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Modeling the quasi-periodic oscillation of Swift J1644+57

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Abstract A 200-second X-ray quasi-periodicity in the $2-8\,\mathrm{keV}$ band from Swift J1644+57 was found by Reis et al. From the onset time of quasi-periodic oscillation (QPO), we show that Swift J1644+57 is a plunging event. This QPO may be related to discrete clumps from the accretion disk falling into a supermassive black hole, then the outflow in the jet may be also discontinuous. We estimate the lifetime of clumps to be about several hundreds seconds and the fraction of clumpy ejecta to be about 30% from the QPO. The other possible model involves the interface between the inflow and jet magnetosphere in the magnetically choked accretion flow. Theory and numerical simulations indicate that a magnetic Rayleigh-Taylor and Kelvin-Helmholtz unstable magnetospheric interface can produce a jet-disk QPO mechanism. This event may be the first evidence of jet-disk QPO. From observations, the two models are comparable.

Key words: accretion, accretion discs — gamma-ray burst: general — radiation mechanism: non-thermal

1 INTRODUCTION

Swift J164449.3+573451 (hereafter Swift J1644+57) was discovered by the *Swift* Burst Alert Telescope (BAT) on 2011 March 28 (Cummings et al. 2011; Burrows et al. 2011). Swift J1644+57 remained bright and variable for a long time, and re-triggered the BAT three times. Levan et al. (2011) estimated the redshift of the optical counterpart of Swift J1644+57 to be $z \sim 0.35$ from the strong emission lines of hydrogen and oxygen. From the observation of the X-ray, optical, infrared and radio transient, it is found that this source is at the center of the host galaxy (Levan et al. 2011; Bloom et al. 2011). This event has been proposed to be a tidal disruption candidate with a jet (Bloom et al. 2011; Levan et al. 2011; Burrows et al. 2011; Zauderer et al. 2011; Reis et al. 2012; Auchettl et al. 2017; Alexander et al. 2017; Bonnerot et al. 2017; Dai et al. 2018). This source may have extracted rotational energy from the black hole (e.g., Lei & Zhang 2011; Shao et al. 2011; Lei et al. 2013; Shen & Matzner 2014; Seifina et al. 2017; Yi et al. 2017). We have constructed a complete scenario for this event (Wang & Cheng 2012; Zou et al. 2013). At earlier times, the central engine ejected shells with higher velocities. They caught up with the outermost slower shell and the consequent reverse shocks produced the early ($1-10^5$ s) X-ray flares (Wang & Cheng 2012). At later times, the central engine generated shells with slower velocities, meanwhile the first shell was decelerated by the medium. Then, ejected shells collide with the decelerating material, and the reverse shocks triggered the late X-ray emission (Zou et al. 2013).

In the later light curves, a 200-second quasi-periodicity with high significance was found in the X-ray band from *XMM-Newton* and *Suzaku* observations (Reis et al. 2012). The *XMM-Newton* observing campaign was carried out 19 days after the BAT trigger with 12 biweekly observations, and the *Suzaku* observation was performed 10 days earlier. The $2-10\,\mathrm{keV}$ power spectra of both the *Suzaku* and *XMM-Newton* observations exhibit a potential quasi-periodic oscillation (QPO) near 5 mHz with quality factor $Q = \nu/\delta\nu \geq 12$ and $\sim$15 for *Suzaku* and *XMM-Newton*, respectively (Reis et al. 2012). The observed QPO at about 5 mHz is statistically highly significant with a significance of 4.33σ (Reis et al. 2012). Burrows et al. (2011) claimed to find no evidence for any statistically significant QPO in the *Swift* X-ray Telescope (XRT) light curve during the first 20 days of observation. Reis et al. (2012) performed a similar Fourier analysis on the same data, and also arrived at the same result. But if zooming into the power spectrum in a narrower frequency range centered at about 5 mHz, a potential QPO feature was also identified at about 6.2 mHz (Reis et al. 2012). Mïller & Gültekin (2011) also located an X-ray QPO with low significance in

Swift J1644+57. Abramowicz & Liu (2012) proposed that the observed QPO belongs to a "3:2 twin peak QPO" associated with a $10^5\,M_\odot$ black hole. Swift J1644+57 is the first tidal disruption event with jet and QPO, so it may give clues on the mechanism of QPO with a jet.

QPOs have been studied in X-ray binaries, in which a neutron star or a black hole is included (Tauris & van den Heuvel 2006). In black hole-X-ray binaries, QPO frequencies may be related to the orbital frequency at the innermost stable circular orbit (ISCO), so QPOs are ideal probes of the strong gravitational field near a black hole. But before we test the strong gravitational fields with QPOs, the mechanism of a QPO must be understood. There are a large number of proposed models for low-frequency QPOs (about $0.1 - 30\,\mathrm{Hz}$) in black-hole binaries, including disk oscillations (Titarchuk & Osherovich 2000), radial oscillations of accretion structures (Chakrabarti & Manickam 2000) and the accretion-ejection instability (Tagger & Pellat 1999). For high-frequency QPOs (HFQPOs, $40 - 450\,\mathrm{Hz}$), Abramowicz & Kluźniak (2001) proposed that the QPO may be related to the harmonic frequencies via a resonance between the coordinate frequencies in general relativity generated by orbiting blobs of accreting matter. Stella et al. (1999) applied general relativity coordinate frequencies and associated beat frequencies to model QPOs in both neutron star and black hole systems. The classical model of a kHz QPO in neutron star sources is the beat frequency model. In this model, one of the kHz QPOs is related to the Keplerian frequency of the orbiting matter and the other kHz QPO represents a beat frequency between the orbiting matter and the spin of the central star (Alpar & Shaham 1985; Lamb et al. 1985; Lamb & Miller 2001).

In this paper, we propose that the QPO of Swift J1644+57 may be related to discrete clumps from the accretion disk falling into the black hole or the interface between the compressed inflow and bulging jet magnetosphere. We find that Swift J1644+57 is a plunging event from the onset time of the QPO in Section 2. We model the QPO in Section 3 and conclude in Section 4.

2 A PLUNGING EVENT DERIVED FROM QPO

If a star with radius $R_\star$ and mass $M_\star$ passes within the tidal radius, $R_T \approx R_\star\,(M_{BH}/M_\star)^{1/3}$, of the black hole with mass M_{BH}, the star will be disrupted. After the star is disrupted, a fraction of about half its mass is placed onto highly eccentric orbits, which returns to the vicinity of the black hole on a timescale (Rees 1988; Ulmer 1999)

$$t_{\rm fb} = \frac{2\pi R_{\rm p}^3}{(GM_{\rm BH})^{1/2}(2R_\star)^{3/2}} = 0.11(\frac{R_{\rm p}}{R_{\rm T}})^3(\frac{M_{\rm BH}}{10^6 M_\odot})^{1/2}(\frac{M_\star}{M_\odot})^{-1}(\frac{R_\star}{R_\odot})^{3/2}\ \mathrm{yr}, \tag{1}$$

where R_p is the pericenter distance. The explicit evolution of the debris is very complex and is dependent on the properties of the black hole and the star. In the tidal disruption event, a large fraction of the debris can circularize and an accretion disk can form due to stream-stream collision after a few orbits (Rees 1988). The circularization time is

$$t_{\rm cir} = n_{\rm orb} t_{\rm fb}, \tag{2}$$

where $n_{\rm orb}$ is the requisite number of orbits for circularization. The value of $n_{\rm orb}$ is greater than unity and probably between 3 and 10. The detection of a QPO about 10 days after the BAT trigger requires that an accretion disk forms shortly after the tidal disruption (Reis et al. 2012). This condition necessitates $n_{\rm orb} \times t_{\rm fb} < 10\,\mathrm{d}$, so the critical fall back time is about $t_{\rm fb} \sim 1\,\mathrm{d}$. For solar-type stars disrupted by a supermassive black hole with mass about $10^6\,M_\odot$,

$$t_{\rm fb} = 0.11\,\mathrm{yr}(\frac{R_p}{R_T})^3 \sim 1\,\mathrm{d} \tag{3}$$

must be satisfied, which gives $R_p \sim 0.29 R_T$. This means that Swift J1644+57 is a plunging event in which the pericenter is likely well within the tidal disruption radius, in agreement with Cannizzo et al. (2011) and Gao (2012).

3 MODELING THE QPO OF SWIFT J1644+57

For the HFQPOs detected in stellar-mass black holes, their frequencies are believed to be related to the Keplerian frequency at the radius of the ISCO. So, this can place important constraints on the masses of the central black holes, because the emission is mainly from the accretion disk. But for Swift J1644+57, the X-ray emission with a power-law spectrum is from a relativistic jet (Bloom et al. 2011; Burrows et al. 2011). The jet emission is also confirmed by radio observations (Zauderer et al. 2011; Berger et al. 2012). We compare this QPO with HFQPOs that are occasionally seen in several black-hole binaries with high coherence. These frequencies appear to be stable, and are regarded as a signature of strong gravity near a rotating black hole. From these objects, a tentative HFQPO-black hole mass relation $f_0 = 931\,(M/M_\odot)^{-1}$ Hz was derived (Remillard & McClintock 2006). Gierliński et al. (2008) concluded that this relation could scale up to supermassive black holes with masses of $10^7\,M_\odot$. The observed frequencies are $2f_0$ and $3f_0$. This gives the central black hole mass of Swift J1644+57 being $3.8 \times 10^5\,M_\odot$ or $5.8 \times 10^5\,M_\odot$, which is consistent with Abramowicz & Liu (2012). However, Cannizzo et al. (2011) estimated the central black hole mass is between $10^6\,M_\odot$ and $10^7\,M_\odot$ based on the decay rates for stellar debris fallback and accretion in a freely expanding super-Eddington disk. Mïller & Gültekin (2011) utilized the fundamental plane of black hole activity and found $\log(M_{BH}/M_\odot) = 5.5 \pm 1.1$. The result is changed to $\log(M_{BH}/M_\odot) = 6.0 \pm 1.1$ when any beaming effect is neglected. Burrows et al. (2011) derived a central black hole mass of $2 \times 10^7\,M_\odot$ based on the Magorrian relation, and a lower limit of $7 \times 10^6\,M_\odot$ based on minimum X-ray variability timescale. So, some of the above derived black hole masses contradict the value from the tentative frequency-mass relation. The QPO from Swift J1644+57 may have a different origin.

We first demonstrate that the X-ray emission is mainly from the jet. The temperature of the thermal radiation from the disk is about (Strubbe & Quataert 2009)

$$T_{\rm d} \sim 2 \times 10^5\, f_{\rm out}^{-1/3} f_{\rm v}^{1/3} (\frac{\dot{M}_{\rm fb}}{\dot{M}_{\rm Edd}})^{-5/12} M_{\rm BH,6}^{-1/4} R_{\rm p,3r_s}^{-7/24}\ {\rm K}, \tag{4}$$

where $r_{\rm s} = 2GM_{\rm BH}/c^2$ is the Schwarzschild radius, $\dot{M}_{\rm fb} \sim M_*/3t_{\rm fb} \times (t/t_{\rm fb})^{-5/3}$, $f_{\rm out}$ is the ratio between the outflowing gas rate and the infalling gas rate, and $f_{\rm v}$ is the ratio of the terminal velocity of gas to escape velocity at the radius $\sim 2\,R_{\rm p}$. If the accretion rate is super-Eddington, only a fraction of $(1 - f_{\rm out})$ can form a disk (Strubbe & Quataert 2009). We can see that the photons that escape from the photosphere are mainly in the ultraviolet (UV) and optical bands with a blackbody spectrum. The disk luminosity is about the Eddington luminosity (Strubbe & Quataert 2009). The jet flux usually would swamp any disk fluxes (see fig. 3 of Burrows et al. 2011). The power-law spectrum is non-thermal (Bloom et al. 2011; Burrows et al. 2011; Berger et al. 2012), so the X-ray emission is not from the disk. Below, we propose two possible models for the QPO in Swift J1644+57.

In the beat frequency model (e.g., Lamb et al. 1985) in order to produce QPO phenomena, we require a high density and discrete accretion flow in the disk. The accretion flow around supermassive black holes is expected to be similar as that around neutron stars (Eardley et al. 1978; McHardy et al. 2006). So for this tidal disruption event, the clumps can form through a similar process as that of Lamb et al. (1985). First, the vertical eruption of the magnetic flux will be amplified by the accretion flow. This strong magnetic flux can produce inhomogeneities in the density and strength of the magnetic field. Second, the clumps can be produced by thermal instability of the inner disk. Third, the Kelvin-Helmholtz instability amplified by the relative motion of the disk plasma and magnetosphere can induce clumps. The formation of clumps is also predicted by numerical simulations. For black hole accretion flow, the Kelvin-Helmholtz instability can also induce clumps (Nowak et al. 1997; Wagoner et al. 2001; Kato 2001; Rezzolla et al. 2003a,b; Li & Narayan 2004; Zhang et al. 2007). Guillochon et al. (2009) performed a three-dimensional (3D) simulation of a main-sequence star deeply penetrating the tidal radius of a massive black hole. At the pericenter radius, different parts of the star orbit with different distances from the black hole, which result in different angular velocities. So the star will eject material, which may form a clump. This scenario is also confirmed by one-dimensional simulations (Laguna et al. 1993; Brassart & Luminet 2008).

Another question is whether the clumps will form with random phases? In this case, it will affect the quality factor of QPO. The accretion flow around supermassive black holes is considered to be similar to that around neutron stars (Eardley et al. 1978; McHardy et al. 2006; Li & Narayan 2004). If the stellar field is not symmetrical, and aligned with the rotation axes of disk and star, the clumps may form with random phases, but this situation is very rare (Lamb et al. 1985). On the other hand, the interaction between clumps and the magnetosphere is greatest at some stellar azimuths. So, the clumps do not form with random phases (Alpar 1986). Even if the clumps form with completely random phases, we can consider that all clumps form at random times but within a narrow range of angles with respect to the axes of the magnetic field. In this case, the QPO can have a high quality factor Q for a wide range of parameters (Alpar 1986). Even if the clumps are distributed randomly, Karas (1999) showed that they can produce a QPO with a high quality factor Q if they are in a narrow range of radius.

Below we discuss whether the clumps can last a long time near the ISCO. Cannizzo et al. (1990) found that the bound material will lie on an orbit with a long period, typically about 1 yr from numerical simulations (Evans & Kochanek 1989). Although the inflow rate is high at the ISCO, the high plasma density may survive a long time (see fig. 2 of Cannizzo et al. 1990). Burkert et al. (2012) studied the evolution of the Galactic center cloud G2 which is already within the tidal disruption radius using a numerical simulation. From their simulation, they predicted that G2 will break up into clumps within the next 30 years and will trigger several active Galactic nucleus events. For plunging event cases, numerical simulations also indicate that the clumps can last a long time (Laguna et al. 1993; Brassart & Luminet 2008; Guillochon et al. 2009). The QPO of Swift J1644+57 existed in the first 20 days after the BAT trigger (Reis et al. 2012), which is consistent with theory and simulations.

So in our following analysis, we shall assume that high density and discrete accretion flow in the disk is satisfied. The characteristic in-fall timescale for an extreme Kerr black hole is

$$t \sim 5r_{\rm s}/v_{\rm K} \sim 5r_{\rm s}/v_{\rm ff}, \tag{5}$$

where $v_{\rm K}$ and $v_{\rm ff}$ are the Keplerian velocity and free fall velocity respectively, and $v_{\rm K} \sim v_{\rm ff} \sim (\frac{GM_{\rm BH}}{5r_{\rm s}})^{1/2}$. In order to produce a 200 sec QPO, the matter falls in discontinuously with a characteristic timescale of about 200 sec. The discontinuous jet is also consistent with the later internal shock model of X-ray flares (Wang & Cheng 2012). Assuming the matter-infall timescale equals the period of QPO, we can obtain

$$\tau_{\rm QPO} \sim 5r_{\rm s}/v_{\rm K} \sim 5r_{\rm s}/v_{\rm ff} = 200 M_{\rm BH,6.12} s\,. \quad (6)$$

We assume that the discrete shells are randomly ejected at times t_i as shot-noise and the lifetime of the shell is τ. Most importantly, the characteristic timescale $\tau_{\rm QPO} = 1/\nu_{\rm QPO}$ corresponds to a periodic modulation injection of the shells. The following equation represents a steady outflow plus clumpy shells with a periodic modulation at a frequency ω_0 (Alpar 1986),

$$\begin{aligned} F(t-t_i;\phi_i) =& A\{1+\beta\cos[\omega_0(t-t_i)+\phi_i]\} \\ & \times \theta(t-t_i)\exp[(t-t_i)/\tau], \end{aligned} \quad (7)$$

where $\omega_0 = 2\pi\nu_{\rm QPO}$, ϕ_i is the azimuthal phase of the ith clump and $|\beta| \leq 1$ (Lamb et al. 1985) is the fraction of discrete shells in the total outflow gas. The lifetime envelope $\theta(t)\exp[t/\tau]$ is chosen for simplicity. The result is not dependent on the form of this envelope (Alpar 1986). The resulting power spectrum can be described as follows (Alpar 1986)

$$P(\omega) = A^2\tau^2\left[\frac{1}{1+\omega^2\tau^2} + \frac{\beta^2}{4}\frac{1}{1+(\omega-\omega_0)^2\tau^2}\right], \quad (8)$$

where τ gives the width of the QPO frequency and $\beta < 1$ represents the percentage of the clumpy component (shells) other than the steady outflow. We add back the amplitude A in Equation (8) and ignore the third term in the original equation of Alpar (1986), because we only consider the positive frequency. The amplitude A could be slowly varying when the accretion rate decreases.

We must note that the QPO only exists in the early stage (about 20 days after the BAT trigger), i.e., *Suzaku* and the first *XMM-Newton* observation. Considering the observational uncertainty, the full-width at half-maximum (FWHM) of the *XMM-Newton* QPO is consistent with that of *Suzaku*. We can use figure 2 of Reis et al. (2012) to estimate the values of τ and β by taking two specific values of ω, i.e., $\omega = \omega_{\rm QPO}$ and $\omega = \omega_{\rm QPO}/2$. At frequency $\omega = \omega_{\rm QPO}$, we can obtain

$$P(\omega = \omega_{\rm QPO}) \approx (A\tau\beta/2)^2 \quad (9)$$

from Equation (8), since $1/(\omega_{\rm QPO}\tau) \ll \beta/2$. In the same way, we also can estimate

$$\begin{aligned} P(\omega = \omega_{\rm QPO}/2) &\approx (2A\tau/\omega_{\rm QPO}\tau)^2 \\ &= (2A/\omega_{\rm QPO})^2 \end{aligned} \quad (10)$$

from Equation (8), since $(\beta/2)^2 \ll 1$. The FWHM is also known as $P(\omega = \omega_{\rm QPO} + \delta\omega) = P(\omega = \omega_{\rm QPO})/2$. Because $P(\omega = \omega_{\rm QPO} + \delta\omega) \approx (A\tau\beta/2\delta\omega\tau)^2$, we obtain $\tau \sim \sqrt{2}/\delta\omega$. Reis et al. (2012) showed that the upper limit of quality factor $Q = \omega/\delta\omega_{\rm QPO} \sim 12$ for *Suzaku* and ~ 15 for *XMM-Newton*, where $\omega_{\rm QPO} = 2\pi\nu_{\rm QPO} \sim 0.03$ rad/s. Therefore, the constraints on τ, β and the clump fraction listed below are only upper or lower limits. So, the lifetime of the shells are

$$\tau \sim Q\sqrt{2}/\omega_{\rm QPO} \sim 562\,{\rm sec} \quad (11)$$

for *Suzaku* observations or

$$\tau \sim Q\sqrt{2}/\omega_{\rm QPO} \sim 720\,{\rm sec} \quad (12)$$

for *XMM-Newton* observations. We also can estimate the value of β as follows. Taking $P(\omega = \omega_{\rm QPO}/2)/P(\omega = \omega_{\rm QPO}) = (4/\beta(\omega/\delta\omega))^2$, we obtain

$$\beta = \frac{4}{(\omega/\delta\omega)\sqrt{P(\omega=\omega_{\rm QPO}/2)/P(\omega=\omega_{\rm QPO})}}. \quad (13)$$

In order to estimate the parameter β, we need to know the ratio between the square of the power spectrum at $\omega_{\rm QPO}/2$ and ω_{QPO}. The power spectra are depicted in figure 2 of Reis et al. (2012). By applying the values displayed in figure 2 of Reis et al. (2012), we can infer $P(\omega = \omega_{\rm QPO}/2)/P(\omega = \omega_{\rm QPO})$ ~1 and ~ 0.75 for *Suzaku* and *XMM-Newton*, respectively. So, $\beta \sim 4/(\omega/\delta\omega)$ ~4/12 for *Suzaku* and ~ 4/15 for *XMM-Newton*, which means the clumpy component comprises about 30%, which is a quite reasonable value.

The *XMM-Newton* QPO frequency (4.7 mHz) looks a bit shorter than that of *Suzaku* (4.81 mHz), although they are statistically consistent. If the QPO frequency actually becomes shorter with time and its amplitude decreases with time, then it also makes the observation difficult at late times. So, only *Suzaku* and the first *XMM-Newton* observation could detect the QPO, but the following 11 observations manifested no QPO signature (Reis et al. 2012).

In our previous papers (Wang & Cheng 2012; Zou et al. 2013), we have also utilized shells and referred to another characteristic timescale $\tau \sim 4.5 \times 10^5 (t/10^6)^{1/4}$ s (Zou et al. 2013), which is related to the duration of the pulse. This longer timescale was first noticed by Saxton et al. (2012). We need to explain their differences. In the early stage, small shells (clumps) with size of $\sim 3r_s$ will first be ejected and combine to form bigger shells (clumps). When these shells further collide with each other, their characteristic timescales will be different. This may be one reason why the later QPO frequency does not show up in other *XMM-Newton* observations. For example if the size increases by a factor of 2 and the QPO frequency decreases by a factor of 2, then the QPO frequency will be hidden inside the red noise.

Because the X-ray emission is from the jet, this QPO is an ideal probe of the jet-disk interaction. Li & Narayan (2004) considered the interface between an accretion disk and a magnetosphere surrounding the accreting mass. Recently, McKinney et al. (2012) performed a detailed simulation of the interface between jet and disk using fully 3D general relativistic magnetohydrodynamics (MHD). For a high spin or thin disk, the polar magnetic field can compress the inflow into a non-axisymmetric "magnetically choked accretion flow" (MCAF) (McKinney et al. 2012), so the standard linear magnetorotational instability is suppressed. McKinney et al. (2012) found that a magnetic Rayleigh-Taylor and Kelvin-Helmholtz unstable magnetospheric interface occurs between the inflow and the jet magnetosphere. This interface can produce a new jet-disk QPO mechanism. The period of the QPO is about $T \sim 70GM_{BH}/c^3 \sim 400M_{BH,6}$ s for $|a/M| = 0.9$ with quality factor $Q > 10$, which is larger than the period of QPO in Swift J1644+57. The reason is that the period of QPO depends on the spin value. For Swift J1644+57, the spin parameter is very high, up to $|a/M| \sim 1.0$ (e.g., Lei & Zhang 2011).

4 CONCLUSIONS AND DISCUSSION

In this paper, we have proposed two possible models for the QPO observed in Swift J1644+57, which is the first disruption event with jet emission and QPO. By considering the QPO to appear about 10d after the disruption, we argue that Swift J1644+57 is a plunging event in which the pericenter distance is likely to be within the tidal disruption radius. Unlike previous QPOs, the disk emission is swamped by jet flux. We also propose two possible models for the 200 s QPO. The first model is related to discrete clumps from the accretion disk which fall into the black hole, then the outflow in the jet may be also discontinuous. The characteristic timescale for the matter in-fall is about 200 s, which is consistent with the period of the QPO. We estimate the lifetime of clumps to be about several hundred seconds and the fraction of clumpy shells is about 30% from the QPO. The second model is related with the magnetospheric interface between the compressed inflow and bulging jet magnetosphere in the MCAF. Recently, McKinney et al. (2012) performed a detailed simulation of the interface between jet and disk using fully 3D general relativistic MHD simulations, and found a new jet-disk QPO. Considering the high spin parameter of the central black hole, the QPO period of Swift J1644+57 is consistent with this jet-disk QPO. This event may be the first evidence of the jet-disk QPO predicated by theory (Li & Narayan 2004; Fu & Lai 2012) and simulation (McKinney et al. 2012). From observations, the two models are comparable. Numerical simulation predicted that the discrete clumps also occur around an intermediate-mass black hole in the case of a white dwarf (Krolik & Piran 2011; Rosswog et al. 2009). But from Equation (6), the period of the QPO is about 10 s for a black hole with mass about $10^5\,M_\odot$, which differs from the observation.

The first model of QPO requires that discrete ejecta must exist. We (Wang & Cheng 2012) have demonstrated that multiple X-ray peaks could result from internal shocks, which are produced by collisions among discrete ejecta. In the first QPO model, we implicitly assumed that the timescale for feeding the black hole (τ_{QPO}) and timescale for injection of shells are the same. Although this assumption is used for the accretion of a supermassive black hole here, it may be also true for stellar mass black holes. It is believed that discrete shells may be randomly ejected in the prompt emission of gamma-ray bursts (GRBs) (Paczynski & Xu 1994; Rees & Meszaros 1994). If this is true then there is a very interesting generalization of our model to the prompt emission of GRBs. Since GRBs are also produced by an accretion-jet mechanism, one may speculate that QPOs also exist in GRBs. QPOs in GRBs with high significance have not been observed. Nine GRB QPO candidates with periods of about $5 - 9$ seconds have been found (Morris et al. 2010), which are consistent with the tidal disruption model of GRBs proposed by Cheng & Lu (2001). For example, Gehrels et al. (2006) identified a possible QPO in GRB 060614 with a period of 9 sec. Lu et al. (2008) proposed that this GRB may be a tidal disruption event and estimated the central black hole mass to be about $10^5\,M_\odot$. Markwardt et al. (2009) reported evidence for quasi-periodical pulsations of 8 sec in the prompt emission of GRB 090709A, but this was questioned by de Luca et al. (2010) and Cenko et al. (2010). By scaling Equation (6) to a stellar type black hole with mass $\sim 3\,M_\odot$, we get $\tau_{QPO} \sim 2 \times 10^{-4}$ sec or 5 kHz for GRB prompt emission. So, our model predicts that kHz QPO could be observed in GRB prompt emission.

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References

Abramowicz, M. A., & Kluźniak, W. 2001, A&A, 374, L19
Abramowicz, M. A., & Liu, F. K. 2012, A&A, 548, 3

Alexander, K. D., Wieringa, M. H., Berger, E., Saxton, R. D., & Komossa, S. 2017, ApJ, 837, 153
Alpar, M. A., & Shaham, J. 1985, Nature, 316, 239
Alpar, M. A. 1986, MNRAS, 223, 469
Auchettl, K., Guillochon, J., & Ramirez-Ruiz, E. 2017, ApJ, 838, 149
Berger, E., Zauderer, A., Pooley, G. G., et al. 2012, ApJ, 748, 36
Bloom, J. S., Giannios, D., Metzger, B. D., et al. 2011, Science, 333, 203
Bonnerot, C., Price, D. J., Lodato, G., & Rossi, E. M. 2017, MNRAS, 469, 4879
Brassart, M., & Luminet, J.-P. 2008, A&A, 481, 259
Burkert, A., Schartmann, M., Alig, C., et al. 2012, ApJ, 750, 58
Burrows, D. N., Kennea, J. A., Ghisellini, G., et al. 2011, Nature, 476, 421
Cannizzo, J. K., Troja, E., & Lodato, G. 2011, ApJ, 742, 32
Cannizzo, J. K., Lee, H. M., & Goodman, J. 1990, ApJ, 351, 38
Cenko, S. B., Butler, N. R., Ofek, E. O., et al. 2010, AJ, 140, 224
Chakrabarti, S. K., & Manickam, S. G. 2000, ApJ, 531, L41
Cheng, K. S., & Lu, Y. 2001, MNRAS, 320, 235
Cummings, J. R., Barthelmy, S. D., Beardmore, A. P., et al. 2011, GRB Coordinates Network, Circular Service, No. 11823, #1 (2011), 11823, 1
Dai, L., McKinney, J. C., Roth, N., Ramirez-Ruiz, E., & Miller, M. C. 2018, ApJ, 859, L20
de Luca, A., Esposito, P., Israel, G. L., et al. 2010, MNRAS, 402, 1870
Eardley, D. M., Lightman, A. P., Payne, D. G., & Shapiro, S. L. 1978, ApJ, 224, 53
Evans, C. R., & Kochanek, C. S. 1989, ApJ, 346, L13
Fu, W., & Lai, D. 2012, MNRAS, 423, 831
Gao, W.-H. 2012, ApJ, 761, 113
Gehrels, N., Norris, J. P., Barthelmy, S. D., et al. 2006, Nature, 444, 1044
Gierliński, M., Middleton, M., Ward, M., & Done, C. 2008, Nature, 455, 369
Guillochon, J., Ramirez-Ruiz, E., Rosswog, S., & Kasen, D. 2009, ApJ, 705, 844
Karas, V. 1999, PASJ, 51, 317
Kato, S. 2001, PASJ, 53, 1
Krolik, J. H., & Piran, T. 2011, ApJ, 743, 134
Laguna, P., Miller, W. A., Zurek, W. H., & Davies, M. B. 1993, ApJ, 410, L83
Lamb, F. K., Shibazaki, N., Alpar, M. A., & Shaham, J. 1985, Nature, 317, 681
Lamb, F. K., & Miller, M. C. 2001, ApJ, 554, 1210
Lei, W.-H., & Zhang, B. 2011, ApJ, 740, L27
Lei, W.-H., Zhang, B., & Gao, H. 2013, ApJ, 762, 98
Levan, A. J., Tanvir, N. R., Cenko, S. B., et al. 2011, Science, 333, 199
Li, L.-X., & Narayan, R. 2004, ApJ, 601, 414
Lu, Y., Huang, Y. F., & Zhang, S. N. 2008, ApJ, 684, 1330
Mïller, J. M., & Gültekin, K. 2011, ApJ, 738, L13
Markwardt, C. B., Gavriil, F. P., Palmer, D. M., Baumgartner, W. H., & Barthelmy, S. D. 2009, GRB Coordinates Network, 9645, 1
McHardy, I. M., Koerding, E., Knigge, C., Uttley, P., & Fender, R. P. 2006, Nature, 444, 730
McKinney, J. C., Tchekhovskoy, A., & Blandford, R. D. 2012, MNRAS, 423, 3083
Morris, D., Battista, F., Dhuga, K., & MacLachlan, G. 2010, American Institute of Physics Conference Series, 1279, 394
Nowak, M. A., Wagoner, R. V., Begelman, M. C., & Lehr, D. E. 1997, ApJ, 477, L91
Paczynski, B., & Xu, G. 1994, ApJ, 427, 708
Rezzolla, L., Yoshida, S., Maccarone, T. J., & Zanotti, O. 2003, MNRAS, 344, L37
Rezzolla, L., Yoshida, S., & Zanotti, O. 2003, MNRAS, 344, 978
Rees, M. J., & Meszaros, P. 1994, ApJ, 430, L93
Rees, M. J. 1988, Nature, 333, 523
Reis, R. C., Miller, J. M., Reynolds, M. T., et al. 2012, Science, 337, 949
Remillard, R. A., & McClintock, J. E. 2006, ARA&A, 44, 49
Rosswog, S., Ramirez-Ruiz, E., & Hix, W. R. 2009, ApJ, 695, 404
Saxton, C. J., Soria, R., Wu, K., & Kuin, N. P. M. 2012, MNRAS, 422, 1625
Seifina, E., Titarchuk, L., & Virgilli, E. 2017, A&A, 607, A38
Shao, L., Zhang, F.-W., Fan, Y.-Z., & Wei, D.-M. 2011, ApJ, 734, L33
Shen, R.-F., & Matzner, C. D. 2014, ApJ, 784, 87
Stella, L., Vietri, M., & Morsink, S. M. 1999, ApJ, 524, L63
Strubbe, L. E., & Quataert, E. 2009, MNRAS, 400, 2070
Tauris, T. M., & van den Heuvel, E. P. J. 2006, Compact stellar X-ray sources, 39, 623
Tagger, M., & Pellat, R. 1999, A&A, 349, 1003
Titarchuk, L., & Osherovich, V. 2000, ApJ, 542, L111
Ulmer, A. 1999, ApJ, 514, 180
Wagoner, R. V., Silbergleit, A. S., & Ortega-Rodríguez, M. 2001, ApJ, 559, L25
Wang, F. Y., & Cheng, K. S. 2012, MNRAS, 421, 908
Yi, S.-X., Lei, W.-H., Zhang, B., et al. 2017, Journal of High Energy Astrophysics, 13, 1
Zauderer, B. A., Berger, E., Soderberg, A. M., et al. 2011, Nature, 476, 425
Zhang, C. M., Yin, H. X., & Zhao, Y. H. 2007, PASP, 119, 393
Zou, Y. C., Wang, F. Y., & Cheng, K. S. 2013, MNRAS, 434, 3463