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Black Hole Magnetospheres and Stationary MHD Flows

ブラックホール磁気圏と定常MHD流

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We study stationary, axisymmetric, ideal MHD flows emanated from a thin accretion disk surrounding a central black hole. In particular, we consider a global field-line configuration of the disk-black hole magnetosphere, where the inflow region exists inside of the outflow region. Using a new procedure for obtaining flow solutions regular at the MHD critical points, we discuss the conditions for magnetic connection of the inner part of the disk to the black hole. Further, asymptotic acceleration of outflows to relativistic speeds is shown to occur in propagation along open field lines extending from the outer part of the disk to infinity.

1. Introduction

In various energetic astrophysical phenomena a black hole surrounded by an accretion disk is believed to play an important role of the central engine. In particular, plasma jets with relativistic speeds are observed in active galactic nuclei, microquasars, and possibly γ -ray bursts. Formation of highly collimated jets strongly suggests the existence of large-scale magnetic fields in the disk-black hole system. Further a magnetic braking of the rapidly rotating black hole or accretion disk via the transport of angular momentum is also expected to be an interesting mechanism of energy supply to ambient plasma.

To understand the efficiency of such magnetic effects, in this talk, we study a stationary, axisymmetric model for the magnetosphere under the influence of gravity due to a rotating black hole. A geometrically thin accretion disk is assumed to be located at the equatorial plane. We discuss magnetic connection of the disk to the black hole and to infinity, by considering ideal MHD flows emanating from the equatorial plane without specifying any details of the disk structure. Our main purpose is to reveal some basic features of the general relativistic MHD flows in relation to energy transport and jet formation.

2. Global Field-Line Geometry

It is well-known that any poloidal plasma flows should propagate along poloidal magnetic field lines to satisfy the axisymmetric, stationary, ideal MHD equations. Further, near the black hole only inflow motion of plasma is allowed due to strong gravity, while only outflow motion is allowed near a distant region apart from the equatorial plane, where any plasma source for accretion does not exist. Then, a direct magnetic coupling of a black hole to infinity may not be realized under the condition of smooth MHD flows.

Therefore it is a plausible assumption that all the field lines threading the black hole are connected to an inner part of the disk. This means the existence of a separatrix which divides the magnetosphere into the inner inflow region and the outer outflow region. Such a global configuration of poloidal field lines can be naturally obtained even if we

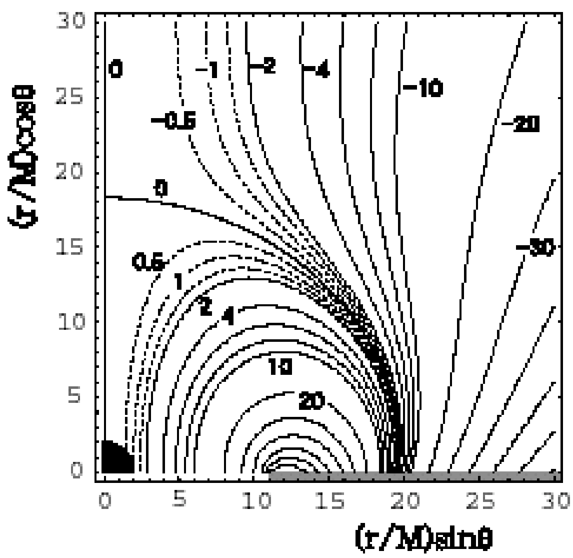

Fig. 1. A typical vacuum solution of poloidal field lines in the disk-black hole system. The magnetic field is generated by disk currents at the equatorial plane [1].

consider vacuum solutions of magnetic fields generated by disk currents [1] (see Fig.1). However, for this vacuum model there exist closed loop field lines in the inflow region, along which no stationary flows are allowed at the equatorial plane between the disk's inner edge and the hole's surface. Any MHD effects may be able to change the field-line configuration to the form drawn schematically in Fig.2 [2], which is the problem to be discussed in the next section.

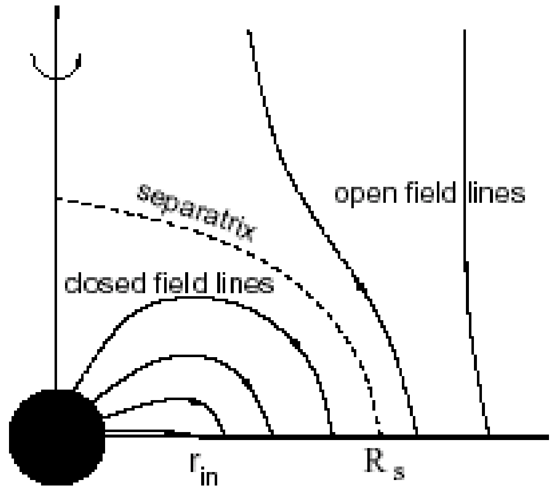

Fig. 2. A schematic configuration of poloidal field lines without closed loops connecting the upper disk surface to the lower one [2].

3. Stationary MHD Flows

For stationary, axisymmetric MHD flows several quantities become constant along each poloidal field line given by $\Psi(r, \theta)$ = constant, where Ψ is the poloidal magnetic flux function. For example, total energy E and angular momentum L carried by MHD flows in a magnetic flux tube are dependent only on Ψ. Because L should be zero on the polar axis, it should vanish also on the separatrix connected to the axis. Then the inflows in the inner region may be assumed to have negative L, if the outflows in the outer region propagate to infinity with positive L. This transport of negative L allows the inflows to carry negative E into the black hole rotating with the constant angular velocity Ω_H larger than the angular velocity Ω_F (which may be dependent on Ψ) of magnetic field lines.

The evolution of Alfven Mach number M along a magnetic field line is described by the so-called poloidal wind equation. If as usual it is solved under an assumed field-line configuration Ψ, we must deal with the problem of regularity at the MHD critical points. We find that in order to avoid such a regularity problem, the Alfven Mach number M should be given as the function of the poloidal electric-to-toroidal magnetic field amplitude ratio ξ (instead of Ψ).

On the hole's surface (i.e., the event horizon) the Alfven Mach number M corresponding to inflow motion of plasma cannot be zero. Then the poloidal wind equation leads to the boundary condition $\xi=1$ on the event horizon, from which we obtain the following inequality (written with the unit c=1)

$$\left|\frac{\partial\Psi}{\partial\theta}\right| \leq \frac{4\pi\eta(E-L\Omega_H)}{(\Omega_H-\Omega_F)^2\sin\theta} . \qquad (1)$$

Here η is the particle number flux in a magnetic flux tube and is dependent only on Ψ. The magnetic flux across the horizon is restricted by the inequality (1). The constants of motion E, L, Ω_F, η will be determined by the condition at the inner part of the disk, where the flux function Ψ is in a range from Ψ_{in} (for the field line emanated from the inner edge) to Ψ_S (for the separatrix). We can claim that if the inequality (1) breaks down for the condition for MHD inflows given at the disk surface, closed loops shown in Fig.1 should appear in the magnetosphere and induce MHD shocks at the equatorial plane.

The MHD inflows with negative E can transport energy from the black hole into the inner part of the disk. Via further energy transport in the disk a huge positive E (much larger than particle's rest mass energy $m_P c^2$) will be supplied to the MHD outflows. However, near the disk surface the dominant portion of energy flux is just the Poynting flux. To produce plasma jets with relativistic speeds, efficient conversion of magnetic energy to kinetic energy should occur in propagation to a large distance beyond the light cylinder radius R_L. From the poloidal wind equation we find that if the field amplitude ratio ξ approaches nearly unity, the kinetic energy begins to be dominant. It is shown that such a dynamical fine-tuning of ξ is realized for jet flows confined within small opening angles at the cylindrical radius larger than $R_L E/m_P c^2$ [3]. Asymptotic collimation of field lines is another important result in this acceleration process.

References

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