Evidence of X-Ray Plateaus Driven by the Magnetar Spindown Winds in Gamma-Ray Burst Afterglows

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Abstract

The central engine of gamma-ray bursts (GRBs) remains an open and cutting-edge topic in the era of multimessenger astrophysics. X-ray plateaus appear in some GRB afterglows, which are widely considered to originate from the spindown of magnetars. According to the stable magnetar scenario of GRBs, an X-ray plateau and a decay phase $\sim t^{-2}$ should appear in X-ray afterglows. Meanwhile, the “normal” X-ray afterglow is produced by the external shock from a GRB fireball. We analyze the Neil Gehrels Swift GRB data, then find three gold samples that have an X-ray plateau and a decay phase $\sim t^{-2}$ superimposed on the jet-driven normal component. Based on these features of the lightcurves, we argue that the magnetars should be the central engines of these three GRBs. Future joint multimessenger observations might further test this possibility, which can then be beneficial to constrain GRB physics.

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629); Magnetars (992)

1. Introduction

The central engine of gamma-ray bursts (GRBs) remains a mystery. Millisecond magnetars (e.g., Usov 1992; Duncan & Thompson 1992; Dai & Lu 1998a, 1998b; Zhang & Mészáros 2001; Bucciantini et al. 2007; Metzger et al. 2011; Du 2020) and black hole (BH) hyperaccretion (e.g., Popham et al. 1999; Narayan et al. 2001; Kohri et al. 2005; Gu et al. 2006; Liu et al. 2007; Kawana et al. 2013; Hou et al. 2014) are two main candidates for GRB central engines. For recent reviews in this area see Liu et al. (2017) and Zhang (2018). GRB prompt emission is generated by the internal shock in the ultrarelativistic jets, and the following afterglow is produced by the external shock (Rees & Mészáros 1992; Shu-Jin Hou 1994; Sari et al. 1998). The lightcurves of prompt emission are usually irregular, but the afterglows generally have five components (e.g., Zhang et al. 2006).

The plateaus (shallow decays) are often seen in X-ray afterglow, and these are usually thought to be caused by energy injected into the jets. The energy may be extracted from rotating magnetars or fallback accretions (e.g., Dai & Lu 1998a; Zhang & Mészáros 2001; Rowlinson et al. 2014; Rea et al. 2015; Liu et al. 2017; Stratta et al. 2018; Du 2020; Huang & Liu 2021). Meanwhile, the superimposed normal decay is dissipated through the interaction between the jet and circumburst medium (e.g., Sari et al. 1998). Their typical decay index is predicted to be $\sim 1.2$, but the observations are in the range of 0–1.5 under different circumstances and conditions (e.g., Sari et al. 1998; Zhang et al. 2006). However, the spindown winds might not be injected into GRB jets, but rather be dissipated behind GRB jets to power X-ray plateaus in the GRB magnetar model (Du 2020). In this scenario, the indices of the decays after plateaus are $\gtrsim 2$ (Zhang & Mészáros 2001).

A magnetar could be born in the center of a massive collapsar or a neutron star (NS) binary merger (e.g., Giacomazzo et al. 2011; Faber & Rasio 2012; Liu et al. 2021). For a hypermassive magnetar, its very short lifetime means that the spindown winds cannot accumulate enough energy to produce observable features (Rosswog et al. 2000). For the supramassive magnetar case, as discussed in Du (2020), it (with a life time $\gtrsim 100$ s) has enough time to power the energetic spindown winds to generate an X-ray plateau followed by a steeper decay (with a decay index $> 3$). This phenomenon is called internal X-ray plateaus, which is understood as the collapse of a supramassive magnetar into a BH after the magnetar’s spindown (e.g., Troja et al. 2007; Rowlinson et al. 2010; Chen et al. 2017; Hou et al. 2018). In the stable magnetar case, the index of the decay following the plateau is $\sim 2$ (Zhang & Mészáros 2001). It is interesting that the X-ray transient CDF-S XT2 with an X-ray plateau and a decay component $\sim t^{-2}$ is well explained by the model of magnetar spindown winds under the stable magnetar scenario (Xue et al. 2019).

We consider that the types of GRB central engines can be judged by similar observational features. Focusing on the model of magnetar spindown winds, we propose the following criteria. First, there should exist an X-ray plateau and a decay component as $\sim t^{-2}$ in X-ray afterglows. However, this rule is not enough to prove that there are magnetars in the center of GRBs, because X-ray plateaus can be explained by involving the off-axis or precessing jets (e.g., Beniamini et al. 2020; Oganesyan et al. 2020; Huang & Liu 2021) and the classical energy injections (e.g., Dai & Lu 1998a; Zhang & Mészáros 2001). Second, additional X-ray radiation with a decay index $\sim 1.2$ originating in the external shock should be superimposed with the plateau and a decay phase (e.g., Sari et al. 1998; Zhang et al. 2006). This additional component indicates that an X-ray plateau with a decay phase as $\sim t^{-2}$ is not produced by the external shock but by the magnetar itself.

By using the above rules on the observations, the coincident sources could be satisfied with the model of magnetar spindown winds and further verify the existence of magnetars. The remainder of this paper is organized as follows. We present our model in...
Section 2. The study of three cases is shown in Section 3. Section 4 contains the conclusions and a brief discussion.

2. Superpositions between GRB Jets and Magnetar Spindown Winds

For a GRB originating from a stable magnetar, as proposed in Du (2020), its X-ray afterglow should be composed of the X-ray radiation from the winds driven by the magnetar spindown and magnetar-driven jets.

The evolution of the spindown luminosity of a magnetar can be expressed as

\[ L_{SD} = \frac{8\pi^4 B_{eff}^2 R_*^6}{3c^3 p^4}, \]

where \( B_{eff} \) is the effective magnetic field strength on the NS surface (including all the contribution that deviates from the dipole magnetic field), \( R_* \) is the equatorial radius, and \( p \) is the NS period (Zhang & Mészáros 2001).

If we consider that \( B_{eff} \) is a constant, the evolution of the X-ray luminosity \( L_W \) produced by the spindown winds is

\[ L_W = L_{W,0} \left( 1 + \frac{t}{\tau} \right)^{-2}, \]

and the characteristic spindown timescale \( \tau \) is

\[ \tau = \frac{3e^3 I P^2}{4\pi^2 B_{eff}^2 R_*^6}. \]

where \( L_{W,0} = \eta L_{SD,0} \) is the initial X-ray luminosity of the spindown wind, \( \eta \) is the efficiency of magnetic energy converting into X-ray emission, \( L_{SD,0} \) is the initial spindown luminosity, \( I \) and \( P \) are the rotational inertia and initial period of the magnetar, and \( t \) is the time from the burst, respectively. There is an X-ray plateau at \( t < \tau \). When \( t \) is much greater than \( \tau \), there is a decay component \( \sim t^{-2} \).

The luminosity of the X-ray emission from the jets, which is called the external shock model, can be empirically given by

\[ L_J = L_{J,0} q^{-1}, \]

where \( L_{J,0} \) is the X-ray luminosity of the jets and \( q \) is the decay index with the typical value \( \sim 1.2 \), as shown in Figure 1.

Since the decay of the X-ray emission from GRB jets is slower than that from spindown winds after \( \tau \) by comparison between Equations (2) and (4), a situation arises where \( L_W \) is always smaller than \( L_J \). There is also the possibility of another situation where the whole afterglow is dominated by the spindown winds. In these situations, the components from nondominant contributions are barely identified through the lightcurve. We are not interested in these situations and will not discuss them here.

It is worth discussing the situation where the X-ray emission is alternately dominated by the spindown winds and GRB jets. In early stage of the X-ray afterglow, the “tail” of prompt emission and the emission from spindown winds may be very strong, so the X-ray emission from GRB jets may be masked. Here we only discuss the times where the early phases of X-ray afterglows are dominated by spindown winds and the later phases are dominated by GRB jets.

Based on the relation of \( L_W = L_J \), we can obtain the solutions as

\[ \begin{align*}
  t_c &= \left( \frac{L_{W,0}}{L_{J,0}} \right)^{\frac{1}{2}} \quad \text{if } t \ll \tau \\
  t_c &= \left( \frac{t}{\tau} \left( \frac{L_{W,0}}{L_{J,0}} \right)^{\frac{1}{2}} \right) \quad \text{if } t \gg \tau. 
\end{align*} \]

Therefore, if there is a “tail” of prompt emission before \( t_0 \), the first solution \( t_c \) is not visible in the lightcurve, and the X-ray emission turns to be dominated by the spindown wind emission until \( t > t_c \). After \( t_c \), the X-ray emission is dominated by the jets. The corresponding lightcurves of the three typical examples is shown in Figure 1.

It needs to be emphasized that the X-ray plateaus can be explained by the off-axis or precessing jets with whichever type of central engine. However, these models cannot explain the decay index changes at a later stage of X-ray afterglows. The inflection means that there are two different components, and this is predicted by the model of the magnetar spindown winds. The X-ray plateaus followed by \( \sim t^{-2} \) decay segments are powered by magnetar spindown winds. The X-ray afterglows following the spindown wind segment are from the standard external shock of the jets.

Figure 1. Schematic diagram of the X-ray lightcurve contributed by magnetar spindown winds and GRB jets. There is a “tail” of prompt emission before \( t_0 \), and the X-ray emission turns to be dominated by the spindown wind emission until \( t > t_c \). After \( t_c \), the X-ray emission is dominated by GRB jets. According to the standard external shock model, the typical value of \( q \) is \( \sim 1.2 \).

Table 1

| GRBs     | \( \alpha_1 \) (Err) | \( \alpha_2 \) (Err) | \( \alpha_3 \) (Err) | \( \alpha_4 \) (Err) |
|----------|----------------------|----------------------|----------------------|----------------------|
| 060413   | 3.46 (0.13)          | 0.12 (0.05)          | 2.89 (0.14)          | 0.52 (0.04)          |
| 061202   | 3.02 (0.17)          | -0.03 (0.06)         | 1.83 (0.05)          | 1.04 (0.29)          |
| 191122A  | 1.99 (0.12)          | 0.17 (0.22)          | 2.72 (0.14)          | 0.60                 |
| 060607A  | 1.13 (0.04)          | 0.49 (0.02)          | 3.48 (0.11)          | 0.98 (0.18)          |

Note. (1) \( \alpha_1 \) denotes the slope of the steep decay component (the “tail” of prompt emission), \( \alpha_2 \) and \( \alpha_3 \) represent the slopes of the plateau and the following decay component, respectively, and \( \alpha_4 \) corresponds the decay index of the component at a later stage. (2) Due to a lack of late-time data, \( \alpha_4 \) is fixed for GRB 191122A. \( \alpha_3 \) for GRB 060607A is \( \sim 3.48 \), which indicates that it is a collapsing NS progenitor and is not suitable for our sample.
3. Samples

According to the model discussed above, we select candidates according to the following criteria: (i) a plateau should exist in the X-ray emission lightcurve; (ii) after the plateau, there is a steeper decay with index ~2; (iii) at the later stage of the X-ray lightcurve, there is another decay component with index ~1.2. This component is the key criterion of our sample.

According to the above criteria, we found three gold samples in the Neil Gehrels Swift GRB data, i.e., GRBs 060413, 061202, and 191122A, as shown in Figure 2. All of them belong to the long-duration GRBs. The data are from the UK Swift Science Data Center at the University of Leicester (Evans et al. 2007, 2009). The afterglows of these bursts all contain multiple components. There are significant flares in GRBs 060413 and 061202. At late times, the decay index of the afterglow can be constrained even though the data are sparse.

We employ the multiple broken-power-law functions to fit their X-ray lightcurves. The fitting results of four indices $\alpha_1$, $\alpha_2$, $\alpha_3$, and $\alpha_4$ are listed in Table 1. The plateau components are all flat with decay indices less than ~0.2. After the plateau, their decay indices are 2.89, 1.83, and 2.72, respectively. These values are basically consistent with the slope of the magnetar spindown process. The indices of the last components are 0.52, 1.04, and 0.60, respectively. Under different circumstances and conditions, the slope range of the lightcurve from the external shock model could be 0–1.5 (e.g., Sari et al. 1998; Zhang et al. 2006), so we reasonably believe that these components come from GRB jets and that the central engines of these three GRBs should be magnetars.

In our samples, only the redshift of GRB 061202 is measured, i.e., $z = 2.25$. The plateau X-ray luminosity $L_W$ can be expressed as

$$L_W = \frac{4\pi D_L^2 F_W}{1 + z},$$

where $D_L$ is the luminosity distance and $F_W$ is the plateau flux. Through fitting, we find that $F_W \sim 1.0 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ and $\tau \sim 1.8 \times 10^4$ s. $L_W$ can then be estimated to be $\sim 4.0 \times 10^{48}$ erg s$^{-1}$. Assuming that the rotational inertia of the magnetar is $10^{45}$ g cm$^2$ and the radius of the NS is 10 km (e.g., Li et al. 2020), we can obtain the isotropic energy of plateau $E_P \sim F_W \tau \approx 2.4 \times 10^{52}$ erg. According to Equations (1) and (3), the effective magnetic field strength on the NS surface $B_{eff}$ and initial period $P_0$ are calculated as $\sim 5.0 \times 10^{14}$ G and...
~1.1 ms, respectively. These values satisfy the magnetar model.

4. Conclusions and Discussion

In this paper, we analyze the shapes of lightcurves produced by magnetar spindown winds that have an X-ray plateau and a decay component as \( t^{-2} \). According to the fireball model of GRBs, the X-ray afterglow is produced by the external shock from jets at the same time. However, the “tail” of prompt emission and the emission from spindown winds may be powerful at the early stage of the X-ray afterglow, so the X-ray emission from the jets may be masked. We only discussed that the early phases of the X-ray afterglow are dominated by the spindown winds and the later phases are dominated by jets. So there is a state transition in the lightcurve—a change in slope at the later stage of the afterglows. We emphasize that the presence of the jet component is very important, because it supports the idea that the X-ray plateau arises from a component with a different origin. By systematically analyzing the X-ray Telescope lightcurves of GRBs detected by the Neil Gehrels Swift observatory, we find three gold samples to be consistent with the model of the magnetar spindown winds. Taking GRB 061202 as an example, the \( E_p, B_{\text{eff}}, \) and \( P_0 \) are estimated. They are all within the ranges of typical magnetar parameters. Since the features of the detectable MeV neutrinos and gravitational waves from (newborn) magnetars and BH hyperaccretion are distinguishable (e.g., Liu et al. 2016; Wei et al. 2019; Wei & Liu 2020), future joint multimessenger observations might provide more evidence of magnetar-driven GRBs.

The above discussion is based on a stable magnetar. If the magnetar is a supramassive one, the corresponding X-ray lightcurve is similar to that in Figure 1, but the spindown time \( \tau \) should be changed to the break time \( t_B \) (corresponding to the collapse time of the magnetar), and the slope of the segment following the plateau should be steeper (with decay index >3). For example, the decay index following the plateau is 3.48 in GRB 060607A, as shown in Figure 3. In some GRBs, the slopes even go up to \( \sim 9 \) (e.g., Troja et al. 2007). The internal X-ray plateaus are thought to go through a spindown process and then collapse into a BH (e.g., Troja et al. 2007; Chen et al. 2017; Hou et al. 2018).

A magnetar might be the central engine of the X-ray transient CDF-S XT2 (e.g., Xiao et al. 2019; Xue et al. 2019), this process only explains the spindown wind of the magnetar and cannot see the slow decay that is powered by an external shock. In our scenario, we consider that the components, including the contributions of the jets and the magnetar spindown winds, are more reliable evidence for the existence of magnetars.

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