

Particle acceleration in force-free magnetospheres around rotating black holes - the outer gap models -

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Abstract

We consider the position of the outer gap in a disk-hole system without solving the Grad-Shafranov equation for the force-free magnetosphere. It is believed that the magnetosphere around the rotating black hole surrounded by the accretion disk, such as active galactic nuclei, mainly causes high energy phenomena. In the force-free magnetospheres of pulsars, it is known that the accelerating electric field arises in a charge depletion region from the so-called Goldreich-Julian charge density and can influence to produce high energy gamma-rays, as the outer gap and polar-cap models. We focus on the magnetosphere of the closed-field configuration in which the magnetic field lines directly connect the hole to the disk, and apply outer gap models of a pulsar to it. As a result, it is shown that gaps can arise in the region with both the closed field from the hole to the disk and the open field from the disk to infinity. We also estimate the size of the gap, the energy of a particle accelerated in the gap, and the energy of gamma rays emitted from the gap.

1 Introduction

Recent observations show that the central engines of active galactic nuclei (AGN), the supermassive black holes, most probably operate as powerful particle accelerators. Also, AGN are possible candidate sites of high energy cosmic ray acceleration, which is supported by Auger observations [1] although there also are arguments against it [2]. At the least, it's considered that particles, such as electrons and protons are accelerated to high energy in AGN. As the way to reveal it, it has been considered that the black hole magnetosphere which is formed by a supermassive black hole in AGN operates on the particle acceleration. Blandford-Znajek process in the force-free black hole magnetospheric model which is the model of a stationary, plasma-filled magnetosphere around a rotating black hole is used to explain extracting the energy from a black hole [3]. It's well known as explanation for the energy of the jet. But, it cannot show the concrete way to accelerate particles. So, as one model, we show that an "outer gap" in the force-free magnetosphere effectively operate particle acceleration.

2 Outer gap and force-free magnetospheric model

The outer gap model is known as a model of γ -ray emission in pulsar magnetospheres and is successful in explaining the observation [4, 5, 6]. This is a strong electric field sustained along a magnetic field line in force-free magnetospheres. In force-free magnetospheres, the charge density should keep the Goldreich-Julian charge density:

$$\rho_{\text{GJ}} = -\frac{1}{4\pi} \nabla \cdot \left(\frac{\delta\Omega}{\alpha} \nabla \Psi \right), \quad (1)$$

where $\delta\Omega \equiv \Omega_F - \omega$, $\Omega_F = \Omega_F(\Psi)$ is angular velocity of the field line, $\Psi(r, \theta)$ is poloidal magnetic flux function, and α and ω are the lapse function and the angular velocity of zero angular momentum

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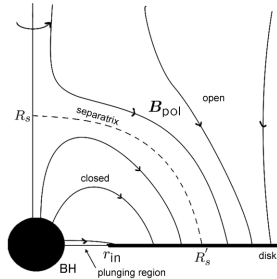


Figure 1: Schematic drawing of a magnetically coupled configuration. The magnetic flux connects from the disk to the black hole inside the separatrix and from the disk to infinity outside the separatrix. The separatrix arrives at the point $r = R_s$ above the pole from the point $r = R'_s$ in the equator.

observers, respectively, and the charge-separated plasma cannot be accelerated. But, the “null charge surface” (or simply “null surface”) where ρ_{GJ} vanishes could be regions with a strong electric field E_{\parallel} sustained along a magnetic field line. Although the emerging E_{\parallel} would act to move available charge into (from) the charge deficient (excess) region if the charge density ρ_e differed significantly from ρ_{GJ} in any region, there is not enough available charge to redistribute near this surface. So, this charge deficit leads to the emergence of the stationary gap. E_{\parallel} is given by the Poisson equation:

$$\nabla \cdot \mathbf{E}_{\parallel} = 4\pi (\rho_e - \rho_{GJ}), \quad (2)$$

where $\rho_e \equiv e(N_+ - N_-)$ is the charge density defined by the difference between positive and negative charges.

Application of the outer gap to black hole magnetospheres was originally examined by Beskin *et al.* [7] and the more quantitative study was developed by Hirotani & Okamoto [8]. However, we regard the outer gap as the particle accelerator for the γ -rays and cosmic rays emission. Since it's considered that the accretion disk is the source of protons and heavy nuclei which are charged particles of cosmic rays, we hope to consider a model that the charged particles flow from the disk to the outer gap and are accelerated there. But this cannot be realized in the black hole magnetospheres with uniform or monopole fields which the past study showed because no magnetic field line connected from the disk to the gap exists in it. Neronov *et al.* showed that it's possible to accelerate the particle flowing from the disk in the gap of the polar region by absence of alignment of the magnetic field with the black hole rotation axis [9]. However, since the magnetosphere which they assumed isn't force-free magnetospheres but vacuum ones, it was inadequate for the plasma-filled ones.

So, we focus on the particle acceleration in the gap and the particle flow from the disk to infinity in the force-free black hole magnetosphere. This is realized by the magnetically coupled configuration of which the most simple model is that all magnetic field lines from the black hole connect to the disk and the magnetic field line outside the separatrix which is the boundary between open field lines and closed field lines connect from the disk to infinity (see Figure.1). Its one model is numerically solved by Uzdensky [10]. We research the position of the outer gap in this topology and consider if it can accelerate the particle from the disk. Also, we roughly estimate the gap width and the voltage drop.

3 The position of the outer gap

Since the outer gap emerges around the null charge surface, we search the position of null charge surface. Although we need to solve the generally relativistic Grad-Shafranov equation for force-free magnetospheres in order to solve $\rho_{GJ} = 0$ (for need of magnetic flux Ψ), we don't solve it exactly. Instead, we use such equation as the second-order derivatives Ψ in the Grad-Shafranov equation is substituted for (1):

$$\rho_{GJ} = \frac{1}{D} \left[\frac{\alpha^3}{4\pi\varpi^2} \frac{\delta\Omega^2\varpi^4}{\alpha^4} \nabla \cdot \left(\frac{\alpha^2}{\delta\Omega\varpi^2} + \omega \right) \cdot \nabla \Psi + \frac{1}{4\pi\alpha} \delta\Omega I \frac{dI}{d\Psi} \right], \quad (3)$$

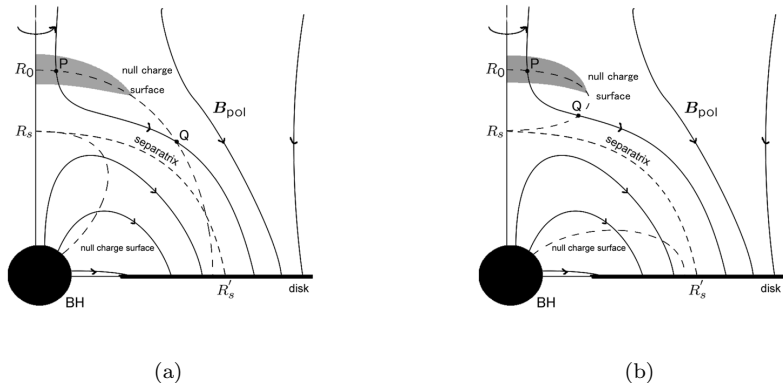


Figure 2: The possible configuration of null charge surfaces to eject from the disk to infinity. Both configurations can accelerate the charged particle flowing along the field to infinity in polar region. Directing our attention to the magnetic flux right outside the separatrix, the region of the gap is the gray region.

where $D \equiv \alpha^2 - \delta\Omega^2\varpi^2$, $\varpi \equiv \sqrt{g_{\varphi\varphi}}$ in Boyer-Lindquist coordinate and $I = I(\Psi)$ is $2/c$ times the poloidal electric current flowing through the circular loop $r = \text{const}$, $\theta = \text{const}$. Of course, it is difficult to solve this equation. So, we expect the position of $\rho_{\text{GJ}} = 0$ by finding it in the polar region, on the equator, and on the vent horizon.

As a result, we found that two surfaces are in the polar region, one surface is near the horizon and one surface is on the equator. One surface in the polar region is on the separatrix and the other is on the corotation point ($\delta\Omega = 0$). The surface on the horizon is on the magnetic field line with the maximal current ($I(dI/d\Psi) = 0$). And, The surface on the equator is on the corotation surface if its surface is on the plunging region which is between the black hole and the disk or between the magnetic field line with the maximal current and the separatrix ($r = R'_s$ in Figure.1) if the corotation surface is on the disk. We can expect the configuration of the null charge surface by connecting their four boundaries. In the expected configurations, the model where particles flowing from the disk are accelerated to infinity is realized in the case where the gap emerges in the open field region near the polar axis (Figure.2). The condition of this model is that the corotation surface in the polar region is outside the separatrix. The difference between two configurations of Figure.2 is a difference of the position between the corotation surface $r = R_0$ and the separatrix $r = R_s$ on the polar axis. They tend to select (b) in Figure.2 if there is the corotation surface near the separatrix or the configuration of the separatrix is oblate ($R_s < R'_s$). Since the inner null charge surface in (a) in Figure.2 always crosses to the inner light surface (which is the surface of $D = 0$ and the singular surface of the Grad-Shafranov equation), appropriate regularity conditions may be selected on this light surface in order to select (a).

Directing our attention to the magnetic field line in the open field region near the separatrix, charged particles moving along this can be accelerated in the gap near the polar axis (gray color region in Figure.2) and can be ejected to infinity. This field line crosses the null charge surface twice, but it's thought that the gap cannot grow around the inside null charge surface (around the point Q), because the direction of the electric field is opposite and the global electric current is interfered. Such region is filled to the Goldreich-Julian charge density with the charge from the disk or the other gap.

4 Rough estimation of the gap width and the voltage drop

We roughly estimate the gap width and the voltage drop by using one-dimensional equations along the magnetic field lines. In particular, high energy γ -rays are observed not only from luminous AGN, such as quasars and blazars (its luminosity is $\gtrsim 10^{43}$ [ergs s $^{-1}$]), but also from low luminosity AGN, such as weak Seyfert (its luminosity is 10^{40} - 10^{43} [ergs s $^{-1}$]). So, we show the luminosity dependence of them.

The following static physical process is considered in the gap. First, the electric field emerges around the null charge surface because of the charge depletions. Secondly, it accelerates the charged particles in the gap and they emit the γ -ray photons by the curvature radiation or the inverse Compton scattering. Finally, the emitted photons generate electrons & positrons with soft background photons by the pair production and are reduced, whereas the charged particles increase. These processes are shown by self-consistently solving the Poisson equation (2), the kinetic equation with the reaction force for γ -ray emission, and the Boltzmann equation of particles and photons. We roughly estimate these equations and get the gap width H and the voltage drop V_{gap} :

$$H \approx 10^{11} \left(\frac{M}{10^8 M_{\odot}} \right)^{0.79} \left(\frac{L}{L_{\text{Edd}}} \right)^{-0.07} \text{ [cm]}, \quad (4)$$

$$V_{\text{gap}} \approx 10^{12} \left(\frac{M}{10^8 M_{\odot}} \right)^{0.36} \left(\frac{L}{L_{\text{Edd}}} \right)^{-0.21} \text{ [V]}, \quad (5)$$

in the case where curvature radiation is dominant and

$$H \approx 10^9 \left(\frac{M}{10^8 M_{\odot}} \right)^{0.80} \left(\frac{L}{L_{\text{Edd}}} \right)^{-0.40} \text{ [cm]}, \quad (6)$$

$$V_{\text{gap}} \approx 10^7 \left(\frac{M}{10^8 M_{\odot}} \right)^{0.40} \left(\frac{L}{L_{\text{Edd}}} \right)^{-1.20} \text{ [V]}, \quad (7)$$

in the case where inverse Compton is dominant. Here, M is the black hole mass, and L is the luminosity of the soft background photon emitted from the disk and is represented by the ratio of the Eddington luminosity. We found that the curvature radiation is dominant because of the gap width being shorter than the width by inverse Compton scattering if L is less than $10^{-5} - 10^{-6} L_{\text{Edd}}$. Its width is 10^{12} [cm] and the energy gained by the proton, electron and so on is 10^{15} [eV]. Also, we found that the more luminosity lowers, the more energy is high.

5 Summary

We considered the outer gap in the force-free magnetosphere with separatrix. We showed the configuration of the outer gap in it and found that the separatrix formed the gap in the polar region which can eject the particle flowing from the disk to infinity. Also, we estimated the gap width and the energy gained by particles by rough estimation. We found that curvature radiation is dominant and the high energy over TeV is got if the Eddington ratio for accretion is low. So, it's thought that the outer gap is expected as the source of the high energy γ -ray and cosmic ray emission.

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