Vortex-Driven Magnetospheric Heating in Primordial Black Holes

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Abstract

The existence of a photon mass or an efficient accretion process might lead to an extremely high magnetic field. This, in turn, induces centrifugal acceleration, which parametrically triggers the excitation of Langmuir waves. In the final stage, through Landau damping, a significant fraction of the amplified electrostatic waves is converted into heat, warming the magnetosphere of primordial black holes.

Keywords: *Vortex-driven magnetic field; primordial black holes; accretion disk*

1. Introduction

Black hole magnetospheres must always rotate due to the presence of an accretion disk. Such an environment is typically threaded by magnetic fields, which, in combination with rotation, can potentially lead to the efficient acceleration of charged particles—a process known as centrifugal acceleration.

In general it is strongly believed that high and very high energy particles might potentially originate from the magnetospheres of black holes (1–3). This mechanism can work in pulsars (4) and wormholes (5) and generally speaking, its efficiency strongly depends on the strength of the magnetic field induction.

Normally, the magnetic induction is estimated within the framework of the equipartition approximation, which assumes that the magnetic energy density is of the same order of magnitude as the black hole's emission luminosity (3).

Recently, it has been shown that if the photon possesses mass, its vortices can generate strong magnetic fields (6). In particular, black holes that trap massive photons can accumulate increasing magnetic fields, and the maximum magnetic induction a black hole can support may be estimated using a natural equipartition condition $M_{BH}c^2 \simeq B^2 R_g^3/8\pi$ leading to

$$B \sim \frac{c^4}{M_{BH}G^{3/2}} \simeq \frac{2.3 \times 10^{20}}{M_n} G, \tag{1}$$

where c is the speed of light, G denotes the gravitational constant, M_{BH} is the black hole's mass, $R_g = GM_{BH}/c^2$ represents the gravitational mass, $M_n = M_{BH}/M_{\odot}$ is a mass normalized by the solar mass $M_{\odot}$. Such a strong magnetic field will lead to extremely efficient magnetocentrifugal mechanism of acceleration.

This process inevitably leads to the excitation of Langmuir waves, which, in due course, undergo Landau damping, thereby heating the magnetosphere. We have investigated this phenomenon in the context of active galactic nuclei. (7)

In this paper we explore the efficiency of the vortex-driven heating in primordial black holes.

The paper is organized as follows: in Sec.2, we briefly outline the mathematical model, apply it to the objects, obtain results, and in Sec. 3, we summarize them.

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2. Discussion and results

By considering the Bondi accretion model, for the stelalr black hole, the accretion rate can be expressed as (9)

$$\dot{M} = \pi \left(\frac{GM_{BH}}{u_{\infty}^2}\right)^2 \rho_{\infty} u_{\infty} \simeq 1.8 \times 10^{15} \times \left(\frac{M_{BH}}{M_{\odot}}\right)^2 \times \left(\frac{10K}{T_{\infty}}\right)^{3/2} g\ sec^{-1}, \tag{2}$$

where $u_{\infty} = n_{\infty} m_p$ is the sound speed in the interstellar medium, $\gamma_a = 5/3$ and $T_{\infty} \simeq 10K$ are the corresponding adiabatic constant and temperature respectively (8), $\rho_{\infty} = n_{\infty} m_m$ is the mass density of the interstellar medium far from the black hole, $n_{\infty} = 1cm^{-3}$ is the corresponding number density, k_B represents the Boltzmann's constant and m_p is the proton's mass.

By assuming that 10% of the total accretion energy is converted into radiation (10), the resulting luminosity can be estimated as follows:

$$L \simeq \eta \dot{M_{BH}} c^2 \simeq 1.7 \times 10^{35} \times \left(\frac{M_{BH}}{M_{\odot}}\right)^2 \times \left(\frac{10K}{T_{\infty}}\right)^{3/2} erg\ sec^{-1}, \tag{3}$$

where $\eta = 0.1$.

It is worth noting that a rotating magnetic field radiates efficiently, leading to a gradual spin-down of the system. By taking the magnetodipole radiation luminosity into account (8)

$$L_{sd} \simeq \frac{B^2 R_g^6 \Omega_0^4}{6c^3}, \tag{4}$$

one can estimate the corresponding time-scale

$$\tau_{sd} \simeq \frac{Mc^2}{L_{sd}} \simeq 1.4 \times 10^{-4} M_n\ sec, \tag{5}$$

where $\Omega_0 \simeq c^3/(GM)$ is the angular velocity of rotation. Equation (5) clearly shows that the deceleration process is highly efficient; therefore, the angular velocity is expected to reach saturation, when the magnetodypole radiation and the emission power are of the same orders of magnitude. Correspondingly, for the saturated angular velocity one obtains

$$\Omega \simeq \left(\frac{6Lc^3}{B^2 R_g^6}\right)^{1/4} \simeq 0.1 \times \left(\frac{M_{\odot}}{M_{BH}}\right)^{3/4} \times \left(\frac{10K}{T_{\infty}}\right)^{3/2} sec^{-1}. \tag{6}$$

The magnetic field lines co-rotate with angular velocity Ω and charged particles are accelerated in the light cylinder region (LC)—a hypothetical surface where the linear rotational velocity equals the speed of light—at a characteristic length scale $R_{lc} = c/\Omega$. The acceleration process continues until the breakdown of the bead-on-the-wire approximation, at which point the relativistic Lorentz factor reaches the following expression: $\gamma_{e,p}^{max} \simeq (eB_{lc}/(2m_{e,p}c\Omega))^{1/2}$, where B_{lc} is the magnetic field induction on the LC surface and we assume that it has a dypolar behaviour $B \propto R^{-3}$. From the aforementioned expression one can straightforwardly check that $\gamma_e^{max} \simeq 4 \times 10^{17}$ and $\gamma_p^{max} \simeq 3 \times 10^{15}$.

Assuming that the magnetosphere is composed of electrons and protons and applying the tools developed in (3, 7), one can straightforwardly obtain the growth-rate of the exponentially amplifying instability

$$\Gamma = \frac{\sqrt{3}}{2} \left(\frac{\omega_e {\omega_p}^2}{2}\right)^{\frac{1}{3}} J_{\mu}(b)^{\frac{2}{3}}. \tag{7}$$

where $\omega_{e,p} \equiv \sqrt{4\pi e^2 n_{e,p}/m_{e,p}\gamma_{e,p}^3}$ is the relativistic plasma frequency of the corresponding specie (electrons and protons), $\gamma_{e,p}$ and $n_{e,p}$ represent the Lorentz factors and number densities respectively, m_e is the electron's mass, $\mu = \omega_e/\Omega$ and $J_{\mu}(x)$ denotes the Bessel function. If one considers beams with $\gamma_e = 10^3$, $\gamma_p = 10^7$, then from Eq. (7) one can estimate the corresponding increment, $\Gamma \simeq 2.8 \times 10^7 sec^{-1}$, which exceeds by many orders of magnitude the spin rate, Ω, indicating that the energy pumping process is extremely efficient.

Zakharov showed that high-frequency pressure pushes particles out of regions with relatively low density (cavities), causing the local density to decrease even further and initiating a collapse process, when electric field and the length-scale of the cavern behave as (7, 11)

$$\mid E \mid \approx \mid E_0 \mid \frac{t_0}{t_0 - t} \tag{8}$$

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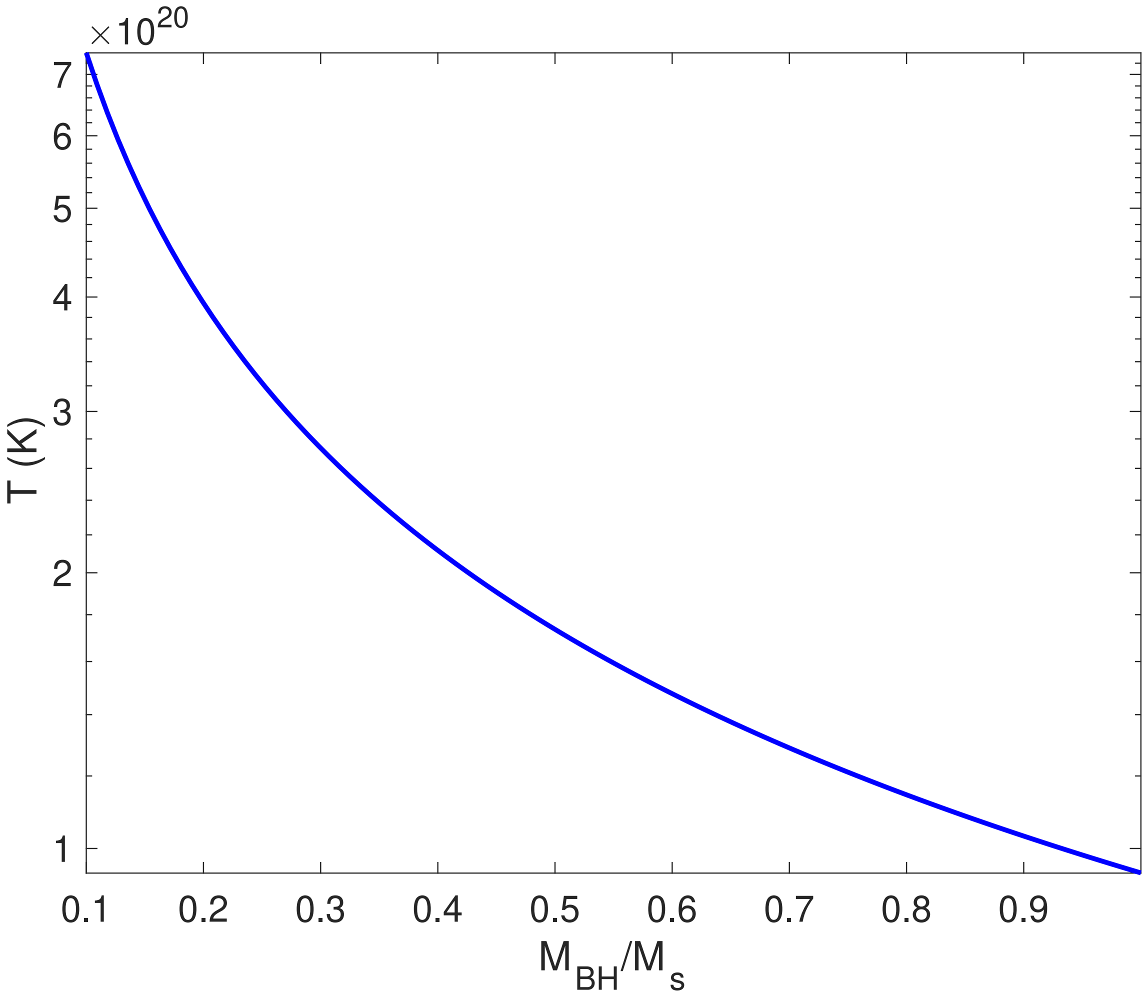

Figure 1. Behaviour of T versus the black hole mass normalized by the solar mass. The set of parameters is: $\kappa = 0.5$, $\gamma_e = 10^3$, $\gamma_p = 10^7$, $\eta = 0.1$.

$$l \approx l_0 \left(\frac{t_0}{t_0 - t}\right)^{-2/3}, \tag{9}$$

where t_0 denotes time when the electric field fully collapses, and $E_0 \approx 4\pi ne\Delta r \exp\left(\Gamma P/4\right)$ is the electrostatic field before the collapse starts, $\Delta r \approx R_{lc}/(2\gamma_{max})$ is a length scale of a narrow region nearby the LC area where the efficient magneto-centrifugal acceleration takes place (2).

The aforementioned equations indicate that, at the critical moment ($t = t_0$), the length scale of the cavities decreases, resulting in the asymptotic behavior of the electrostatic field.

Assuming that a fraction κ, of the total energy is converted into heat, the temperature of the surrounding environment can be estimated

$$T \simeq \left(\frac{\kappa c E^2}{32\pi\sigma}\right)^{1/4}. \tag{10}$$

Figure 1 shows the temperature as a function of black hole mass. The parameter set used is: $\kappa = 0.5$, $\gamma_e = 10^3$, $\gamma_p = 10^7$, $\eta = 0.1$. It is evident from the figure that the magnetospheric temperature can reach extremely high values.

A similar process may occur in the magnetospheres of other astrophysical objects, suggesting the need for further investigation,

3. Summary

By examining the magnetocentrifugal acceleration mechanism, we have explored the potential for heating within black hole magnetospheres.

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It has been shown that vortex-driven magnetic fields can lead to highly efficient particle acceleration.

Magneto-centrifugally accelerated particles trigger the excitation of Langmuir waves, which undergo exponential amplification by extracting energy from the system's rotation.

This process leads to Langmuir collapse, during which a significant fraction of energy is transferred to the magnetosphere, heating it up to temperatures as high as $10^{20}K$.

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