To Power the X-Ray Plateaus of Gamma-Ray Bursts through Larger Amplitude Electromagnetic Waves

Shuang Du\textsuperscript{1,2}

\textsuperscript{1} State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, People’s Republic of China; dushuang@pku.edu.cn
\textsuperscript{2} Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, People’s Republic of China

Received 2020 March 16; revised 2020 July 23; accepted 2020 August 12; published 2020 September 23

Abstract

The origin of the gamma-ray burst (GRB) X-ray plateau, especially the internal plateau, is still unclear, but it could be related to a GRB’s magnetar central engine. It is generally believed that the spin-down power of the magnetar is injected into forward external shock; however, we propose here that most of the power will be dissipated behind the GRB jet through a larger amplitude electromagnetic wave. Based on this proposal, the relevant physical conditions and observational implications are analyzed and discussed, and various kinds of X-ray light curves could be reproduced. Although the chromatic multiband afterglow in the standard external afterglow fireball model is still a matter of debate, we can naturally explain this feature through this proposal, i.e., the electrons generating the X-ray plateau and emitting the optical afterglow are accelerated by different mechanisms. It is emphasized that both the GRB jet and the spin-down wind should have significant observational consequences in the magnetar scenario, and should be focused equally in GRB physics.

Unified Astronomy Thesaurus concepts: Neutron stars (1108); Gamma-ray bursts (629); X-ray astronomy (1810)

1. Introduction

Neutron stars (NSs)/magnetars are widely considered to interpret gamma-ray burst (GRB) observations, such as prompt emission (Duncan & Thompson 1992; Usov 1992, 1994; Dai & Lu 1998a; Kluźniak & Ruderman 1998; Spruit et al. 2001; Bucciantini et al. 2007), extended emission (Metzger et al. 2008, 2011; Gompertz et al. 2013; Gibson et al. 2017), X-ray flares (Dai et al. 2006), and X-ray plateaus (as well as optical rebrightening, Dai & Lu 1998b; Zhang & Mészáros 2001; Rowlinson et al. 2013; Tang et al. 2019). Alternatively, these features can also be interpreted if GRB central engines are black hole (BH) disk systems (Narayan et al. 1992; Mochkovitch et al. 1993; Woosley 1993; Popham et al. 1999; King et al. 2005; Rosswog 2007; Barkov & Pozanenko 2011; Beniamini & Mochkovitch 2017). However, it is worth noting that some observational facts related to the X-ray plateaus have yet to be explained under either the NS scenario or the BH scenario.

Generally, the plateau followed by a power-law decay with an index of $q < -3$ is called an “internal plateau” (e.g., GRB 070110, Troja et al. 2007; GRB 090515, Rowlinson et al. 2010). For clarity, in this paper, we call plateaus with $q > -3$ “ordinary plateaus” (e.g., GRB 060729, Evans et al. 2007). A number of models are proposed to explain both types of X-ray plateaus. Some interpretations do not depend on specific central engines but invoke a jet with an appropriate distribution of bulk Lorentz factor (Rees & Mészáros 1998; Uhm & Beloborodov 2007), a structured GRB jet (Eichler & Granot 2006; Toma et al. 2006; Yamazaki 2009), a jet with evolving microphysical parameters (Ioka et al. 2006; Pannaralescu et al. 2006), a jet with delayed deceleration (Granot & Kumar 2006; Shen & Matzner 2012; Duffell & MacFadyen 2015), a jet that exchanges with circumburst medium (Kobayashi & Zhang 2007; Shao & Dai 2007), and a jet viewed slightly off-axis (Beniamini et al. 2020). These models may account for the ordinary plateaus but usually do not work for the internal plateaus due to the steep decay segments.

The leading model to explain both the ordinary plateaus and internal plateaus suggests a long-lasting central engine. Without considering the interaction between the assumed long-lasting magnetized wind and GRB jet, Lyutikov & Camilo Jaramillo (2017) proposed that the ordinary X-ray plateaus can be produced through the interaction of the wind with the shocked circumburst medium. But there must be an interaction between the wind and the GRB jet, since the assumed Lorentz factor of the wind, $\sim 10^6$, is much larger than that of the GRB jet. And there should be a very weak interaction between the wind and the circumburst medium, since the circumburst medium is swept up by the GRB jet. To account for the internal plateau, we note that energy dissipation of the continuous outflow should trace the energy release of the central engine. Let us have a brief review.

Under the long-lasting BH-disk central engine scenario (Kumar et al. 2008), the different segments of outflow, as well as the light curve, are related to the accretion of different parts of the GRB progenitor star, i.e., the X-ray plateau corresponds to the accretion of a certain region of the progenitor star. But this model can only be applied to the collapsar. Even if one believes that this long-lasting accretion is also true for short GRBs, as shown by their erratic rapidly variable prompt-emission light curves, the accretion, as well as the GRB jets, should be intermittent and inhomogeneous. Then a rapidly variable “late prompt” emission produced by the intermittent and inhomogeneous long-lasting outflow should be observed but not the smooth plateau (e.g., GRB 070110, Troja et al. 2007). It is not accurate to believe that the energy release of the intermittent and inhomogeneous jet is smooth (e.g., Ghisellini et al. 2007; Beniamini & Mochkovitch 2017).
Under the magnetar scenario, on the one hand, the ordinary plateau would be powered by the spin-down wind of the stable magnetar with a certain braking index. On the other hand, the spin-down-induced gravitational collapse of the unstable magnetar could account for the steep decay of internal plateau phenomenologically (Rowlinson et al. 2013). However, it is generally believed that the energy of spin-down wind will be directly injected into the forward external shock (e.g., Dai & Lu 1998b; Zhang & Mészáros 2001), and thus the decay following the internal plateau should be a normal decay (decay index $\sim -1.2$, Zhang et al. 2006) instead of a steep decay after the magnetar collapses. Because, either before or after energy injection, the X-ray is emitted by the electrons accelerated by forward external shock, some authors suggest that there may be some unknown internal dissipation in the magnetized winds (Fan & Xu 2006; Yu et al. 2010).

Given the natural correspondence between the collapse of the magnetar and the steep decay of the internal plateau, we prefer the magnetar scenario. In Section 2, we introduce the applicability of the GRB NS/magnetar model and propose that the GRB jet and the spin-down wind might evolve separately. In Section 3, we discuss some implications of this proposal. Section 4 includes a discussion and summary. Throughout this paper, parameters without primes are in the lab frame, and parameters with primes are in the rest frame comoving with the spin-down wind.

2. Why Is an NS/Magnetar Needed?

GRBs can be classified into two categories based on duration $T_{90}$ (Kouveliotou et al. 1993): short GRBs with $T_{90} < 2$ s and long GRBs with $T_{90} > 2$ s. Observations confirm that short GRBs at least originate from double NS mergers (GW170817/GRB170817A association; Abbott et al. 2017), and long GRBs originate from massive star collapses (e.g., GRB/type-Ic supernova associations; Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003). The central remnants of these catastrophes are still uncertain. As illustrated in Section 1, the BH-disk system should not generate a smooth X-ray plateau due to the inhomogeneous accretion, hence we turn to the NS central engine.

For an NS–NS merger, the merger remnant may be an NS or a BH, which depends on the total mass of the binary and the equation of state of NSs. A precise measurement shows that the upper limit of the rest mass of an NS should satisfy $M_{\text{TOV}} > 1.97 M_\odot$ (Antoniadis et al. 2013). GW170817/GRB 170817A indicates $M_{\text{TOV}}$ may be $\sim 2.2 M_\odot$ (Margalit & Metzger 2017, alternatively, see Cromartie et al. 2019) or greater (Yu et al. 2018). In this sense, the maximum mass that a rotating NS can support will be $\sim 2.6 M_\odot$. Therefore, if the total mass distribution of extragalactic double NS systems is similar to that of in the Milky Way, i.e., $M_{\text{tot}} \in (2.5 M_\odot, 2.9 M_\odot)$ (Lazarus et al. 2016; Stovall et al. 2018; see Özel & Freire 2016 for a review), the remnant of NS–NS merger can be a supramassive/hypermassive NS (even a stable NS). For massive star collapse, since an NS can be born in a supernova explosion, the center of the long GRB associated with the supernova can also be an NS (stable, supramassive, and hypermassive). Therefore, the NS/magnetar scenario is reasonable at least for some of the GRBs.

To avoid the complication of the magnetar scenario, mentioned in Section 1 by which the standard energy injection under the magnetar scenario can only produce an ordinary plateau followed by a power-law decay with an index of $q \sim -1.2$, we suggest an improved scenario in which most of the spin-down power of magnetar is usually not injected directly into the forward external shock but continuously dissipated behind the GRB jet independently (mainly through large amplitude electromagnetic waves, LAEMWs, see below). Notably, once LAEMWs can keep the energy dissipation of the spin-down wind tracing the spin-down power (which is stronger than the external-shock-induced X-ray emission of the GRB jet), the collapse of the magnetar will naturally correspond to the steep decay of the internal plateau. In this case, the GRB jet and the spin-down wind evolve separately, so that both the GRB jet and the spin-down wind should have significant observational consequences.

It is worth noting that this proposal does not depend on the type of plateaus to be applicable for both the ordinary and the internal plateaus. Interestingly, if one believes the X-ray transient CDF-S XT2 (Xue et al. 2019) is powered by a magnetar\footnote{Then the plateau models associated with GRB jets cannot explain this transient (see, e.g., Oganesyan et al. 2020).}, our proposal can also be consistent with the implication that the energy release of the spin-down wind has nothing to do with the GRB jet. In Section 3, we discuss some implications of our proposal. We will focus on the internal plateaus, since the discussion can be naturally generalized to the ordinary plateaus.

3. Implications of the Idea

3.1. LAEMWs

In order to explain the observed excess in infrared radiation from Crab Nebula, Usov proposed that synchrotron radiation from electrons accelerated in the field of LAEMWs (Usos 1975, also see Usos 1994; Melatos & Melrose 1996) can explain this observation. In this section, we apply this concept to GRB X-ray internal plateaus. Let us introduce LAEMWs first.

For a rotating NS with inclined dipole magnetic field in vacuum, the magnetic dipole radiation generated by this magnetic dipole can be solved analytically under a given accuracy. But in reality the NS is contained in a magnetosphere filled with plasma due to the unipolar induction effect (Goldreich & Lynden-Bell 1969). Therefore, this low-frequency magnetic dipole radiation will be screened at near distance.

Nevertheless, the rotational energy of the NS must be extracted by the approximately isotropic outflow (spin-down wind) consisting of plasma and magnetic field frozen inside. Certainly, since there is an inclination angle between the rotation axis and the magnetic axis of the NS, the frozen magnetic field in the spin-down wind along the rotation axis (as well as the GRB jet) can be alternating direction (i.e., striped magnetic field, see, e.g., Coroniti 1990; Usos 1999; Spruit et al. 2001). As the spin-down wind moves away from the NS and the wind density decreases, there is a moment that displacement currents cannot be screened any more and an induced electric field occurs. Eventually, the striped magnetic field is transformed into low-frequency electromagnetic waves, i.e., LAEMWs, in the far field.
3.2. How Does the Spin-down Wind Dissipate?

In this subsection, we discuss how the spin-down wind can be dissipated through LAEMWs. To generate an almost flat X-ray plateau and a steep decay, energy of the spin-down wind should be released rapidly and smoothly. Therefore, (i) the spin-down wind should initially be highly magnetized, i.e.,

\[
\sigma = \frac{B^2}{4\pi \Gamma_w \rho c^2} \gg 1, \tag{1}
\]

\[
\frac{B^2}{4\pi} \approx L_{sd}, \tag{2}
\]

where \(\sigma\) is the magnetization, \(B\) is the magnetic field strength, \(\rho\) is the mass density, \(v\) is the speed of the spin-down wind, \(S\) is the cross area, \(c\) is the speed of light, \(L_{sd}\) is the spin-down power, and \(\Gamma_w\) is the bulk Lorentz factor of the spin-down wind; (ii) the spin-down power should be balanced by the magnetic-energy dissipation rate, \(L_{\text{dis}}\), approximately, i.e.,

\[
\frac{L_{sd}}{L_{\text{dis}}} = \frac{B^2 S v}{4\pi n_e P_e S l} \sim 1, \tag{3}
\]

where \(n_{\pm}\) is the number density of accelerated electrons (and positrons), \(P_e\) is the synchrotron radiation power of a single electron, and \(l\) is the distance that the wind travels per second; (iii) when the magnetic energy in the volume \(S v\) is totally dissipated, electrons should also be cooled down, i.e., the radiative lifetime of these electrons, \(\tau\), satisfies

\[
\tau = \frac{E_e}{P_e} < \sim 1 \text{ s}, \tag{4}
\]

where \(E_e\) is the energy of a single electron. Condition (i) enables the energy of the spin-down wind to almost be totally released once the magnetic energy is completely dissipated. Conditions (ii) and (iii) guarantee that the magnetic energy can be dissipated rapidly and the energy of the accelerated electrons does not accumulate, so that the corresponding light curve remains flat.

For magnetic-field-dominated relativistic wind, according to conditions (ii) and (iii), we have

\[
\frac{B_{d}^2}{4\pi n_e P_e} = \frac{B_{d}^2}{4\pi n_e P_e \Gamma_w} \sim 1 \text{ s}, \tag{5}
\]

and

\[
\frac{E_e}{\Gamma_w P_e} \approx \frac{5 \times 10^8}{\Gamma_w \gamma_e B_{d}^2} < 1 \text{ s}, \tag{6}
\]

where \(\gamma_e\) is the Lorentz factor of electrons.

Note that the plateau usually appears at \(t_d \sim 100\) s after the burst, and the spin-down wind at least dissipates at a location \(r_d = c t_d \sim 10^{12}\) cm away from the source. Since the magnetic field in the spin-down wind is dominated by the toroidal component at a large distance from the source and by the dipole magnetic field in the light cylinder, the magnetic field strength at \(r_d\) is (see also Usov 1994)

\[
B_{d} \approx B_{\text{dip}} \left( \frac{R_w}{r_d} \right)^3 \left( \frac{r_d}{r_L} \right)^{-1} \times \left( \frac{B_{\text{dip}}}{3 \times 10^4 \text{ Gs}} \right) \left( \frac{P}{1 \text{ ms}} \right)^{-2} \text{ Gs,} \tag{7}
\]

where \(B_{\text{dip}}\), \(r_L = c p / 2 \pi\), and \(P\) are the surface magnetic field strength, the light cylinder radius, and the spin period of the magnetar, respectively. The method to derive the typical values of \(B_{\text{dip}}\) and \(P\) can be found in Du et al. (2016, 2019). For simplicity, we adopted a radius of the magnetar of \(R_w = 10^6\) cm. To get Equation (7), we also assume that the magnetic energy release is not important before the spin-down wind reaching \(r_d\). The reason for this is that instabilities that cause magnetic field dissipation need time to propagate. The typical propagating timescale is the Alfvén crossing time over the length scale in which the magnetic field in the outflow changes. This gives a distance from the source \(r \sim 10^{12}\) cm (Spruit et al. 2001) beyond which the magnetic energy release becomes important. It is clear that \(r \sim 10^{12}\) cm matches \(r_d\) well.

The typical energy of synchrotron emission is

\[
\varepsilon = 1.7 \left( \frac{\gamma_e}{10^2} \right)^2 \left( \frac{B_{d}}{10^7 \text{ Gs}} \right) \text{ keV.} \tag{8}
\]

Combining Equations (7) and (8), we find that when \(B_{d} \sim 10^7\) Gs and \(\gamma_e \sim 10^2\), electrons can emit X-ray photons at \(r_d \sim 10^{12}\) cm. Meanwhile Equation (6) can be easily satisfied. According to the fast dissipation condition, i.e., Equation (5), if most electrons in the spin-down wind are accelerated, then

\[
n_{\pm} = 7.2 \times 10^9 \left( \frac{\gamma_e}{10^2} \right)^2. \tag{9}
\]

Now, the question is what mechanism accelerates these electrons. We have argued that the spin-down wind is continuously dissipated behind the GRB jet, so that without internal collisions (Zhang & Yan 2011) the ordered striped magnetic field in the spin-down wind may be hard to dissipate into X-ray emission violently (see Périé 2016 for review).³ As introduced in Section 3.1, LAEMWs may be another way. The critical condition for the emergence of LAEMWs is that the number density, \(n_{\pm}\), decreases to the Goldreich–Julian density

---

³ Strictly speaking, \(l\) should be the radiative damping length of LAEMWs. However, to result in a plateau instead of a rising light curve during the hydrodynamic evolution timescale of the spin-down wind, \(\sim \gamma_{r_0} \Gamma_w \rho \simeq 10^2\) cm as discussed later in this subsection, the order of magnitude of \(\Gamma_w \rho\) should be \(\sim 10\) (see Section 3.4), and there is \(l/c \sim 1\). This argument is also consistent with the estimations of Asseo et al. (1978) and Usov (1994). Therefore, we simply consider \(l\) to be the distance that the wind travels per second.

³ To convert the magnetic energy of spin-down wind into kinetic energy to produce a GRB, some other mechanisms are proposed (e.g., Drenkhahn & Spruit 2002; Lyubarsky 2010). But the prediction of these mechanisms is not supported by the observation that GRBs are produced by relativistic jets rather than approximately isotropic spin-down winds (Mooley et al. 2018; Izzo et al. 2019). Therefore, we do not consider these mechanisms.
The Astrophysical Journal, 901:75 (7pp), 2020 September 20

Du

\begin{equation}
R_\gamma = 2c\Delta t \Gamma_{\text{jet}}^2 = 1.0 \times 10^{15} \left( \frac{\Gamma_{\text{jet}}}{10^2} \right)^2 \text{cm},
\end{equation}

if the Lorentz factor of the relativistic jet launched from the binary NS merger satisfies \( \Gamma_{\text{jet}} \gg 1 \) initially. Accordingly, if the dissipation of the spin-down wind follows the generation of gamma-ray photons, there is \( r_d \sim R_\gamma \). Therefore, the parameters derived through Equations (6), (7), and (8) turn to

\begin{align}
B_d &\approx B_{\text{dip}} \frac{R_w}{r_c} \left( \frac{r_e}{r_d} \right)^{-1} \\
&= 1.3 \times 10^4 \left( \frac{r_d}{10^{15}\text{ cm}} \right)^{-1} \times \left( \frac{B_{\text{dip}}}{3 \times 10^{14}\text{ Gs}} \right) \left( \frac{P}{1\text{ ms}} \right)^{-2} \text{ Gs},
\end{align}

\begin{equation}
\varepsilon = 1.7 \left( \frac{\gamma_e'}{3.3 \times 10^4} \right)^2 \left( \frac{B_d}{10^4\text{ Gs}} \right) \text{ keV},
\end{equation}

\begin{equation}
n_\pm = 7.2 \times 10^6 \left( \frac{\gamma_e'}{3.3 \times 10^4} \right)^{-2}.
\end{equation}

However, the condition of emerging LAEMWs is still satisfied. Because, at this time, the critical number density is

\begin{align}
n_{\text{cr}} &= 1.0 \times 10^9 \left( \frac{r_d}{10^{15}\text{ cm}} \right)^{-1} \\
&\times \left( \frac{B_{\text{dip}}}{3 \times 10^{14}\text{ Gs}} \right) \left( \frac{P}{1\text{ ms}} \right)^{-3} \text{ cm}^{-3}.
\end{align}

One still has \( n_\pm \sim n_{\text{cr}} \).

It is worth noting that if the \( \sim 1.7 \) s time delay between GW170817 and GRB 170817A is caused by a delayed jet launch or acceleration of the jet from the nonrelativistic case to extreme relativicity (Mochkovitch et al. 1993), there is no need to demand \( R_\gamma \sim 10^{15} \) cm. But one cannot rule out the possibility that the initial X-ray photons due to the dissipation of spin-down wind can be detected earlier than the GRB prompt emission (e.g., \( r_d \sim 10^{12} \) cm, \( R_\gamma \sim 10^{15} \) cm), as long as the initial interval, \( \Delta L \), between the spin-down wind and the jet satisfies

\begin{equation}
\Delta L < \frac{R_\gamma}{2\Gamma_{\text{jet}}^2} \\
= 5.0 \times 10^{10} \left( \frac{R_\gamma}{10^{15}\text{ cm}} \right) \left( \frac{\Gamma_{\text{jet}}}{10^2} \right)^{-2} \text{ cm}.
\end{equation}

Therefore, this feature provides a chance to test our proposal.

3.4. Interaction between the Spin-down Wind and GRB Jet

When the spin-down wind reaches \( r_d \), the magnetic energy would not be totally dissipated to power the X-ray plateau. Part of the magnetic energy may convert to the kinetic energy of the remnant spin-down wind. Energy conservation gives

\begin{equation}
\eta (1 + \sigma_0) \Gamma_w = (1 + \sigma_d) \Gamma_{w,d},
\end{equation}

where \( \sigma_0 \) and \( \sigma_d \) are the magnetization before and after the spin-down wind dissipation, \( \Gamma_w \) and \( \Gamma_{w,d} \) are the Lorentz factors of

Figure 1. Schematic diagram of the relation between the spin-down wind and the GRB jet under \( \Gamma_{w,d} > \Gamma_{\text{jet}} > \Gamma_w \). The black curves denote the magnetic lines. The vertical bar at \( r_d \) is the place in which the spin-down wind dissipates. The approximate isotropic spin-down wind is cut into a trapezoid to fit the size of the image (these stipulations are also applied to Figures 2 and 3). Since \( \Gamma_w < \Gamma_{\text{jet}} \) initially, an interval will exist between the spin-down wind and the GRB jet. When the spin-down wind reaches \( r_d \), the magnetic-energy dissipation results in the X-ray plateau and leads to the acceleration of the remnant spin-down wind. Consequently, the Lorentz factor of the remnant spin-down wind may satisfy \( \Gamma_{w,d} > \Gamma_{\text{jet}} \). After the last spin-down wind (far left of the bigger trapezoid) reaches \( r_d \) (at time \( t_c \)), steep decay begins. And then, the faster remnant wind eventually catches up with the GRB jet at time \( t_c \), so that a flare-like X-ray bump appears.

(Usov 1994)

\begin{equation}
n_{\text{cr}} = 1.0 \times 10^9 \left( \frac{r_d}{10^{12}\text{ cm}} \right)^{-1} \times \left( \frac{B_{\text{dip}}}{3 \times 10^{14}\text{ Gs}} \right) \left( \frac{P}{1\text{ ms}} \right)^{-3} \text{ cm}^{-3}.
\end{equation}

Since \( n_\pm \propto r^{-2} \) and \( n_{\text{cr}} \propto r^{-1} \), comparing Equations (9) and (10), one can find that the dissipation of magnetic energy via LAEMWs will be important when the spin-down wind reaches \( \sim r_d \). It is worth mentioning that before the first data point was observed, the Chandra Telescope had pointed at CDF-S XT2. That is to say, the X-ray emission of CDF-S XT2 appears suddenly without a gradual brightening as shown in its light curve. This feature is consistent with our scenario that the spin-down wind dissipates immediately when it reaches \( r_d \).
the spin-down wind before and after the dissipation, and \( \eta \) is the efficiency with which magnetic energy is converted into kinetic energy. Since the circumburst medium is swept up by the GRB jet, we assume that \( \Gamma_w \) and \( \Gamma_{w,d} \) are constants. From Equation (17), one has

\[
\Gamma_{w,d} \sim 10^2 \left( \frac{\eta}{0.1} \right) \left( \frac{\Gamma_w}{10} \right)
\]

(18)

with \( \sigma_0 \sim 10^2 \) and \( \sigma_d \sim 1 \).

Note that there could be an interval between the spin-down wind and GRB jet, e.g., \( \Gamma_w < \Gamma_{w,d} < \Gamma_{jet} \) due to the initial mass loading of the wind or the delayed spin-down wind launch induced by fall-back accretion. If the acceleration of the remnant spin-down wind satisfies \( \Gamma_{w,d} > \Gamma_{jet} \) (see Equation (18)), the remnant spin-down wind will catch up with the GRB jet (i.e., the case shown in the upper panel of Figure 1), so that a collision can happen. Through the collision, the forward shock propagating in the GRB jet can always be produced; however, the emergence of reverse shock depends on the residual magnetic field in the spin-down wind. The critical condition is that the pressure of the shocked jet matter equals the magnetic pressure of the spin-down wind (Zhang 2018), i.e.,

\[
\frac{4}{3} \Gamma_{w,jet}^2 \Gamma_{jet} n_w m_p c^2 \sim \frac{4}{3} \Gamma_{w,d}^2 n_w m_p c^2 \sim \frac{B^2}{8 \pi}
\]

(19)

where \( \Gamma_{w,jet} \) is the relative Lorentz factor between the wind and jet. For rough dimensional analysis, we assume that the ratio of the baryon number density of the spin-down wind to the baryon number density of the jet, \( n_w/n_{jet} \), is approximate to the ratio of the spin-down luminosity to the jet power. Therefore, combining Equations (1) and (19) gives

\[
\sigma_{crit} \sim \frac{8}{3} \Gamma_{w,d}^2 \frac{n_w}{n_{jet}} \approx 7 \times 10^{3} \left( \frac{\Gamma_{w,d}}{50} \right) \left( \frac{n_{jet}}{10^3} \right),
\]

(20)

where \( \sigma_{crit} \) is the critical magnetization.

When the magnetar collapses, the emitting of spin-down wind stops. After the last spin-down wind passes the radius \( r_d \) (at time \( t_b \)), steep decay begins. As we proposed, the total X-ray light curve of the GRB with an internal plateau is composed of two parts: (a) the brighter X-ray plateau and steep decay generated by the dissipation of spin-down wind, (b) the less luminous normal decay with decay index \( \sim -1.2 \) generated by the interaction between the GRB jet and its surrounding medium. The steep decay should be powered by the residual magnetic energy in the spin-down wind. Therefore, the dissipation of magnetic energy in the remnant spin-down wind follows the observed X-ray luminosity of the steep decay segment, i.e.,

\[
\frac{V}{4\pi} \frac{d(B^2)}{dt} = L(h_b) \left( \frac{t}{t_b} \right)^\eta,
\]

(21)

where \( V = 4\pi r_\text{eff}^2 \Delta h \) is the volume of the spin-down wind with \( r \) being the time after the burst and \( \Delta h \) being the thickness of the spin-down wind; \( L(h_b) \) is the X-ray luminosity at time \( t_b \). Note that when \( V \propto r^2 \) and \( \sigma \propto B^2 \) (see Equation (1)), one has

\[
\frac{d(\sigma)}{dt} \propto t^{q-2}
\]

(22)

from Equation (21). According to Equation (22), there is

\[
\frac{\sigma_c}{\sigma_d} \sim \left( \frac{h_b}{\tau_c} \right)^{q+1},
\]

(23)

where \( \sigma_c \) is the magnetization of the spin-down wind at the collision, and \( \tau_c \) is the time when the spin-down wind collides with the GRB jet. Substituting Equation (17) into Equation (23) gives

\[
\sigma_c = \sigma_d \left( \frac{h_b}{\tau_c} \right)^{q+1}
\]

(24)

with

\[
\sigma_d = \left( \frac{\eta (1 + \sigma_0) \Gamma_{jet}}{\Gamma_{w,d}} - 1 \right).
\]

(25)

Considering that the isotropic energy of some GRB X-ray plateaus can be as high as \( \sim 10^{52} \text{erg} \) (e.g., GRB 170714A, Du et al. 2019), \( \eta \) at most \( \sim 0.1 \) since most of the energy from spin-down wind is released in X-ray emission. On the basis of \( -q > 3 \) for the steep decay, nonnegligible mass loading (see Equation (20)) and Equations (24) and (25), to get \( \sigma_c > \sigma_{crit} \), the value of \( \sigma_0 \) is too large to be reasonable. Therefore, it is expected that the reverse shock can always be developed when the spin-down wind catches up with the GRB jet. Correspondingly, a flare-like X-ray bump would be produced (see the lower panel of Figure 1, e.g., GRB 070110, Troja et al. 2007; and GRB 170714A, Hou et al. 2018) according to the internal
3.5. The Independently Evolved GRB Jet and Spin-down Wind

As discussed above, the dissipation of spin-down wind is independent of the GRB jet. Since the opening angle of the spin-down wind (approximately isotropic) is much larger than that of the GRB jet ($\sim 10^6$), there is a situation in which only the radiation from the spin-down wind is observed. In other words, an X-ray plateau without the corresponding GRB can be detected, such as, CDF-S XT2. This could be an important phenomenon that can distinguish our model from the standard energy injection scenario, since under the standard energy injection scenario, the energy of the wind can only be converted into X-ray emission when the spin-down wind is injected into the GRB jet, i.e., the X-ray plateau must be associated with a GRB.

On the other hand, GRBs are transient events, while spin-down winds from NSs will last for a long time. These spin-down winds will exert long-lasting impacts on the evolutions of pulsar wind nebulae. There is a conflict between theories and observations: the spin-down wind is usually dominated by the Poynting flux with $\sigma \gg 1$, but the analyses of the Crab Nebula have $\sigma \ll 1$ (e.g., Begelman & Li 1994, see Péri 2016 for a review). The spin-down wind should be abruptly dissipated before reaching termination shock. The problem is, how does the strong magnetized spin-down wind become the weak magnetized wind? As we suggested, part of the magnetic energy in the spin-down wind is converted into the kinetic energy of the spin-down wind before the wind reaching Crab Nebula (see also Coroniti 1990).

These two different observations could be regarded as observational support for our model.

4. Discussion and Summary

In the above, the acceleration of electrons during the magnetic energy release in the spin-down wind is not discussed, since this is a complicated problem in astrophysics and beyond the scope of this paper. Nonetheless, the acceleration of electrons through LAEMWs is not sensitive to $\sigma_0$, as long as $\sigma_0 \gg 1$, but depends on the ratio of spin-down power to the flux of electrons (Usov 1994). To get a suitable Lorentz factor (e.g., $\gamma_e \sim 10^2$), the number density of electrons should satisfy Equation (9).

In this paper, we propose an improved proposal to explain the GRB internal plateaus under the magnetar scenario by which the magnetized spin-down wind can almost be completely dissipated through LAEMWs behind the GRB jet. In this scenario, the interaction between the remnant spin-down wind and the jet may result in a flare-like or a faint X-ray bump following the steep decay. In particular, the acceleration mechanism of electrons in the spin-down wind under our scenario can be different from that of the standard external-shock scenario, and thus the multiband afterglow light curve of these two may show different features. For example, during the plateau segment (including the ordinary plateau, if the magnetar is stable), the multiband afterglow of the former is chromatic; however, the latter is more likely achromatic. This difference may be useful for distinguishing the origins of the plateaus.

It is worth noting that although we claim that the spin-down wind can be dissipated via LAEMWs, the proposal that the spin-down power is not injected into the forward external shock but continuously dissipated behind the GRB jet is
compatible with other mechanisms as long as they can dissipate the spin-down wind instantaneously at a certain distance from the GRB central engine. For example, if the Lorentz factor has an appropriate distribution in the spin-down wind (e.g., with a slower head and faster tail due to time-evolution mass loading), the spin-down wind will shrink enough during traveling, and then there may be a certain time in which the striped magnetic field can be dissipated through the magnetic reconnection induced by the self-compression of the wind. We believe that LAEMWs are a much simpler and more natural mechanism to power the X-ray plateaus in GRB physics.

Determining the origin of the plateaus has more than just astronomical implications. It is also important for understanding the equation of state of supranuclear matter, a problem relevant to nonperturbative quantum chromo-dynamics (QCD, see, e.g., Xu 2018). Although we have entered the era of multimessenger astronomy, the current gravitational-wave detectors cannot provide effective information on the remnant of the GW170817-like event. However, GRB X-ray plateaus may provide opportunities to achieve this goal, as well as the cognition of the nonperturbative QCD, since the observational behavior of the plateau is strongly related to the life of a supramassive/hypermassive NS and thus to the stiffness of the equation of state (i.e., $\rho_{\text{TOV}}$).

We thank the anonymous referee for very useful comments that have allowed us to improve our paper. We thank Professors Yongquan Xue and Huirong Yang for useful discussions and valuable comments. We thank Professor Renxin Xu and Dr. Xuhao Wu for helping us with the English expression. We thank Xianggao Wang for helping us to find the sample, GRB 150910A, to test our model after we explained our model to him. This work was supported by the National Natural Science Foundation of China (grant Nos. 11673002, and U1531243), the National Key R&D Program of China, and the Strategic Priority Research Program of Chinese Academy Sciences (grant No. XDB23010200).

ORCID iDs
Shuang Du © https://orcid.org/0000-0001-5247-5559

References
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, ApJL, 848, L13
Antoniadis, J., Freire, P. C. C., Wex, N., et al. 2013, Sci, 340, 448
Asseo, E., Kennel, C. F., & Pellat, R. 1978, A&A, 65, 401
Bartoli, G. V., & Pellat, R. 1978, A&A, 65, 401
Bartoli, G. V., & Pellat, R. 1978, A&A, 65, 401
Beniamini, P., Duque, R., Daigne, F., et al. 2020, MNRAS, 492, 2847
Beniamini, P., & Mochkovitch, R. 2017, ApJ, 835, 206
Margalit, B., & Metzger, B. D. 2017, ApJ, 850, L19
Melatos, A., & Melrose, D. B. 1996, MNRAS, 279, 1168
Metzger, B. D., Giannios, D., Thompson, T. A., Bucciantini, N., & Quataert, E. 2011, MNRAS, 413, 2031
Metzger, B. D., Quataert, E., & Thompson, T. A. 2008, MNRAS, 385, 1455
Mochkovitch, R., Hernanz, M., Isenberg, J., & Martin, X. 1993, Natur, 361, 236
Mooley, K. P., Deller, A. T., Gillies, O., et al. 2017, ApJ, 848, L34
Narayan, R., Paczyński, B., & Piran, T. 1992, ApJ, 395, L83
Oates, F., & Freire, P. 2016, ARA&A, 54, 401
Panaitescu, A., Mészáros, P., Burrows, D., et al. 2006, MNRAS, 369, 2059
Pétri, J. 2016, JPhPh, 82, 63582052
Popham, R., Woosley, S. E., & Fryer, C. 1999, ApJ, 518, 356
Rees, M. J., & Meszaros, P. 1994, ApJ, 430, L93
Rees, M. J., & Meszaros, P. 1998, ApJ, 496, L1
Rosswog, S. 2007, MNRAS, 376, L48
Rowlinson, A., O’Brien, P. T., Metzger, B. D., & Tanvir, N. R., & Levan, A. J. 2013, MNRAS, 430, 1061
Rowlinson, A., O’Brien, P. T., Tanvir, N. R., et al. 2010, MNRAS, 409, 531
Shao, L., & Dai, Z. G. 2007, ApJ, 660, 1319
Shen, R., & Matzner, C. D. 2012, ApJ, 744, 36
Spruit, H. C., & Drenkhahn, G. 2001, A&A, 369, 2161
Stanek, K. Z., Matheson, T., Garnavich, P. M., et al. 2003, ApJL, 591, L17
Stovall, K., Freire, P. C. C., Chatterjee, S., et al. 2018, ApJL, 854, L22
Tang, C. H., Huang, Y. F., Geng, J. J., & Zhang, Z. B. 2019, ApJ, 848, 151
Toma, K., Ioka, K., Yamazaki, R., & Nakamura, T. 2006, ApJ, 640, L139
Troja, E., Cocanham, G., O’Brien, P. T., et al. 2007, ApJ, 665, 599
Uhm, Z. L., & Beloborodov, A. M. 2007, ApJ, 665, L93
Usoskin, V. V. 1975, ApSS, 32, 375
Usoskin, V. V. 1992, Natur, 357, 472
Usoskin, V. V. 1994, MNRAS, 267, 1035
Usoskin, V. V. 1999, in ASP Conf. Series 190, Gamma-Ray Bursts: The First Three Minutes, ed. J. Poutanen & R. Svensson (San Francisco, CA: ASP), 153
Usoskin, S. E. 1993, ApJ, 405, 273
Xu, R. A. 2018, SCMPA, 61, 109531
Xie, Y. Q., Zheng, X. C., Li, Y., et al. 2019, Natur, 568, 198
Yamazaki, R. 2009, ApJL, 690, L118
Yu, Y.-W., Cheng, K. S., & Cao, X.-F. 2010, ApJ, 715, 477
Yu, Y.-W., Liu, L.-D., & Dai, Z.-G. 2018, ApJL, 861, 114
Zhang, B. 2018, The Physics of Gamma-Ray Bursts (Cambridge: Cambridge Univ Press)
Zhang, B., Fan, Y. Z., Dyks, J., et al. 2006, ApJ, 642, 354
Zhang, B., & Mészáros, P. 2001, ApJL, 552, L35
Zhang, B., & Yan, H. 2011, ApJL, 726, 90