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A model of fast radio bursts: collisions between episodic magnetic blobs

Long-Biao Li[1,2], Yong-Feng Huang[1,2], Jin-Jun Geng[1,2] and Bing Li[1,2,3]

[1] School of Astronomy and Space Science, Nanjing University, Nanjing 210046, China; *hyf@nju.edu.cn*
[2] Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210046, China
[3] Particle Astrophysics Division, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

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Abstract Fast radio bursts (FRBs) are bright radio pulses from the sky with millisecond durations and Jansky-level flux densities. Their origins are still largely uncertain. Here we suggest a new model for FRBs. We argue that the collision of a white dwarf with a black hole can generate a transient accretion disk, from which powerful episodic magnetic blobs will be launched. The collision between two consecutive magnetic blobs can result in a catastrophic magnetic reconnection, which releases a large amount of free magnetic energy and forms a forward shock. The shock propagates through the cold magnetized plasma within the blob in the collision region, radiating through the synchrotron maser mechanism, which is responsible for a non-repeating FRB signal. Our calculations show that the theoretical energetics, radiation frequency, duration timescale and event rate can be very consistent with the observational characteristics of FRBs.

Key words: accretion — accretion disks — magnetic reconnection — radio continuum: general

1 INTRODUCTION

Fast radio bursts (FRBs) are intense transient flares with a high flux and millisecond duration at radio wavelengths. The first FRB was discovered from a search of archival Parkes survey data (Lorimer et al. 2007). Interestingly, there might be more than one class of FRBs: e.g. repeating and non-repeating ones (Keane et al. 2016; Palaniswamy et al. 2018). To date, one repeating FRB and 29 non-repeating FRBs have been reported (Petroff et al. 2016)[1], but their physical nature still remains unknown. Non-repeating FRBs are found to be generally unresolved, whereas the repeating bursts of FRB 121102 are resolved with a temporal structure. Most FRBs have high dispersion measures (DMs) of $300 \sim 1500\,\mathrm{pc\,cm^{-3}}$, which are defined as the line-of-sight integral of the free electron number density. These DMs typically exceed the contribution from electrons in our Milky Way by a factor of ~ 10 (Li et al. 2017). Lorimer et al. (2007) and Thornton et al. (2013) proposed that a large DM should be largely attributed to the contribution from the ionized intergalactic medium (IGM), and the DM contribution from the host galaxy is estimated as $\mathrm{DM_{host}} \leq 100\,\mathrm{pc\,cm^{-3}}$, which means that FRBs' redshifts would be in the range of $z \sim 0.3 - 1$. Thus, FRBs seem to have an extragalactic or even cosmological origin (e.g. Caleb et al. 2016; Li et al. 2017). Fortunately, the extragalactic origin is confirmed by the repeating source FRB 121102, which allows a precise sub-arcsecond localization and for the first time shows an association with a host galaxy (Chatterjee et al. 2017; Marcote et al. 2017; Tendulkar et al. 2017). The observed fluences and the cosmological redshift of $z = 0.193$ imply that FRBs from the source of 121102 have a typical energy of $E_{\rm iso} \sim 10^{39}\,\mathrm{erg}$ (Chatterjee et al. 2017), if the bursts are isotropic.

FRBs' short durations ($\sim$ a few ms) and high brightness require that their sources should be compact, and the emission should be coherent (Katz 2014; Luan & Goldreich 2014). There are a lot of progenitor models proposed to explain FRBs. For non-repeating FRBs, the models include double compact star mergers (Totani 2013; Mingarelli et al. 2015), interaction of companions

[1] An FRB catalog can be found at *http://www.frbcat.org.*

with the magnetic field of extragalactic pulsars (Mottez & Zarka 2014), collisions of asteroids with neutron stars (NSs) (Geng & Huang 2015), collapses of supermassive NSs into black holes (BHs) (Falcke & Rezzolla 2014; Zhang 2014), magnetar giant flares (Kulkarni et al. 2014; Lyubarsky 2014), giant radio pulses from pulsars (Connor et al. 2016; Cordes & Wasserman 2016), the inspiral of double NSs (Wang et al. 2016), and collisions between an NS and a white dwarf (WD) (Liu 2017). For repeating bursts, the proposed models include asteroids falling randomly onto NSs (Dai et al. 2016; Bagchi 2017), intermittent accretion of materials by an NS from a WD companion (Gu et al. 2016), "cosmic comb" model (Zhang 2017), an active remnant NS after a binary NS merger (Yamasaki et al. 2017), episodic relativistic $e^{\pm}$–beam from an active galactic nucleus (AGN) interacting with a surrounding cloud (Vieyro et al. 2017) or active young remnants of magnetars (Murase et al. 2016; Beloborodov 2017; Kashiyama & Murase 2017; Metzger et al. 2017). In our work, we focus on non-repeating FRBs.

We note that in BH X-ray binaries and AGNs, episodic jets have been observed frequently (e.g. Fender & Belloni 2004; Chatterjee et al. 2009). Episodic jets are intermittent and in the form of discrete moving plasma blobs. They could be generated through magnetohydrodynamical processes as described by Yuan et al. (2009). In this paper, we argue that FRBs can be produced during the merger of a WD with an intermediate-mass BH. Mass transfer from the WD to the BH can generate a transient accretion disk around the BH. Due to shear and turbulent motion of the accretion flow, a flux rope system near the disk is expected. When the equilibrium of the flux rope is broken due to the accumulation of energy and helicity, episodic magnetic blobs are ejected. A collision between two blobs will lead to a catastrophic magnetic reconnection, which then generates a non-repeating FRB via synchrotron maser emission. Our article is organized as follows. In Section 2, we briefly describe the ejection process of episodic magnetic blobs. In Section 3, properties of synchrotron maser emission in the plasma blobs are calculated, and the model results are compared with observations. Finally, our discussion and conclusions are presented in Section 4.

2 EJECTION OF EPISODIC MAGNETIC BLOBS

For a compact binary system consisting of a BH and a WD companion, when the WD fills its Roche lobe, mass transfer can occur and material will flow from the WD to the BH. For a WD with high enough mass, the mass transfer rate should be super-Eddington (Dong et al. 2018), which will trigger a runaway accretion process, leading the WD to merge with the BH. In this case, a transient accretion disk can be formed around the BH. It has been suggested that such a merging system can generate some kinds of gamma-ray bursts (Dong et al. 2018). In the frame of our work, we argue that the transient accretion disk can eject a few episodic magnetic blobs, which then produce FRBs via the collision between two adjacent blobs.

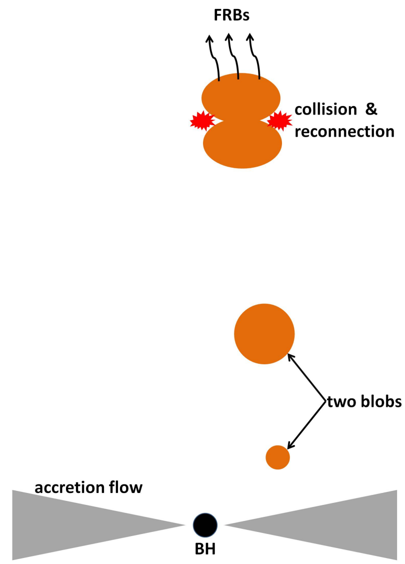

Fig. 1 Schematic illustration of the collision between two episodic blobs. Two consecutive magnetic blobs are ejected from a transient accretion disk. Their collision at a relatively large distance results in catastrophic magnetic reconnection.

Accretion disks actually widely exist around BHs and other kinds of compact stars. High speed wind from accretion disks can lead to the formation of a large scale corona around the accreting system. According to Yuan et al. (2009), closed magnetic field lines, which emerge continuously from the accretion flow to the corona, are twisted and deformed due to turbulence in the accretion flow, producing a flux rope system in the corona. With the accumulation of energy and tension, equilibrium in the system would be broken when the threshold is reached. The flux rope is thrust outward, generating an episodic jet. As the accretion goes on, the above process repeats and a new blob will be produced. In our modeling, two consecutive magnetic blobs moving relativistically at different speeds would collide, resulting in magnetic reconnection and leading to the release of a large amount of free magnetic energy. The energy is dissipated via a synchrotron maser to power the observed FRBs. A schematic illustration of the overall picture of our model is shown in Figure 1.

Let us consider a transient accretion disk surrounding a central BH with a mass of $M_{\rm BH} = 100\,M_\odot$. The disk is assumed to be an advection-dominated accretion flow (ADAF, e.g. Narayan & Yi 1994; Abramowicz et al. 1995; Narayan & Yi 1995; Chen & Beloborodov 2007). A flux rope system is expected to form in this accretion flow (Yuan et al. 2009). Taking the mean mass accretion rate to be $\dot{M} = 10^{22}\,{\rm g\,s^{-1}}$, we then obtain the temperature of the equatorial plane of the disk as (e.g. Narayan et al. 2001; Beloborodov 2003; Yuan & Zhang 2012)

$$T_c = 9.2\times10^7\alpha_{-1}^{-0.25}\dot{M}_{22}^{0.25}m_2^{-0.5}r^{-0.625}\,{\rm K}\,, \quad (1)$$

where α_{-1} is the viscous parameter in units of 0.1, $m_2 = M_{\rm BH}/100\,M_\odot$ and $r = R/R_{\rm s}$ is the dimensionless radius, with $R_{\rm s} = 2GM_{\rm BH}/c^2$ being the Schwarzschild radius. Note that the convention of $Q = 10^x Q_x$ will be used throughout the paper.

Due to the topological structure of the magnetic field, the available free magnetic energy is large in the flux rope region where the magnetic blob forms. Similar to a coronal mass ejection in the Sun, the total available free magnetic energy of one blob is $E_{\rm free} \approx 0.5\times(1/12\,B_0^2\,V)$ (Lin et al. 1998; Yuan & Zhang 2012). Here, B_0 is the magnetic induction intensity and $V = 4\pi R^3/3$ is the volume of the flux rope system. Blackman et al. (2008) and Sorathia et al. (2012) have calculated the strength of the magnetic field with respect to the thermal pressure of the gas ($P_{\rm gas}$) or the radiation pressure ($P_{\rm rad}$). They defined a parameter $\beta = P_{\rm mag}/P$ to denote the ratio of the magnetic pressure over the gas or radiation pressure. Sorathia et al. (2012) demonstrated that a simple relation of $\alpha/\beta \approx 0.5$ usually exists between α and β. For a radiation-pressure-dominated ADAF, $P_{\rm gas}$ is generally much smaller than $P_{\rm rad}$, so that the gas pressure can be neglected and $\beta = P_{\rm mag}/P_{\rm rad}$.

For a given β, the magnetic induction intensity B_0 can be derived from

$$P_{\rm mag} = \frac{B_0^2}{8\pi} = \beta P_{\rm rad} = \beta\frac{4\sigma}{3c}T_c^4, \quad (2)$$

which gives

$$B_0 = 7.2\times10^6\alpha_{-1}^{-0.5}(\beta/0.2)^{0.5}\dot{M}_{22}^{0.5}m_2^{-1}(r/50)^{-1.25}\,{\rm G}. \quad (3)$$

Thus, the available free magnetic energy of one blob near the accretion disk is

$$E_{\rm free} = 2.1\times10^{40}\alpha_{-1}^{-1}(\beta/0.2)\dot{M}_{22}m_2(r/50)^{0.5}\,{\rm erg}. \quad (4)$$

We see that this energy is large enough to meet the requirement for the FRB energy budget.

When the flux rope system suddenly loses its equilibrium, a plasma blob can be violently ejected. The blob is subsequently accelerated by the magnetic pressure gradient (Tchekhovskoy et al. 2010; Kumar & Zhang 2015), moving far away from the accretion flow. Initially, the magnetic blob should be almost stationary and in the non-relativistic phase, but its size can increase, i.e., it is expanding adiabatically with a speed of $\sim c$. The non-relativistic phase lasts for the magnetic reconnection timescale at the base of the flux rope, i.e., $t_0 \sim 2r_{\rm b}/v_{\rm rec} = 1.0(v_{\rm rec}/10^{-2}c)^{-1}m_2(r/50)\,{\rm s}$ (Yuan & Zhang 2012), where $r_b \sim 0.1R \sim 3.0\times10^8 m_2(r/50)\,{\rm cm}$ is the initial radius of the blob. So, the size of the blob expands to $\Delta \sim c\,t_{\rm tec} \sim 3.0\times10^{10}m_2(r/50)\,{\rm cm}$, when the blob transitions from the non-relativistic phase to the relativistic phase.

Fast reconnection leads to a decrease in the magnetic field with radius, which causes effective acceleration of the plasma blob. At a distance of $\sim\Delta$, the blob enters the relativistic phase with a typical Lorentz factor $\Gamma \sim \sigma_0^{1/3}$ (Granot et al. 2011), where σ_0 is the initial magnetization parameter at the base of the accretion flow.

3 SYNCHROTRON MASER EMISSION FROM THE COLLISION

Let us consider two adjacent blobs ejected as mentioned above. We assume that the preceding one moves at a smaller speed, while the latter has a higher bulk Lorentz factor. The faster blob will finally catch up with the earlier slower one. Their collision will lead to a strong shock, similar to what happens in GRBs. These two blobs are initially separated by $d = c\,\Delta t$ (with the faster one lagging behind the slower one), where $\Delta t = z_{\rm rope}/v_{\rm A} = 5.0(\beta/0.2)^{-0.5}m_2(r/50)^{1.5}\,{\rm s}$ is the time interval between the two consecutive blobs, $z_{\rm rope}$ is the height of the flux rope and is adopted as $z_{\rm rope} = 2.5\,R = 3.7\times10^9 m_2(r/50)\,{\rm cm}$, $v_{\rm A} = B_0/\sqrt{4\pi\rho}$ is the Alfvén speed and $\rho = 7.6\times10^{-6}\alpha_{-1}^{-1}m_2^{-2}\dot{M}_{22}(r/50)^{-1.5}\,{\rm g\,cm^{-3}}$ is the density of the corona/ADAF (e.g., Horiuchi et al. 1988; Narayan & Yi 1995; Yuan & Zhang 2012; Meyer-Hofmeister et al. 2017). Assuming that the two blobs have different Lorentz factors of $\Gamma_{\rm fast}$ and $\Gamma_{\rm slow}$ ($\Gamma_{\rm fast} > \Gamma_{\rm slow}$), the corresponding collision radius is $r_{\rm col} \approx 2\,\Gamma^2\,c\,\Delta t$ (Zhang & Yan 2011). Note that hereafter, $\Gamma_{\rm fast}$ is shortened to Γ. The collision of these two highly magnetized blobs is supersonic, resulting in catastrophic magnetic reconnection in the area involved. The reconnection releases a large amount of magnetic energy and forms a shock wave, which propagates through the magnetized, cold plasma within the blobs.

Due to the reconnection and turbulence, a large fraction of the magnetic energy is converted into kinetic energies of particles, which is responsible for particle acceleration and emission, finally powering the radio radiation. The magnetic field in the comoving frame of the plasma blobs decreases as $B' \propto 1/z'$ (Lyubarsky 2009), and the emission volume after the collision is $V_{\rm col} \approx f r_{\rm col}^2 (\Delta/\Gamma)$ (expressed in the observer's frame), where f is the ratio of the solid angle of the emission region with respect to 4π, and it can be adopted as $f \sim \frac{\Delta}{2\pi r_{\rm col}}$. For the emission occurring at a distance $r_{\rm col}$ from the central engine, the energy release is comparable to $E_{\rm free}$. Together with Equations (3) and (4), the Lorentz factor of the bubbles in the collision radius is

$$\Gamma \sim 42.1(\beta/0.2)^{0.5}(r/50)^{-0.5}. \tag{5}$$

The corresponding collision radius is thus

$$\begin{aligned} r_{\rm col} &\approx 2\Gamma^2 c\Delta t \\ &= 5.3\times10^{14}(\beta/0.2)^{0.5} m_2 (r/50)^{0.5}\,{\rm cm}. \end{aligned} \tag{6}$$

After the two consecutive blobs collide, the internal dissipation process would form a forward shock that leads to synchrotron maser emission and shows up as an FRB. As a viable radiation mechanism for FRBs, synchrotron maser emission has been extensively discussed by many authors. Lyubarsky (2014) suggested that FRBs could result from the interactions of magnetic pulses with plasma within the nebula surrounding magnetars. These interactions can produce relativistic, magnetized shocks, leading to synchrotron maser emission and yielding FRBs. Lu & Kumar (2018) also discussed possible conditions in which synchrotron maser emission can produce FRBs. They suggested that the energy may come from the dissipation of free energy in an outflow, which itself may be produced by the interaction between an external shock and the circumstellar medium in the forward shock region, or by internal dissipation processes such as magnetic reconnections and collisions between shells.

In our modeling, we also consider the synchrotron maser emission as the main radiation mechanism. Since plasma within the blobs is highly magnetized, the forwardly shocked zone should also be highly magnetized. Similar to Lyubarsky (2014), the inverse population is assumed to be formed at the plasma energy levels of about $m_{\rm e}c^2\Gamma$, and the synchrotron maser emission predominantly proceeds at the Larmor rotation frequency of the plasma, i.e. $\nu' = eB'/(2\pi m_{\rm e} c\Gamma)$. Hence, the typical radiation frequency in the observer's frame can be estimated as

$$\begin{aligned} \nu_{\rm obs} &= \nu'\Gamma = \frac{eB'_{\rm col}}{2\pi m_{\rm e} c} \\ &= 1.2\,\alpha^{-0.5}\dot{M}_{22}^{0.5} m_2^{-1}(r/50)^{-0.75}\,{\rm GHz}. \end{aligned} \tag{7}$$

After the collision, the outflow is moving towards the observer with a Lorentz factor of Γ. The scale of the maser emission area can be roughly estimated as $2\Delta/\Gamma^2$. Thus the timescale of maser emission, i.e., the observed FRB duration, is

$$t_{\rm FRB} \sim \frac{2\Delta}{\Gamma^2 c} \sim 1.2\,(\beta/0.2)^{-1} m_2 (r/50)^2\,{\rm ms}\,. \tag{8}$$

The DMs of FRBs are believed to be mainly contributed by the ionized IGM, and the contribution from the local environment near the FRB engine should be small. Let us estimate the intrinsic DM of the FRB source in our scenario. Given that the central BH mass is $\sim 100\,M_\odot$ and the accretion rate is $\sim 10^{22}\,{\rm g\,s^{-1}}$, the electron number density of the corona/ADAF can be roughly estimated as $n_{\rm e} = n_p = \rho/m_p \sim 4.6\times10^{18}\alpha_{-1}^{-1} m_2^{-2}\dot{M}_{22}(r/50)^{-1.5}\,{\rm cm^{-3}}$ (e.g., Horiuchi et al. 1988; Narayan & Yi 1995; Yuan & Zhang 2012; Meyer-Hofmeister et al. 2017). According to the vertical density distribution of the corona, the electron density at the top of the flux rope is $n_{\rm e,rope} \sim n_{\rm e}\exp(-z_{\rm rope}^2/H_{\rm c}^2) = 1.3\times10^{11}\alpha_{-1}^{-1} m_2^{-2}\dot{M}_{22}(r/50)^{-1.5}\,{\rm cm^{-3}}$, in which H_c refers to the scale height of the corona/ADAF and is roughly $0.6R$ (Meyer et al. 2007; Kara et al. 2016; Qiao & Liu 2017). Assuming that there is a wind outflow extending from the accretion system, a conservative estimation on the DM contribution from the wind is ${\rm DM_{Wind}} \sim \int_{z_{\rm rope}}^{\infty} n_{\rm e,rope}\exp(-z^2/z_{\rm rope}^2)dz \approx 22.1\alpha_{-1}^{-1} m_2^{-1}\dot{M}_{22}(r/50)^{-0.5}\,{\rm pc\,cm^{-3}}$. On the other hand, the electron number density of blobs in the emission region is $n_{\rm e,col} \approx n_{\rm e,rope}(2r_b/\Delta)^3 = 1.0\times10^6\alpha_{-1}^{-1} m_2^{-2}\dot{M}_{22}(r/50)^{-1.5}\,{\rm cm^{-3}}$, so that the DM contribution from the plasma within the blob itself can be calculated as ${\rm DM_{col}} \sim n_{\rm e,col}\Delta \approx 0.01\alpha_{-1}^{-1} m_2^{-1}\dot{M}_{22}(r/50)^{-0.5}\,{\rm pc\,cm^{-3}}$. Therefore, we see that the accretion disk system itself will only contribute a negligible portion to the total DM in our model.

Recent studies suggest that the event rate of FRBs is in the range of 2000–7000 ${\rm Gpc^{-3}\,yr^{-1}}$ within a maximum redshift of $z_{\rm max} = 1$ (Li et al. 2017; Bhandari et al. 2018), while the expected rate of WD-BH mergers is $\sim 10^4\,{\rm Gpc^{-3}\,yr^{-1}}$ (Cowperthwaite & Berger 2015). Therefore, the event rate of FRBs is very consistent with that of WD-BH mergers. From the above derivations, we see that the theoretical durations, typical radiation frequencies, energetics and event rate are all consistent with the observed features of FRBs.

4 DISCUSSION AND CONCLUSIONS

In this article, we argue that non-repeating FRBs could originate from episodic magnetized plasma blobs ejected from transient accretion disks around BHs. The transient disk can be formed when a WD merges with a $100\,M_\odot$ BH. Due to the turbulence of the ADAF around the intermediate-mass BH, some closed magnetic field lines will be continuously twisted and deformed. They can emerge from the accretion disk and rise into the corona, resulting in a huge flux rope system in the corona. When the magnetic energy of the flux rope accumulates and reaches saturation, the system loses its equilibrium, ejecting an episodic magnetic blob, whose free magnetic energy could be as high as 2.1×10^{40} erg. In this way, a few episodic magnetic blobs can be launched from the transient accretion disk. We show that the collision between two consecutive ejections can lead to catastrophic magnetic reconnection, which releases a large amount of free magnetic energy and forms a forward shock. The shock propagates through the magnetized, cold plasma within the blobs in the collision region, which radiates via synchrotron maser emission to produce a non-repeating FRB. Our calculations suggest that the main observed features of FRBs, such as their energetics, radiation frequency, duration and event rate, can all be satisfactorily explained. Also, the intrinsic DM contribution from the accretion system itself is negligibly small in our model.

In our modeling, episodic jets are generated by a transient ADAF disk. The viscous timescale of the ADAF disk is

$$t_{\rm vis} = R/v_{\rm r} = 10.4\,\alpha_{-1} m_2 (r/50)^{1.5}\,{\rm s}\,,$$

where $v_{\rm r}$ is the radial velocity. Comparing this expression with the timescale Δt described in Section 3, one can find $\Delta t < t_{\rm vis}$, which means that on a typical viscous timescale, the flux rope system can eject 2–3 magnetic bubbles. We assume that the blob is initially at rest, and the non-relativistic timescale is $t_0 \sim 2\,r_{\rm b}/v_{\rm rec}$. However, both the initial size of the bubble and the reconnection velocity are poorly constrained, so Δ can only be roughly estimated. Meanwhile, the time interval between two adjacent blobs increases with the increase of r in the accretion disk, which is $\Delta t \propto r^{1.5}$. It means that for a smaller $r \leq 10$, the condition of $\Delta t \leq t_0$ would be met, which leads the two blobs to collide in the non-relativistic phase. On the other hand, a larger r will allow for a longer Δt and a larger Δ, which may generate a much larger $r_{\rm col}$ and a correspondingly lower magnetic strength at the collision radius. This would lead the radiation frequency to be significantly lower than the observed frequencies of typical FRBs.

It is interesting to note that Scholz et al. (2017) recently tried to search for the persistent X-ray counterpart of FRB 121102. They finally reported an upper limit on the persistent X-ray luminosity at the level of $3 \times 10^{41}\,{\rm erg\,s^{-1}}$ (Scholz et al. 2017). We thus need to examine whether there is any persistent X-ray emission above this upper limit in our modeling. Let us consider the release of the potential energy of the accreted material in our scenario. The power can be easily estimated as $L \simeq \frac{GM\dot{M}}{3R_{\rm s}} = 1.5 \times 10^{42}\,{\rm erg\,s^{-1}}$ by taking $M = 100\,M_\odot$ and $\dot{M} = 10^{22}\,{\rm g\,s^{-1}}$, where the innermost stable circular orbit is assumed to be at $3R_{\rm s}$. This value seems to be higher than the constraint presented by Scholz et al. (2017). But if we assume a reasonable efficiency of ≤ 0.1 for converting the potential energy into X-ray emission (Gruzinov 1998), then the X-ray luminosity will be less than $1.5 \times 10^{41}\,{\rm erg\,s^{-1}}$ and will not conflict with the observational limit. Most importantly, note that the ADAF disk in our scenario is a transient disk. Once the accretion process stops and the accretion disk disappears, no X-ray emission will be generated at all. Thus we basically do not expect any persistent X-ray emission in our model. It is consistent with the observational constraint by Scholz et al. (2017).

We have considered the ADAF disk as the source for episodic jets in our work. However, it is still possible that a system with high accretion rate is a neutrino-dominated accretion flow (NDAF). For an NDAF, the time interval between two blobs is usually longer than that in ADAF, so that the flux rope system may eject only one blob in a stable timescale, i.e., $t_{\rm vis,NDAF}/\Delta t_{\rm NDAF} \propto 0.8\,(r/50)^{-0.35}$. In this case, no FRBs could be generated.

Although episodic jets have been observed in many BH systems such as X-ray binaries and AGNs, it is quite difficult to image them due to their small sizes. With large diameter radio telescopes becoming available, such as the Five-hundred-meter Aperture Spherical radio Telescope (FAST) (Nan et al. 2011), it is expected that the FRB sample can increase at a rate of ~ 5 events per 1000 hours of observation time (Li et al. 2017). When more FRBs are observed and localized, we may be able to get more useful information on these interesting central engines that launch episodic magnetic blobs.

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