Jet precession in neutrino-cooled disks for gamma-ray bursts: The effects of the mass and spin of a black hole*

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(Received 22 January 2012; revised manuscript received 3 March 2012)

We present a model of jet precession driven by a neutrino-cooled disk around a spinning black hole to explain the quasi-periodic features observed in some gamma-ray burst light curves. The different orientations of the rotational axes between the outer part of a neutrino-cooled disk and a black hole result in precessions of the central black hole and the inner part of the disk. Hence, the jet arising from the neutrino annihilation above the inner disk is driven to precession. We find that the period of precession is positively correlated with the mass as well as the spin of a black hole.

Keywords: accretion, accretion disks, black hole physics, gamma rays, bursts

PACS: 98.62.Mw, 97.60.Lf, 98.70.Rz **DOI:** 10.1088/1674-1056/21/6/069801

1. Introduction

An S- or Z-shaped jet has been observed for many extragalactic radio sources[1] such as Blazars.[2] In Refs. [3] and [4] it was suggested that a tilted accretion disk surrounding a black hole would induce the precession of the black hole and result in an S-shaped jet in the centre of active nuclei, on the basis of the model for the galactic object SS 433.[5] In Ref. [6] it was indicated that the evolution of the half-opening angle of the magnetic flux in a black hole horizon would be modulated by the precession of the jet, which is powered by Blandford–Znajek and magnetic coupling mechanisms. They argued that the modulated evolution of the half-opening angle may play a role in gamma-ray burst (GRB) light curves. The central engine of a GRB can be regarded as a system involving a stellar black hole and a neutrino-dominated accretion flow.[7−13] The different directions of the angular momenta of two compact objects and the anisotropic fall-back mass in a collapsar may induce the precession between a black hole and disk. In this scenario, the inner part of the disk is driven by the black hole in the accretion process. The different orientations of the rotational axes between the outer part of a neutrino-cooled disk and a black hole result in the precessions of the central black hole and the inner part of the disk. Hence, the jet arising from the neutrino annihilation above the inner disk is driven to precession (see Fig. 1), and the global GRB light curves could be modulated by the jet precession on the accretion timescale of the GRB central engine. Both the temporal and spectral evolution in the GRB pulse may be caused by the viewing effect due to jet precession.[11] In the present paper, we concentrate on the investigation of the relationship between the precession period and the mass, as well as the spin of the black hole.

The rest of the paper is organized as follows. In Section 2, we present the equations of our jet precession model. In Section 3, we demonstrate our numerical results, and we give our conclusions and discussion in Section 4.

2. Model

We consider a spinning black hole surrounding a tilted accretion disk in which its rotation axis is misaligned with that of the black hole. Its angular momentum is $J_{\rm BH} = aGM/c^2$, where M is the black hole mass, and a is the dimensionless specific angular momentum, $0 \leq a \leq 1$ (see Fig. 1). Since $\mathrm{d}J = 2\pi r^2 \Sigma \upsilon_\phi \mathrm{d}r$ for a ring with radius r in the disk with width $\mathrm{d}r$, we obtain $J = \mathrm{d}J/\mathrm{d}(\ln r) = 2\pi r^3 \Sigma \upsilon_\phi$, where Σ is the surface density of the disk and υ_ϕ is the rotational velocity of the disk material. Due to the Lense–Thirring effect,[14] the disk material within critical radius $r_{\rm p}$, which is defined as $J(r_{\rm p}) = J_{\rm BH}$,

*Project supported by the National Basic Research Program of China (Grant No. 2009CB824800), the National Natural Science Foundation of China (Grant Nos. 10833002, 11003016, 11073015, and 11103015), and the Natural Science Foundation of Fujian Province, China (Grant No. 2010J01017).

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will be aligned with the equatorial plane of the black hole. Meanwhile, the outer part of the disk ($r > r_{\rm p}$) still has enough angular momentum to keep its original orientation. This makes the black hole precess together with the inner disk, and a precessing jet arising from the neutrino annihilation above the inner disk is therefore driven.[8] The precession rate Ω of the central black hole and the inner disk is given by[5]

$$\Omega = 2GJ(r)/c^2r^3. \tag{1}$$

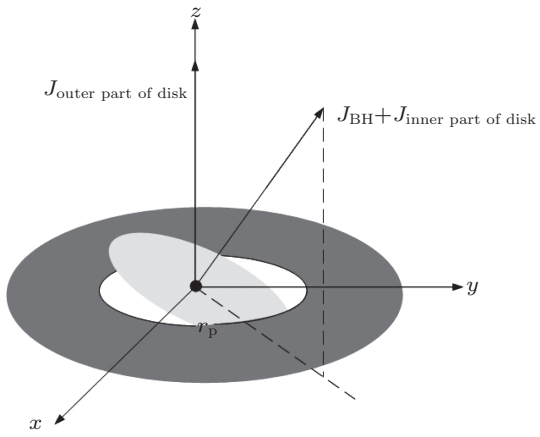


Fig. 1. Schematic diagram of a precessing system.

With the equation of mass accretion rate

$$\dot{M} = -2\pi r\Sigma v_r, \tag{2}$$

the precession period P can be written as[11]

$$P = \pi c^{3/2}G^{-1/2}Ma^{1/2}v_r^{3/2}\dot{M}^{-3/2}v_\phi^{-3/2}, \tag{3}$$

where v_r is the radial inflow velocity.

Here, we simulate the period related to the spin of the black hole. The general relativistic correction factors can be expressed as[6,11,15]

$$A = 1 - \frac{2GM}{c^2r} + \left(\frac{aGM}{c^2r}\right)^2, \tag{4}$$

$$B = 1 - \frac{3GM}{c^2r} + 2a\left(\frac{GM}{c^2r}\right)^{3/2}, \tag{5}$$

$$C = 1 - 4a\left(\frac{GM}{c^2r}\right)^{3/2} + 3\left(\frac{aGM}{c^2r}\right)^2, \tag{6}$$

$$D = \int_{r_{\rm ms}}^{r} (xr)^{-1/2}\left[\frac{x^2c^4}{2G^2} - \frac{3xMc^2}{G} + 4\left(\frac{xa^2M^3c^2}{G}\right)^{1/2} - \frac{3a^2M^2}{2}\right] \times \left[\frac{x^2c^4}{G^2} - \frac{3xMc^2}{G} + 2\left(\frac{xa^2M^3c^2}{G}\right)^{1/2}\right]^{-1} {\rm d}x, \tag{7}$$

where $r_{\rm ms}$ is the marginal stable radius that is defined as the inner boundary of the disk.

The conservation of mass equation remains valid, while the hydrostatic equilibrium in the vertical direction leads to a corrected expression for the half thickness of the disk,[6,11,15]

$$H \simeq \left(\frac{c_{\rm s}}{\Omega_{\rm K}}\right)\left(\frac{B}{C}\right)^{1/2}, \tag{8}$$

where $c_{\rm s}$ and $\Omega_{\rm K}$ are the sound speed and the Keplerian angular velocity, respectively. The viscous shear $T_{r\phi}$ is also corrected as

$$T_{r\phi} = -\alpha p\left(\frac{A}{BC}\right)^{1/2}, \tag{9}$$

and the angular momentum equation can be simplified as[11]

$$T_{r\phi} = \frac{\dot{M}\Omega_{\rm K}}{4\pi H}\left(\frac{D}{A}\right)^{1/2}. \tag{10}$$

Furthermore, the total pressure is composed of

$$P = P_{\rm gas} + P_{\rm rad} + P_{\rm e} + P_\nu, \tag{11}$$

where $P_{\rm gas}$, $P_{\rm rad}$, $P_{\rm e}$, and P_ν are the gas pressure from nucleons, the radiation pressure of photons, the degeneracy pressure of electrons, and the radiation pressure of neutrinos, respectively. Detailed expressions of the pressure components are given in Ref. [8].

Considering the energy conservation, the energetic balance is written as

$$Q_{\rm vis} = Q_{\rm adv} + Q_\nu, \tag{12}$$

where $Q_{\rm vis}$, $Q_{\rm adv}$, and Q_ν are the viscous heating, the advective cooling and the neutrino radiation cooling rate per unit area, respectively. The heating rate $Q_{\rm vis}$ is expressed as

$$Q_{\rm vis} = \frac{3GM\dot{M}}{8\pi r^3}\frac{D}{B}. \tag{13}$$

The cooling rate expressions can be found in Ref. [8].

3. Results

We numerically solve Eqs. (2)–(12) for P by giving α, $\dot{M}$, M, and a. Here we take $\dot{M} = 1M_\odot\ {\rm s}^{-1}$.

Figures 2 and 3 show the variations in the precession period P with the mass and spin of the black hole, respectively. The period of precession positively correlated with the mass as well as the spin of the black hole.

The central black hole would rapidly rotate in a collapsar scenario. Due to the fact that the compact object merges, the spin of the black hole is not strictly as high as in the collapsar scenario. In Fig. 2, an evident positive correlation exists between the precession period P and the black hole spin a. The corresponding variation in the precession period is from about 7 s to 21 s (or 0.67 s to 0.80 s) and a is from 0.1 to 0.998 with viscosity parameter $\alpha = 0.1$ (or 0.01), mass accretion rate $\dot{M} = 1M_\odot$ s^{-1}, and the mass of the black hole $M = 3M_\odot$. Since the increase in black hole spin leads the critical radius $r_{\rm p}$ to increase, the corresponding angular velocity of accreted material decreases, so the precession period increases.

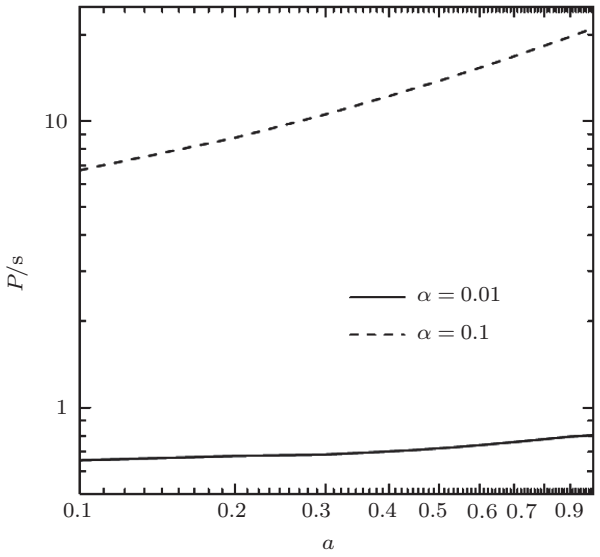


Fig. 2. Curves of the precession period, P, versus the dimensionless specific angular momentum of the black hole, a, with the viscosity parameter, $\alpha = 0.01$ (solid line) and 0.1 (dashed line), mass accretion rate $\dot{M} = 1M_\odot$ s^{-1} and the mass of the black hole $M = 3M_\odot$.

Generally, we consider that the mass range of a black hole is about $2M_\odot$–$10M_\odot$.[8] In Fig. 3, the variation of the precession period is from about 17 s to 37 s (or 0.71 s to 0.90 s) when the black hole mass M varies from $2M_\odot$ to $10M_\odot$ with viscosity parameter $\alpha = 0.1$ (or 0.01), mass accretion rate $\dot{M} = 1M_\odot$ s^{-1}, and black hole spin $a = 0.9$. The increase in the critical radius $r_{\rm p}$ due to the increase in black hole mass results in the other positive correlation between P and M, with a similar reason in Fig. 2.

From these figures, we notice that if taking a reasonable set of these parameters $(\alpha, M, \dot{M})$ in the collapsar scenario, the derived period is consistent with the pulse duration in GRBs. The typical timescale of pulses in GRB prompt emission is below 1 s, which can be considered as the typical jet precession period. We present this period with a low viscosity parameter. Moreover, the periodicity of about 9 s observed in the gamma-ray light curve of GRB 060614[16] can be explained using our model. Based on our model, we find that both the light curve and the $E_{\rm p}$-tracing-flux behaviour in a GRB pulse will be due to an on-axis/off-axis cycle (also see figure 1) of the light of sight of a given observer to a precessing jet.[11]

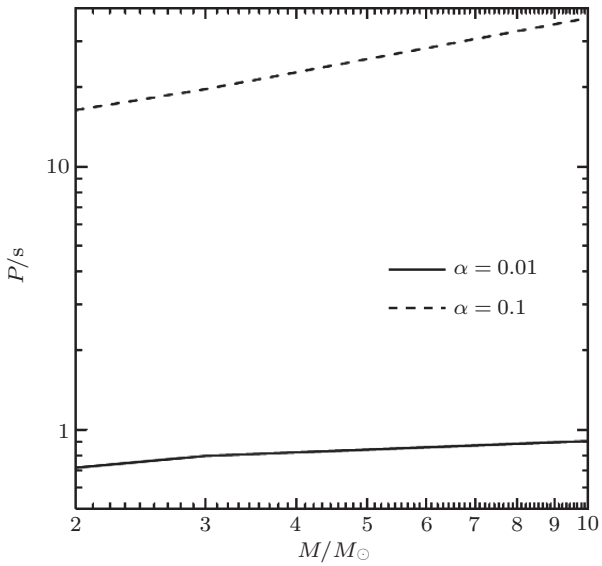


Fig. 3. Curves of precession period, P, versus the mass of a black hole, $M/M_\odot$, with the viscosity parameter, $\alpha = 0.01$ (solid line) and 0.1(dashed line), mass accretion rate $\dot{M} = 1M_\odot$ s^{-1} and dimensionless specific angular momentum of black hole $a = 0.9$.

4. Conclusions and discussion

In this paper, we present a model of jet precession driven by a neutrino-cooled disk around a spinning black hole. The different rotations of the outer region ($r \geq r_{\rm p}$) of a neutrino dominated/cooled accretion disk may result in precessions of the central black hole and the inner part of the disk. Hence, a precessing jet would arise due to the neutrino annihilation above the inner part of the disk. One cannot predict a periodic behaviour with the light curve based on our model. The numeric results show that the precession period is a function of the mass and the spin of a black hole, and we find positive correlations between the precession period and the mass or spin of a black hole. We can estimate the mass or spin of a black hole according to our model when the other parameters of this system are known through other observational methods.

In a hyper-accreting system, accretion evolution will make the mass and angular momentum of the black hole and the disk increase or decrease,[17] and

hence make the evolution of the precession period. Furthermore, the nutation would make the observed light curve too complicated to analyse the periodicity. Thus the calculation or simulation of the time-dependent evolution of this system should be visited.

In our next work, we will discuss the gravitational wave from this precession system. In contrast to the gamma-rays and afterglow emission from an ultra-relativistic fireball, the gravitational radiation should be emitted near the central engine, which is different from that in the case of neutron stars.[18] Gravitational waves are expected to be significant in this black hole-inner disk precession system. It is possible for LIGO, LISA, DECIGO or BBO to be detected.[19]

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