“Black Hole Aurora” in a Black Hole Magnetosphere

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Abstract

I present a model of high-energy emission sources generated by a standing magnetohydrodynamical (MHD) shock in a black hole magnetosphere. The black hole magnetosphere would be constructed around a black hole and an equatorial accretion disk, and can be considered as a model for a central engine of active galactic nuclei (AGNs) and gamma-ray bursts (GRBs). From the analysis of MHD shock conditions for accreting plasma onto a black hole, we obtain the restrictions on the flow's physical parameters, and examine the distribution of the shock front. Then, we find that an off-equatorial Aurora-like shaped hot plasma region is possible by the MHD shock formation when the magnetosphere rapidly rotates; the hot plasma region locates close to the event horizon. The emission from this off-equatorial sources would carry new information about the strong gravitational field to us.

1 Introduction

A black hole magnetosphere would be constructed around a black hole and an equatorial disk (see Fig. 1a) [1, 2]. The global magnetic field in the magnetosphere should be generated by the disk. Along the magnetic field lines, the plasma fluid ejected from the disk surface stream inward and outward by the dominant gravitational force and centrifugal force, respectively [3]. The outgoing plasma would make a relativistic jet/wind, which may be observed in systems of AGNs and GRBs. Here, to understand the astrophysical phenomena around a black hole, we consider ingoing flows and discuss the condition of MHD shocks [4]. The ingoing MHD flow ejected from a plasma source with low velocity must be super-magnetosonic at the event horizon, so that the two magnetosonic surface are require in front and behind the shock front (see Fig. 1b). By the generation of the MHD shock, a very hot plasma region can be formed near the event horizon [5]. Such a hot plasma region can be considered as a source of high energy radiation, which gives us information of the strong gravitational field in addition to the (magnetized) plasma state. Of course, some part of the radiation emitted from the hot plasma will fall into the black hole because of gravitational lens effects, but we can expect that huge energy can be released at the very hot shocked plasma region and considerable flux will be obtained. In the following sections, we introduce transmagnetosonic accretion flows [7] and apply the shock condition in §2. Then, in §3, we treat *negative* energy MHD inflows [3] and discuss the energy release of the rotational energy of the black hole at the shocked region. In §4, we present the outline of radiative MHD shocks [8] for obtaining the energy spectrum and the image of a shocked region.

2 MHD Accretion with MHD Shock

We consider MHD flows in a stationary and axisymmetric magnetosphere of a rotating black hole (see, e.g., [3, 9]). The background metric 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 assume ideal MHD condition and the polytropic relation. In these situations, there are five field-aligned flow parameters; the total energy E, the total angular momentum L, the angular velocity of the magnetic field line Ω_F, the number flux per flux-tube η and the entropy. The critical conditions at the Alfvén point and the magnetosonic points restrict the acceptable ranges of these parameters (see [7] for the details). To obtain a shocked black hole accretion solution, it is

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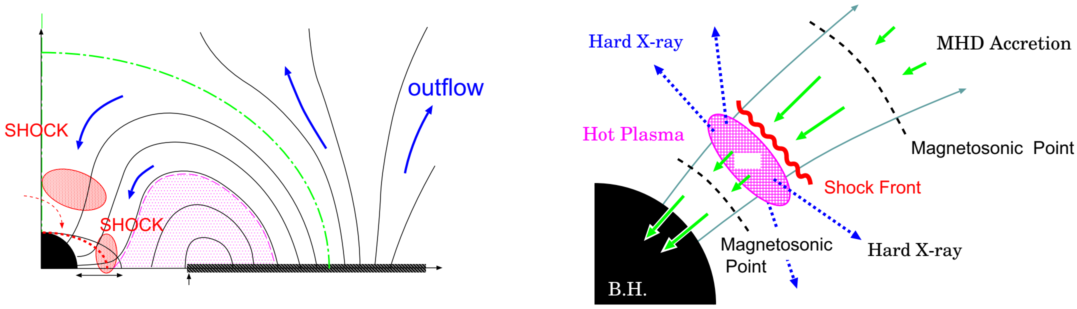

Figure 1: (a) A model of the black hole magnetosphere. Ingoing MHD flows stream along the disk–black hole connected magnetic field lines. Because of the loop-shaped magnetic field configuration, off-equatorial shock is possible. (b) MHD shock in black hole accretion. After passing through *first* magnetosonic point, the MHD inflow can make the MHD shock. The postshocked sub-magnetosonic flows must pass through the *second* magnetosonic point again before reaching the event horizon.

necessary to find the two transmagnetosonic solutions; that is, the upstream and downstream solutions. At the shock location, where the shock conditions must be satisfied, the super-magnetosonic branch of the upstream solution is connected to the sub-magnetosonic branch of the downstream solution. After the shock, the inflow must pass through the second magnetosonic point again, and then can fall into the horizon. The upstream and downstream solutions would have different energy and angular momentum because of the radiation loss, but the conservation of the angular velocity and the number flux between the upstream and downstream solutions is assumed at present. Recently, Fukumura, Takahashi & Tsuruta [6] investigates the accretion solutions with the fast MHD shock. Figure 2 shows the possible shock range in the poloidal plane. When the angular velocity of the magnetic field lines are rather faster than the Kepler velocity estimated at the footpoint of the field line, the shock can be generated, while for slowly rotating magnetic field lines there are no shock fronts. The energy E and angular momentum L are also restricted within the certain ranges of parameter spaces. It is interesting that for faster rotating case the acceptable parameter range for the shock front shifts toward the polar region; the MHD shock formation near the equatorial region is forbidden. Such a situation may not be stable when we consider inflows originated from the equatorial thin disk, which rotates with Kepler velocity. However, when high-energy MHD fluid ($E \gg m_p$) falls along faster rotating magnetic field line, the MHD shock is generated in the high-latitude region of the black hole. Thus, a ring shaped hot region would be observed close to the black hole like an aurora (see Fig. 3).

3 High Energy Radiation powered by Rotating Black Hole

Rotational energy of a black hole can be extracted by magnetic field lines [3, 10]. The extracted energy is carried to the magnetosphere in the form of outgoing Poynting flux, and would be converted to some kinds of fluid energy related to the radiative process directly. Then, the extracted hole's energy can be observable for us. However, in the treatment of the force-free (magnetically dominated limit) magnetosphere, realistic conversion mechanisms are not clear, although some ideas may be proposed. We are now discussing the MHD accretion onto a black hole. Although the MHD inflow takes the fluid energy into the hole, which is positive at the plasma source, the total (fluid + magnetic) energy can be *negative* from the plasma source to the horizon. In general, we understand that the kinetic energy of the upstream MHD flow converts to the thermal and magnetic energies of the downstream flow at the fast MHD shock. When the negative energy accrete onto the black hole (i.e., energy extraction by MHD flows), we can also expect the energy conversion from the extracted hole's energy to the radiative energy at the MHD shock. By considering the regularity condition at the Alfvén point, which is related to the amount of jump of the energy and angular momentum between the preshock and postshock solutions, we find the necessary condition for doing such a energy release process (Takahashi & Takahashi 2007, in preparation). To complete the black hole's rotational energy release at the MHD shock, we must link this

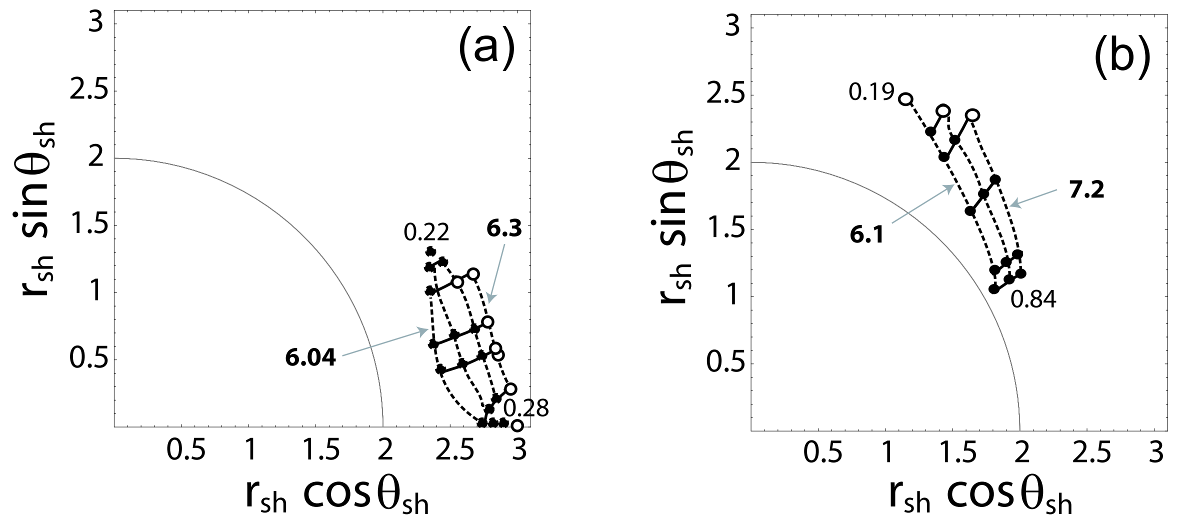

Figure 2: The possible range of the fast MHD shock front for (a) $\Omega_F = 0.1m$ and (b) $\Omega_F = 0.2m$ [6]. The solid curves show $L\Omega_F/E =$ constant, and the dotted curves show the $E/m_p =$ constant, where m_p is the particle's rest-mass energy. The radial magnetic field lines are assumed.

Alfvénic necessary condition to the requirement by the regularity conditions at the fast magnetosonic points, consistently. That remains to be proved.

4 Radiative MHD Shock

Although we discuss the activity of plasma around a black hole in the frame work of general relativity, the shocks and emission process are essentially local phenomena, which can be treated by special relativity. We have discussed the global shocked accretion solutions, which are two transmagnetosonic solutions with a MHD shock as mentioned above, in Boyer-Lindquist coordinates. To introduce the radiative process in the MHD shock solution, Takahashi & Takahashi [8] discuss this problem in the local plasma frame, and then transform the physical quantities in the local frame to that of the curved spacetime; in actual numerical calculation, three kinds of reference frames are utilized; that is, the Boyer-Lindquist frame, Zero-Angular Momentum Observer (ZAMO) frame and the fluid rest frame. Compared with the global solution (plasma density, temperature, etc) denoted in curves spacetime, the restrictions on the local plasma quantities are also determined. When radiation process (synchrotron radiation, bremsstrahlung, inverse Compton scattering, etc.) are specified, local energy spectrum at radiative shock is obtained. In order to calculate the observed spectrum and image of the radiative MHD shock around a black hole, null geodesics from the black hole area to us should be calculated exactly. Such calculations include the Doppler effects of plasma motion and general relativistic effects such as bending of light, gravitational redshift and frame dragging effects. Thus, we present a theoritical tool to find the evidence of black holes in the observed spectrum and the images (see [8] for details).

5 Summary

The general relativistic MHD is applied to a black hole magnetosphere, and transmagnetosonic ingoing flows are discussed. The MHD shock conditions are also discussed, and the possibility of very hot shocked plasma region is indicated very close to the black hole. We can expect that the high energy emission from this hot plasma bring to us *additional* information about the black hole spacetime; the polar region emission including this information can be distinct from the emissions from the equatorial plasma source, which have investigated by many authors in models of black hole accretion. In this stage, expected energy spectrum from the off-equatorial MHD shock is not clear. We need a realistic model of the black hole

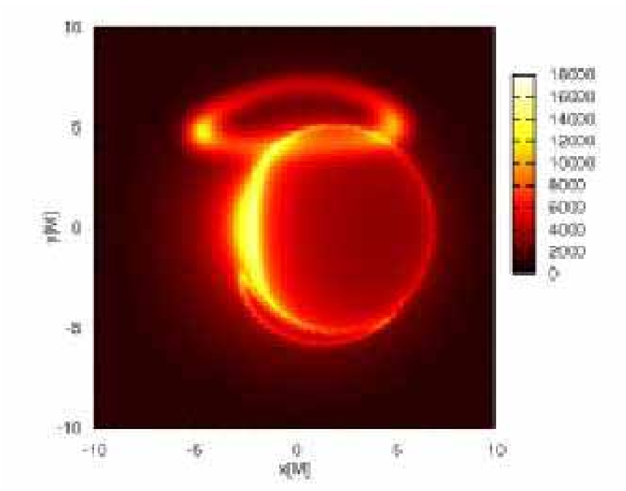

Figure 3: Image of the radiative MHD shock with radiatively inefficient accretion flows (RIAF) around a Kerr black hole [8]. The split-monopole magnetic field is assumed. The shape of the emission region is just like a aurora (black hole aurora). In this calculation, the shock in the Northern hemisphere is considered, but the ghost of the shock is also seen in the Southern hemisphere because of the gravitational lens effect. The crescent-shaped bright area, which is the radiation from RIAF, is cased by the Doppler boosting.

magnetosphere with a magnetized accretion disk. Then, we will find the evidences of the existence of *real* black holes (not the candidate) in observational data.

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