Variability of the giant X-ray bump in GRB 121027A and its possible origin

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ABSTRACT

The giant X-ray bump of GRB 121027A observed by Swift is different from the typical X-ray flares in gamma-ray bursts. The observed structural variability in the rise and decay phases of the bump has four components. Of these four components, only the data in the bump from about 5300 to about 6100 s is of good enough quality to be analysed using the stepwise filter correlation method. A 86±9 s periodic oscillation is postulated, which is confirmed by the Lomb–Scargle method. A jet precession model is proposed to account for this variability.

Key words: accretion, accretion discs – black hole physics – gamma-ray burst: individual: GRB 121027A.

1 INTRODUCTION

Gamma-ray bursts (GRBs) are dramatic astronomical phenomena (Zhang & Mészáros 2004; Mészáros 2006). The prompt emissions of GRBs last from a few milliseconds to thousands of seconds. The statistics of their durations follow a bimodal distribution (Kouveliotou et al. 1993), and therefore GRBs can be classified as short- or long-duration GRBs. They are believed to originate in the mergers of two compact objects (see e.g. Eichler et al. 1989; Paczyński 1991; Narayan, Paczyński & Piran 1992; Bogomazov, Lipunov & Tutukov 2007) or in the collapsars of massive stars (see e.g. Woosley 1993), respectively. Despite the different progenitors, a rotating black hole (BH) surrounded by a neutrino-dominated accretion flow (NDAF, see e.g. Popham, Woosley & Fryer 1999; Narayan, Piran & Kumar 2001; Gu, Liu & Lu 2006; Liu et al. 2007, 2008, 2010a,b, 2012a,b, 2013; Sun et al. 2012; Li & Liu 2013; Kawanaka, Piran & Krolik 2013; Xue et al. 2013) will be formed, powering GRBs via neutrino annihilation or the Blandford-Znajek mechanism (Blandford & Znajek 1977).

A tilted accretion disc surrounding a supermassive BH leads to the precession of the BH and results in an S- or Z-shaped jet, as observed in galaxies (e.g. Lu & Zhou 2005). The jet precession caused by the system of the BH and disc can also explain some periodic variabilities of X-ray binaries, such as SS 433 (Sarazin, Begelman & Hatchett 1980). The quasi-periodic features observed by BATSE in the gamma-ray light-curves suggest that GRB jets may be precessed (see e.g. Blackman, Yi & Field 1996; Portegies Zwart, Lee & Lee 1999). In the central engine of GRBs, either the misalignment of the angular momenta of two compact objects or the anisotropic fall-back mass in the collapsar may induce precession between the BH and the accretion flow. Based on the Bardeen–Petterson effect (Bardeen & Petterson 1975), we suggest that in the jet precession model the BH can capture the inner part of the NDAF to conform with the direction of the angular momentum, whereas the outer part of the NDAF causes the BH and inner part to precess (Liu et al. 2010a; Liu & Xue 2012). The model can be used to explain the temporal structure and spectral evolution of GRBs (Liu et al. 2010a), to simulate almost all types of GRB gamma-ray light-curves (Portegies Zwart et al. 1999; Lei et al. 2007), and to predict the intensities of the gravitational waves from GRBs (Romero, Reynoso & Christiansen 2010; Sun et al. 2012). However, compared with the observations of the gamma-ray emission, there is little X-ray observational evidence of precession in GRBs.

In the paper, we will analyse the variability of the X-ray bump in GRB 121027A and discuss its possible origin using our jet precession model. In Section 2, we describe the Swift/XRT observations of GRB 121027A and use the stepwise filter correlation method, coupled with the Lomb–Scargle method, to present an analysis of the quasi-periodic X-ray light-curve from about 5300 to about 6100 s since trigger. In Section 3, the jet precession model is introduced. For reasonable properties of the BH in the centre of collapsar, the
The X-ray light-curve of GRB 121027A. The blue symbols represent the Windowed Timing mode data, which include the earlier Windowed Timing settling mode data. The black symbols represent the photon counting mode data. The red line is the fitting line. The light-curve of the XRT afterglow consists of six parts, namely four power-law decay fragments, a flare and a giant bump. A giant bump is very rare in the X-ray light-curves of GRBs. The model can explain the X-ray light-curve of GRB 121027A. The conclusions and discussion are presented in Section 4.

2 X-RAY DATA ANALYSIS OF GRB 121027A

\(\text{Swift}/\text{XRT}\) began observation 67.4 s after GRB 121027A trigger and received about \(2.4 \times 10^8\) s of data (Evans, Page & Osborne 2012). This object is a typical ultra-long GRB (e.g. Peng et al. 2013; Levan et al. 2014), with a redshift of about 1.773 (Tanvir et al. 2012; Kruehler et al. 2012). Fig. 1 shows the \(\text{Swift}/\text{XRT}\) light-curve, using data downloaded from the UK Swift Science Data Centre at the University of Leicester (Evans et al. 2007, 2009). The X-ray light-curve of GRB 121027A has six components: a step decay phase from about 70 to about 200 s with a temporal index of about 1.8; a flare from about 200 to about 500 s; another steep decay phase after the flare from about 500 to about 1000 s with a power index of about 7; a giant bump from about 1 to about 20 ks; a plateau phase from about 20 to about 100 ks (or from about 1 to about 100 ks) with a decay index of about 0.34; and another normal decay phase from about 100 ks to the end with a temporal index of about 1.44. It is rare that two continuous step decay phases with different temporal indexes exist in the afterglow.

Most of the light-curve components are easily understood, except for the giant bump, which is the most interesting phenomenon in observations of GRB 121027A (e.g. Peng et al. 2013; Wu, Hou & Lei 2013). Various models have been proposed, including the fall-back accretion process in collapsars (Wu et al. 2013) and a blue supergiant progenitor (e.g. Stratta et al. 2013). The shape of the particular X-ray bump of GRB 121027A is quite different from that of typical X-ray flares in GRBs. Furthermore, careful analysis of the substructures of the light-curve in the X-ray bump reveals that there are many violent oscillations. There are some substructures in the light-curve from about 1170 to about 1210 s, from about 5300 to about 6100 s, from about 11 200 to about 12 000 s, and from about 16 400 to about 17 600 s, as shown in Fig. 2, which are quite different from the smooth light-curves of the typical X-ray afterglow in GRBs. The red lines represent the link lines of the data in Figs 2(a) and (d), and the smooth curves for the data in Figs 2(b) and (c). Obviously, the time-scales of oscillations in the four parts of the bump are from about tens of seconds to hundreds of seconds, which indicates that there may exist a rough time evolution in the light-curve from about 1170 to about 17 600 s.

The stepwise filter correlation (SFC) method is used to decompose the variability components of light-curves (see e.g. Gao, Zhang & Zhang 2012). The method can identify significant clustering structures of a light-curve in the frequency domain, but it cannot give the statistical significance and locations of the structures. It is based on a low-pass filter technique and progressively filters the high-frequency signals. It then performs a correlation analysis between each adjacent pair of filtered light-curves. The correlation coefficient as a function of the filter frequency displays a prominent ‘valley’ feature around the frequency of the ‘slow’ variability component, which can be used to analyse the periodic signals. A detailed description can be found in Gao et al. (2012), who analysed 266 GRBs observed by BATSE. Lei, Zhang & Gao (2013) applied the method to Sw J1644+57 and found a 2.7-d period.

We use the SFC method to process the data of the giant bump. However, the quality of most of the data is not good. Only the data from about 5300 to about 6100 s can be analysed in detail. For the observations from about 1170 to about 1210 s and from about 16 400 to about 17 600 s, the data are too scarce to be analysed by the SFC method. For the data from about 11 200 to about 12 000 s, there is no indication of period by analysis using the method, because the modulation of flux and the fluence are too small.

For the observations from about 5300 to about 6100 s, because the data from \(\text{Swift}/\text{XRT}\) observations do not coincide with the bins, we first use the insert method to make the data suitable to analyze for subsequent analysis. The errors of the data are taken as 5 per cent of the flux. We first perform an analysis of the light-curve as shown in Fig. 3(a). Using the insert method, the 86-s dip clearly shows up in Fig. 3(b), which implies that there may be a time structure lasting \(~86\) s, corresponding to about 31 s in the rest frame. As shown in the light-curve, it can be seen that the modulation of the flux after about 5700 s is very significant and that there are some roughly equally spaced peaks that contain the periodic signal and dominate the analytic results. In contrast, any pattern in the data before about 5700 s is uncertain, because the small amplitude cannot be analysed by the SFC method alone.

Following Gao et al. (2012), we used Monte Carlo simulation to evaluate the error range of the period and quantify the significance for the detection of such quasi-periodic oscillations. First, for each time bin with an observed count rate \(C\) and count rate error \(\sigma_c\), which is taken as 5 per cent of the flux, we generated a mock count rate by randomly generating data based on a normal distribution with \((C, \sigma_c)\). One thousand mock light-curves were generated, and we applied the SFC method to each mock light-curve and checked whether the 86-s quasi-period existed. We propose that the percentage of mock light-curves that contain the 86-s quasi-period, \(c\), can be treated as the significance parameter. It turns out that \(c = \sim 99.2\) per cent for data from 5300 to 6100 s. Second, to estimate the period error, we performed the Monte Carlo simulation again but allowed the random seed error for each time to be \(\sigma\) of the original count rate error, thus generating the data based on a normal distribution with \((C, \sigma_c)\), and then identified the quasi-period, if it existed. Fig. 3(c) shows the distribution of the quasi-period for mock light-curves. The distribution fitting parameters, with a statistical average of the period and its variance, are 84.24 and 7.65 s (1\(\sigma\) error). We thus propose to use \(76.6 \sim 91.9\) s as the quasi-period error; that is, the period is \(86.9^{+5.9}_{-0.4}\) s.
3 JET PRECESSION MODEL AND APPLICATIONS TO GRB 121027A

Although the progenitors of the two types of GRBs may be different, their central engines are similar, as described by the BH hyper-accretion model. This system drives an ultra-relativistic jet to produce both the prompt gamma-ray emission and the afterglow in the low-energy bands, whose orientation coincides with the direction of the angular momentum of the BH (e.g. Popham et al. 1999; Liu et al. 2007; Liu et al. 2010a; Liu & Xue 2012). The difference in the direction of the angular momentum between the BH and disc can cause the disc to tilt and the jet to precess (Liu et al. 2010a; Sun et al. 2012).

According to equations (1), (2) and (5) of Sun et al. (2012) and equations (5.6) and (5.7) of Popham et al. (1999), the analytic expression of the precession period $P$ can be expressed as

$$P \approx 2793 a_*^{17/13} \left( \frac{M}{M_\odot} \right)^{7/13} \left( \frac{\dot{M}}{M_\odot s^{-1}} \right)^{-30/13} \alpha^{36/13} \text{s}$$

(Hou et al. 2014), where $a_*$ and $M$ are respectively the dimensionless spin parameter ($0 < a_* < 1$) and the mass of the BH, and $\dot{M}$ and $\alpha$ are respectively the accretion rate and the viscosity parameter of the disc.

If the X-ray bumps or flares originate from the BH hyper-accretion processes, we can relate the observed X-ray luminosity $L_{X,\text{iso}}$ of the bumps or flares to the mass accretion rate $\dot{M}$ through

$$\dot{M} = \eta^{-1} c^{-2} L_{X,\text{iso}}$$

(2)

where $\eta$ includes the beaming effect and efficiency of converting accretion material to X-ray radiation. Regarding power mechanisms, both neutrino annihilation and magnetic processes are included in the above equation.

For GRB 121027A, if the bump originates from the fall-back accretion process (e.g. Wu et al. 2013), precession between the BH and disc may occur because of the possible anisotropic distribution of the angular momentum of the fall-back material. From equation (1), following the BH hyper-accretion process, the BH mass increases, and the mass and angular momentum of the disc decrease, which may cause the precession period to increase with time. Thus, the change of the BH accretion system can result in the evolution of $P$. 

In addition, we used the Lomb–Scargle method (Scargle 1982) to examine the results from the SFC method, which is based on the discrete Fourier transform and is usually used to analyse the period of exoplanets. As shown in Fig. 3(d), if we set the range of the possible period from 80 to 100 s and analyse the data from 5300 to 6100 s by the method, a ~86-s periodicity with a confidence of 97.3 per cent is obtained. Such a result is consistent with the analysis by the SFC method.

Figure 2. Owing to the limitation of the satellite orbit and observation mode conversion, there are only four fragments observed in the giant bump, corresponding to the four panels. It is obvious that the best profile is from about 5300 to about 6100 s. The red lines represent the link lines of the data in (a) and (d), and the smooth curves those for the data in (b) and (c).
of the period. Unfortunately, except for the data from about 5300 to about 6100 s, we cannot analyse the oscillations of the data in the bump to estimate the evolution.

We can further test our jet precession model with the possible quasi-periodic variability of the bump. The average X-ray luminosity $L_{X,\text{iso}}$ from about 5300 to 6100 s is about $4.8 \times 10^{49} \text{ erg s}^{-1}$ (Wu et al. 2013). We reasonably assume that $\eta$ is about 15 per cent, so $\dot{M}$ is estimated by equation (2) as nearly $1.8 \times 10^{-4} \text{ M}_\odot \text{ s}^{-1}$. If we consider the effect of the magnetic field in NDAF models, the low accretion rate can ignite the disc to maintain neutrino emission (e.g. Kawanaka et al. 2013; Luo et al. 2013). If the Blandford-Znajek mechanism is taken to power GRBs, the accretion rate required to cause ignition can be even lower (Barkov & Komissarov 2010).

Because the duration of the burst in the rest frame corresponds to the viscous time-scale, which is inversely proportional to the viscosity parameter, a long-duration accretion process requires a low viscosity parameter. For an accretion time-scale of about 10 000 s, $\alpha$ can be estimated as $1.0 \times 10^{-4}$ by $\alpha \sim t_{\text{visc}}^{-1}$ (e.g. Hou et al. 2014). The spin parameter $a_*$ is naturally assumed to be 0.9 after a hyper-accretion process lasting thousands of seconds (e.g. Wu et al. 2013). The precession period is about $31^{+2}_{-1.5}$ s for GRB 121027A in the rest frame; the mass of the BH can be calculated as about $10^{+3}_{-2.0} \text{ M}_\odot$ with equation (1). After thousands of seconds of the hyper-accretion process, the final mass of the BH is consistent with predictions from collapsar models (e.g. Popham et al. 1999), which indicates that the jet precession model may naturally explain the origin of the bump in GRB 121027A.

**4 CONCLUSIONS AND DISCUSSION**

We roughly analysed the time-scales of oscillations in the four parts of the bump of GRB 121027A. Our results indicated that here may be time evolution in the bump, and there may be $86^{+5}_{-9}$ s periodic signals from about 5300 to about 6100 s using the SFC method. This was confirmed by the Lomb–Scargle method. If the bump originates from the fall-back accretion process, the quasi-periodic oscillations may be caused by jet precession in the BH–NDAF system. Our model (Liu et al. 2010a) can explain the behaviour, and the final properties of the BH are consistent with the predictions of collapsar models. Thus a possible way to test or estimate the mass of the BH in the centre of a GRB is to use observations of the quasi-periodic oscillations of light-curves.

To analyse the prompt emission, Gao et al. (2012) used the SFC method on 266 GRBs in the BATSE sample. Although no quasi-periodic oscillations were claimed in their work, they found that the majority of the bursts had clear evidence of a ‘slow’ variability component superposed on a rapidly varying time sequence. Furthermore, we searched all the Swift/XRT samples. The light-curves of Figure 3. (a) The light-curve of the giant bump from about 5300 to about 6100 s. The red vertical lines show intervals of $\sim 86$ s. (b) Analysis of the data of the upper plane using the SFC method (Gao et al. 2012). The red dotted lines show the error of the period. (c) Distribution of quasi-periodic signatures, which are derived from the Monte Carlo simulation method for the data from about 5300 to about 6100 s. The red solid line is the Gaussian fit, which yields quasi-periodic signatures of $84.24 \pm 7.65$ s (1σ error). The red dotted lines show the error of the period. (d) Analysis of the data of the upper plane using the Lomb–Scargle method (Scargle 1982).
most flares and afterglows are smooth, and thus quasi-periodic oscillations do not exist. For the ultra-long GRBs, we found a possible example of a quasi-periodic signal in the data of GRB 101225A. We used the SFC method to analyse its data from about 4950 to about 7300 s, and did not find periodic signals.

Furthermore, Fan, Zhang & Proga (2005) suggested that if the jet powering the late X-ray flares is launched via magnetic processes, such as in GRB 050724, the radiation of the flares is expected to be linearly polarized. For the bump of GRB 121027A, given the requirement for the accretion rate (\(\sim 1.8 \times 10^{-4} M_\odot \text{s}^{-1}\)) in the jet precession model, the jet is possibly dominated by the magnetic field. A bump that includes quasi-periodic signals may be a candidate source for linearly polarized radiation. Future GRB observations by the POLAR detector (Bao et al. 2012) may test this possibility.

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