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LETTERS

Origin of power-law X-ray emission in the steep power-law state of X-ray binaries *

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Abstract We present a new explanation for the origin of the steep power-law (SPL) state of X-ray binaries. The power-law component of X-ray emission is the synchrotron radiation of relativistic electrons in highly magnetized compact spots orbiting near the inner stable circular orbit of a black hole. It has a hard spectrum that extends to above MeV energies, which is determined by the electron acceleration rate. These photons are then down-scattered by the surrounding plasma to form an observed steep spectrum. We discuss the relevance of the model to high-frequency quasi-periodic oscillations and the extremely high luminosity of the SPL state.

Key words: accretion, accretion disks — black hole physics — radiation mechanisms: nonthermal — X-rays: binaries

1 INTRODUCTION

The physical origin of the steep power-law (SPL) state, which generates high-frequency quasi-periodic oscillations (HFQPOs), extremely high luminosity and spectra that extend to above MeV, remains one of the outstanding problems in understanding black-hole binaries (BHBs). Most models describing the spectra of the SPL state invoke inverse Compton scattering of seed photons from the disk in a nonthermal corona (Zdziarski & Gierliński 2004; Zdziarski et al. 2005). The origin of the nonthermal electrons has led to models with complicated geometry and feedback mechanisms. Alternative models involve bulk motion Comptonization in the context of a converging sub-Keplerian flow within $50R_g$ of the black hole (BH) (Titarchuk & Shrader 2002; Turolla et al. 2002), where R_g is the Schwarzschild radius. The frequencies of HFQPOs are as fast as the dynamical ones at the inner stable circular orbit (ISCO) of Schwarzschild BHs. Models of HFQPOs involve resonance oscillation modes occurring at specific radii, where the radiating source orbit has the coordinate frequencies that scale like a defined ratio in the Kerr metric (Merloni et al. 1999; Abramowicz & Kluźniak 2001; Remillard et al. 2002; Abramowicz et al. 2003; Kluźniak et al. 2004; Schnittman & Bertschinger 2004; Török et al. 2005; Schnittman 2005; Schnittman & Rezzolla 2006). Schnittman & Bertschinger (2004) and Schnittman (2005) developed a geodesic hot spot model to explain the

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X-ray light curves, in which a collection of "hot spots" or small regions of excess emission move in geodesic orbits near the ISCO. The hot spot model is characterized by the BH mass and spin, the disk inclination angle and simple hot spot properties, such as size, shape and over-brightness.

Current models of the SPL state are deficient in terms of specifying the radiation mechanisms that would imprint a given oscillation mode into the X-ray light curve, such as the radiation component of hot spots. In fact, the HFQPOs are commonly tied to a hard X-ray component, rather than the thermal component that can be directly attributed to the accretion disk. It is unlikely that the HFQPOs come from a cool, thermal spot whose thermal photons are further upscattered by a hot corona. From the photon spectra of the SPL state, there appears to be a hot corona with Compton parameter $y \sim 1$, whose lower energy bands (2–6 keV) have a smaller amplitude modulation. It is difficult to explain the larger significance of HFQPO detections in the higher energy bands (6–30 keV) relative to the signal in the lower energy bands (2–6 keV).

In X-ray binaries, the observed X-ray spectra are fitted by several components, which include a multicolor disk, a power-law or cut-off power-law, a correlation for interstellar absorption, a relativistic Fe line, and a smeared edge. In an SPL state, a power-law component has a steep spectrum and extends to the MeV energy band. The X-ray emission includes the disk emission contribution. The disk mainly contributes to soft X-ray emission as a thermal component. This component is comparable with the power-law component when the X-ray emission is divided into several components through spectral fitting. In this paper, we focus on the origin of the power-law component and propose a new scenario where the X-rays are the synchrotron radiation of highly magnetized compact spots orbiting near the ISCO and have a hard spectrum that extends to MeV energies determined by the electron acceleration rate. These photons are then down-scattered by the surrounding plasma and form an observed steep spectrum. In the innermost disk region, the spot moves like a test particle in the BH field and modulates the observed X-ray flux with HFQPOs through its synchrotron emission. The coordinate frequencies of the orbital motion with a defined ratio present a pair of HFQPOs (Schnittman & Bertschinger 2004; Schnittman 2005). In Section 2, we present the basic relations determining the synchrotron radiation of a magnetized compact spot orbiting near the ISCO and give the Compton scattering mechanism that forms a steep spectrum in high energy bands. In Section 3, we conclude with a discussion of a still open question about the SPL state based on the new scenario.

2 SYNCHROTRON EMISSION AND COMPTON SCATTERING PROCESSES

We assume there is an emitting spot with size $R_{\rm s}$ in the comoving frame where high energy electrons are isotropically distributed in a plasma with random magnetic field directions. The spot has a Doppler factor δ due to its motion relative to the observer, in which the electrons emit synchrotron radiation. In the observer frame, the total energy of the spot is related to the comoving energy density ε by $E = \varepsilon R_{\rm s}^3 \delta$. If a fraction f of this energy is radiated during the observed timescale $R_{\rm s}/(c\delta)$, the observed luminosity is given by

$$E = 4\varepsilon f R_{\rm s}^2 c \delta^4, \tag{1}$$

where the factor of δ^4 comes from the observed luminosity with a beaming effect. We assume that a fraction ε_B of the energy density ε is the magnetic field, then we can estimate the magnetic field B as

$$B = \Big(\frac{8\pi\varepsilon_B L}{f R_{\rm s}^2 c \delta^4}\Big). \tag{2}$$

For an electron with energy $\gamma m_e c^2$, the ratio of the radiative cooling time $t_{\rm syn}$ to the dynamical timescale $t_{\rm d}$ is given by

$$\frac{t_{\rm syn}}{t_{\rm d}} = \frac{6\pi m_{\rm e} c}{\sigma_T \gamma B^2} = 3.0\times 10^{-3}\Big(\frac{L}{L_{\rm Edd}}\Big)^{-1}\Big(\frac{R_{\rm s}}{R_g}\Big)\Big(\frac{f}{\varepsilon_B}\Big)\gamma\delta^4, \tag{3}$$

where $L_{\rm Edd}$ is the Eddington luminosity of the black hole. The condition of efficient electron synchrotron emission is where the dynamical time $t_{\rm d}$ is larger than the cooling time $t_{\rm syn}$. Because the ratio of the two timescales strongly depends on δ, we estimate whether the Doppler factor δ is large from the velocity v_ϕ of the spot orbiting near the ISCO,

$$v_\phi = \frac{r \sin i}{2\pi(r^{3/2} \pm a)}, \tag{4}$$

where a is the spin momentum of the BH, and i is the inclination angle of the spot's orbital plane with respect to the spin axis of the BH. We find the maximum velocity observed to be less than ten percent of light speed and δ is close to one. In the following discussion, we ignore the beaming effect of the spot. If ε_B and f are the same value and $L/L_{\rm Edd}$ is not small, $t_{\rm syn}$ would be much less than $t_{\rm d}$ for relativistic electrons. Therefore, the synchrotron radiation is effective for relativistic electrons in a compact magnetized spot orbiting near the ISCO.

Here, we consider whether the synchrotron can extend to MeV energies. The electrons of the spot are assumed to be accelerated by a specific mechanism. The spectrum of the accelerated electrons determines the energy spectrum of synchrotron radiation. The most general assumption for the spectrum of accelerated electrons is the power-law spectrum with an exponential cutoff at energy γ_0

$$N(\gamma) = N_0 \gamma^{-\alpha} \exp(-\gamma/\gamma_0), \tag{5}$$

where α is the spectral index of the electron. The energy cutoff γ_0 in the spectrum of electrons is determined by the balance between the electron acceleration and cooling times (Guilbert et al. 1983; de Jager et al. 1996).

The acceleration time of electrons is usually given in the following general form

$$t_{\rm acc} = \eta \frac{\gamma m_{\rm e} c}{e B_\perp}. \tag{6}$$

It is assumed that the magnetic field is distributed isotropically, e.g. $B_\perp = \sqrt{2/3}B$. The parameter $\eta \geq 1$ presents the rate of acceleration which could be energy-dependent. In different astrophysical environments, η remains a rather uncertain model parameter due to its highly uncertain acceleration mechanism.

The synchrotron cooling time is given by

$$t_{\rm syn} = \frac{6\pi m_{\rm e} c}{\sigma_T \gamma B^2}. \tag{7}$$

Then the energy cutoff γ_0 is determined by the condition $t_{\rm acc} = t_{\rm syn}$ as

$$\gamma_0 = \sqrt{\frac{6\pi e}{\sigma_T}} B^{-1/2} \eta^{-1/2}. \tag{8}$$

The high energy cutoff of synchrotron emission is given by

$$\epsilon_0 = \frac{3ehB\gamma_0^2}{4\pi m_{\rm e} c} = \frac{9}{4}\alpha_f^{-1} m_{\rm e} c^2 \eta^{-1} = 160\eta^{-1}\ {\rm MeV}, \tag{9}$$

which depends only on the parameter η, where $\alpha_f = 1/137$ is the fine-structure constant. Thus, in the regime of acceleration with $\eta \leq 100$, the synchrotron radiation emitted by a magnetized compact spot can result in an effective production of hard X-rays that extend to above MeV bands.

In addition, electrons are cooled within the spot region. To satisfy physical conditions for radiation, the cooling time has to be smaller than the crossing time, $R_{\rm s}/c$, which yields the minimum magnetic field of

$$B_{\rm min} = \left(\frac{6\pi m_{\rm e} c^2}{\sigma_T R_{\rm s}}\right)^{1/2}. \tag{10}$$

Then, comparing Equations (2) and (10), we obtain the minimum magnetic field

$$B_{\min} = \left(\frac{6\pi m_{\rm e}c^2}{\sigma_T}\right)^{2/3}\left(\frac{fc}{8\pi\varepsilon_B L}\right)^{1/3} \simeq 8.6\times 10^2\left(\frac{f}{\varepsilon_B}\right)^{1/3}\left(\frac{L}{L_{\rm Edd}}\right)^{-1/3}\left(\frac{M}{10M_\odot}\right)^{-1/3}. \quad (11)$$

Non-relativistic or relativistic shock acceleration is the most widely accepted theory for the acceleration of nonthermal particles (Blandford & Eichler 1987; Heavens & Drury 1988; Kirk et al. 2000). The produced electron spectrum has a spectral index of $\alpha = 2.5-3.0$ typically found in the optically thin synchrotron emission of AGNs. The hard X-rays of its synchrotron emission have the photon index of $\alpha_{\rm p} = 1.7-2.0$, which is not consistent with the observed index of an SPL state. In fact, the hard X-ray synchrotron photons will be down-scattered by the surrounding corona to form a softer spectrum. Since the energy of hard photons is higher than the electron energy in the corona, the Comptonization of photons by electrons is unavoidable. The change of the photon spectrum satisfies the equation (Sunyaev & Titarchuk 1980)

$$Z^{-2}\frac{d}{dZ}(Z^4F) - \beta F = -\beta f(Z)Z^{-3}, \quad (12)$$

where $Z = \frac{h\nu}{m_{\rm e}c^2}$, $\beta^{-1} = \frac{3}{\pi^2}(\tau_0 + \frac{2}{3})^2$ corresponding to the mean number of scatterings, τ_0 is the optical depth through the corona and $f(Z)$ is the original spectrum of hard photons. The solution of the above equation is given as

$$F(Z) = \frac{\beta}{Z}\exp(-\beta/Z)\int_Z^\infty f(\zeta)\exp(\beta/\zeta)\frac{d\zeta}{\zeta}. \quad (13)$$

For a power-law spectrum of hard photons $f(Z) \propto Z^{-\alpha_{\rm p}}$ and a corona with $Z/\beta \gg 1$ corresponding to large optical depth ($\tau_0 \gg 1$), we obtain that the Compton scattered spectrum steepens as $F(Z) \propto Z^{-\alpha-1}$. This corresponds to the observed spectrum with a photon index of 2.4–3.0 in the SPL state.

For hard X-ray synchrotron photons ($h\nu \gg 1$), the net effect of the Compton scattering process is a transfer of energy from a photon to an electron. Since the average fractional energy change per scattering is large for high energy photons, the spectral shape at higher energy bands is seriously affected by Compton scattering. In fact, large amplitude fluctuations appear in the higher energy bands based on the X-ray light curves. This implies that most HFQPOs appear more often in higher energy bands. The light curves actually have large amplitude fluctuations in the higher energy bands, as these scattered photons get smoothed out over time. Furthermore, the higher harmonic modes are successfully damped in the scattering process, as is the fundamental peak (Schnittman & Rezzolla 2006).

3 DISCUSSION

We have proposed a new explanation of the emissive origin of the SPL state of an X-ray binary. Our model is based on two standard processes, in which the hard X-ray photons with a power-law spectrum extending to above MeV energies are first produced by synchrotron radiation of magnetized compact spots orbiting near the ISCO. These photons are then down-scattered by the thermal electrons of the surrounding corona to form the observed steep spectrum. The high energy cutoff of the spectrum is only determined by the electron acceleration rate in the spot. In the model, we show that the spot must be small ($R_{\rm s} \sim R_g$) and have a high magnetic field to become an efficient synchrotron source. Since the efficiency and the absolute flux ($\propto R_{\rm s}^2B^3$) of synchrotron radiation depend on the luminosity $L/L_{\rm Edd}$, this implies that the SPL state tends to dominate BHB spectra as luminosity approaches the Eddington limit (McClintock & Remillard 2006).

In a compact spot, its synchrotron emission and following Compton down-scattering process are able to produce the SPL spectrum. As in the hot spot model proposed by Schnittman & Bertschinger

(2004) and Schnittman (2005), the synchrotron spots with different lifetimes move in geodesic orbits near the ISCO and can produce the X-ray light curve with the HFQPO power spectra. This is why the HFQPOs appear in the SPL state and not others. The high energy photons tend to transfer energy into the electrons in the surrounding plasma and form steeper energy spectra; measuring the energy spectra of the different QPOs' peaks would prove extremely valuable in understanding X-ray emission and scattering mechanisms. There are some important messages in the relationship between the power-law emission and the QPO properties. In the sources that exhibit the HFQPOs with a 3:2 frequency ratio, the low frequency QPO appears when the power-law flux is very strong, whereas the high frequency one appears when the power-law flux is weaker (Remillard et al. 2002, 2006). This implies that the power-law photons most likely come from emitting spots. They are affected by Compton scattering since these scattered photons from the spots, generated in outward orbits with low frequency QPO, are less smoothed. The fact that the HFQPOs are seen most clearly in high energy bands challenges the notion that the hard X-ray photons come from the thermal photons of the accretion disk and are then upscattered by a hot corona, since the Compton scatterings seriously dampen the amplitude modulation of the light curves in high energy bands.

The current model proposes that hard photons with energy extending to the MeV range are produced by the synchrotron spots moving in geodesic orbits near the ISCO. The orbiting frequencies of the spots represent the QPO frequencies (Schnittman 2005). It implies that the hard photons tend to show HFQPO. Then these photons go away and are easily Compton down-scattered by the electrons in the surrounding plasma. The higher energy photons are more seriously affected by Compton scattering. Larger amplitude fluctuations appear in the higher energy bands. Therefore, the current model predicts that the large amplitude HFQPOs appear to be more significant in higher energy bands. In most models, the hard photons are produced by a nonthermal coronal Compton up-scattering of soft photons from the disk (Zdziarski et al. 2005). Higher energy photons are not easily produced by Compton scattering because the probability of so many up-scatterings is small. Larger amplitude fluctuations do not easily appear in the higher energy bands. This implies that large amplitude HFQPOs appear less in higher energy bands. Alternative models of high photon production involve bulk motion Comptonization in the context of a converging sub-Keplerian flow within $50R_g$ of the BH (Titarchuk & Shrader 2002; Turolla et al. 2002), but it is not clear how to relate these models to HFQPOs. In fact, the larger significance of HFQPO detections in the higher energy bands supports the current model.

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