the MHD fluid ejected from the disk surface streams inward due to the dominant gravitational force of the black hole.

Although in many previous works equatorial accretion flows have been discussed, by considering the black hole magnetosphere, we expect naturally off-equatorial inflows streaming along the loop-like magnetic field lines. So, we also expect the shock formation near the polar region of the black hole (see Fukumura et al. 2007, for adiabatic shocks). Of course, the shock formation by equatorial accretion flows would be possible within the required physical conditions. However, the emission from the off-equatorial MHD shock would include the information for the “magnetosphere” (i.e., the configuration of the magnetic fields) around a black hole, and would enable us to find the information for the black hole spacetime related to the radiation.

We are interested in the energy conversion from the accreting plasma’s energy, which is composed of the kinetic part and the magnetic part, to the radiative energy at the inner-most region of the black hole magnetosphere. This is because such energy conversion by the shock formation would be related to the generation of huge radiative energy in the hole’s deep gravitational potential. Furthermore, in addition to the plasma’s kinetic energy, the rotational energy of the black hole may also be converted to the radiative energy (see Figure 1(b)). For a fast MHD shock on accretion onto a black hole, about 10% of the upstream flow’s energy (including the rest-mass energy of a particle) can convert to the thermal energy of the downstream flow (Takahashi et al. 2006). This means that the plasma temperature becomes so high across the shock front. Such a hot plasma region can be considered as a source of high-energy radiation, which gives us both the information for the strong gravitational field and the state of magnetized plasma around the black hole. Of course, some part of the radiation emitted from the hot plasma will fall into the black hole because of the strong gravitational lens effects.5 Nevertheless, we can

5 The escape rate of photons from the ergosphere is almost 10%, and this rate becomes larger for a larger spin value (see Takahashi & Takahashi 2010).
expect that huge radiative energy can be released at the very hot shocked plasma region, and considerable radiation flux will be obtained for us.

In this Letter, we discuss energy release by shocked MHD accretion onto a rapidly rotating black hole. In Section 2, we introduce trans-fast magnetosonic accretion flows and apply the shock condition to the flows. Here, we adopt the method of Takahashi & Tomimatsu (2008) for solving trans-fast magnetosonic flow solutions. Then, we can easily obtain the solutions without critical condition analysis at the magnetosonic points. In Section 3, we show negative energy postshock MHD inflows that indicate the energy extraction from a rotating black hole and discuss the released energy at the shocked region. In Section 4, we summarize our MHD shock models.

2. MHD ACCRETION WITH MHD SHOCK

We consider MHD flows in a stationary and axisymmetric magnetosphere around a rotating black hole. The background metric $g_{\mu\nu}$ is written by the Boyer–Lindquist coordinate with $c = G = 1$. The basic equations for MHD flows are the equation of the particle number conservation, the equation of motion, and Maxwell equations. We also assume the ideal MHD condition and the polytropic relation for the plasma flows. There are five field-aligned flow parameters on the flows; that is, the total energy $E$, the total angular momentum $L$, the angular velocity of the magnetic field line $\Omega_F$, the number flux per flux tube $\eta$, and the entropy $S$ (see Camenzind 1986a, 1986b; Takahashi et al. 1990, for the definitions of these flow parameters). The accreting flow onto a black hole must pass through the slow magnetosonic point without the regularity conditions. To obtain a physical solution that is smooth everywhere, the complicated parameter search for satisfying regularity conditions is required (Takahashi 2002). To avoid the heavy task, we will introduce the ratio of the poloidal and toroidal components of the magnetic field as (Takahashi & Tomimatsu 2008)

$$\beta \equiv \frac{B_\phi}{B_p},$$

(3)

to specify a magnetic flux tube for the purpose of solving the relativistic Bernoulli Equation (1). That is, the poloidal magnetic field is related to the toroidal magnetic field through the function $\beta(r, \theta)$, which is assumed to be regular at magnetosonic points, where we do not assume the concrete function for the poloidal magnetic field. We eliminate $B_p$ in Equation (1) by Equation (3) and also eliminate $B^2_\phi$ by Equation (2). Then, Equation (1) can be

\[
\hat{e}^2 - \alpha - M^4 (\alpha B^2_p + B^2_\phi) = 0, \tag{1}
\]

where $\hat{e} \equiv \hat{E} - \Omega_F \hat{L}$ with $\hat{E} \equiv E/\mu_c$ and $\hat{L} \equiv L/\mu_c$. The enthalpy for cold flows is denoted by $\mu_c = m_{\text{part}}$, where $m_{\text{part}}$ is the particle’s mass. The terms $B_p \equiv B_p/(4\pi \mu_c \eta)$ and $B_\phi \equiv B_\phi/(4\pi \mu_c \eta \rho_0)$ are introduced to non-dimensionalize, and the latter is given in terms of the relativistic Alfvén Mach number and the flow parameters:

$$B_\phi = \frac{G_\phi \hat{E} + G_\phi \hat{L}}{\rho_0 (M^2 - \alpha)}, \tag{2}$$

where $G_\phi \equiv g_{\phi\phi} + \hat{g}_{\phi\phi} \Omega_F$, $G_\phi \equiv g_{\phi\phi} + \hat{g}_{\phi\phi} \Omega_F$, and $\alpha \equiv G_\phi + G_\phi \Omega_F$. The relativistic Alfvén Mach number $M$ is defined by $M^2 \equiv (u_p^2 - u^2_{AW})/\eta \rho_0 u_p^2 B_p^2$, where $u_p$ is the poloidal velocity, the Alfvén velocity $u_{AW}$ is defined as $u_{AW}^2 \equiv \alpha B^2_p/(4\pi \mu_c n)$, and $n$ is the number density of the plasma (see also Camenzind 1986a, 1986b; Takahashi et al. 1990).

Differentiating Equations (1) and (2) along a magnetic field line, we obtain the velocity gradient at any point and see the critical point in flow solutions. That is, the flow solution becomes singular at the magnetosonic points and the Alfvén points without the regularity conditions. To obtain a physical solution that is smooth everywhere, the complicated parameter search for satisfying regularity conditions is required (Takahashi 2002). To avoid the heavy task, we will introduce the ratio of the poloidal and toroidal components of the magnetic field as (Takahashi & Tomimatsu 2008)
reduced to the quadratic equation of $M^2$. As a result, we obtain trans-magnetosonic solutions easily without the analysis for the critical conditions of the magnetosonic points. Although the toroidal magnetic field has several constraints at some points along the flow (i.e., the event horizon, the Alfvén point, the Anchor point, etc.), the typical feature of $B_\phi$ for a given $B_r$ has been discussed in Takahashi (2002) by using the standard critical point analysis. So, we can apply it to make a reasonable test function for $B_\phi(r, \theta)$. For example, we can introduce it as a simple form of

$$\beta^2 = (-g_{\phi\phi})(\Omega_F - \omega_H)^2[1 + C (\Delta/\Sigma)].$$

(4)

where $C$ is a constant. The parameter $C$ is introduced to specify the discontinuity of $B_\phi$ at the shock front, where $B_{\phi}$ is the components of the magnetic field parallel to the shock front.

Now, we will consider shocked MHD accretion onto a black hole. To obtain a shocked black hole accretion solution, it is necessary to set up two trans-magnetosonic solutions, which correspond to the upstream and downstream solutions. At the shock location, where the shock conditions are required, the upstream super-fast magnetosonic solution is connected to the downstream sub-fast magnetosonic solution within suitable ranges for the field-aligned flow parameters. After the shock, the sub-fast magnetosonic inflow passes through the second fast magnetosonic point and then it falls into the horizon. In general, the downstream solution would have different values for the field-aligned parameters from the upstream solution due to the radiation loss at the shock front. Hereafter, we assume the conservation of the angular momentum of the flow $L$, the angular velocity $\Omega_\phi$ of the magnetic field line, and the number flux $n$ across the shock front, while the energy of the flow jumps across the shock front, that is, $E_{\text{up}} > E_{\text{down}}$.

The conditions for the MHD shock formation in the general relativistic framework are summarize by, e.g., Lichnerowicz (1967, 1976); that is, the particle number, the energy–momentum, and the magnetic flux are conserved across the shock (see also Appl & Camenzind 1988; Takahashi et al. 2002, 2006). For an isothermal MHD shock in cold plasma flow, from the jump condition for the radial component of the energy–momentum conservation, we obtain the simple relation of

$$\left(M^2 + \frac{1}{2} \beta^2\right)_{\text{up}} = \left(M^2 + \frac{1}{2} \beta^2\right)_{\text{down}},$$

(5)

where for the sake of simplicity we assume that $B_{\phi\text{up}} = B_{\phi\text{down}}$, $|B_{\phi\text{up}}| < |B_{\phi\text{down}}|$ (for the fast-magnetosonic shock) and the shock front is normal to the upstream flow in the poloidal plane. The value for $\beta^2$ (i.e., the value for $C$) increases across the fast-magnetosonic shock, and then the Mach number decreases; that is, the kinetic energy of the flow is released there.

3. HIGH-ENERGY RADIATION POWERED BY A ROTATING BLACK HOLE

Rotational energy of a rapidly rotating black hole can be extracted by MHD inflows with negative energy due to the interaction between magnetic and gravitational fields in the black hole spacetime (Blandford & Znajek 1977; Takahashi et al. 1990). The extracted energy is carried to the magnetosphere in the form of outgoing Poynting flux. If the extracted energy is converted to some kinds of fluid’s energy related to the radiative process directly, it may be observable for us. However, in the framework of the original Blandford–Znajek (BZ) process in the force-free magnetosphere, realistic conversion mechanisms from the magnetic energy to the other form are still not clear, because in the force-free approximation the inertia of matters is ignored.

We are now discussing MHD accretion onto a black hole. The MHD inflow takes the fluid energy into the black hole (that is, the kinetic energy, the internal energy, and the rest-mass energy of the fluid), which is positive at the plasma source. However, the situation of energy extraction from a rotating black hole can also be described in the MHD magnetosphere. In this case, the negative energy MHD inflow ($E < 0$) is realized, where it is required that the Alfvén point of the flow considered is located close to the inner light surface in addition to the condition for the BZ process; both the Alfvén point and the inner light surface need to posit inside the ergosphere (Takahashi et al. 1990). By considering negative energy MHD inflows, the rotational energy of the black hole can be carried in the surrounding magnetosphere as the outward energy flux to the distant region directly (McKinney & Gammie 2004; McKinney 2006) or indirectly by way of an equatorial disk (Li 2002; Wang et al. 2003). In the latter case, the extracted energy from the black hole is deposited onto the disk and then it converts to the thermal energy of the disk plasma and/or the kinetic energy of the outgoing disk winds.

Now, at the fast MHD shock, we understand that the kinetic energy of the upstream MHD flow converts to the thermal and magnetic energies of the downstream flow. The most efficient energy conversion to radiation would be achieved by isothermal shock; where it is assumed that the thermal energy generated at the shock front escapes from the shocked plasma immediately. When the negative energy accretes onto the black hole as the postshock flow, we can also expect that the extracted hole’s energy would convert to the radiative energy at the shock front (see Figure 1(b)). By considering the regularity condition at the Alfvén point, which is related to the amount of the jump of energy and angular momentum between the preshock and postshock solutions, we find the necessary condition for such an energy release process (M. Takahashi & R. Takahashi 2010, in preparation).

Figure 2 shows two examples of solutions for shocked accretion onto a black hole. After passing through the Alfvén point $A_{\text{up}}$ and fast magnetosonic point $F_{\text{up}}$, the accretion flow becomes super-fast magnetosonic, and then it falls into the black hole. When the MHD shock arises at the radius labeled $S$ or $S'$ on the accreting flow (see the vertical downward arrows), the postshock flow becomes sub-fast magnetosonic. Then, the postshock flow must become super-fast magnetosonic again by passing through the fast magnetosonic point $F_{\text{down}}$ or $F'_{\text{down}}$ located between the shock front and the event horizon. Note that the branch of the postshock solution labeled $S$ connects to the Alfvén point $A_{\text{down}}$, and it is also a shock-free accretion solution. On the other hand, the postshock flow solution labeled $S'$ shows an unphysical solution as a shock-free solution, because the branch of the solution does not connect to the Alfvén point and diverges outside the shock location. We cannot accept such a divergent solution as a shock-free solution streaming from the plasma source to the horizon. However, by considering the shock formation, this solution $S'$ can survive as a physical postshock flow solution in the region within the shock radius.

At last, we consider the conditions for the formation of the postshock solution with negative energy and the possible range of the amount of the energy extracted from the black hole. Figure 3 shows the relation between the energy of the postshock...
flow $E_{\text{down}}$ and the shock radius $r_{sk}$ for the accretion flow onto the black hole with $a = 0.8m$. The energy of the preshock flow solution is set to $E_{\text{up}} = 1.0$ and the angular velocity of the magnetic field lines is set to $\Omega_F = 0.4\Omega_{\text{max}}$, where $\Omega_{\text{max}}$ is the maximum value for the field line for existing in the plasma region that is located between the inner and outer light surfaces (see Takahashi et al. 1990). Some thick curves in Figure 3 correspond to the different values of $C_{\text{down}}$ for the postshock solution, and we set $C_{\text{up}} = -5.0$ for the preshock flow solution. Although we consider the case where the shock front is generated inside the ergosphere, the postshock flow with negative energy ($E < 0$) is possible. This means the extraction of the hole’s rotational energy by the ingoing MHD flow. The minimum energy of the postshock flow $E_{\text{min}}$ is given by $E = L\Omega_F < 0$. The extracted energy can be released at the shock front where the hot plasma region is generated. From the hot plasma in the shock front, the observable energy output is expected; e.g., in the form of high-energy radiation, bulk motion of outgoing plasma flows, etc.

4. CONCLUDING REMARKS

We have discussed global shocked accretion solutions in a black hole magnetosphere, which are composed of two trans-magnetosonic solutions with an MHD shock where the general relativistic MHD has been applied to the accretion flows. Then, we have shown the possibility of a very hot shocked plasma region very close to the event horizon. At this stage, in the study of the black hole magnetosphere, the expected energy spectrum from the MHD shock is not clear. Nevertheless, we newly point out the possibility of the energy extraction from the black hole through the MHD shock with the negative energy in the postshock flow. In this Letter, we show the possibility of shocked accretion solutions with negative energy ($E < 0$), while the dependence of flow parameters (i.e., $E_{\text{up}}$, $\Omega_F$, $a$, $L_{\text{up}}$) and flow’s latitude will be presented in the next paper (M. Takahashi & R. Takahashi 2010, in preparation).

To complete the black hole’s rotational energy release at the MHD shock, we must investigate the structure of the shocked hot plasma region. Although the value of the released energy depends on the field-aligned flow parameters, we can estimate the plasma density and temperature there by the help of the accretion disk models that give the boundary condition for the magnetosphere. We need a realistic model of the black hole magnetosphere with a magnetized accretion disk. Although we assume a given magnetic field line, the configuration may be unstable. Then, the dynamical behaviors of the field configuration should also be investigated by helping numerical simulations (e.g., Koide et al. 2006; McKinney & Gammie 2004; McKinney 2006). Then, a significant amount of X-rays and gamma rays would be estimated. In order to take into account such radiation effects in the general relativistic plasma, we should formulate the local radiation effects of MHD fluid by using the energy–momentum tensor with the local heat flux, in addition to the fluid part and the electromagnetic part. Then, we will find the evidence for real black holes in the observational data (e.g., the spectrum in the high-energy range, the short-time variability, the radio image of black hole shadow, X-ray polarization, etc.). That is, we expect that the high-energy emission from this hot plasma brings to us additional information about the black hole spacetime; especially, the polar region emission including this information can be distinct from the emissions from the equatorial plasma source, which have been investigated by many authors in the models of accreting gas disk.

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