RAA 2015 Vol. **15** No. **2**, 207–214 doi: 10.1088/1674–4527/15/2/005
http://www.raa-journal.org *http://www.iop.org/journals/raa*

Research in Astronomy and Astrophysics

Dynamics and collisions of episodic jets from black holes and accretion disk systems *

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Received 2014 April 2; accepted 2014 June 4

Abstract In many astrophysical black hole systems, episodic jets of plasma blobs have been observed, which are much faster and more powerful than continuous jets. A magnetohydrodynamical model was proposed by Yuan et al. to study the formation of episodic jets in Sgr A*. By taking Sgr A* and a stellar mass black hole as examples, we modify the model of Yuan et al. by including the effects of relativity, and further study the relativistic motion and expansion of episodic jets of plasma blobs. Then we study the collision between two consecutive ejections in the modified model, and calculate the magnetic energy released in the collision. Our results show two consecutive blobs can collide with each other, and the released magnetic energy is more than 10^{50} erg, which supports the idea that a gamma-ray burst is powered by the collision of episodic jets, as suggested by Yuan & Zhang.

Key words: accretion, accretion disks — black hole physics — magnetohydrodynamics (MHD) — ISM: jets and outflows — gamma-ray bursts: general

1 INTRODUCTION

There are two kinds of jets in astrophysical accreting systems: continuous jets and episodic jets. Continuous jets are steady and thought to be associated with large-scale open magnetic fields. Episodic jets are intermittent and associated with flare emission. Episodic jets are much faster and more powerful than continuous jets (Fender & Belloni 2004). They are most evidently observed in Galactic microquasars, such as GRS 1915+105 (Mirabel & Rodríguez 1994; Mirabel et al. 1998; Fender et al. 1999), GRO J1655–40 (Hjellming & Rupen 1995) and XTE J1550–564 (Corbel et al. 2002). They have also been observed in active galactic nuclei (AGNs), appearing as knots or blobs, such as in the active galaxy 3C 120 (Marscher et al. 2002) and NGC 4258 (Doi et al. 2013).

In the supermassive black hole in the Galactic center, Sgr A*, episodic jets have been detected, but no continuous jet has been observed (Yuan et al. 2009). Radio, infrared and X-ray flares, which are delayed with respect to the peaks in the light curves at different wavebands (Yusef-Zadeh et al.

* Supported by the National Natural Science Foundation of China.

2006), occur several times per day in Sgr A* (Eckart et al. 2006). The ejection and expansion of plasmoids from the accretion flow cause the delays associated with the fast rise and slow decay in the brightness and the polarization of the flare emission (van der Laan 1966; Yusef-Zadeh et al. 2006). By analogy with a coronal mass ejection on the Sun, Yuan et al. (2009) proposed a magnetohydrodynamical (MHD) model to study the formation of episodic jets in Sgr A* (see fig. 1 in their paper). If continuous jets correspond to a smooth solar wind component, Yuan et al. (2009) suggest that the transient episodic jets result from the disruption of closed field lines in the corona above the accretion disk. In their model, a flux rope forms while the magnetic field deforms by the shear and turbulence of the accretion flow. Energy and helicity slowly accumulate. When its value reaches a threshold, the system then loses its equilibrium and the flux rope is ejected outward by the magnetic compression force in a catastrophic way. This idea is similar to the catastrophic theory of solar eruption (see, e.g. Forbes & Priest 1995; Lin & Forbes 2000, for details). Their calculations show that the plasmoid can attain a relativistic speed ($0.8c$, where c is the light speed) in about 35 min.

Observations of gamma-ray bursts (GRBs) show erratic light curves, which suggest that the GRB central engine launches an episodic outflow. Observations of some GRBs by *Fermi* indicate GRBs have a magnetic origin. Therefore, Yuan & Zhang (2012) have proposed an intrinsically episodic magnetically dominated jet model for the GRB central engine on the basis of the MHD model built by Yuan et al. (2009). They suggest GRBs are produced by the collision of magnetically dominated episodic plasma blobs. They suppose that plasma blobs could be continuously produced in the accretion flow around a stellar mass black hole. After one magnetic blob is ejected, the process repeats again, then another magnetic blob is successively ejected. If two consecutive blobs could be accelerated and collide with each other at a large radius, this process would produce a GRB. Fast reconnection and the subsequent turbulence occur in this process, by which the magnetic energy is quickly and efficiently converted into radiation (Lazarian & Vishniac 1999; Zhang & Yan 2011; Yuan & Zhang 2012; McKinney & Uzdensky 2012).

The model for episodic jets proposed by Yuan et al. (2009) was built using classical mechanics. However, the speed of the plasmoid ejecta approaches the speed of light, and the effects of relativity are unavoidable. The effects of special relativity influence the mass of the plasma blobs and consequently impact their movement when the plasma blobs move at nearly the speed of light. We therefore modify and improve their model by including the effects of relativity in this work. However, we neglect the effects of general relativity in our calculations because the initial position of the plasma blobs is far away from the center of the black hole (about $10\,r_{\rm g}$, where $r_{\rm g}$ is the Schwarzschild radius).

In this paper, we modify the model of Yuan et al. (2009) by including the effects of relativity in Section 2. In Section 3, we study the dynamical process and expansion of episodic jets for parameters appropriate for the black hole in our Galactic center and a stellar mass black hole system, and investigate the collision between two consecutive plasma blobs. Finally, we discuss our results and summarize this work in Section 4.

2 MODIFICATION OF THE EPISODIC JETS MODEL

Based on the similar morphology and characteristics between the outflow components in accreting black holes and in the Sun, Yuan et al. (2009) built a model (see fig. 1 in their paper) describing the magnetic outflows of accreting black holes in light of current understanding of magnetic outflows in the solar environment.

In this work, we modify their model by adding the relativistic effects and further study the properties of episodic jets. We do not deduce all equations in detail in this work, but rather only briefly summarize the results that we are using, so readers are referred to Lin & Forbes (2000), Yuan et al. (2009) and Meng et al. (2014) for details.

A flux rope forms when the magnetic field deforms by shear and turbulence from the accretion flow. In the absence of the current sheet, the field potential $A_{\rm cs}$ is as follows (Lin & Forbes 2000)

$$A_{\rm cs}(z) = \frac{I_0}{c}\left[2J\ln\left(\frac{z+ih}{z-ih}\right) + i\ln\left(\frac{z+\lambda}{z-\lambda}\right)\right], \tag{1}$$

where $z = x + yi$. Using the general relation $B_{\rm cs}(z) = -\partial A_{\rm cs}(z)/\partial z$, we obtain an expression for the magnetic field when the system reaches the critical point as follows

$$B_{\rm cs}(z) = 2i\frac{I_0}{c}\frac{h^2\lambda + z^2\lambda + 2hJ(z^2-\lambda^2)}{(h^2+z^2)(z^2-\lambda^2)}\,. \tag{2}$$

The details of the main derivations for the equation of the motion of flux rope can be referenced in Meng et al. (2014). Magnetic energy and helicity slowly accumulate in the accretion flow around a black hole. When its value reaches a threshold, the system loses its equilibrium, magnetic reconnection occurs and the flux rope is ejected as a plasma blob. The upward motion of the plasma blob is governed according to the first order approximation, given by

$$m\gamma^3\frac{d^2h}{dt^2} = \frac{1}{c}|\boldsymbol{I}\times\boldsymbol{B}_{\rm ext}|_h - F_{\rm g}, \tag{3}$$

where m is the total mass inside the plasma blob per unit length, $\gamma = 1/\sqrt{1-v^2/c^2}$ is the Lorentz factor, h is the height of the plasma blob from the disk, $F_{\rm g}$ is the gravitational force, $\boldsymbol{I}$ is the current in the flux rope and $\boldsymbol{B}_{\rm ext}$ is the total magnetic field from all the sources except $\boldsymbol{I}$, which includes those inside the disk, on the corona and in the current sheet. We chose (x, y) coordinates with $y = 0$ being the magnetic axis and $x = 0$ being perpendicular to the plane of the magnetic axis (see Fig. 1). We suppose that the flux rope is initially located at $(x, y) = (5\,r_{\rm g}, 10\,r_{\rm g})$, where $r_g \equiv 2GM/c^2$ is the the Schwarzschild radius of the black hole.

The power related to the kinetic energy of the plasma blob is given by

$$\begin{aligned}\frac{dW_{\rm KE}}{dt} &= \frac{d\left[m(\gamma-1)c^2\right]}{dt}\\ &= m\gamma^3\dot{h}\frac{d^2h}{dt^2}\\ &= \frac{IB_{\rm ext}\dot{h}}{c} - \frac{GM\gamma m}{(H_0+h)^2}\dot{h}\\ &= \frac{{B_0}^2\lambda^4}{8h{L_{PQ}}^2}\left[\frac{{H_{PQ}}^2}{2h^2} - \frac{(p^2+\lambda^2)(h^2-q^2)+(q^2+\lambda^2)(h^2-p^2)}{h^2+\lambda^2}\right]\dot{h}\\ &\quad -\frac{GM\gamma m}{(H_0+h)^2}\dot{h}\,,\end{aligned} \tag{4}$$

where $H_{PQ} = \sqrt{(h^2-p^2)(h^2-q^2)}$, $L_{PQ} = \sqrt{(\lambda^2+p^2)(\lambda^2+q^2)}$, $G = 6.67\times10^8$ cm^3 g^{-1} s^{-2} is the gravitational constant and M is the mass of the black hole.

At the critical point, the energy in the magnetic field of the flux rope is

$$W_{\rm mc}(z) = \frac{1}{8\pi}\int B^2_{\rm cs}(z)dV = \frac{L}{8\pi}\int B^2_{\rm cs}(z)dS\,, \tag{5}$$

where L is the length of the flux rope and S is the cross-sectional area of the separatrix bubble (see Fig. 1) located inside the boundary $A_{\rm cs}(z) = A_0 = I_0\pi/c$.

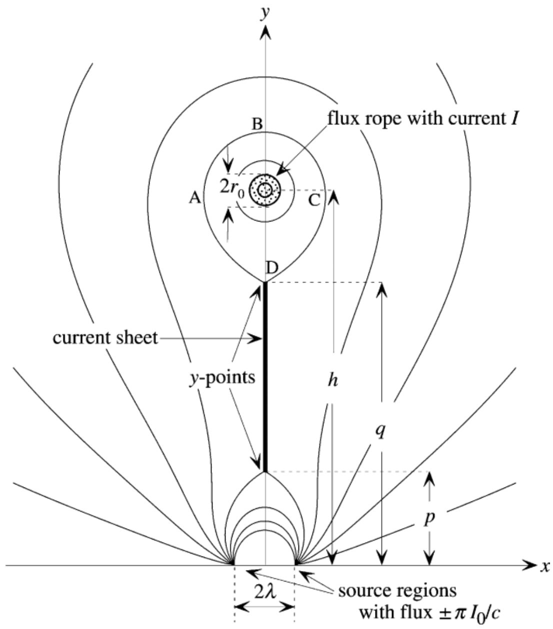

Fig. 1 A diagram of the flux rope configuration is given by Lin & Forbes (2000). The height of the center of the flux rope and the lower and the upper tips of the current sheet are denoted as h, p and q, respectively. The distance between the magnetic source regions on the coronal disk is 2λ. A, B, C and D denote four specific points at the edge of the separatrix bubble such that the size of the bubble is measured either as ΔD, the span between A and C, or as Δh, the span between B and D.

The magnetic energy accumulates in the magnetic configuration prior to the eruption. After catastrophic loss of equilibrium, magnetic flux is brought from the environment around the disrupting magnetic field into the ejecta blob through the current sheet. When the ejected plasma blob moves far away from the accretion flow, its magnetic energy is twice the magnetic energy in the flux rope when the catastrophe occurs, which is

$$W_{\rm mp} = 2W_{\rm mc}\,. \tag{6}$$

Since the highly ionized plasma and the magnetic field are frozen to one another (Priest 1982), the plasma is confined in the nearby magnetic configuration. Plenty of the magnetic flux associated with plasma in the corona is brought from the background to the ejecta by magnetic reconnection through the current sheet. The Alfvén velocity is $V_{\rm A} = |B_y(0^{\pm}, y_0)|/\sqrt{4\pi\rho(y_0)}$. Therefore, the total m inside the rope increases with time as follows (Lin et al. 2006)

$$\begin{aligned}\frac{dm}{dt} &= B_0 M_{\rm A}\sqrt{\frac{\rho_0}{\pi}}\frac{\lambda^2(q-p)(h^2+\lambda^2)}{(h^2-y_0^2)(y_0^2+\lambda^2)} \\ &\quad\times\sqrt{\frac{f(y_0)(q^2-y_0^2)(y_0^2-p^2)}{(\lambda^2+p^2)(\lambda^2+q^2)}}\,,\end{aligned} \tag{7}$$

where $f(y)$ is a dimensionless function describing the plasma density distribution in the corona, and is related to the mass-density distribution $\rho(y)$, where $\rho(y) = \rho_0 f(y)$, with ρ_0 being the mass density on the surface of the disk. Because there is no existing model for the density distribution of a magnetic corona above an accretion disk, we follow the assumption given by Yuan et al. (2009) that uses the density distribution of the solar model to consider the mass density in the accretion disk corona. Therefore, $f(y)$ takes the form (e.g. see Lin et al. 2006, and references therein) as follows

$$f(y) = a_1 z^2(y) e^{a_2 z(y)} [1 + a_3 z(y) + a_4 z^2(y) + a_5 z^3(y)], \quad (8)$$

where $z(y) = \lambda/(\lambda+y), a_1 = 0.001272, a_2 = 4.8039, a_3 = 0.29696, a_4 = -7.1743, a_5 = 12.321,$ with $f(0) = 1$.

A modification of the episodic jets model that includes the effects of relativity is embodied in Equations (3) and (4). Taking Equations (4) and (7) together with equations (24)–(26) in Meng et al. (2014), we can restudy the dynamical properties of the system following the catastrophe.

3 APPLICATION OF THE MODEL AND RESULTS

Based on studies of the accretion flow and its corona in Sgr A* (De Villiers et al. 2003; Yuan et al. 2003, 2009) and stellar mass black holes in the context of GRBs (Yuan & Zhang 2012), we restudy the dynamics of episodic jets and investigate the collision between consecutive ejections. The corona is magnetically dominated and force-free to the zeroth order. The rate of magnetic reconnection $M_{\rm A}$ is taken here as 0.01. Because the distribution of the density and magnetic field of the corona along the vertical height are unknown, we adopt the well-studied models for the solar environment (Lin et al. 2006). The distance between the two point-sources is $2\lambda_0$ where $\lambda_0 = 5\,r_{\rm g}$, and the length of the flux rope is $L = 2\lambda_0$.

Following Yuan et al. (2009), we chose the masses of the blobs per unit length to be $m_1 = 4.54\times 10^3$ g cm^{-1} and $m_2 = 4.54 \times 10^4$ g cm^{-1}, and the magnetic field to be $B_0 = 2I_0/(c\lambda_0) = 16$ G for Sgr A* in our calculation. The Schwarzschild radius for its black hole is 5.9×10^{11} cm. Solving equations mentioned in Section 2, we can describe some physical properties about the blob ejected outward after the system loses its equilibrium for the case of Sgr A*. Curves denoting a lighter blob and heavier blob with the dashed line and solid line respectively in the following figures show the model results. It is shown in Figure 2(a) that the blob can be easily accelerated to a relativistic speed and quickly obtain a large Lorentz factor.

When the blobs move far away from the black hole, they undergo expansion, because the cross-sectional area of the plasma blob increases, as shown in Figure 3(a). Although magnetic reconnection causes some of the plasma in the corona to be absorbed into the blob, the total mass of the blob remains almost constant because the density of the plasma in the corona is very low.

Taking Sgr A* as an example, Yuan et al. (2009) calculated the relations of speed versus time and speed versus height for the plasma ejecta. In their results, the plasma blob could eventually be accelerated to $0.8c$. Here we note that it was the motion of the center of the ejecta that was investigated, and the evolution of the internal structure of the ejecta was not studied in that work. Furthermore, it was not consistent with the observations that episodic jets showed relativistic features with a large Lorentz factor. So, we calculate the Lorentz factor versus time for episodic jets of plasma blobs for both cases of a supermassive black hole and a stellar mass black hole. Our results show that plasma blobs obtain a large Lorentz factor and are quickly accelerated to a relativistic speed. We further look into the evolution of the cross-section of the plasma blobs, and notice the fast expansion of the plasma blobs, namely the evolution of the internal structures of the ejecta, is quantitatively studied as well in the present work.

In the same way, we can also calculate the dynamical properties of episodic jets in a stellar mass black hole. For the stellar mass black hole, the masses of the two plasma blobs per length are $m_1 = 6.15 \times 10^{19}$ g cm^{-1} and $m_2 = 6.15 \times 10^{20}$ g cm^{-1}, respectively, and the magnetic field is $B_0 \approx 10^{15}$ G (see Yuan & Zhang 2012). The Schwarzschild radius of the black hole is 8.85×10^5 cm. In Figures 2(b) and 3(b), we can find that the blobs ejected from the accretion flow of the stellar mass black hole undergo almost the same process as that of Sgr A*. Because of the strong magnetic field,

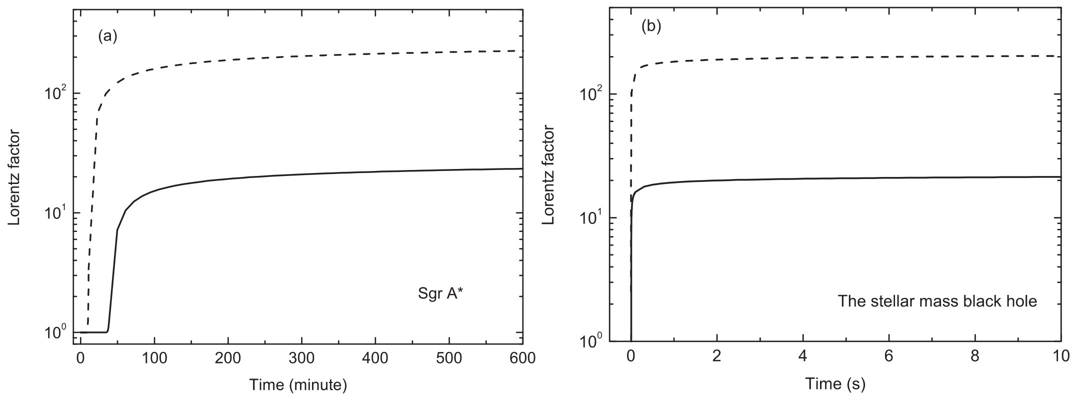

Fig. 2 The evolution of the Lorentz factor of the blob as a function of time for Sgr A* (a) and the stellar mass black hole (b). The solid line is for heavy blobs and the dashed line is for light blobs. The blob with mass per length m_2 is defined as a heavy blob and the blob with mass per length m_1 is defined as a light blob.

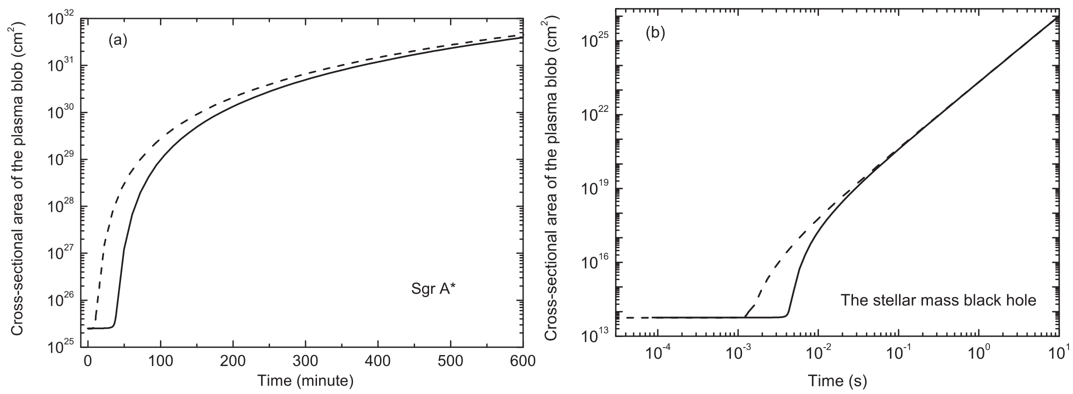

Fig. 3 The evolution of the cross-sectional area of the plasma blob as a function of time for Sgr A* (a) and the stellar mass black hole (b). The cross-sectional area of the blob is measured by A, B, C and D (see Fig. 1). The solid line is for heavy blobs and the dashed line is for light blobs.

the timescale of acceleration is much shorter and the blobs obtain a larger Lorentz factor in the case of the stellar mass black hole.

Next, we study the process of the collision between two plasma blobs based on the modified model. A flux rope forms in the corona of the accretion flow surrounding the central black hole. When the catastrophe occurs, the flux rope is ejected outward as a plasma blob (Blob I). We assume that, after time $1600GM/c^3$ (Yuan et al. 2009), a successive ejection occurs for Sgr A*. Another flux rope with less mass is moving as the second plasma blob (Blob II). Blob II is accelerated faster than Blob I, and both of them undergo expansion in motion, so the two blobs will collide with each other. We now study this process in our model, and evaluate the magnetic energy carried by the two blobs by Equations (5) and (6). After the blobs escape from the accretion disk, the magnetic energies carried by Blob I and Blob II are 1.35×10^{40} erg and 1.34×10^{40} erg for Sgr A*, respectively. Blob II later collides with Blob I at point "Pc," then they merge and form a single one. Figure 4(a) shows this process for Sgr A*. In this process, magnetic energy is released by reconnection and turbulence. The released energy is about 1.34×10^{40} erg, and is responsible for particle acceleration and radiation, and powering the observed phenomenon.

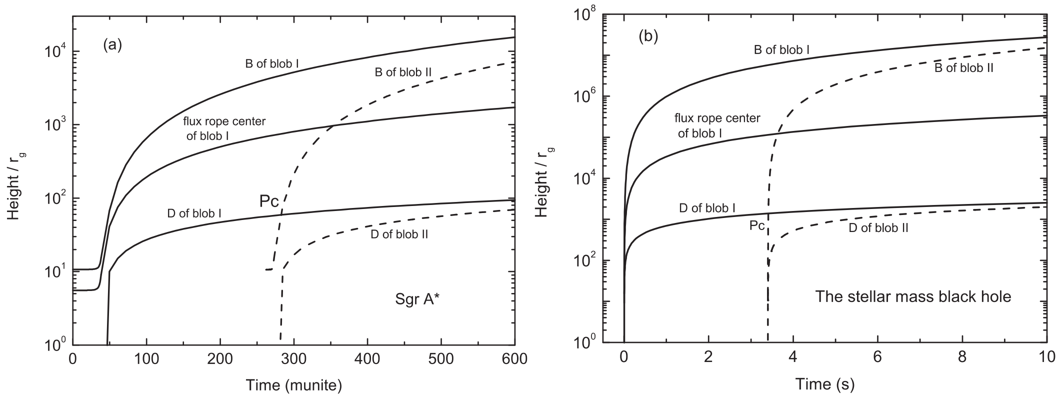

Fig. 4 The evolutions of the top, bottom and height of the plasma blob as a function of time for Sgr A* (a) and the stellar mass black hole (b). The top of the blob is measured at point B, and the bottom of the bubble is measured at point D (see Fig. 1). Point "Pc" is the position where two plasma blobs start to collide with each other.

The same process of collision can occur in the stellar mass black hole system (see Fig. 4(b)). In this case, the time interval for a successive ejection is about 3.4 s, which is evaluated by Yuan & Zhang (2012). Magnetic energy carried by Blob I and Blob II are 1.796×10^{50} erg and 1.762×10^{50} erg, respectively. The released energy is about 1.762×10^{50} erg, when the collision between the two plasma blobs happens.

Our calculations show a collision can happen between two consecutive ejections from a black hole and accretion disk systems, because expansion of the blobs makes it easy for the collision to occur between two consecutive ejections. The height of the collision is lower than that estimated by Yuan & Zhang (2012) after considering the expansion of the blobs in our calculation. When the bottom of Blob I collides with the top of Blob II, the magnetic reconnection occurs in the area of collision, and an enormous amount of magnetic energy starts to be released. By performing the integral in the corresponding magnetic configuration, we show that the plasma blobs produced by the stellar mass black hole have magnetic energy of more than 10^{50} erg. The collision between them can cause more than 10^{50} erg magnetic energy to be released, which is the same as estimated by Yuan & Zhang (2012). Therefore, our calculations support the theory that collisions among several such blobs can power a GRB, as suggested by Yuan & Zhang (2012).

4 DISCUSSION AND CONCLUSIONS

We modify the episodic jet model (Yuan et al. 2009) by taking into account the relativistic effect, so that the modified MHD model is more universally applicable. We restudy the dynamics of the plasma blobs in our model by taking examples of Sgr A*, the supermassive black hole in the Galactic center, and a stellar mass black hole formed in the central engine of GRBs. In both cases, our calculations show that the blobs can quickly attain a large Lorentz factor, and are moving outward at relativistic speeds; they are expanding when they are ejected outward; the total mass of the blobs remains constant during the whole process.

In the work of Yuan & Zhang (2012), the collision of episodic jets was proposed as the triggering mechanism for a GRB. They estimated the magnetic energy of episodic jets of plasma blobs on the basis of ADAF and NDAF models. However, they did not describe the kinetic or dynamic properties of the consecutive episodic jets during the propagations. In the present work, the above issues that were not investigated by Yuan & Zhang (2012) have been considered. In addition, we also investigate the evolution in the internal structure of the ejecta. We notice that the volume of the ejecta expanded quickly as a result of the continuous supply of magnetic flux from the reconnection region. Therefore, the front of the ejecta apparently moves faster than the center, and the rear moves slower. This directly results in the collision of the two ejecta occurring much earlier than the two centers meet, and the location of the collision must be closer to the disk than originally expected.

As one more parameter, we calculate the magnetic energy carried by the plasma blobs based on our model by integrating the corresponding magnetic configuration, and our results support the idea of Yuan & Zhang (2012) that a GRB is powered by the collision of episodic jets. We also point out that for a given strength of the background magnetic field, the energetics of the ejecta and the consequent collision are governed by the scale of the eruption at the beginning. For example, Yuan & Zhang (2012) found that as the disrupting magnetic configuration possesses a scale of $L = 2\lambda_0$, the energy released during the collision of two ejecta was around 10^{50} erg. In order to produce a long GRB of 10^{51} erg (Frail et al. 2001; Liang et al. 2008; Racusin et al. 2009), multiple ejecta collisions were needed. We notice that as the initial scale of the disrupting configuration increases to $L = 5\lambda_0$, the energy released can be up to 10^{51} erg in a single collision. Therefore, a GRB may be powered by the collision between two consecutive blobs.

Acknowledgements This work was supported by the National Basic Research Program of China (973 program, 2011CB811403 and 2013CBA01503), the National Natural Science Foundation of China (NSFC, Grant Nos. 11273055 and 11333007), and Chinese Academy of Sciences (Grant Nos. KJCX2-EW-T07 and XDB09040202). F. Y. was supported by the NSFC (Grant Nos. 11121062 and 11133005).

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