A new class of gamma-ray bursts from stellar disruptions by intermediate mass black holes

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ABSTRACT

It has been argued that the long gamma-ray burst (GRB) of GRB 060614 without associated supernova (SN) has challenged the current classification and fuel model for long GRBs, and thus a tidal disruption model has been proposed to account for such an event. Since it is difficult to detect SNe for long GRBs at high redshift, the absence of an SN association cannot be regarded as the solid criterion for a new classification of long GRBs similar to GRB 060614, called GRB 060614-type bursts. Fortunately, we now know that there is an obvious periodic substructure observed in the prompt light curve of GRB 060614. We thus use such periodic substructure as a potential criterion to categorize some long GRBs into new class bursts, which might have been fueled by an intermediate-mass black hole (IMBH) gulping a star, rather than a massive star collapsing to form a black hole. Therefore, the second criterion to recognize these new class bursts is if they fit the tidal disruption model. From a total of 328 Swift GRBs with accurate measured durations and without SN association, we find 25 GRBs satisfying the criteria for GRB 060614-type bursts: 7 of them are with known redshifts, and 18 with unknown redshifts. These new bursts are \( \sim 6\% \) of the total Swift GRBs, which are clustered into two subclasses: Type I and Type II with considerably different viscous parameters of accretion disks formed by tidally disrupting their different progenitor stars. We suggest that the two different kinds of progenitors are solar-type stars and white dwarfs: the progenitors for 4 Type I bursts with viscous parameter of around 0.1 are solar-type stars, and the progenitors for 21 Type II bursts with viscous parameter of around 0.3 are white dwarfs. Potential applications of this new class of GRBs as cosmic standard candles are discussed briefly.

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1. Introduction

Recently the peculiar long-duration GRB 060614 poses a great challenge to the widely accepted concept that long gamma-ray bursts (GRBs) are the consequences of core collapse of very massive stars. GRBs are normally classified into two groups: the long-duration bursts ($T_{90} > 2$ s) and short ones ($T_{90} < 2$ s) (Kouveliotou et al. 1993), where $T_{90}$ is defined as the time interval in which the integrated photon counts increase from 5% to 95% of the total counts. Several nearby long GRBs were observed to be firmly associated with core-collapse supernovae (SNe), and meanwhile the “collapsar” model of massive star explosions leading to long GRBs has been well developed (Woosley & Bloom 2006). On the other hand, short GRBs are hypothesized to be formed by the coalescence of binary compact stars, and hence with no SN connection (Nakar 2007). The prompt light curve of GRB 060614 as detected by the Swift Burst Alert Telescope (BAT) instrument displayed an initial short spike lasting for $\sim 4$ s followed by an extended component lasting for $\sim 100$ s, the latter being softer than the former in energy. This is a long burst by the above definition. The measured redshift of its host galaxy is as low as 0.125 (Price et al. 2006). However, despite its promising proximity, surprisingly no SN was observed to accompany the GRB down to very deep detection limits (Della Valle et al. 2006a; Fynbo et al. 2006; Gal-Yam et al. 2006).

Various solutions have been proposed for the missing-SN puzzle of GRB 060614: First, the GRB perhaps did not take place at $z = 0.125$ at all, but at much higher redshift so that its associated SN was below the detection limit. Cobb et al. (2006) claimed that the proximity of the GRB line of sight to the $z = 0.125$ galaxy was a chance coincidence; however Campisi & Li (2008) found that the chance coincidence probability is less than 0.02%, thus ruling out the chance coincidence assumption with high confidence. Alternatively, the GRB could be produced with a very faint core-collapse SN (Tominaga et al. 2007; Fryer et al. 2007), similar to the ones described by Turatto et al. (1998), Pastorello et al. (2004, 2007) and Valenti et al. (2009). Finally, this long GRB was not a consequence of the core-collapse of a massive star, and hence a novel mechanism is needed. For example, King et al. (2007a) suggested that the merger of a massive white dwarf with a neutron star can make a long-duration GRB.

Recently, Lu et al. (2008) proposed a new mechanism to produce GRBs, namely the tidal disruption of a star by an intermediate mass black hole (IMBH). In this scenario, both the long duration and the lack of an associated SN, as observed in GRB 060614, are naturally expected. Furthermore, the model can well explain a probable 9-s periodicity found in the prompt BAT light curve of GRB 060614 between 7 and 50 s. Such a substructure seems difficult to fit into either the collapsar scenario or compact star mergers. It is thus natural to investigate if GRB 060614 is just the first of this new class of GRBs, which is the purpose
of this paper.

We focus on the periodic substructure in the prompt light curve of a burst, since for most GRBs it is impossible to tell if an SN is associated or not, due to their high redshifts. A general picture of the tidal disruption model is given in Section 2, where important physical quantities are defined. The selection criteria, and the selected GRB060614-like events in the Swift samples, are described in Section 3. We do statistical studies on these bursts, and combine the statistical results with the model to give predictions in Section 4. Our conclusion and discussions are given in Section 5.

2. The Tidal Disruption Model for gamma-ray bursts

2.1. The model description

Tidal disruption of a star by an IMBH is analogous to the case for a supermassive black hole. A star, which happened to be close enough to the black hole, was distorted and squashed into a pancake by the strong tidal forces of the black hole. Once the star is tidally disrupted by the black hole, the squashed debris finally falls into the black hole’s horizon, forming a transient accretion disk around the black hole. During the early high accretion rate stage (near the Eddington rate), the inner region of the disk should be dominated by radiation pressure. In this case, the disk within the spherization radius \( R_{\text{sp}} \) is thermally unstable (Shakura & Sunyaev 1973), and the material in this inner region is likely broken into many blobs. When the blobs are dragged into the black hole, the seed magnetic field anchored in the blobs can be amplified, forming a strong and ordered poloidal field, which in turn threads the black hole with a mass-flowing ring in the inner region of the disk and extracts a large amount of rotational energy, creating two counter-moving jets along the rotation axis of the black hole (Blandford & Znajek 1977). As in the conventional GRB model, each jet pointed toward the observer, produces one mini-burst lasting over a blob’s free-falling timescale (Lu et al. 2008). Consequently, many mini-bursts should be produced for the tidal disruption event. Assuming that the in-falling process of the blobs into the black hole is neither uniform nor completely unsystematic, they may fall in groups quasi-periodically and this behavior should be modulated by the Keplerian timescale, forming a periodic sub-burst. All of these mini-bursts in the sub-burst add together to form a GRB, and the duration of the GRB is determined by the time when all the blobs with the spherization radius are removed and fall into the black hole at the marginally stable radius. Note that the blobs in each group randomly fall into the black hole, so small dispersion between sub-bursts’ durations may exist. This model can reasonably explain all the observed basic features of the unusual GRB060614, including the duration, the total energy, the periodic substructure,
and most importantly, the absence of SN link (Lu et al. 2008). The general picture of the tidal disruption model for such a GRB is plotted in Figure 1.

For convenience, we introduce the following dimensionless quantities throughout this paper:

\[ M_5 = \frac{M_{bh}}{10^5 M_\odot}, \dot{m} = \frac{\dot{M}}{\eta M_{\text{Edd}}}, \]

where \( \dot{M}_{\text{Edd}} = 3 \times 10^{-2} \eta_{0.1}^{-1} M_5 M_\odot \text{yr}^{-1} \) is the Eddington accretion rate, \( \eta \) is the energy conversion factor and \( \eta_{0.1} = \eta/0.1 \). Subsequently, the key physical parameters related to the tidal disruption model derived by Lu et al. (2008) are briefly described.

### 2.2. The three timescales and one relation

According to Lu et al. (2008), there are three useful timescales related to explain the observations of GRB060614: the mini-burst duration, \( T_{\text{pulse}} \), the sub-burst period, \( T_k \), and the duration of the whole GRB, \( T_{90} \). For instance, the three timescales are marked in the prompt light curve of GRB060614 in Figure 2. They can be calculated by

\[ T_{\text{pulse}} \approx 3M_5 \text{s}, \]
\[ T_k \approx 50\hat{r}_{\text{ms}}^{3/2}M_5 \text{s}, \]
\[ T_{90} \approx 50\alpha^{-1}\hat{r}_{\text{ms}}^{3/2}M_5 \text{s}, \]

where \( \alpha \) is the viscous parameter, \( 0 \leq \alpha \leq 1 \), and \( \hat{r}_{\text{ms}} \) is the dimensionless radius of the marginally stable circular orbit around a non-spinning in units of \( 6GM/c^2 \), i.e., \( \hat{r}_{\text{ms}} = 1 \).

From Equations (2) and (3), we can obtain a linear relation between the duration of the bursts and the period of the substructure

\[ T_k = \alpha T_{90}. \]

Equation (4) shows that the slope of the linear relation corresponds to the viscous parameter of the disk. This relation could be very useful for the classification of the GRBs.

Nevertheless, the viscous parameter, \( \alpha \), is uncertain, which is considered to be related to the structure and physical properties of the disk, especially the magnetic fields of the disk; recent numerical studies of the magnetorotational instability viscosity mechanism (Balbus & Hawley 1991) have shown that the value of the viscosity parameter depends upon the magnetism of the disk and sufficiently strong magnetic fields in the disk are necessary for a large viscosity parameter (e.g., \( \alpha > 1 \); Pessah et al. 2007). Note that the disk considered
here is formed through the black hole gulping a star, indicating that the disruption of a different star by black holes will give a different disk, then the different viscosity of the disk. To apply Equation (4) to certain GRBs, different values of $\alpha$ indicate different GRB subclasses, depending on the progenitors of the bursts.

2.3. The energy for a GRB

The tidal disruption model (Lu et al. 2008) can predict the isotropic energy of a GRB, $E_{\text{iso}}$, given the beaming factor of $\Gamma$,

$$E_{\text{iso}} \simeq E_{\text{tot}} \times \Gamma,$$  \hspace{1cm} (5)

where $10 \leq \Gamma \leq 1000$, and $E_{\text{tot}}$ is the total energy of a GRB, which is from the rotational energy of black holes extracted by the BZ process (Blandford & Znajek 1977),

$$E_{\text{tot}} \simeq 2.46 \times 10^{51} \alpha^{-1} M_5 \left[ \frac{(2.52 \dot{m})^{7/64} - 1}{2.52 \dot{m} - 1} \right] A^2 f(A) N_{\text{tot}} \text{ erg},$$ \hspace{1cm} (6)

where $N_{\text{tot}}$ is the total number of mini-bursts in the whole GRB, $A$ is the dimensionless angular momentum of the black hole, and $f(A) = 2/3$ for $A \rightarrow 0$ and $f(A) = \pi - 2$ for $A \rightarrow 1$ (Lee et al. 2000).

Substituting Equation (4) into Equation (6) to eliminate the viscous parameter $\alpha$, the expression of $E_{\text{iso}}$ can be rewritten as

$$E_{\text{iso}} \simeq 2.46 \times 10^{51} \frac{T_{90}}{T_k} \left[ \frac{(2.52 \dot{m})^{7/64} - 1}{2.52 \dot{m} - 1} \right] \Gamma M_5 A^2 f(A) N_{\text{tot}} \text{ erg}.$$ \hspace{1cm} (7)

Given $A^2 f(A) = 0.02$ and $\dot{m} = 1$, Lu et al. (2008) consistently explained the properties of GRB 060614. Since the purpose of this work is searching for GRBs similar to GRB 060614 and then analyzing these bursts’ properties, it is reasonable to assume that the adoption of $A^2 f(A) = 0.02$ and $\dot{m} = 1$ is still suitable. Therefore, we use these values to other bursts hereafter in this paper. Note that $E_{\text{iso}}$ is the most important physical quantity for using GRBs to investigate cosmology, such as the relation of Amati et al. (2002). Equation(7) shows that the isotropic energy only depends on the prompt gamma-ray emission light curve of a burst and the beaming factor of each individual burst, if the tidal disruption model for GRB 060614 can be generalized to other bursts similar to GRB 060614. This is in favor of $E_{\text{iso}}$ of each burst as a calibrated candle to study cosmology. We will discuss this later.
3. Searching for gamma-ray bursts similar to GRB060614

3.1. The criteria and Samples

Assuming that the tidal disruption model for GRB060614 can be generalized to investigate other gamma-ray bursts similar to GRB060614, called GRB060614-type bursts, we propose three criteria to identify this new class of bursts: (1) the bursts must be long-duration bursts \((T_{90} > 2 \text{ s})\) without SN association; (2) the bursts should have an obvious periodic substructure (sub-burst) in the prompt light curves of the bursts, and the periodic substructure is composed of more than three mini-bursts; and (3) the burst should satisfy the relation indicated by the tidal disruption model: \(T_k = \alpha T_{90}\). The three criteria must be all satisfied for each burst identified.

According to the above criteria, we select the samples among the 393 GRBs discovered by the Swift BAT before 2008 October 1. There are 330 long-duration bursts with accurately measured \(T_{90}\). For these 393 GRBs, we first exclude two GRBs with established SN associations: GRB060218 \((\text{Pian et al. 2006})\) and GRB050525A \((\text{Della Valle et al. 2006b})\). From the rest 328 GRBs, we identified 24 new bursts. The prompt light curve of GRB060614 is shown in Figure 2 and the light curves of the newly selected 24 samples are shown in Figure 3. All of them are from a public online database\(^1\). Tables 1 and 2 list all the physical quantities related to the 25 samples (including GRB060614), where Table 1 corresponds to 7 samples with measured redshifts, and Table 2 is for the rest 18 samples with unknown redshifts. The data are derived by combining the observations and the model. The details are summarized as follows.

3.2. The observed quantities

(1) From a public online database\(^2\), we can obtain the duration \((T_{90})\) of the 25 GRB 060614-type bursts, and the redshifts \((z_{\text{obs}})\) of 7 GRB 060614-type bursts including GRB 060614 itself.

(2) Based on the appearance of the observed light curves of the bursts shown in Figures 2 and 3, we extract the number, \(N_{\text{sub}}\), and the duration, \(T_k\), of the sub-bursts. First our attempt of power density spectrum (PDS) analysis failed in this process. Taking GRB070223 as an example, whose light curve (see Figure 3) shows obvious quasi-periodic substructures,

\(^1\text{http://grb.physics.unlv.edu/xrt/xrtweb/web/sum.html}\)
\(^2\text{http://swift.gsfc.nasa.gov}\)
we present its PDS (the analysis is based on a 64 ms BAT light curve data, 15-350 keV and $T_{-20}$ s to $T_{+110}$ s ) in Figure 4. No significant signal was found in the PDS. We then propose two explanations for this failure. First, the extreme complexity of the light curves and the sensitive dependence of PDS on the noise properties sometimes prevent the PDS analysis from detecting the obvious structures in the light curves; second, as we said in Section 2, the scatter of sub-bursts’ durations may lower the detection significance of the sub-burst structure in the PDS. Consequently, we obtain the results of sub-bursts by a visual inspection method. In the following, we describe the detailed process of identifying sub-bursts and estimating their durations from the light curves of the 25 GRB060614-type bursts by the visual inspection method. We want to stress two important features of the GRB060614-type bursts’ light curves that will be taken as our selection priors: (1) pulses in the light curves tend to gather into several groups which are considered as candidates for sub-bursts; and (2) quasi-periodic substructures exist in the light curves. The 25 light curves are consequently classified into three cases (details are presented in Tables 1 and 2). Case I (2/25): all of the candidates for sub-bursts are separated by quiescent periods (since our analysis is based on existing light curves whose backgrounds have been taken out, we define quiescent period here as the period during which no significant peak can be recognized visually). Case II (19/25): all of the candidates for sub-bursts join together. Case III (4/25): some of the candidates for sub-bursts are separated by quiescent periods and others join together. For Case I, $N_{sub}$ is easily obtained. We then take the average value of sub-bursts’ durations as $T_k$.

For Case II, we first find out the highest peak in each sub-burst candidate, and then find out the minimum of the valley between the two adjacent highest peaks. These valleys, together with the beginning of the first sub-burst candidate and the end of the last sub-burst candidate, are taken as the candidates for the beginning or end of these candidate sub-bursts, whose corresponding times are labeled as $t_i$ ($i = 1 \ldots n + 1$), where $n$ is the number of candidate sub-bursts. Since the real sub-bursts should satisfy the quasi-periodic property requirement, the values of all $t_{i+1} - t_i$ should be approximately the same. We calculate $T = \langle t_{i+1} - t_i \rangle$ as the first estimate to $T_k$. For each sub-burst candidate, if $t_{i+1} - t_i < 0.5T$ or $t_{i+1} - t_i > 1.5T$, we reject the sub-burst candidate corresponding to $t_{i+1}$, and repeat the above procedure with the remaining $n - 1$ candidates until all the candidates satisfy the criterion. Finally, we obtain $N_{sub}$ and take the value of $T = \langle t_{i+1} - t_i \rangle$ as $T_k$.

For Case III, some sub-bursts could be first identified similar to Case I, and we take the average value of these sub-bursts’ durations $T$ as the first estimate to $T_k$, and then identify other sub-bursts through the same procedure for Case II. Finally we also take the average value of the durations of these sub-bursts as $T_k$ in Case III. We note that in all the cases, we cannot give the exact error of $T_k$ introduced by the visual inspection method.

(3) Following the peak-finding algorithm proposed by Li & Fenimore (1996), we obtain
the total number of mini-bursts, \( N_{\text{tot}} \), and the corresponding timescale of \( T_{\text{pulse}} \). We use a linear function \( B(t) \) to fit the burst background between the pre-burst and post-burst regions, where \( t \) is the time. The whole burst region is divided into many count bins. Corresponding to the mini-burst time, \( t_{\text{pulse}} \), there is a peak bin with a count of \( C_p \). This peak bin is assumed as having more counts than the neighboring bins around it. The condition for \( C_p \) is satisfied if

\[
C_p - C_{1,2} \geq N_{\text{var}} \sqrt{C_p},
\]

where \( N_{\text{var}} \) is a constant parameter, and \( N_{\text{var}} = 5 \), \( C_1 \) and \( C_2 \) are the counts in two of the neighboring bins at \( t_1 \) and \( t_2 \), where \( t_1 < t_p < t_2 \) (see (Li & Fenimore 1996) for details of the peak-finding algorithm). Searching through the whole burst light curve, all peaks can be found. Assuming that each peak count corresponds to a mini-burst, the total mini-burst number, \( N_{\text{tot}} \), in each GRB can be determined immediately. Combining the assumption of the tidal disruption model, we can get

\[
T_{\text{pulse}} = \frac{N_{\text{sub}} T_k}{N_{\text{tot}}},
\]

where \( T_k, N_{\text{sub}} \) and \( N_{\text{tot}} \) are derived as in the above discussion.

(4) The isotropic energy for seven known redshift bursts, \( E_{\text{iso}}^{\text{KB08}} \), are from Kocevski & Butler (2008). This will be used as evidence to check the tidal disruption model by comparing with the model predictions.

### 3.3. The model quantities

In this subsection, we address and generalize the physical quantities predicted by the tidal disruption model for the GRB 060614 (Lu et al. 2008), such as, the masses of black holes, the isotropic energy, and the redshifts related to all 25 samples.

(1) The existence of IMBHs is still hotly debated and for which astronomers are still searching for direct evidence (Heger & Woosley 2002; Portegies Zwart et al. 2004; Miller & Hamilton 2002; Gebhardt et al. 2005). Recent theoretical work, however, has given their possible density and occurring rate in the Milky Way. If these predictions are confirmed by observations, there could be 1,000-10,000 IMBHs in our native Galaxy. One way to estimate the masses of IMBHs is the tidal disruption model for GRBs. From Equation (2), we find that the periodic timescale, \( T_k \), is linearly related to the masses of black holes assuming \( r_{\text{ms}} = 1 \) (Lu et al. 2008). Rewriting Equation (2), we have

\[
M_5 \simeq 0.02 T_k.
\]
Substituting $T_k$ estimated according to the burst observations (in Subsection 3.2) into Equation (10), we can immediately obtain $M_5$ for the 25 samples, which are listed in Tables 1 and 2. The results show that the masses of the black holes range from $5 \times 10^3 M_\odot$ to $9 \times 10^4 M_\odot$. These are the typical masses of IMBHs discussed by Miller & Hamilton (2002). The distribution of $M_5$ for the 25 GRB 060614-type bursts is plotted in the left panel of Figure 5.

(2) Adopting $A^2 f(A) = 0.02$, $\dot{m} = 1$ (see Section 2 for the definition of $A^2 f(A)$ and $\dot{m}$), and substituting $M_5$, $T_{90}$ and $T_k$ into Equation (7), we can immediately calculate the isotropic energy, $E_{\text{iso}}^{\text{pre}}$, as long as we know the beaming factors for each GRB. Since we have not obtained the beaming factors for all the 25 samples, for rough estimation of $E_{\text{iso}}^{\text{pre}}$, we uniformly take the average value of 500 for $\Gamma$, whose observational range is $10 \leq \Gamma \leq 1000$, as the beaming factor for all the 25 samples. The results are listed in Tables 1 and 2. The middle panel of Figure 5 plots the distribution of $E_{\text{iso}}^{\text{pre}}$ for the 25 samples.

(3) The redshifts for the 25 samples can also be predicted. It is known that the relation between the isotropic energy, $E_{\text{iso}}$, and the fluence, $F_\gamma$, of GRBs, satisfies
\[ E_{\text{iso}} = 4\pi d_L^2 F_\gamma, \tag{11} \]
where $d_L$ is the distance between a GRB and the observer, which can be calculated by (Carroll et al. 1992)
\[ d_L = \frac{1 + z}{H_0} \int_0^z [(1 + x)^2(1 + x\Omega_M) - x(2 + x)\Omega_\Lambda]^{-1/2}dx, \tag{12} \]
where $x$ is an integral variable for the redshift; $\Omega_M$, $\Omega_\Lambda$ and $H_0$ are the cosmological constant parameters and Hubble constant, respectively. To compare with the $E_{\text{iso}}^{\text{BK08}}$, we adopt $\Lambda$CDM cosmology, that is: $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 71\text{kms}^{-1}\text{Mpc}^{-1}$. Combining Equations (11) and (12), we can numerically calculate the redshift, $z$. The distribution of the predicted redshifts for 25 samples is plotted in the right panel of Figure 5.

4. Statistical relations and predictions

Based on observations and our theoretical model, Subsections 2.2 and 2.3 have considered the physical quantities related to the 25 GRB 060614-type bursts. The statistical analysis and the predictions based on these quantities will be addressed in detail.

It is important to examine if the tidal disruption model, which is successful for the case of GRB 060614 (Lu et al. 2008), can be generalized to explain the other 24 bursts selected in this paper. We first consider the relation between $E_{\text{iso}}^{\text{BK08}}$ and $E_{\text{iso}}^{\text{pre}}$ for the seven known
redshift samples. We plot the data of $E_{iso}^{KB08}$ and $E_{iso}^{pre}$ in Figure 6. Using the least-squares fitting, we find a linear relation

$$\log(E_{iso}^{KB08}) = (0.997 \pm 0.03) \log(E_{iso}^{pre}),$$

where the adjusted $R$-square value is $\sim 0.999$. This indicates that the isotropic energy predicted by the model agrees well with those given by the observations (Kocevski & Butler 2008). We thus believe that the tidal disruption model can be successfully generalized to study the properties of the other GRB060614-type bursts. More observed isotropic energy for the rest 18 unknown redshift GRB060614-type bursts can be used to check such relation in the future if their host galaxy’s redshifts can be measured.

It is interesting to note that the isotropic energy of GRBs is one of the best rulers to measure the expansion of the universe (Amati et al. 2002). Since $E_{iso}^{pre}$ predicted by the tidal disruption model is only related to $T_{90}$ and $T_k$, we can thus study cosmology using only the prompt light curves of the bursts and the redshifts of their host galaxies.

We then plot the data of $z_{obs}$ and $z_{pre}$ for the seven known redshift samples in Figure 7. The relation fitted by the least-squares method follows:

$$z_{obs} = (1.10 \pm 0.12) z_{pre},$$

where the adjusted $R$-square is 0.93. This again indicates that the redshifts predicted agree well with those observed, which further prove that the tidal disruption model is correct for the new class of bursts, such as GRB060614-type bursts discussed in this paper. The predictions of the 18 unknown redshift GRB060614-type bursts will be tested by the further observations.

The relations of both $E_{iso}^{pre} - E_{iso}^{KB08}$ and $z_{pre} - z_{obs}$ argue that the tidal disruption model can work well for the 25 new class bursts. We plot the data of $T_k$ and $T_{90}$ in Figure 8. We find interestingly that the relation between $T_k$ and $T_{90}$ for the 25 samples can be well fitted by two linear curves with different slopes: four of the samples, i.e., GRB060210, GRB060614, GRB080602, and GRB080503, follow the linear relation

$$T_k = (0.08 \pm 0.003) T_{90}, \quad (13)$$

and the rest 21 of the samples follow

$$T_k = (0.27 \pm 0.013) T_{90}, \quad (14)$$

respectively. The slope of the former curve is about 0.08, and the later one is 0.27.

Comparing with Equations (13) and (14) with Equation (4), we get two values of viscous parameters, $\alpha_1 = 0.08$ and $\alpha_2 = 0.27$, respectively. Both of them fall well in the typical
range of $\alpha \sim 0.1-0.4$ inferred from observations of unsteady accretion disks, such as in the outbursts of dwarf novae and X-ray transients (King et al. 2007b). It is known that the viscous parameter depends on the detailed structure and the magnetic field of the disk, because more strongly magnetized allows more efficient angular momentum transfer in the disk, and thus results in larger values of $\alpha$ (Pessah et al. 2007). Here in our model the transient disk is formed by the IMBHs disrupting stars, thus different structure and magnetic field of the disk will be produced by the disruptions of different type of stars. If white dwarfs, instead of regular stars, are tidally disrupted by black holes (Frolov et al. 1994; Fryer et al. 1999; Rosswog et al. 2009), much more strongly magnetized disk with higher viscous parameter can be produced, because during the contraction process which forms the white dwarf, magnetic fields are significantly amplified due to magnetic flux conservation (Tout et al. 2004). As a matter of fact, white dwarfs can only be tidally disrupted by IMBHs, because they will simply fall into supermassive black holes without being tidally disrupted, due to their much smaller sizes than regular stars. Similarly, neutron stars, though have much higher surface magnetic fields than those of white dwarfs, will fall into IMBHs directly without being tidally disrupted. We thus postulate that the linear relations between $T_k$ and $T_{90}$ given in Equations (13) and (14) divide 25 GRB 060614-type bursts into two subclasses: 4 of them are Type I, corresponding to IMBHs gulping to solar-type stars, and the rest 21 bursts are Type II, which are produced by the IMBHs disrupting white dwarfs, respectively. The ratio of Type I to Type II is about 1:5, suggesting that white dwarfs are much more abundant than solar-type stars around IMBHs; this possibility is discussed in the end.

5. Discussion and conclusion

We have identified a new class of GRBs, called GRB 060614-type bursts, which is produced by IMBHs tidally disrupting stars. To select out these GRB 060614-types, we have used criteria based on the observation features of GRB 060614 and our tidal disruption model, and searched through all the GRBs discovered by Swift BAT until 2008 October 1.

(1) We found 25 GRB 060614-type bursts from the 328 Swift GRBs with accurately measured durations and without SN association; 4 bursts (GRB060210, GRB060614, GRB080602, and GRB080503) are Type I, and the rest 21 bursts are Type II. These new GRB 060614-type bursts make 6% of the total Swift GRBs, composed of 1% Type I and 5% Type II.

(2) We derive the distributions of the IMBH’s masses of the 25 bursts, as well as the isotropic energies and redshifts for the 18 bursts with unknown redshifts, predicted by the tidal disruption model. The statistical studies show that the masses of the IMBHs are from $5 \times 10^3 M_\odot$ to $9 \times 10^4 M_\odot$ (in the left panel of Figure 5), the isotropic energies predicted are
well consistent with those given by Kocevski & Butler (2008), and the redshifts predicted are also agreed well with observations. These results confirm the tidal disruption model, and may possibly provide a new standard candle to study the cosmology.

(3) We obtain statistically that the relation between the substructure period and the duration of the 25 GRB 060614-type bursts is fitted by two linear curves with slopes (viscous parameters of their disks) of 0.08 and 0.27, respectively. This indicates that 25 GRB 060614-type bursts are composed of 2 subtypes called Type I and Type II, corresponding to two different progenitors for their productions through the tidal disruption. We postulate that the progenitors for 4 Type I bursts are most likely solar-type stars, and those for the 21 Type II bursts are probably white dwarfs.

Finally, we discuss the event rate ratio between Type I and Type II bursts. Gebhardt et al. (2005) found evidence for an IMBH of mass of about $2 \times 10^4 M_\odot$, residing in a globular cluster G1, which makes globular cluster as the most popular candidate to probe IMBHs. In young star clusters, high-mass stars segregate through energy equipartition; as a result, the heavier stars sink to the center while the lighter stars move to the outer halo. This process is called “mass segregation” (Spitzer 1969, 1987). Through dynamical friction, most massive stars tend to concentrate toward the center and drive the system to core collapse (Gürkan et al. 2004). As shown in a number of numerical studies (e.g., Portegies Zwart et al. 2004; Gürkan et al. 2004), very high initial central densities might lead to a rapid core collapse and segregation of massive stars, and trigger a runaway merger of massive stars, leading to the formation of an IMBH. It is naturally suggested that the less massive stars, not involved in the runaway process but were also migrating toward the clusters’ centers, may eventually end as white dwarfs, neutron stars or black holes. Neutron stars and black holes, driven by dynamical frictions, will also migrate toward the center, due to their larger masses, so only white dwarfs (and some low mass stars) will remain (Heyl 2008; Heyl & Penrice 2009). On the other hand, due to the mass segregation mentioned above, those much less massive stars, such as the solar-type stars, may migrate there much later on the average. Therefore in the vicinity of IMBHs in centers of star clusters, the space density of white dwarfs should be much higher than that of solar-type stars, explaining naturally the much higher event rate of Type II bursts discussed above. We thus predict that the central region of the G1 cluster harboring an IMBH should contain many more white dwarfs than solar-type stars. However, without further extensive studies, which are beyond the scope of this present work, we cannot predict or explain quantitatively the suggested 5:1 ratio between white dwarfs and solar-type stars.

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REFERENCES

Amati, L., et. al., 2002, A&A, 390, 81
Balbus, S. A., & Hawley, J. F. 1991, ApJ, 376, 214
Blandford, R.D., & Znajek, R.L., 1977, MNRAS, 179, 433
Campisi, M. A., & Li, L. 2008, MNRAS, 391, 935
Carroll,S.M., Press,W.H., & Turner,E.L. 1992, ARA&A, 30, 499
Cobb, B. E., et al. 2006, ApJ, 651, 85
Della Valle, M., et al., 2006a, Nature, 444, 1050
Della Valle, M. et al. 2006b, ApJ, 642, L103
Frolov, V. P., Khokhlov, A. M., Novikov, I. D., Pethick, C. J., 1994, ApJ, 432, 680
Fryer, C. L., Woosley, S. E., Herant, Marc, Davies, M. B., 1999, ApJ, 520, 650
Fryer, C. L., Hungerford, A. L., & Young, P. A. 2007, ApJ, 662, L55
Fynbo J.P.U. et al., 2006, Nature, 444, 1047
Galan, A., et al., 2006, Nature, 444, 1053
Gebhardt, K., Rich, R.M., & Ho, L.C., 2005, ApJ, 634, 1093
Gürkan, M.A., Freitag, M. & Rasio, F.A., 2004, ApJ 604, 632
Heger, A., & Woosley, S.E., 2002, ApJ, 567, 532
Heyl, J., 2008, MNRAS, 390, 622
Heyl, J. & Penrice, M. 2009, MNRAS, 397, L79
King, A., Olsson, E., & Davies, M. B. 2007, MNRAS, 374, L34
King, A., Pringle, J. E., & Livio, M. 2007, MNRAS, 376, 1740
Kouveliotou, C., et al., 1993, ApJ, 413, L101
Kocevski, D., & Butler, N., 2008, ApJ, 680, 531
Lee, H.K., Wijers, R.A.M.J., & Brown, G.E., 2000, Phys. Rep., 325, 83
Li, H., Fenimore, E.E., 1996, ApJ, 469, 115
Lu, Y., Huang, Y.F., and Zhang, S.N., 2008, ApJ, 684, 1330
Miller, M.C., & Hamilton, D.P., 2002, MNRAS, 330, 232
Nakar, E. 2007, Phys. Rep., 442, 166
Pastorello, A., et al. 2004, MNRAS, 347, 74
Pastorello, A., et al. 2007, Nature 449, E1
Pessah, M. E., Chan, C.-k., & Psaltis, D. 2007, ApJ, 668, L51
Pian, E., et al., 2006, Nature, 442, 1011
Portegies Zwart, S. F., Baumgardt, H., Hut, P., Makino, J., McMillan, S. L. W., 2004, Nature, 428, 724
Price, P. et al. 2006, GCN Report #5275
Rosswog, S., Ramirez-Ruiz, E., Hix, W. R., 2009, ApJ, 695, 404
Shakura, N.I., & Sunyaev, R.A., 1973, A&A, 24, 337
Spitzer, L.J., 1969, ApJ, 158, L139
Spitzer, L.J., 1987, Dynamical Evolution of Globular Clusters (Princeton, NJ: Princeton Univ. Press)
Tominaga, N., et al. 2007, ApJ, 657, L77
Tout, C. A., Wickramasinghe, D. T., & Ferrario, L. 2004, MNRAS, 355, L13
Turatto, M., et al. 1998, ApJ, 498, 129
Valenti, S., et al. 2009, Nature, 459, 674
Woosley, S., & Bloom, J.S. 2006, ARA&A, 44, 507

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Table 1. *Swift* Gamma-Ray Bursts of GRB060614-type with known redshifts

| GRB   | $T_{90}$\(^a\) (s) | $T_k$\(^d\) (s) | $T_{\text{pulse}}$\(^b\) (s) | $(z^{\text{obs}})\(^a\)$ | $N_{\text{tot}}$\(^b\) | $\log(E_{\text{iso}}^{KB08})\(^c\)$ (ergs) | $M_5$\(^b\) | $\alpha$\(^b\) | $\log(E_{\text{iso}}^{\text{pre}})\(^b\)$ (ergs) | Case\(^e\) |
|-------|------------------|-----------------|-----------------|-----------------|-------------|----------------------------|-------|-----|-----------------|-------|
| 050505| 58.9             | 25              | 1.21            | 4.27            | 62          | 53.18                      | 0.50  | 0.42 | 53.11           | II    |
| 051109a| 37.2             | 15              | 0.98            | 2.346           | 46          | 52.36                      | 0.30  | 0.40 | 52.78           | II    |
| 060116| 105.9            | 22              | 0.7             | 4               | 126         | 53.32                      | 0.44  | 0.21 | 53.67           | II    |
| 060210| 255              | 20              | 0.8             | 3.91            | 100         | 53.62                      | 0.40  | 0.08 | 53.95           | II    |
| 060614| 102              | 9               | 1.2             | 0.125           | 30          | 51.03                      | 0.18  | 0.09 | 51.75           | II    |
| 060926| 8                | 2.5             | 0.28            | 3.208           | 36          | 51.97                      | 0.05  | 0.31 | 52.00           | II    |
| 061007| 75.3             | 26              | 0.65            | 1.261           | 120         | 54.18                      | 0.52  | 0.35 | 53.50           | III   |

\(^a\)From http://swift.gsfc.nasa.gov

\(^b\)Estimated in this work

\(^c\)From Kocevski & Butler (2008)

\(^d\)Estimated by visually inspecting the prompt $\gamma$-ray light curves of the samples

\(^e\)Classified cases of light curves in the process of identifying sub-bursts and their durations
Table 2. 18 Gamma-Ray Bursts of GRB 060614-type with unknown redshifts

| GRB    | $T_{90}^a$ (s) | $T_k^d$ (s) | $N_{tot}^b$ | $T_{pulse}^b$ (s) | $M_5^b$ | $\alpha^b$ | $(z^{pre})^b$ | log($E_{iso}^{pre})^b$ (ergs) | Case$^c$ |
|--------|----------------|-------------|-------------|-------------------|---------|-----------|---------------|--------------------------------|---------|
| 050117 | 166.6          | 45          | 141         | 0.96              | 0.90    | 0.27      | 3.27          | 53.92                          | II      |
| 050306 | 158.3          | 33          | 186         | 0.89              | 0.66    | 0.21      | 3.31          | 54.01                          | II      |
| 050326 | 29.3           | 13          | 19          | 2.05              | 0.26    | 0.44      | 0.71          | 52.29                          | I       |
| 050607 | 26.4           | 10          | 26          | 1.15              | 0.20    | 0.38      | 2.32          | 52.38                          | II      |
| 050717 | 85             | 16          | 55          | 1.16              | 0.32    | 0.19      | 1.93          | 53.21                          | II      |
| 060102 | 19             | 6           | 19          | 0.95              | 0.12    | 0.32      | 2.61          | 52.10                          | II      |
| 060105 | 54.4           | 20          | 57          | 1.05              | 0.40    | 0.37      | 1.08          | 53.04                          | III     |
| 060306 | 61.2           | 20          | 63          | 0.95              | 0.40    | 0.33      | 2.78          | 53.13                          | I       |
| 060424 | 37.5           | 11          | 60          | 0.73              | 0.22    | 0.29      | 3.59          | 52.90                          | II      |
| 060510a| 20.4           | 8           | 25          | 0.64              | 0.16    | 0.39      | 0.72          | 52.25                          | II      |
| 061028 | 106.2          | 40          | 117         | 1.03              | 0.80    | 0.38      | 6.36          | 53.64                          | II      |
| 070223 | 88.5           | 26          | 95          | 0.82              | 0.52    | 0.29      | 4.23          | 53.47                          | II      |
| 080212 | 123            | 31          | 198         | 0.47              | 0.62    | 0.25      | 5.3           | 53.93                          | II      |
| 080328 | 90.6           | 24          | 83          | 0.87              | 0.48    | 0.26      | 1.99          | 53.42                          | III     |
| 080409 | 20.2           | 8           | 21          | 0.76              | 0.16    | 0.40      | 1.88          | 52.17                          | II      |
| 080503 | 170            | 15          | 33          | 0.91              | 0.30    | 0.09      | 3.34          | 53.29                          | II      |
| 080602 | 74             | 5           | 33          | 0.61              | 0.10    | 0.07      | 1.95          | 52.93                          | III     |
| 080723a| 17.3           | 8           | 18          | 1.33              | 0.16    | 0.46      | 2.13          | 52.04                          | II      |

$^a$From http://swift.gsfc.nasa.gov

$^b$Estimated in this work

$^c$Classified cases of light curves in the process of identifying sub-bursts and their durations

$^d$Estimated by visually inspecting the prompt $\gamma$-ray light curves of the samples
Fig. 1.— Scheme describing the general picture of the tidal disruption model for GRB 060614. The upper panel shows an IMBH gulping a solar-type star and triggers an intense blast of gamma rays. The lower panel emulates the above processes using a flash.
Fig. 2.— Observed timescales in the light curve of GRB 060614 in the tidal disruption model: $T_{\text{dura}}$ corresponds to the duration, $T_k$ is the periodicity of the sub-burst, and $T_{\text{pulse}}$ corresponds to the mini-burst timescale.
Fig. 3.— BAT light curves of all 24 selected GRB060614-types downloaded from http://swift.gsfc.nasa.gov/docs/swift/archive/grb_table.html
Fig. 4.— Power spectrum of the 64 ms BAT light curve in the 15-350 keV band from $T_{-20}$ s to $T_{+110}$ s of GRB070223. The red line denotes the threshold for the detection of sinusoidal signals at the 3σ confidence level.
Fig. 5.— Distributions for the black hole masses, the isotropic energy, and the redshifts for 25 GRB 060614-type bursts. $N$ is the number of GRBs.
Fig. 6.— Isotropic energy from Kocevski & Butler (2008) compared with those predicted by this model for seven known redshift samples. The square refers to GRB 060614, and the crosses stand for the six GRB 060614-type bursts. The solid line refers to the least-squares fitting: \( \log(E_{iso}^{KB08}) = (0.997 \pm 0.03) \log(E_{iso}^{pre}) \) with the adjusted R-square of 0.999.
Fig. 7.— Redshifts from observations compared with the redshifts given by this model. The square refers to GRB060614, and the crosses stand for the six GRB 060614-type bursts. The solid line refers to the least-squares fitting: $z^{\text{obs}} = (1.10 \pm 0.12)z^{\text{pre}}$ with the adjusted $R$-square of 0.93.
Fig. 8.— Relation between the GRB duration and the substructure period: the square refers to GRB 060614, the crosses denote the known redshift samples, and the circles denote the unknown redshift samples. The dashed and solid lines are the least-squares fitting for two different slopes, which correspond to two different viscous parameters of the disk.