The Second Plateau in X-Ray Afterglow Providing Additional Evidence for Rapidly Spinning Magnetars as the GRB Central Engine

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Abstract

Evidence for the central engine of gamma-ray bursts (GRBs) has been collected in the Neil Gehrels Swift data. For instance, some GRBs show an internal X-ray plateau followed by very steep decay, which is difficult interpret within the framework of a black hole (BH) central engine, but is consistent within a rapidly spinning magnetar engine picture. The very steep decay at the end of the plateau suggests a sudden cessation of the central engine, which is explained as the collapse of a supramassive magnetar into a BH when it spins down. Here we propose that some additional evidence, such as a second X-ray plateau feature, would show up if the fallback accretion could activate the newborn BH and sufficient energy could be transferred from the newborn BH to the GRB blast wave. With a systematic data analysis for all long GRBs, we find three candidates in the Swift sample, i.e., GRBs 070802, 090111, and 120213A, whose X-ray afterglow lightcurves contain two plateaus, with the first one being an internal plateau. We find that in a fairly loose and reasonable parameter space, the second X-ray plateau data for all 3 GRBs could be interpreted with our proposed model. Future observations are likely to discover similar events, which could offer more information on the properties of the magnetar, as well as the newborn BH.

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

1. Introduction

Gamma-ray bursts (GRBs) have been extensively explored since their discovery more than 50 yr ago, but the nature of the GRBs’ central engine remains a mystery. In the literature, two main kinds of central engine have been discussed: hyper-accreting black holes (BH) or rapidly spinning magnetars (Zhang 2018, for a review). It has long been proposed that some interesting signatures in some GRB’s X-ray afterglow could help us to determine their central engines (Dai & Lu 1998; Rees & Mészáros 1998; Zhang & Mészáros 2001; Nousek et al. 2006; Zhang et al. 2006). For instance, systematic analysis of the Swift GRB X-ray afterglow shows that bursts with X-ray plateau features likely have rapidly spinning magnetars as their central engines (Liang et al. 2007; Tang et al. 2019; Zhao et al. 2019). In particular, when the X-ray plateau is followed by a steep decay with temporal decay index $\alpha \geq 3$, hereafter called “internal X-ray plateaus,” the sharp decay at the end of the plateau is difficult to interpret within the framework of a BH central engine, but is consistent within a magnetar engine picture, where the abrupt decay is understood as the collapse of a supramassive magnetar into a BH after the magnetar spins down (Troja et al. 2007; Lyons et al. 2010; Rowlinson et al. 2010, 2013; Lü & Zhang 2014; Lü et al. 2015; de Pasquale et al. 2016; Gao et al. 2016b; Zhang et al. 2016; Sarin et al. 2020).

Recently, Chen et al. (2017) proposed that if the sudden drop after the internal plateau indeed indicates the collapse of a supramassive NS into a BH, signatures from this newborn BH should be expected. For instance, for long GRBs, if a fraction of the envelope material falls back and activates the accretion onto the newborn BH (Kumar et al. 2008a, 2008b; Wu et al. 2013; Gao et al. 2016a), the hyper-accreting BH system can launch a relativistic jet via the Blandford–Znajek (BZ) mechanism (Blandford & Znajek 1977). Supposing a fraction $\xi$ of the jet energy would undergo internal dissipation, some detectable signals, such as an X-ray bump following the internal plateau, are expected (Chen et al. 2017). Searching through Swift-XRT data archive, the authors found a particular case, GRB 070110, that showed a small X-ray bump following its internal plateau, and successfully interpreted its multi-band data with their model. But it is worth noting that for GRB 070110, Troja et al. (2007) found the optical data indicate a decaying lightcurve feature sitting underneath the X-ray plateau without showing the rapid drop for the “internal plateau,” which means unlike the X-ray band, the optical emission trend could be hardly disturbed by the late central engine activity.

Note that most internal plateaus are not found to be followed by the X-ray bump, possibly because late-time fallback processes are intrinsically weak or the energy fraction for the internal dissipation ($\xi$) is relatively small. For the latter situation, a food fraction $1 - \xi$ of the BZ jet energy would continuously inject into the GRB blast wave, which may generate a second plateau in the X-ray afterglow, if the injected energy is comparable or even larger than the blast wave kinetic energy. We thus propose that GRBs with two X-ray plateaus (the first one is internal plateau) may provide further support to the magnetar central engine model.

In this work, we first study how the energy injection from the fallback accretion onto the newborn BH would alter the GRB afterglow emission and analyze the influence of model parameters on the theoretical lightcurves. In Section 3, we systematically search for GRBs with two X-ray plateaus from the Swift-XRT sample. Considering that long GRBs, which are likely related to the core-collapse of massive stars (Woosley 1993; MacFadyen & Woosley 1999), more easily have enough envelope material to provide late-time fallback accretion than short GRBs, which have been proposed to originate from the merger of two neutron stars (Eichler et al. 1989; Narayan et al. 1992) or the merger of a neutron star and a BH
(Paczyński 1991), here we focus on long GRB samples. We find three candidates, GRB 070802, GRB 090111, and GRB 120213A, whose second plateaus could be well fitted by the model. The conclusion and implications of our results are discussed in Section 4. Throughout the paper, the convention $Q = 10^9 Q_9$ is adopted in c.g.s. units.

2. Model Description

Rapidly spinning magnetars have long been proposed as candidate GRB central engines. In this scenario, a collimated jet could be launched by invoking (1) hyper-accretion onto the NS (Zhang & Dai 2009, 2010; Bernardini et al. 2013); (2) magnetic bubbles from a differentially millisecond proto-NS (Dai et al. 2006); (3) or from a protomagnetar wind (Metzger et al. 2011). The internal dissipation of the jet could power the prompt gamma-ray emission of a GRB and the interaction between the jet and the ambient medium could produce a strong external shock that gives rise to bright broadband afterglow emission (Gao et al. 2013, for a review). After launching the jet, the magnetar would also eject a near-isotropic Poynting-flux-dominated outflow, the internal dissipation of which could power a bright X-ray emission, whose temporal profile would follow the spin-down profile of the magnetar, i.e., $\tau^2$ at early stages, and decay as $\tau^{-2}$ after the magnetar spins down (Zhang & Mészáros 2001). If this emission component is brighter than the external shock afterglow emission, an X-ray plateau appears. Sometimes the central engine magnetar might be a supramassive NS, which can collapse to a BH when a good fraction of its rotational energy is lost and the centrifugal support can no longer support gravity. In this case, the X-ray plateau emission suddenly stops and follows by a sharp decay at the end of the plateau, due to the abrupt cessation of the magnetar’s central engine. This explains the internal X-ray plateau discovered in both long and short GRBs (Troja et al. 2007; Lyons et al. 2010; Rowlinson et al. 2010, 2013; Lü & Zhang 2014; Lü et al. 2015). After the collapse of the magnetar, if a fraction of the envelope material (especially for long GRBs) falls back and activates the accretion onto the newborn BH, the rotational energy of the BH could be extracted via the BZ mechanism, and a good fraction of the energy would eventually inject into the afterglow blast wave. If the injected energy is comparable or even larger than the blast wave kinetic energy, the broadband afterglow lightcurve could be significantly altered; for instance, a second plateau in the X-ray afterglow may emerge. Figure 1 presents a physical picture for several emission components at different temporal stages. Here we focus on studying how the energy injection from the fallback accretion onto the newborn BH would alter the GRB afterglow emission and analyze the influence of model parameters on the theoretical lightcurves.

2.1. The Fallback Accretion onto the Newborn BH

Assuming the fallback accretion could trigger the energy extraction from the newborn BH via the BZ mechanism, in this case, the BZ power from a BH with mass $M$ and angular momentum $J_\text{c}$ could be estimated as (Lee et al. 2000; Li 2000; Wang et al. 2002; Lei et al. 2005, 2013, 2017; McKinney 2005; Lei & Zhang 2011; Chen et al. 2017; Liu et al. 2017; Lloyd-Ronning et al. 2018)

$$L_{\text{BH}} = 1.7 \times 10^{30} a^2 m_\ast^2 B_{\gamma 15}^2 F(a) \text{ erg s}^{-1},$$

where $m_\ast = M_\odot / M$ is the dimensionless BH mass and $a = J_\ast / (GM_\odot^2)$ is the dimensionless spin parameter of the BH. Here, $F(a) = [(1 + q^2)/q][q + 1/q] \arctan (q - 1),$ $q = a/(1 + \sqrt{1 - a^2}),$ and $B_{\gamma 15}$ is the magnetic-field strength threading the BH horizon in units of $10^{15} \text{ G}.$ The evolution of the BZ jet power depends on $m_\ast,$ $a,$ and $B_\ast.$

The evolution of the BH spin and mass governed the competition between spin up by accretion and spin down by the BZ mechanism. The evolution equations of the BH mass $M$ and the BH spin $a$ are given by Wang et al. (2002) as

$$\frac{dM}{dt} = M c^2 E_{\text{ms}} - L_{\text{BH}},$$

and

$$\frac{da}{dt} = \frac{(ML_{\text{ms}} - T_{\text{BZ}}) c}{GM_\ast^2} - \frac{2a(M c^2 E_{\text{ms}} - L_{\text{BH}})}{M c^2},$$

where $M$ is the BH accretion rate, and $T_{\text{BZ}}$ is BZ magnetic torque (Li 2000; Lei & Zhang 2011; Lei et al. 2017):

$$T_{\text{BZ}} = 3.36 \times 10^{45} a^2 q^{-1} m_\ast^2 B_{\gamma 15}^2 \times F(a) g \text{ cm}^2 \text{ s}^{-2},$$

where $E_{\text{ms}}$ and $L_{\text{ms}}$ are the specific energy and the specific angular momentum at the innermost radius $r_{\text{ms}}$ of the disk (Novikov & Thorne 1973):

$$E_{\text{ms}} = (4 \sqrt{R_{\text{ms}}} - 3a)/(\sqrt{3} R_{\text{ms}}),$$

$$L_{\text{ms}} = (GM_\ast / c)(2(3 \sqrt{R_{\text{ms}}} - 2a))/(\sqrt{3} \sqrt{R_{\text{ms}}}^3).$$
Here, $R_{\text{ms}} = r_{\text{ms}}/r_g$ and $r_g = GM_*/c^2$. The innermost stable radius of disk is (Bardeen et al. 1972)

$$r_{\text{ms}} = r_g[(3 + Z_1/(3 + Z_1 + Z_2))]^{1/2},$$

where $Z_1 \equiv 1 + (1 - a^2)^{1/3}/(1 + a)^{1/3} + (1 - a^{1/3})$ and $Z_2 \equiv (3a^2 + Z_1^{2/3})$ for $0 < a < 1$.

The strength of the magnetic field is the major uncertainty in estimating the BZ jet power. By assuming the ram pressure of the innermost part of the disk balances the magnetic pressure on the BH horizon (Moderski et al. 1997), one can estimate the magnetic-field strength $B_c$,

$$B_c^2 = \frac{8\pi}{G} \frac{M_c}{\pi r_g^2},$$

where $r_g$ is the radius of the BH horizon.

With this assumption, the BH accretion rate could be written as a function of mass accretion rate and BH spin, i.e., (Wu et al. 2013; Chen et al. 2017)

$$L_{\text{BZ}} = 9.3 \times 10^{53} \frac{a^2 m F(a)}{(1 + \sqrt{1 - a^2})^2} \text{erg s}^{-1},$$

where $m = \dot{M}/(M_\odot \text{s}^{-1})$ is the dimensionless BH accretion rate. The accretion rate of BH can be estimated by adopting a simple model described in Kumar et al. (2008a)

$$M \approx \frac{M_\odot}{\tau_{\text{vis}}},$$

where the viscous timescale $\tau_{\text{vis}} \approx 1/\alpha \Omega_K$, where $\alpha$ is the standard dimensionless viscosity parameter, and $\Omega_K$ is the Kepler angular velocity of the accretion disk.

The mass of the disk $M_d$ evolves with time, increasing as a result of fallback from the envelope and decreasing as a result of accretion. Thus, (Kumar et al. 2008a; Lei et al. 2017)

$$M_d = M_{d0} - M.$$  

Combining Equations (10) and (11), the accretion rate onto the BH (Kumar et al. 2008a; Lei et al. 2017) can be obtained as

$$\dot{M} = \frac{1}{\tau_{\text{vis}}} e^{-t/\tau_{\text{vis}}} \int_{t_0}^{t} e^{t'/\tau_{\text{vis}}} M_{d0} dt'.$$

The evolution of the fallback accretion rate is described with a broken power law as (Chevalier 1989; MacFadyen et al. 2001; Zhang et al. 2008; Dai & Liu 2012)

$$M_{d0} = M_p \left[ \frac{(t - t_0)}{(t_p - t_0)} \right]^{-1/2} + \frac{1}{2} \left[ \frac{(t - t_0)}{(t_p - t_0)} \right]^{5/3} - 1,$$

where $t_0$ is the start time of the fallback accretion in the local frame, $t_p$ is the peak time of fallback, and $M_p$ is the peak fallback rate.

For the rapid accretion case, $\tau_{\text{vis}} \ll t$, the BH accretion rate would follow the fallback rate, i.e., $M = M_{d0}$. For a large value of the viscosity timescale $\tau_{\text{vis}}$, the BH accretion rate would be flat until $t > \tau_{\text{vis}}$, and then start to decline with time; see Figure 7 in Lei et al. (2017).

### 2.2. Energy Injection into the GRB Afterglow Blast Wave

The energy flow from the BH process would continuously inject into the external shock, and cause a significant rise in the Lorentz factor of the blast wave $\Gamma$, which may produce a second plateau following the steep decay. Huang et al. (2000) proposed a generic dynamical model to describe the dynamical evolution of GRB outflow, which has been widely applied for modeling the afterglow lightcurve. Based on their model and the injection energy into account, the evolution equation of the outflow’s bulk Lorentz factor can be written as (Liu & Chen 2014)

$$\frac{d\Gamma}{dM_{\text{sw}}} = -\frac{1}{2M_{\text{ej}} + 2\Gamma M_{\text{sw}}} \left[ \Gamma^2 - 1 - \frac{E_{\text{BZ}}}{c^2} \right] dt,$$

where $M_{\text{sw}}$ is the swept-up mass by shock, and $M_{\text{ej}}$ is the initial mass of the GRB outflow. The blast wave energy continuously increases with time, due to the continuously injected energy from the BH process into the blast wave.

The initial kinetic energy of the GRB outflow can be estimated as $E_0 = \Gamma_0 M_\odot c^2$, and the injected energy from the BZ process can be calculated as $E_{\text{inj}} = \int (1 - \xi) L_{\text{BZ}} dt$. The total energy in the blast wave could be expressed as

$$E_{\text{tot}} = E_0 + E_{\text{inj}}.$$  

We introduce a parameter $\eta = E_{\text{inj}}/E_0$ to denote the ratio between the injected energy and the initial energy in blast wave. For $\eta > 1$, the injected energy is dominated in the total energy of the blast wave, otherwise the initial kinetic energy of GRB outflow is dominated.

In order to obtain the shock dynamical evolution, three additional differential equations are required (Huang et al. 2000). The evolution of the radius of shock $R$, the swept-up mass $M_{\text{sw}}$, and the opening angle of the jet $\theta$ are described by Huang et al. (2000) as

$$\frac{dR}{dt} = \sqrt{\frac{\Gamma^2 - 1}{\Gamma}} c \Gamma \left( \frac{\Gamma + \sqrt{\Gamma^2 - 1}}{\Gamma} \right)^3,$$

$$\frac{dM_{\text{sw}}}{dR} = 2\pi R^2 (1 - \cos \theta) n m_p,$$

$$\frac{d\theta}{dt} = c_s (\Gamma + \sqrt{\Gamma^2 - 1}) R,$$

where $n$ is the number density of the unshocked ISM and $c_s$ is the sound speed,

$$c_s^2 = \frac{\dot{\gamma}(\dot{\gamma} - 1)(\Gamma - 1)}{1 + \dot{\gamma}(\Gamma - 1)} c^2,$$

where the adiabatic index $\dot{\gamma} = (4\Gamma + 1)/(3\Gamma)$.

For an electron with energy $\gamma_m e^2 c^2$ in the comoving frame of the shock, the observed frequency from synchrotron emission is (Rybicki & Lightman 1979)

$$\nu(\gamma_e) = \frac{3}{4\pi} \gamma_e^2 \frac{q_e B''}{m_e c^3},$$

where $m_e$ is the electron mass, $q_e$ is the electron charge, the bulk Lorentz factor $\Gamma$ is introduced by transferring the shock comoving to the observer rest frame, and $B''$ is the magnetic-field strength in the shock comoving frame. In GRB problems, one usually assumes the magnetic-field density ($B''^2/8\pi$) is a fraction of the internal energy of the post-shocked medium with a shock equipartition parameter $\epsilon_e$. Therefore, the comoving...
magnetic field is in the form of (Sari et al. 1998)

\[ B' = (32\pi m_p c_B n)^{1/2} \Gamma_c. \]  

(21)

The energy distribution of shock accelerated electrons is usually assumed to be a power law, with \( N(\gamma_e)d\gamma_e \propto \gamma_e^{-p}d\gamma_e. \) The minimum Lorentz factor of the electron, \( \gamma_{min} \), could be obtained by the conservation laws of particle number and energy. Assuming a constant fraction \( \epsilon_e \) of the post-shock internal energy goes into the electrons, one has (Sari et al. 1998)

\[ \gamma_{min} = \epsilon_e \left( \frac{p - 2}{p - 1} \right) \frac{m_p}{m_e} (\Gamma - 1). \]  

(22)

Another critical electron Lorentz factor is the cooling Lorentz factor \( \gamma_c \). When \( \gamma_c > \gamma_{min} \), electrons would lose most of their energies by synchrotron radiation, otherwise the cooling caused by the radiation can be ignored. If synchrotron radiation is dominated, the cooling Lorentz factor is given by (Sari et al. 1998)

\[ \gamma_c = \frac{6\pi m_e c}{\sigma_T B^2 t}, \]  

(23)

where \( t \) refers to time in the rest frame of the observer, \( \sigma_T \) is the Thomson cross section.

As shown in Equation (20), electrons with different Lorentz factors \( \gamma_e \) have different radiation frequencies \( \nu(\gamma_e) \). Two characteristic frequencies, \( \nu_m = \nu(\gamma_{min}) \) and \( \nu_c = \nu(\gamma_c) \) would determine the synchrotron spectrum. The evolution of these frequencies with time can be derived from shock dynamics.

For a given dynamical time \( t \), if \( \gamma_c > \gamma_{min} \), it means only a small fraction of electrons could be cooled. This is called slow-cooling regime. In this case, for an observational frequency \( \nu \), the synchrotron spectrum is described as a broken power law characterized by \( \nu_m \) and \( \nu_c \) as follows (Sari et al. 1998):

\[ F_\nu = \begin{cases} \frac{(\nu/\nu_m)^{3/2}F_{\nu,\text{max}}}{\Gamma_{\text{inj}}^{3/2}}, & \nu < \nu_m \\ \frac{(\nu/\nu_m)^{(p-1)/2}F_{\nu,\text{max}}}{\Gamma_{\text{inj}}^{(p-1)/2}}, & \nu_m < \nu < \nu_c, \\ \frac{(\nu_c/\nu)^{-1/2}F_{\nu,\text{max}}}{\Gamma_{\text{inj}}^{1/2}}, & \nu_c < \nu \end{cases}, \]  

(24)

On the other hand, for \( \gamma_c < \gamma_{min} \), all the accelerated electrons could be cooled in the dynamical timescale \( t \). This is called the fast-cooling regime. The radiation spectrum of the shock is (Sari et al. 1998)

\[ F_\nu = \begin{cases} \frac{(\nu/\nu_c)^{3/2}F_{\nu,\text{max}}}{\Gamma_{\text{inj}}^{3/2}}, & \nu < \nu_c \\ \frac{(\nu/\nu_c)^{-1/2}F_{\nu,\text{max}}}{\Gamma_{\text{inj}}^{1/2}}, & \nu_c < \nu < \nu_m, \\ \frac{(\nu_m/\nu)^{-1/2}F_{\nu,\text{max}}}{\Gamma_{\text{inj}}^{1/2}}, & \nu_m < \nu \end{cases}, \]  

(25)

where \( F_{\nu,\text{max}} \) is the observed peak flux at luminosity distance \( D_L \) from the source, which can be estimated as (Sari et al. 1998)

\[ F_{\nu,\text{max}} = N_{e,\text{tot}} \frac{m_e c^2 \sigma_T}{12\pi q_\epsilon D_L^2} B' \Gamma, \]  

(26)

where \( N_{e,\text{tot}} = 4\pi n R^2/3 \) is the total number of sweep-up electrons in the post-shock medium.

With the dynamics and radiation equations described above, we can calculate the time-dependent spectra of the blast wave emission and the lightcurves for any observational frequencies. For the purposes of this work, we focus on the X-Ray lightcurve within the Swift-XRT energy band (0.3–10 keV). Note that the dominant radiation mechanism for X-ray afterglow emission is synchrotron radiation (Mészáros & Rees 1997; Sari et al. 1998), therefore inverse Compton mechanism is ignored in our calculation.

2.3. Influence of the Model Parameters on the X-Ray Lightcurve

In this subsection, we show the numerical results of our model. Here, we explore the influence of the model parameters on the theoretical X-ray lightcurves. There are several free parameters in our model, which can be divided into two categories. The first category is related to the BZ process and the newborn BH, including the initial mass of the newborn BH \( M_{*0} \), the initial BH spin \( a_0 \), the viscosity timescale of disk \( \tau_{\text{vis}} \), the peak time of fallback \( t_p \), and the peak fallback rate \( \dot{M}_p \). The second category is associated with the external shock, including the initial kinetic energy of GRB outflow \( E_0 \), the initial bulk Lorentz factor of GRB outflow \( \Gamma_0 \), the initial opening angle of the jet \( \theta_0 \), the equipartition parameters for the magnetic field and electrons \( \epsilon_B \) and \( \epsilon_e \), and the electron distribution index \( p \).

For the first category, considering that the newborn BH is produced by the collapse of a supermassive NS, the initial mass of the BH, \( M_{*0} \), should be close to the maximum mass of NS, which should be between 2 and 3 solar mass (Lattimer 2012). Within this range, the exact value of \( M_{*0} \) hardly affects the BZ power. Here we adopt \( M_{*0} = 2.2 M_\odot \) as a fiducial value. The influence of \( a_0 \), \( \tau_{\text{vis}} \), and \( t_p \) are shown in Figure 2. We find that: (1) a larger value of \( a_0 \) leads to a more luminous and longer duration plateau; (2) a longer viscosity timescale of disk \( \tau_{\text{vis}} \) results in a longer duration, but lower luminous plateau, which is understandable, since according to Equation (12), a larger value of \( \tau_{\text{vis}} \) corresponds to a slower and weaker BH accretion; (3) a larger value of \( t_p \) leads to lower-luminosity lightcurves.

For the second category, the initial opening angle of the jet hardly affects the final results. Here we adopt \( \theta_0 = 0.1 \) as a fiducial value. The influences of \( \Gamma_0 \), \( n \), \( \epsilon_B \), \( \epsilon_e \), and \( p \) are shown in Figure 2. We find that: (1) when \( n \) is larger, the blast wave collects more material in a higher-density ISM, which leads to a more luminous lightcurve; (2) since synchrotron radiation intensity increases with the magnetic energy density and the electron energy in the external shock, the increase of \( \epsilon_B \) and \( \epsilon_e \) brightens the X-ray flux; (3) the value of \( \Gamma_0 \) mainly affects the early behavior of the lightcurve, but not the late behavior when energy injection happens; and (4) the value of \( p \) mainly affects the decline slope of the lightcurve.

In order to better reflect the injected energy \( E_{\text{inj}} \) and the initial kinetic energy of the blast wave \( E_0 \), we test the influence of parameter \( \eta \equiv E_{\text{inj}}/E_0 \) instead of \( \dot{M}_p \) and \( E_0 \). As expected, the larger the \( \eta \) value, the more significant the lightcurve rebrightening (see Figure 2).

3. Sample Selection and Interpretation

3.1. Data Reduction and Sample Selection

For the purposes of this work, we systemically search sources consisting of two X-ray plateaus, where the first one should be an “internal plateau” followed by a steep decay. The XRT lightcurve data were downloaded from the Swift/XRT team website6 (Evans et al. 2007, 2009), and processed with HEASOFT v6.12. There were 1291 GRBs detected by

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6 http://www.swift.ac.uk/xrt_curves/
Swift/XRT between 2004 February and 2017 July, with 625 GRBs having well-sampled XRT lightcurves, which includes at least 6 data points, excluding the upper limit. XRT lightcurves for all selected samples are then fitted with a multi-segment broken power-law function (in logarithmic scale). Here we adopt the multivariate adaptive regression spline (MARS) technique (e.g., Friedman 1991) to fit the lightcurves. The MARS technique can automatically determine both variable selection and functional form, resulting in an explanatory predictive model. Some previous works have proven that MARS can automatically fit the XRT lightcurve with a multi-segment broken power-law function (results in general consistent with fitting results provided by the XRT GRB online catalog (Evans et al. 2007, 2009)), detect and optimize all breaks, and record all break times and power-law indices for each segment (see Zhang et al. 2014 and Zhao et al. 2019 for details). Here we treat the adjacent segments with an index difference smaller than 0.3 as one component when calculating the segment time span, in order to avoid the potential overfitting problem from the MARS technique. With the fitting results provided by MARS, we searched for candidates with two shallow decay components, where segments with decay slopes shallower than 0.65 and time spans in log scale larger than 0.4 dex are defined as the shallow decay components.7 For the purposes of this work, we add one more criterion for the

Figure 2. Influence of the model parameters on the X-ray lightcurve. Except as noted in each subfigure, in the calculation we take a set of fiducial values for the model parameters: $E_0 = 10^{52} \text{erg}$, $\Gamma_0 = 100$, $n = 1 \text{ cm}^{-3}$, $\theta_0 = 0.1$, $\epsilon_e = 0.1$, $\epsilon_B = 10^{-4}$, $\rho = 2.5$, $a_0 = 0.1$, $\tau_{vis} = 10^5 \text{s}$, $t_p = 10^4 \text{s}$, and $\eta = 30$.

7 Based on the early-year Swift observations, Liang et al. (2007) performed a systematic analysis for the shallow decay component of the GRB X-ray afterglow, and they found that the distribution of the shallow decay slope ($\alpha_s$) is a normal distribution, that is, $\alpha_s = 0.35 \pm 0.35$ (quoted errors are at the 1σ confidence level). Recently, Zhao et al. (2019) revisited the analysis with an updated sample and found that with a larger sample, the distribution of $\alpha_s$ is still a normal distribution with $\alpha_s = 0.43 \pm 0.22$. In this work, we adopt a 1σ region upper boundary of $\alpha_s$ as the selection criteria for the first and second plateau features.
Notes.

For the first plateau.

For the second plateau.

sample selection, i.e., the decay slope following the first shallow decay component should be $\geq 3$. Eventually, we find three long GRBs (GRB 070802, GRB 090111, and GRB 120213A) meeting all our requirements.

GRB 070802 triggered the BAT at 07:07:25 UT on 2007 August 2. $T_{90}$ is 16.4 s $\pm$ 1.0 s. The time-averaged spectrum from $T + 4.9$ s to $T + 23.2$ s is best fitted by a single power-law (SPL) function and the power-law index of the spectrum is $\Gamma_s = 1.79 \pm 0.27$. The fluence in the 15–150 keV band is $S_f = 2.8 \pm 0.5 \times 10^{-7}$ erg cm$^{-2}$ (Cummings et al. 2007). The XRT began taking data 138 s after the trigger (Barthelmy et al. 2007). The fitting result of XRT data provided by MARS is shown in Figure 3. It is worth noting that in this case, the fitting curve given by the online XRT catalog is a little different from that given by MARS. Since there are few data points in the late stage, the online catalog takes all the data after the first plateau into one segment, which is considered a normal decay component. According to its own algorithm, however, MARS automatically fits the late data with two segments, and the second segment has a decline slope of less than 0.65. In this case, we take GRB 070802 as one of our candidates, but with relatively weak evidence. The X-ray fluence and photon index for the two shallow decay segments are listed in Table 1. The UV/Optical Telescope (UVOT; Roming et al. 2005) starts to collect data 141 s after the trigger. No new source was found in the UVOT observations at the location of the refined XRT position (Kuin & Immler 2007). Prochaska et al. (2007) observed the afterglow of GRB 070802 with the ESO VLT + FORS. From the detection of several Fe lines in a 30 minute spectrum starting on August 2.378 UT, the redshift was measured as $z = 2.45$. Krühler et al. (2008) presented the optical and near-infrared photometry of the afterglow obtained with the multichannel imager GROND. Unfortunately, the late optical data points are also scarce, and there is no data point around the time when the second X-ray plateau emerges. The late optical-IR data could be basically consistent with a single decay segment, such that the optical emission trend might be different from the X-ray band, just like what is found for the case of GRB 070110 (Troja et al. 2007). On the other hand, as shown in the next section, the late optical-IR data could also be well fitted by our proposed model simultaneously with the X-ray data.

The BAT triggered and located GRB 090111 at 23:58:21 UT on 2009 January 11. $T_{90}$ is 24.8 $\pm$ 2.7 s. The time-averaged spectrum from $T - 2.9$ s to $T + 25.6$ s is best fitted by a SPL function. The power-law index of the time-averaged spectrum is $\Gamma_s = 2.37 \pm 0.17$. The fluence in the 15–150 keV band is $S_f = 6.2 \pm 0.6 \times 10^{-7}$ erg cm$^{-2}$ (Stamatikos et al. 2009). XRT observations started at 76.6 s after the trigger (Hoversten & Sakamoto 2009). The fitting result of XRT data provided by MARS is shown in Figure 3. The X-ray fluence and photon index for the two shallow decay segments are listed in Table 1. Note that GRB090111 has data more difficult to interpret mainly due to the orbital gap around thousands of seconds, where the data could also be interpreted as a flare followed by a decay (this would also be consistent with the variation in hardness ratio seen in the XRT data). The UVOT starts collecting data 86 s after the trigger. No source was detected by the UVOT at the X-ray afterglow position (Hoversten & Sakamoto 2009). No prompt ground-based observation was
reported, probably due to the vicinity (46°) to the Sun (Margutti et al. 2009).

GRB 120213A triggered the BAT at 00:27:19 UT on 2012 February 12. $T_{90}$ is 48.9 ± 12.5 s. The time-averaged spectrum from $T - 6.31$ s to $T + 74.46$ s is best fitted by a SPL function. The power-law index of the time-averaged spectrum is $\Gamma_c = 2.37 ± 0.09$. The fluence in the 15–150 keV band is $S = 1.9 ± 0.1 \times 10^{-6}$ erg cm$^{-2}$ (Baumgartner et al. 2012). The XRT began collecting data 54 s after the trigger (Oates & Sakamoto 2012). The fitting result of XRT data provided by MARS is shown in Figure 3. The X-ray fluence and photon index for the two shallow decay segments are listed in Table 1. For this case, there is fairly clear evidence for a second shallow decay component, but unfortunately the data do not extend to when the shallow decay stops or to when the slope of the later time emission decays. The UVOT started collecting data 58 s after the trigger. No optical afterglow consistent with the XRT position and no prompt ground-based observation were reported (Oates & Sakamoto 2012).

### 3.2. Model Application to Selected GRBs

In this section, we apply the model described in Section 2 to interpret the X-ray lightcurve data of GRBs 070802, 090111, and 120213A. Since the first X-ray plateau data could be explained with magnetar spin-down power (Troja et al. 2007; Lyons et al. 2010; Rowlinson et al. 2010, 2013; Liu & Zhang 2014; Liu et al. 2015), here we focus on fitting the second X-ray plateau data by considering that the second plateau is produced by energy injection from the newborn BH driving BZ power. In order to minimize the $\chi^2$ of the fitting, a Markov Chain Monte Carlo (MCMC) method is adopted. In our MCMC fitting, the emcee code (Foreman-Mackey et al. 2013) is used with a Walkers number of 160 and $10^4$ burn-in iterations in the ensemble. The total number of observational data points available is not enough to constrain all the model parameters. In order to reduce the number of free parameters in our fitting, we fix several parameters at their typical values. For instance, we set $E_0 = 10^{52}$ erg, $\Gamma_0 = 100$, $n = 1$ cm$^{-3}$, $\theta_0 = 0.1$, $\epsilon_b = 0.1$, $\epsilon_{p} = 10^{-4}$, $\beta = 2.5$, and we only take the initial BH spin $a_0$, the viscosity timescale of disk $\tau_{\text{vis}}$, the peak time of the fallback $t_p$, and the ratio between the injected energy and initial kinetic energy $\eta$ as free parameters. We set the allowed ranges for the four free parameters in our fitting as: $a_0 = [0, 1]$, $\log_{10} \tau_{\text{vis}} = [t_0, t_1]$, $\log_{10} t_p = [t_0, t_1]$, $\log_{10} \eta = [-3, 3]$. Here, $t_0$ is the ending timescale of the internal plateau, which can also be used as the start time of the fallback accretion, and $t_1$ is the time of the last observational data point; their values for each burst are shown in Figure 3.

Figure 4 shows our fitting results for three selected GRBs, where the upper panel shows the fitting lightcurves and the lower panel shows the corresponding corner plot of the posterior probability distribution for the fitting. We can see that the second plateau for all three GRBs could be well fitted with our $\sigma$ confidence parameter level are $a_0 = 0.68^{+0.15}_{-0.24}$, $\log_{10} \tau_{\text{vis}} = 4.50^{+0.45}_{-0.38}$, $\log_{10} t_p = 4.12^{+0.13}_{-0.05}$ s. Note that the late optical-IR afterglow data of GRB 070802 could also be well fitted by our proposed model simultaneously with the X-ray data (in Figure 4, we show the data and fitting result for the $K_s$ band as an example). For GRB 090111 and GRB 120213A, due to the lack of redshift measurement, we adopt $z = 1$ in our analysis. In this case, for GRB 090111, the model parameters at the $1\sigma$ confidence level are $a_0 = 0.7^{+0.14}_{-0.18}$, $\log_{10} \tau_{\text{vis}} = 4.09^{+0.08}_{-0.08}$, $\log_{10} t_p = 2.79^{+0.19}_{-0.10}$, and for GRB 120213A, the results are $a_0 = 0.69^{+0.14}_{-0.19}$, $\log_{10} \tau_{\text{vis}} = 5.43^{+0.28}_{-0.23}$, $\log_{10} t_p = 1.63^{+0.44}_{-0.30}$, and $\log_{10} t_p = 3.95^{+0.26}_{-0.17}$.

From the fitting results, we find that the constraints on model parameters are relatively loose, mainly due to the lack of enough high-quality observation data. Even in this case, some general conclusions could still be made: for all three GRBs, (1) the fallback accretion model could easily explain the second X-ray plateau data with fairly loose parameter requirements. Note that in the fitting, we have fixed several model parameters, which means the parameter constraints could become even looser if these parameters were also released. (2) The constraints on $\eta$ are relatively tight. $\eta$ was constrained to the order of 10–100, inferring that the BZ power must be 10 or 100 times larger than the initial GRB blast wave kinetic energy, in order to produce the second X-ray plateau feature. (3) Although the allowed parameter spaces are wide, $a_0$ tends to have a large value, and the distribution peaks are larger than 0.6, which is expected since larger $a_0$ would easily give larger BH power. (4) The distributions of the viscosity timescale of disk $\tau_{\text{vis}}$ are also wide. The distribution peaks of $\tau_{\text{vis}}$ are relatively large, inferring that the fallback accretion all falls into the slow accretion regime. (5) The distributions for the peak time of the fallback $t_p$ tend to peak around the ending times of the internal plateau, which are around 10$^{-1}$–10$^0$s. Taking this as the start time of the fallback accretion, the minimum radius around which matter starts to fall back could be estimated as $r_{\text{fr}} \sim 2.8 \times 10^{11} (M_r/2.2M_\odot)^{1/3}(t_0/10^4 s)^{2/3}$, which is consistent with the typical radius of a Wolf–Rayet star.

The fitting mass fallback rate $\dot{M}_f$ for these three GRBs reaches the peak value around 10$^{-4}$$M_\odot$ s$^{-1}$ at the time of 10$^{-5}$–10$^0$s. It is interesting to check whether such a mass fallback rate at that time could be supplied by the progenitor envelope. Here we estimate the mass supply rate from the envelope with the presupernova structure models (e.g., Suwa & Ioka 2011; Woosley & Heger 2012; Matsumoto et al. 2015; Liu et al. 2018), i.e.,

$$ M_{\text{env}} = \frac{dM_{\text{env}}}{dt} = \frac{dM_r}{dr} \frac{dt}{dr} = \frac{2M_r}{t_{\text{ff}}} \left( \frac{\rho}{\bar{\rho}} - 1 \right), $$

in which $\bar{\rho} = 3M_r/(4\pi r^3)$ is the average density within radius $r$, $M_r$ is the mass coordinate of a shell, and $t_{\text{ff}} = (3\pi/2(2G\bar{\rho})^{1/2}(\pi/8GM_r))^{1/2}$ denotes the freefall timescale. By taking some representative progenitor density profiles with different metallicities and masses from Liu et al. (2018) and the references therein, we reproduce the mass supply rate changing with time for those progenitor models. In our calculations we set the time when the central accumulated mass reaches $M_r = M_0 = 2.2 M_\odot$ (our fiducial value of the mass of a newborn magnetar) as the zero-time reference point, i.e., we take $t = t_0(r _0)$

$$ - t_0(t_0), \quad M_r = M_0 + \int_{r_0}^{t_0} 4\pi r^2 p dr, $$

where $r_0$ is the radial coordinate for which the enclosed mass is $M_0$. As shown in Figure 5, we find that our fitting resulted in mass fallback rates compatible with the theoretical mass supply rate of some low-metallicity massive progenitor stars such as those ones with $M_\odot < 10^{-5}$, $M_\odot < 80 M_\odot$, $M_\odot < 40 M_\odot$, and $M_\odot < 20 M_\odot$, and so on. The solar metallicity stars
might not be so available to serve as the progenitors for our sample. Based on the fitting results, the magnetic-field strength of the newborn BH ($B_0$) for these three GRBs reaches the peak value around $10^{13-14}$ G, at time $10^{3-10}$ s. According to the dipole spin-down model, one can make estimate the surface magnetic field $B_0$ and the initial spin period $P_0$ of the rapidly spinning magnetar with the first plateau data for all three GRBs in our sample (Rowlinson et al. 2013; Lü et al. 2015). Here we adopt constant values of the moment of inertia $I = 1.5 \times 10^{45}$ g cm$^2$ and radius $R = 10$ km for a typical neutron star. For GRB 070802, the plateau luminosity and break time are $L_0 = 1.4 \times 10^{47}$ erg s$^{-1}$, $t_b = 1 \times 10^{4}$ s, respectively; one can thus derive $P_0 < 4.64 \times 10^{-3}$ s and $B_0 < 2.59 \times 10^{15}$ G. For GRB 090111, the plateau luminosity and break time are $L_0 = 2.9 \times 10^{47}$ erg s$^{-1}$, $t_b = 427$ s, respectively; one can derive $P_0 < 1.55 \times 10^{-2}$ s and $B_0 < 4.19 \times 10^{16}$ G. For GRB 120213A, the plateau luminosity and break time are $L_0 = 2.2 \times 10^{47}$ erg s$^{-1}$, $t_b = 4.57 \times 10^{3}$ s, respectively; one can derive $P_0 < 5.44 \times 10^{-3}$ s and $B_0 < 4.49 \times 10^{15}$ G. We find that the magnetic-field strength of the newborn BH is comparable or slightly lower than the magnetic-field strength of the magnetar, which is understandable if we consider that the magnetic flux should be roughly conserved when the magnetar collapses into the BH, and some magnetic energy might dissipate due to the interaction between the magnetosphere and the fallback flow (Lloyd-Ronning et al. 2019).

4. Discussion and Conclusions

In Swift’s 15 years operation, it has provided many observations of GRB X-ray afterglow, which provides information valuable for understanding the GRB central engine. One particular example is the discovery of an internal X-ray plateau, (a plateau followed by a very steep decay phase), which is commonly taken as evidence of a rapidly spinning magnetar as the central engine. The very steep decay at the end of the plateau suggests a sudden cessation of the central engine, which is understood as the collapse of a supramassive magnetar into a BH when it spins down. If this interpretation is correct, the fallback accretion from the envelope of progenitor star into the newborn BH could generate some detectable signatures.

Here we propose that the energy extracted from the newborn BH could be continuously injected into the GRB blast wave. In this scenario, we find that with appropriate parameters for the fallback accretion and newborn BH, it is possible to produce a second plateau following the steep decay phase of the internal plateau. With a systematic search through the Swift-XRT.

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8 Here we take the break time $t_b$ of the first plateau as the lower limit of characteristic spin-down time, and take the plateau luminosity $L_0$ as the characteristic spin-down luminosity (see detailed methods in Lü et al. 2015). The redshift for GRB 070802 is taken as $z = 2.45$ and the redshift for GRB 090111 and GRB 120213A is taken as 1.
sample, we find three interesting long GRBs, i.e., GRBs 070802, 090111, and 120213A, whose X-ray afterglow lightcurves contain internal X-ray plateau followed by a second plateau. Here we focus on fitting the second X-ray plateau for these three GRBs with our proposed model. We find that in a fairly loose and reasonable parameter space, the second X-ray plateau data could be interpreted with our model.

It is worth noting that the quality of current observation data is not good enough to completely eliminate the degeneracy of parameters. In our sample, GRB 090111 has the most observational data points in the period of the second plateau. GRBs 070802 and 120213A only have four data points in the period of the second plateau. Even in this case, some general conclusions could still be reached, for instance, in order to interpret the second plateau; the initial spin of the newborn BH tends to have larger value (the peak of its posterior probability distribution is larger than 0.6); the later injected energy should be 10 or 100 times larger than the initial GRB blast wave kinetic energy; and the viscosity timescale of disk tends to be large, inferring that the fallback accretion all falls into the slow accretion regime (Lei et al. 2017). The mass fallback rate reaches the peak value around $10^{-4} M_{\odot}$ s$^{-1}$ at time $10^3-10^4$s, which is compatible with the late mass supply rate of some low-metallicity massive progenitor stars. Based on the fitting results, one can infer total accreted masses $M_{\text{acc}} \sim 0.08-0.26 M_{\odot}$ and fallback radii $r_{\text{fb}} \sim a few \times 10^{11}$ cm, which is consistent with the typical radius of a Wolf-Rayet star. Combining the X-ray data of the internal plateaus of the three GRBs with the magnetic dipole radiation model of the magnetar, we coarsely estimate the strength of the magnetic field of the magnetar before its collapse to a BH. We find the magnetic field is strong enough to drive a BZ jet.

If our interpretation is correct, the three GRBs with two X-ray plateaus provide additional evidence for rapidly spinning magnetars as GRB central engines. Note that most GRBs with “internal plateaus” do not show a second X-ray plateau, which means for most cases the fallback accretion may be relatively weak, such that the injected energy is smaller than the initial kinetic energy of a GRB blast wave. Future observations are likely to discover similar events, which could offer more information on the properties of magnetars as well as newborn BHs.

In this paper, we ignore the mass into the outflow from the disk, which will reduce the accretion rate onto the BH horizon during late central engine activity. Usually, the distribution of accretion rate with disk radius is simply described with a power-law model due to the poor knowledge of the disk outflow. The effects of such an outflow are thus highly dependent on the uncertain power-law index parameter. The existence of a disk outflow may also be important to comprehend the baryon-loading into the GRB jet (Lei et al. 2013, 2017) and $^{56}$Ni synthesis for associated supernovae (Song & Liu 2019). We look to future general-relativistic magnetohydrodynamic simulations for a better understanding.

We adopt a simple model to describe the evolution of the fallback accretion rate. For long GRBs, the envelope of the progenitor star is considered the mass supply of the fallback accretion (Kumar et al. 2008a). The evolution of fallback accretion rate is thus a good tracker of the structure of the progenitor envelope (Liu et al. 2018). We will explore the time-dependent fallback accretion rate and the expected afterglow lightcurves from long GRBs with progenitors of different masses, angular velocities, and metallicities in the future, and constrain the characteristics of stars by comparing the second plateau data with our model.

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Software: XSPEC (Arnaud 1996), HEAsoft (v6.12; Nasa High Energy Astrophysics Science Archive Research Center (Heasarc), 2014), root (v5.34; Brun & Rademakers 1997), emcee (v3.0rc2; Foreman-Mackey et al. 2013), corner (v2.0.1; Foreman-Mackey 2016).

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References

Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17

Bardeen, J. M., Press, W. H., & Teukolsky, S. A. 1972, ApJ, 178, 347

Barthelmy, S. D., Evans, P. A., Gehrels, N., et al. 2007, GCN, 6692, 1

Figure 5. Comparison of the fitting mass fallback rate and the mass supply rate for progenitor stars with different metallicities and masses. The fitting mass fallback rates of the three GRBs, i.e., GRB 070802, GRB 090111, and GRB 120213A are denoted by the dashed line, the dashed-dotted line, and the dotted line, respectively. The mass supply rates of the progenitor stars are denoted by the solid colored lines, using the nomenclature as Liu et al. (2018), i.e., the signs s, o, v, and u represent the metallicity values $Z = Z_{\odot}, 10^{-2} Z_{\odot}, 10^{-3} Z_{\odot}$, and $10^{-4} Z_{\odot}$, and the numbers beside the signs denote the progenitor masses in unit of solar mass.

![Figure 5](image-url)
| Authors                                      | Year | Journal          | Page(s) |
|---------------------------------------------|------|------------------|---------|
| Chen, W., Xie, W., Lei, W.-H., et al.       | 2017 | ApJ              | 849,119 |
| Brun, R., & Rademakers, F.                  | 1997 | NIMPA            | 389,81  |
| Chevalier, R. A.                            | 1989 | ApJ              | 346,847 |
| Cummings, J., Barbier, B., Barthelmy, S. D.| 2007 | GCN              | 6699,1  |
| Dai, Z. G., & Liu, R.-Y.                    | 2012 | ApJ              | 759,58  |
| Dai, Z. G., & Lu, T.                        | 1998 | PhilTr           | 81,4301 |
| Dai, Z. G., Wang, X. Y., Xu, X. F., et al.  | 2006 | Sci              | 311,1127|
| de Pasquale, M., Oates, S. R., Racusin, J.  | 2016 | ApJ              | 455,1027|
| Bernardini, M. G., Campana, S., Ghisellini, G., et al. | 2013 | ApJ            | 775,67  |
| Blandford, R. D., & Znajek, R. L.          | 1977 | MNRAS            | 179,433 |
| Moderski, R., Sikora, M., & Lasota, J.      | 1997 | Proc. of the Int. Conf., Relativistic Jets in AGNs, | 110 |
| Novikov, I. D., & Thorne, K. S.             | 1973 | Nature           | 340,126 |
| Evans, P. A., Beardmore, A. P., Page, K. L.| 2007 | A&A              | 469,379 |
| Evans, P. A., Beardmore, A. P., Page, K. L.| 2009 | MNRAS            | 397,1177|
| MacFadyen, A. I., Woosley, S. E.            | 1999 | ApJ              | 726,107 |
| MacFadyen, A. I., Woosley, S. E.            | 2002 | ApJ              | 670,565 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2001 | ApJ              | 550,410 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2003 | ApJ              | 524,262 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2004 | ApJ              | 400,803 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2005 | ApJ              | 540,803 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2006 | ApJ              | 642,354 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2007 | ApJ              | 552,135 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2008 | ApJ              | 679,639 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2009 | ApJ              | 883,9   |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2010 | ApJ              | 705,461 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2011 | ApJ              | 718,841 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2012 | ApJ              | 823,156 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2013 | ApJ              | 475,266 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2014 | ApJ              | 679,639 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2015 | ApJ              | 883,9   |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2016 | ApJ              | 705,461 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2017 | ApJ              | 718,841 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2018 | ApJ              | 823,156 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2019 | ApJ              | 475,266 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2020 | ApJ              | 679,639 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2021 | ApJ              | 883,9   |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2022 | ApJ              | 705,461 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2023 | ApJ              | 718,841 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2024 | ApJ              | 823,156 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2025 | ApJ              | 475,266 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2026 | ApJ              | 679,639 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2027 | ApJ              | 883,9   |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2028 | ApJ              | 705,461 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2029 | ApJ              | 718,841 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2030 | ApJ              | 823,156 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2031 | ApJ              | 475,266 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2032 | ApJ              | 679,639 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2033 | ApJ              | 883,9   |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2034 | ApJ              | 705,461 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2035 | ApJ              | 718,841 |
| MacFadyen, A. I., Woosley, S. E., & Heger, A.| 2036 | ApJ              | 823,156 |