

## GRB 200612A: An Ultralong Gamma-Ray Burst Powered by Magnetar Spinning Down (Post-print)

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### Abstract

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### Full Text

#### Preamble

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#### GRB 200612A: An Ultralong Gamma-Ray Burst Powered by Magnetar Spinning Down

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## Abstract

GRB 200612A could be classified as an ultralong gamma-ray burst due to its prompt emission lasting up to 1020 s and the true timescale of the central engine activity  $t_{\text{burst}} \gtrsim 4 \times 10^4$  s. The late X-ray light curve with a decay index of  $\alpha = 7.53$  is steeper than the steepest possible decay from an external shock model. We propose that this X-ray afterglow can be driven by dipolar radiation from the magnetar spin-down during its early stage, while the magnetar collapsed into a black hole before completing its spin-down, resulting in a very steep decay of the late X-ray light curve. The optical data show that the light curve is still rising after 1.1 ks, suggesting a late onset. We show that GRB 200612A's optical afterglow light curve can be fitted with the forward shock model using a Gaussian structured off-axis jet. This represents a special case among GRBs, as it may be an ultralong gamma-ray burst powered by a magnetar in an off-axis observation scenario.

**Key words:** (stars:) gamma-ray burst: individual (GRB 200612A) -(stars:) gamma-ray burst: general -stars: magnetars

## 1. Introduction

As the most energetic events in astronomy, gamma-ray bursts (GRBs) have been extensively studied. GRBs with prompt emission duration less than 2 s are classified as short GRBs, while those lasting more than 2 s are called long GRBs. In the duration histogram, short GRBs peak at 0.2–0.3 s, while long GRBs peak at 20–30 s (Kouveliotou et al. 1993) and range from 2 s up to several hundred seconds in the observer frame.

Some GRBs have been reported with extraordinary durations of  $10^4$  s, known as ultralong GRBs. It has been debated whether these constitute a distinct new class of events or are simply similar to long GRBs. The former hypothesis suggests that the progenitors of ultralong GRBs may be blue supergiants (Gendre et al. 2013; Nakauchi et al. 2013; Levan et al. 2014; Huang et al. 2020), while the latter proposes that ultralong GRBs share the same progenitors as long GRBs, representing the tail of the long GRB duration distribution (Virgili et al. 2013; Evans et al. 2014). Zhang et al. (2014) proposed defining ultralong GRBs based on the true timescale of central engine activity ( $t_{\text{burst}}$ ). The  $t_{\text{burst}}$  distribution of their “good” sample shows an apparent bimodal distribution with a narrow, significant peak at 355 s and a wider, less significant peak at  $2.8 \times 10^4$  s. Gao et al. (2017) obtained similar results with a narrow, significant peak at 173.8 s

and a wider, less significant peak at  $2.75 \times 10^4$  s.

As an example of an ultralong case, GRB 101225A shows that plateau and extremely sharp flux drop could be present in X-ray afterglow, which may be driven by a newborn magnetar (Lü et al. 2018; Zou et al. 2019). Both the normal long GRB model and the blue supergiant model launch ultra-relativistic jets. Usually, we assume on-axis observations, but some off-axis GRBs have been observed, such as GRB 170817A (Abbott et al. 2017). An observer at  $\theta_v < \theta_j$ , where  $\theta_v$  is the viewing angle and  $\theta_j$  is the jet half-opening angle, should see a light curve very similar to that for an on-axis observer. An observer at  $\theta_v > \theta_j$  will see a rising light curve at early times, peaking when the jet Lorentz factor is  $\sim 1/\theta_v$ , and approaching that seen by an on-axis observer at later times (Woods & Loeb 1999; Granot et al. 2002).

GRB 200612A is a special case that may be an ultralong gamma-ray burst driven by a magnetar spinning down in an off-axis scenario. The structure of the paper is as follows. The observations are presented in Section 2. In Section 3, we perform analyses of the afterglow. Then, in Section 4, we model the light curves. Our conclusions and discussion are given in Section 5.

## 2. Observations

GRB 200612A triggered the Swift Burst Alert Telescope (BAT) on 2020 June 12 at 04:39:37 UT (denoted as  $T_0$  in this paper). The mask-weighted light curve shows a complex structure that starts at  $\sim T_0 - 20$  s and lasts until  $\sim T_0 + 200$  s. The estimated  $T_{90,\text{BAT}} = 171.48 \pm 19.74$  s (15–350 keV) (Markwardt et al. 2020; Sonbas et al. 2020). At 04:49:38.68 UT ( $T_0 + 10$  minutes), the Fermi Gamma-Ray Burst Monitor triggered and located GRB 200612A. The Fermi GBM team reported detecting this burst and provided  $T_{90,\text{GBM}} \sim 88$  s (50–300 keV) in a GCN circular, while also reporting  $T_{90,\text{GBM}} = 984 \pm 65$  s. The light curves from Fermi/GBM and Swift/BAT are presented in Figure 1. GRB 200612A was also detected by Konus-Wind (Svinkin et al. 2020), whose observations show four emission episodes in the interval from  $\sim T_0$  to  $\sim T_0 + 1020$  s, leading to its classification as an ultralong GRB. As observed by Konus-Wind, the burst had a fluence of  $1.1 \times 10^{-4}$  erg  $\text{cm}^{-2}$  (Svinkin et al. 2020).

The Swift X-Ray Telescope (XRT) began observing the field at 04:41:04.7 UT ( $T_0 + 87.7$  s). The enhanced Swift/XRT position is R.A., decl. (J2000) = 20h10m48.49s,  $-45^\circ 21' 57.8''$  with an uncertainty of  $1.5''$ . The Swift Ultraviolet/Optical Telescope (UVOT) took a finding chart exposure of 150 s with the white filter starting at  $T_0 + 95$  s. However, no credible afterglow candidate was found in their initial data products.

The MASTER-OAFA robotic telescope located in Argentina (OAFA observatory of San Juan National University) was pointed to GRB 200612A at 2020 June 12 04:47:52 UT ( $T_0 + 495$  s). They found an optical transient within the Swift error box (R.A. = 302.679, decl. =  $-45.3569$ ,  $r = 0.05$ ) with magnitude 17.9 at  $T_0 + 1050$  s (Lipunov et al. 2020) and 17.5 mag at  $T_0 + 1172$  s (Tiurina 2020).

The 60 cm BOOTES-3/YA robotic telescope at NIWA Lauder in Otago (New Zealand) began observing the position reported by Swift/XRT at 09:51:32 UT ( $\sim 5.2$  hr after trigger). In the co-added image (20 exposures of 60 s each in the clear filter), no source was found at the position, with an upper limit of 20.3 mag (Hu et al. 2020).

We observed the field of GRB 200612A with the LCO 1 m Sinistro instrument starting at 2020 June 14 00:45:34 UT ( $T_0 + 1.84$  days), obtaining four images in the  $R$ -band (300 s exposures each). A weak source was found within the Swift error box. Figure 2 shows the  $R$ -band image of the field of GRB 200612A taken at  $T_0 + 1.84$  days. The data reduction was carried out following the standard routine in the IRAF package (Tody 1986). Photometric analysis yields  $R = 22.90 \pm 0.35$ , not corrected for Galactic extinction.

### 3. Data Analysis

We fit the X-ray light curve with both a single power-law function and a broken power-law function of the form  $F(t) = F_1 [(t/t_b)^{-\alpha_1\omega} + (t/t_b)^{-\alpha_2\omega}]^{-1/\omega}$ , where  $F_1$  is the flux at the break time ( $t_b$ ),  $\alpha_1$  and  $\alpha_2$  are the afterglow flux decay indices before and after  $t_b$ , respectively, and  $\omega$  is a smoothness parameter representing the sharpness of the break.

Five phases comprise this X-ray light curve (Figure 3). Phases I and II form a flare with  $\alpha = -0.16$  and peak at  $t = 170$  s, fitted to a broken power-law function with  $\alpha = 0.93$  and a break time at  $t = 3$  s. Phase III rises from  $\sim 300$  s, after which the Swift satellite suffers from Earth occultation, resulting in no data between 380 and 3700 s. Phases IV and V show decay indices of  $\alpha = 0.07$  and  $\alpha = 7.53$ , respectively. The steep decay in Phase V is inconsistent with an external shock model. The steepest possible decay from an external shock occurs after a jet break, with the post-jet-break decay slope being at most  $p$ , where  $p$  is the electron spectral index (Rhoads 1999; Sari et al. 1999). Afterglow modeling suggests  $p$  is typically between 1.5 and 3; however,  $\alpha = 7.53$  obviously deviates from this range.

According to the definition of  $t_{\text{burst}}$  proposed by Zhang et al. (2014) and Gao et al. (2017), we obtained  $t_{\text{burst}} \gtrsim 4.01 \times 10^4$  s for this GRB, aligning with the definition of ultralong GRBs.

### 4. Model and Result

The X-ray light curve of GRB 200612A breaks to a steep decay at  $t_b$ , which is far too steep for a jet break. A rapid drop of the X-ray flux with a decay index steeper than  $-3$  following a plateau is considered evidence of a magnetar collapsing into a black hole (Troja et al. 2007). We propose that a newborn magnetar powered this X-ray emission and collapsed to form a black hole at  $t_b$ , resulting in the extremely steep decay of Phase V.

The newborn magnetar spins down by losing rotational energy through two

channels: electromagnetic dipolar radiation and gravitational wave radiation (Shapiro & Teukolsky 1983). The electromagnetic emission luminosity evolves as  $L(t) = L_{\text{MD}}(1+t/\tau)^{-2}$ , where  $L_{\text{MD}}$  is the characteristic spin-down luminosity and  $\tau$  is the characteristic spin-down timescale. Since this burst lacks a measured redshift, we assume  $z = 2.27$  based on the average redshift from long GRB samples (Campisi et al. 2010).

The optical data show that the light curve is still rising after  $\sim 1.1$  ks, indicating a late onset. The onset time distribution in the GRB population ranges from 30 to 3000 s (Liang et al. 2013). The off-axis jet model may explain the observed late onset of the afterglow (Granot et al. 2002; Sato et al. 2021). A jet with a large Lorentz factor produces strong relativistic beaming, making the afterglow emission very dim for an off-axis observer. As the jet decelerates, the beaming effect weakens, leading to a rising afterglow light curve.

We attribute GRB 200612A' s optical emission to forward shock emission from an axisymmetric Gaussian structured off-axis jet. The external forward shock model (Sari et al. 1998; Huang et al. 1999) requires several parameters to calculate multiband afterglow emission: the isotropic-equivalent kinetic energy  $E_{K,\text{iso}}$ , the initial bulk Lorentz factor  $\Gamma_0$ , the ambient interstellar matter (ISM) density  $n_0$  (assumed uniform), the shock energy fractions going to electrons and magnetic fields ( $\epsilon_e$  and  $\epsilon_B$ ), the electron spectral index  $p$ , the jet opening half-angle  $\theta_j$ , and the viewing angle  $\theta_v$ .

We consider a Gaussian structured jet with isotropic-equivalent kinetic energy and mass given by  $E_{K,\text{iso}}(\theta) = E_{K,\text{iso},0} \exp(-\theta^2/2\theta_c^2)$  and  $M_{\text{iso}}(\theta) = M_{\text{iso},0} \exp(-\theta^2/2\theta_c^2)$ , where  $\theta$  is the polar angle with respect to the jet axis and  $\theta_c$  is the characteristic angle. Both quantities are truncated to zero when  $\theta$  exceeds the truncation angle  $\theta_w$ . The initial Lorentz factor at angle  $\theta$  is set as  $\Gamma_0(\theta) = (E_{K,\text{iso}}(\theta)/M_{\text{iso}}(\theta))^{1/2}$ .

We performed a Markov Chain Monte Carlo exploration of the multidimensional parameter space using emcee (Foreman-Mackey et al. 2013). The one- and two-dimensional marginalized posterior distributions for the Gaussian jet model fits are shown in Figure 4. The parameter estimation priors and marginalized posteriors are reported in Table 1, with optimal fitting results shown in Figure 5. Both X-ray and optical data are well described by the model.

## 5. Conclusions and Discussion

GRB 200612A' s prompt emission lasting  $\sim 1020$  s and central engine activity timescale  $t_{\text{burst}} \gtrsim 4 \times 10^4$  s classify it as an ultralong gamma-ray burst. The X-ray light curve drops rapidly with a decay index of  $\sim -7$  after the break time  $t_b \sim 3 \times 10^4$  s, signaling that the central engine has turned off.

The newly born magnetar' s dipolar radiation could power the X-ray emission before  $t_b$ , with its subsequent collapse into a black hole causing the sharp light curve decay. This burst' s redshift has not been directly measured; we assume

$z = 2.27$ . We estimate the characteristic spin-down luminosity to be  $L_{\text{MD}} \sim 1.7 \times 10^{48} \text{ erg s}^{-1}$  and the characteristic spin-down timescale to be  $\tau \sim 6.4 \times 10^3 \text{ s}$ . The collapse into a black hole is projected to occur at  $t_b \sim 2.8 \times 10^4 \text{ s}$ . With the fluence of  $1.1 \times 10^{-4} \text{ erg cm}^{-2}$  (Svinkin et al. 2020), the isotropic X-ray energy released during the magnetic dipole radiation epoch is  $E_{X,\text{iso}} \sim 1.7 \times 10^{52} \text{ erg}$ . We define the radiative efficiency for a magnetar converting spin-down energy to radiation as  $\eta_X = E_{X,\text{iso}} / (E_{X,\text{iso}} + E_{K,\text{iso}})$ , obtaining  $\eta_X \sim 0.88$ . Furthermore, we estimate the dipolar magnetic field strength as  $B \sim 2.6 \times 10^{15} \text{ G}$  and the initial spin period as  $P_0 \sim 1.0 \text{ ms}$ , where  $Q_n$  denotes  $Q/10^n$  in cgs units. Taking the moment of inertia  $I = 10^{45} \text{ g cm}^2$  and radius  $R = 10^6 \text{ cm}$ , we derive  $B \sim 2.6 \times 10^{15} \text{ G}$  and  $P_0 \sim 1.0 \text{ ms}$ . These values are in good agreement with typical magnetar parameters.

The optical data show that the light curve is still rising after  $\sim 1.1 \text{ ks}$ , exhibiting a late onset consistent with off-axis observer characteristics. We model the optical afterglow using an off-axis Gaussian structured jet model and find a viewing angle of  $\theta_v \sim 11.1^\circ$  and truncation angle  $\theta_w \sim 5.7^\circ$ . Since  $\theta_w > \theta_v$ , the prompt emission can be observed.

As shown in Figure 6, although the duration  $T_{90}$  of GRB 200612A is much smaller than several famous ultralong GRBs—for instance, GRB 101225A ( $T_{90} > 7000 \text{ s}$ ; Levan et al. 2014), GRB 111209A ( $T_{90} \sim 10000 \text{ s}$ ; Golenetskii et al. 2011), and GRB 121027A ( $T_{90} \sim 6000 \text{ s}$ ; Levan et al. 2014)—it still occupies the same region as ultralong GRBs reported by Huang et al. (2020) (magenta dots in Figure 6) and lies near ultralong GRB 091024A ( $T_{90} = 1300 \text{ s}$ ; Virgili et al. 2013).

GRB 101225A is a famous ultralong GRB with  $T_{90} > 7000 \text{ s}$  and  $t_{\text{burst}} \gtrsim 1.07 \times 10^5 \text{ s}$  (Campana et al. 2011; Thöne et al. 2011; Nakauchi et al. 2013; Levan et al. 2014; Zhang et al. 2014; Gao et al. 2017). Its X-ray afterglow exhibits a normal power-law decay segment ( $F \propto t^{-1.21 \pm 0.02}$ ) followed by an extremely sharp flux drop ( $F \propto t^{-6.35 \pm 0.34}$ ). The possible origin of ultralong GRB 101225A may be consistent with magnetar spin-down emission dominating before collapsing to a black hole at a later time (Lü et al. 2018; Zou et al. 2019). The decay index is consistent with Phase V ( $\alpha = 7.53$ ) of GRB 200612A within the errors. The similarity of the light curves suggests that GRB 200612A and GRB 101225A may share the same origin.

Classifying GRBs by duration is a rough approach. Virgili et al. (2013) adopt a critical duration of 1000 s, while Levan et al. (2014) suggest that ultralong burst high-energy emission should last  $\sim 10^4 \text{ s}$ . However, the origin of ultralong bursts remains debated. Tidal disruption events (Shcherbakov et al. 2013; MacLeod et al. 2014) and GRBs with blue supergiant progenitors (Nakauchi et al. 2013) are potential explanations. Meanwhile, Virgili et al. (2013) propose that ultralong GRBs may represent the tail of the duration distribution of the long GRB population. In this study, we do not attempt to ascertain the progenitor of GRB 200612A. Instead, we utilize dipolar radiation from a magnetar and external shock radiation from an off-axis jet to model the afterglow light curve of this

burst.

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## References

- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, *ApJL*, 848, L13
- Campana, S., Lodato, G., D'Avanzo, P., et al. 2011, *Natur*, 480, 69
- Campana, S., Mangano, V., Blustin, A. J., et al. 2006, *Natur*, 442, 1008
- Campisi, M. A., Li, L. X., & Jakobsson, P. 2010, *MNRAS*, 407, 1972
- Cucchiara, A., Veres, P., Corsi, A., et al. 2015, *ApJ*, 812, 122
- Dai, Z. G., & Lu, T. 1998, *A&A*, 333, L87
- Evans, P. A., Willingale, R., Osborne, J. P., et al. 2014, *MNRAS*, 444, 250
- Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, *PASP*, 125, 306
- Frederiks, D., Golenetskii, S., Aptekar, R., et al. 2016, *GCN*, 20141, 1
- Gao, H., Ren, A.-B., Lei, W.-H., et al. 2017, *ApJ*, 845, 51
- Gendre, B., Stratta, G., Atteia, J. L., et al. 2013, *ApJ*, 766, 30
- Golenetskii, S., Aptekar, R., Mazets, E., et al. 2011, *GCN*, 12663, 1
- Granot, J., Panaitescu, A., Kumar, P., & Woosley, S. E. 2002, *ApJL*, 570, L61
- Hou, S.-J., Liu, T., Xu, R.-X., et al. 2018, *ApJ*, 854, 104
- Hu, Y. D., Fernandez-Garcia, E., Castro-Tirado, A. J., et al. 2020, *GCN*, 27919, 1
- Huang, Y., Luo, Q., Zhang, B., & Xiong, S. 2020, *SSPMA*, 50, 129504
- Huang, Y. F., Dai, Z. G., & Lu, T. 1999, *MNRAS*, 309, 513
- Kouveliotou, C., Meegan, C. A., Fishman, G. J., et al. 1993, *ApJL*, 413, L101
- Levan, A. J., Tanvir, N. R., Starling, R. L. C., et al. 2014, *ApJ*, 781, 13
- Liang, E.-W., Li, L., Gao, H., et al. 2013, *ApJ*, 774, 13
- Lipunov, V., Gorbovskey, E., Kornilov, V., et al. 2020, *GCN*, 27917, 1
- Lü, H.-J., & Zhang, B. 2014, *ApJ*, 785, 74
- Lü, H.-J., Zou, L., Lan, L., & Liang, E.-W. 2018, *MNRAS*, 480, 4402
- MacLeod, M., Goldstein, J., Ramirez-Ruiz, E., Guillochon, J., & Samsing, J. 2014, *ApJ*, 794, 9
- Markwardt, C. B., Barthelmy, S. D., Cummings, J. R., et al. 2020, *GCN*, 27924, 1
- Nakauchi, D., Kashiyama, K., Suwa, Y., & Nakamura, T. 2013, *ApJ*, 778, 67
- Nicastro, L., in 't Zand, J. J. M., Amati, L., et al. 2004, *A&A*, 427, 445
- Rhoads, J. E. 1999, *ApJ*, 525, 737
- Sari, R., Piran, T., & Halpern, J. P. 1999, *ApJL*, 519, L17
- Sari, R., Piran, T., & Narayan, R. 1998, *ApJL*, 497, L17

- Sato, Y., Obayashi, K., Yamazaki, R., Murase, K., & Ohira, Y. 2021, MNRAS, 504, 5647
- Shapiro, S. L., & Teukolsky, S. A. 1983, Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects (New York: Wiley)
- Shcherbakov, R. V., Pe'er, A., Reynolds, C. S., et al. 2013, ApJ, 769, 85
- Sonbas, E., Gronwall, C., Klingler, N. J., et al. 2020, GCN, 27915, 1
- Starling, R. L. C., Wiersema, K., Levan, A. J., et al. 2011, MNRAS, 411, 2792
- Svinkin, D., Golenetskii, S., Aptekar, R., et al. 2020, GCN, 27922, 1
- Thöne, C. C., de Ugarte Postigo, A., Fryer, C. L., et al. 2011, Natur, 480, 72
- Tiurina, N. 2020, GCN, 27920, 1
- Tody, D. 1986, Proc. SPIE, 627, 733
- Troja, E., Cusumano, G., O'Brien, P. T., et al. 2007, ApJ, 665, 599
- Virgili, F. J., Mundell, C. G., Pal'shin, V., et al. 2013, ApJ, 778, 54
- Woods, E., & Loeb, A. 1999, ApJ, 523, 187
- Zauderer, B. A., Berger, E., Margutti, R., et al. 2013, ApJ, 767, 161
- Zhang, B., & Mészáros, P. 2001, ApJL, 552, L35
- Zhang, B.-B., Burrows, D. N., Zhang, B., et al. 2012, ApJ, 748, 132
- Zhang, B.-B., Zhang, B., Murase, K., Connaughton, V., & Briggs, M. S. 2014, ApJ, 787, 66
- Zou, L., Zhou, Z.-M., Xie, L., et al. 2019, ApJ, 877, 153

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