Gamma-Ray Burst Prompt Emission Spectrum and $E_p$ Evolution Patterns in the ICMART Model

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Abstract

In this paper, we simulate the prompt emission light curve, spectrum, and $E_p$ evolution patterns of gamma-ray bursts (GRBs) within the framework of the Internal-collision-induced Magnetic Reconnection and Turbulence (ICMART) model. We show that this model can produce a Band-shaped spectrum, whose parameters ($E_p$, $\alpha$, $\beta$) could follow the typical distribution of GRB observations, as long as the magnetic field and the electron acceleration process in the emission region are under appropriate conditions. On the other hand, we show that for one ICMART event, $E_p$ evolution is always a hard-to-soft pattern. However, a GRB light curve is usually composed of multiple ICMART events that are fundamentally driven by the erratic activity of the GRB central engine. In this case, we find that if one individual broad pulse in the GRB light curve is composed of multiple ICMART events, the overall $E_p$ evolution could be disguised as an intensity-tracking pattern. Therefore, mixed $E_p$ evolution patterns can coexist in the same burst, with a variety of combined patterns. Our results support the ICMART model as a competitive model to explain the main properties of GRB prompt emission. The possible challenges faced by the ICMART model are also discussed in detail.

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

1. Introduction

Gamma-ray bursts (GRBs) are the most luminous explosions in the universe. Their bursty emission in the hard-X-ray/soft-$\gamma$-ray band is usually called “prompt emission” (Zhang 2018). The temporal structure of the prompt emission exhibits diverse morphologies (Fishman & Meegan 1995), which can vary from a single smooth pulse to extremely complex light curves with many pulses overlapping in a short duration. Gao et al. (2012) proposed that prompt emission light curves are typically the superposition of an underlying slow component and a more rapid fast component, where the fast component tends to be more significant at high energies and becomes less significant at lower frequencies (Vetere et al. 2006).

The photon number spectrum of prompt emission, for both the time-resolved spectrum and the time-integrated spectrum, can usually be fitted with a broken power law known as the Band function (Band et al. 1993):

$$N(E) = \begin{cases} \frac{A E^{\alpha}}{(100 \text{ keV})^\alpha} \exp\left(-\frac{E}{E_0}\right), & E < (\alpha - \beta)E_0 \\ \frac{A}{100 \text{ keV}} \left(\frac{(\alpha - \beta)E_0}{100 \text{ keV}}\right)^{\alpha - \beta} \exp\left(-\frac{E}{(\alpha - \beta)E_0}\right) \times \left(\frac{E}{100 \text{ keV}}\right)^{\beta}, & E \geq (\alpha - \beta)E_0 \end{cases}$$

(1)

where $A$ is the normalization factor, $E_0$ is the break energy in the spectrum, $\alpha$ and $\beta$ are the low-energy and high-energy photon spectral indices with $\alpha$ in the range $(-2, 0)$ and $\beta$ in the range $(-4, -1)$ (Preece et al. 2000). The peak energy of the $E^2 N(E)$ spectrum ($E_p = (2 + \alpha)E_0$) is distributed over several orders of magnitude but clusters around 200–300 keV (Preece et al. 2000; Goldstein et al. 2013). For bright bursts, two types of evolution pattern between $E_p$ and $\nu$, the frequency, the $\nu$ evolution can be disguised as an intensity-tracking pattern. Therefore, mixed $E_p$ evolution patterns can coexist in the same burst, with a variety of combined patterns. Our results support the ICMART model as a competitive model to explain the main properties of GRB prompt emission. The possible challenges faced by the ICMART model are also discussed in detail.

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the electron number excess problem (Daigne & Mochkovitch 1998; Shen & Zhang 2009), the missing bright photosphere problem (Zhang & Pe’er 2009; Daigne & Mochkovitch 2002), and so on.

In order to solve these problems, it has been proposed that GRB outflows should be Poynting flux-dominated instead of matter-dominated. Significant magnetic dissipation may occur to power GRB prompt emission through different mechanisms, including the MHD-condition-broken scenarios (Usov 1994; Zhang & Mészáros 2002), the radiation-dragged dissipation model (Mészáros & Rees 1997), the slow dissipation model (Thompson 1994; Drenkhahn & Spruit 2002; Giannios 2008; Beniamini & Giannios 2017), current-driven instabilities (Lytikov & Blandford 2003), and forced magnetic reconnection (Zhang & Yan 2011; McKinney & Uzdensky 2012; Lazarian et al. 2019). In this work, we focus on one representative model, i.e., the Internal-collision-induced Magnetic Reconnection and Turbulence (ICMART) model (Zhang & Yan 2011). This model invokes a magnetically dominated outflow powered by a central engine with magnetization factor $\sigma > 1$. Similar to the internal shock model, mechanical collisions between minishells would distort the ordered magnetic field and trigger fast magnetic seeds, which would induce relativistic magnetohydrodynamic (MHD) turbulence in the interaction regions. The turbulence further distorts the magnetic lines, resulting in a reconnection cascade and thus a significant release of the stored magnetic field energy (an ICMART event). The particles, either accelerated directly in the reconnection region or accelerated randomly in the turbulence region, would radiate synchrotron radiation photons to power the observed GRB prompt emission.

A global simulation of an ICMART event has been presented in Deng et al. (2015), which shows significant energy dissipation when two highly magnetized blobs collide. Minijet-like reconnection events are seen from the simulation, even though local simulations are needed to display minijets on much smaller scales. On the other hand, Monte Carlo simulations have been performed to simulate the prompt emission light curves within the framework of the ICMART model (Zhang & Zhang 2014). They show that the ICMART model can produce highly variable light curves with both fast and slow components, where the fast component is caused by many local Doppler-boosted minijets due to turbulent magnetic reconnection and the slow component is due to the runaway growth and subsequent depletion of these minijets. However, since these simulations were focusing on the temporal structure, they assumed that the radiation intensity arising from each reconnection event had the same spectral form (e.g., a Band function with $\alpha = -1$, $\beta = -3$, and $E_p = 300$ keV in the observer frame), which made them ineffective in testing the properties of the prompt emission spectrum.

In this work, we will further revise the previous simulation, by considering the evolution of the magnetic field with respect to radius and using a fast cooling synchrotron spectrum to calculate the energy spectrum for each reconnection event, in order to judge whether the ICMART model could generate the Band spectrum and interpret the observed $E_p$ evolution patterns.

2. Simulation Methods

Within the ICMART scenario, a highly magnetized central engine would eject an unsteady outflow with variable Lorentz factors and luminosities but a nearly constant degree of magnetization. For simplicity, the outflow can be represented as a succession of discrete shells with variable Lorentz factors. Mechanical collisions between minishells would distort the magnetic field configurations and induce MHD turbulence, which will further distort the magnetic field and eventually trigger an ICMART event. Our simulation starts by tracking a shell with mass $M_{\text{sh}}$, Lorentz factor $\Gamma_0$, and magnetized factor $\sigma_0 = E_p,0/E_{K,0}$, ($E_{\text{m},0}$ marks the initial magnetic energy and $E_{K,0}$ marks the initial kinetic energy), when the shell expands to radius $R_0$ and the reconnection cascade has been triggered.

Numerical simulations have shown that the reconnection-driven magnetized turbulence could self-generate additional reconnections (Takamoto et al. 2015; Kowal et al. 2017; Takamoto 2018), inferring that the number of magnetic reconnections would increase exponentially. Here we assume that each reconnection event ejects a bipolar outflow and triggers two more reconnection events $^2$ (Zhang & Zhang 2014). Assuming the number of magnetic reconnections generated within the $1/\Gamma_0$ cone is $n_\text{r}$, the total number of magnetic reconnections $N_{\text{cone}}$ could be estimated as $N_{\text{cone}} \approx \sum_{n=1}^{n_\text{r}} 2^n$. The duration of each reconnection in the lab frame could be estimated as

$$T_{\text{r},\text{lab}} \sim \frac{\Gamma_0}{\sigma_0} \left( \frac{L'}{10^{14} \text{cm}} \right)^2 \left( \frac{v_{\text{in}}}{10^9 \text{cm s}^{-1}} \right) \text{s},$$

where $L'$ is the size of the magnetic reconnection and $v_{\text{in}}'$ is the inflow velocity of the magnetic field line. Hereafter, parameters denoted by primes are in the rest frame of the jet bulk. Note that this duration timescale is about $T_{\text{r},\text{obs}} \sim 0.1$ s in the observer frame and therefore the reconnections cascade lasts for $n_{\text{r}}T_{\text{r},\text{obs}}$ in the observer frame.

For each reconnection event, the magnetized factor of the reconnection area drops from $\sigma_0$ to 1. Thus the dissipated magnetic energy is approximately equal to $(\sigma_0 - 1)/\sigma_0$ times the magnetic energy within the reconnection area. We assume that half of the dissipated magnetic energy is used to boost the kinetic energy of the jet and the other half is initially distributed to electrons (Drenkhahn & Spruit 2002), and then gets converted to photons through synchrotron radiation. Some of the photons that beam toward the observer are recorded as the prompt emission of the GRB.

In order to simulate the observed GRB spectrum, three rest frames need to be invoked: (1) the rest frame of the jet bulk; (2) the rest frame of the minijet; (3) the rest frame of the observer (here we ignore the effect of cosmological expansion). Hereafter, parameters denoted by double primes are in the rest frame of the minijet. The quantities in these three frames are

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1 It is worth noticing that rather than the mechanical collisions, the kink instability may be the cause of the magnetic turbulence but the physical processes involved are similar (Lazarian et al. 2019).

2 Lacking detailed numerical simulations for a reconnection/turbulence cascade, the specific index of magnetic reconnection growth is still unknown. Here we assume each reconnection would trigger two more new reconnection events. The uncertainty brought by this assumption will not affect our analysis results about spectrum and $E_p$ evolution (because these results are already the superposition effect of sufficient magnetic reconnection events), but might affect the time when our simulated light curve would reach the peak.
connected through two Doppler factors, i.e.,
\[ D_1 = \frac{1}{\Gamma(1 - \beta_{\text{bulk}} \cos \theta)}, \]
\[ D_2 = \frac{1}{\gamma(1 - \cos \phi)}, \]  
where \( \gamma \approx \sqrt{1 + \sigma} \) is the relative Lorentz factor of a minijet with respect to the jet bulk (Zhang & Zhang 2014), \( \beta_{\text{bulk}} \) and \( \beta \) are the corresponding dimensionless velocities with respect to \( \Gamma \) and \( \gamma \), \( \theta \) is the latitude of the minijet, i.e., the angle between the line of sight and the direction of the bulk at the location of the minijet, and \( \phi \) is the angle between the direction of the minijet and the direction of the bulk in the bulk comoving frame. In our simulation, we trace each minijet to calculate its radiation intensity and photon energy distribution in the direction of the observer, and stack the simultaneously arriving photons from all minijets to obtain the overall light curve and the corresponding time-resolved spectrum.

In the rest frame of the minijet, the synchrotron radiation power at frequency \( \nu' \) is given by (Rybicki & Lightman 1979)
\[ P_{\nu'} = \frac{\sqrt{3} q_e B''_e}{m_e c^3} \int_{\gamma_{\text{m}}}^{\gamma_{\text{m}}} \left( \frac{dN'_{\gamma'}}{d\gamma'} \right) F' \left( \nu' \right) d\gamma'. \]  
where \( q_e \) is the electron charge, \( \nu' = 3 \gamma_e^2 q_e B''_e / (4 \pi m_e c) \) is the characteristic frequency of an electron with Lorentz factor \( \gamma_e \), \( B''_e \) is the comoving magnetic field strength in the emission region, and \( F'(x) = x \int_x^{\infty} K_{1/3}(\xi) d\xi \) where \( K_{1/3}(x) \) is the modified Bessel function of order one-third. Lacking full numerical simulations of magnetic turbulence and reconnection, the comoving magnetic field strength \( B''_e \) in the minijet is rather difficult to estimate directly. Here we introduce a free parameter \( k \) to connect \( B''_e \) with the bulk magnetic field strength via \( B''_e = \sqrt{k} B'/\gamma \). The value of \( k \) is justified by limiting \( E_{\gamma'} \) in the simulation results to be consistent with the observational data. We assume \( B''_e \) decays with the radius of the bulk as
\[ B''_e(R) = \frac{B''_{e,0}}{R_{0}} \frac{R}{R_{0}}^{-b}, \]  
where \( b \) would be much larger than 1, due to the rapid consumption of magnetic energy in the reconnection process. Considering the conservation of magnetic flux, the bulk magnetic field strength \( B' \) decreases as the jet expands. The radial part of the magnetic field decreases as \( B'_r \propto R^{-2} \) while the transverse part decreases as \( B'_t \propto R^{-1} \). At a large radius one has a transverse-dominated magnetic field
\[ B'(R) = \frac{B'_0}{R_{0}} \frac{R}{R_{0}}^{-1}, \]  
where \( B'_0 \) is the initial magnetic strength of the bulk.

The electron number density could be estimated with the continuity equation (Uhm & Zhang 2014):
\[ \frac{\partial N''_{\gamma'}(\gamma', t'')}{\partial t''} = - \frac{\partial}{\partial \gamma'} \left[ \gamma''_{\gamma'} N''_{\gamma'}(\gamma', t'') \right] + Q(\gamma', t''), \]  
where \( \gamma''_{\gamma'} \) denotes the electron cooling rate and \( Q(\gamma', t'') \) denotes the injected source function. Electrons would suffer both radiative and adiabatic cooling (Uhm & Zhang 2014), so that
\[ \frac{d}{dt''} \left( \frac{1}{\gamma''_{\gamma'}} \right) = \frac{\sigma_T B'^2}{6 \pi m_e c} \frac{d}{dt''} + \frac{2}{3} \left( \frac{1}{\gamma''_{\gamma'}} \right) \frac{d \ln R}{dt''}, \]  
where \( \sigma_T \) is the Thomson scattering cross section. The distribution of the accelerated electrons is usually assumed to be a power-law function,
\[ Q(\gamma_{\gamma'}) = Q_0 \left( \frac{\gamma_{\gamma'}}{\gamma_{\text{m}}(t_{\infty})} \right)^{-p}, \]  
where \( Q_0 \) is a normalization factor, and \( \gamma_{\text{m}}(t_{\infty}) \) and \( \gamma_{\text{M}}(t_{\infty}) \) are the minimum and maximum injected electron Lorentz factors. \( \gamma_{\text{m}}(t_{\infty}) \) could be calculated as
\[ \gamma_{\text{M}}(t_{\infty}) = \frac{6 \pi q_e}{\sqrt{\sigma_T B'^2_0}}. \]  
One can use the law of electron number and energy conservation to solve \( Q_{\text{e},0} \) and \( \gamma_{\text{m}}(t_{\infty}) \) for a specific reconnection event, which should require
\[ Q_{\text{e},0}(t'_{\infty} - t'_{\infty}) \int_{\gamma_{\text{m}}(t'_{\infty})}^{\gamma_{\text{m}}(t'_{\infty})} \left( \frac{\gamma_{\gamma'}}{\gamma_{\text{m}}(t_{\infty})} \right)^{-p} d\gamma' = \int_{t'_{\infty}}^{t'_{\infty}} L(t')^2 \nu_{\gamma} d\nu', \]  
and
\[ \frac{1}{2} \frac{dE_{\gamma'}_{\text{inj}}}{dt'} = \int_{t'_{\infty}}^{t'_{\infty}} \int_{\gamma_{\text{m}}(t_{\infty})}^{\gamma_{\text{m}}(t_{\infty})} Q_{\text{e},0}(t'_{\infty}) \left( \frac{\gamma_{\gamma'}}{\gamma_{\text{m}}(t_{\infty})} \right)^{-p} d\gamma' dt' \left( \gamma_{\gamma'} - 1 \right)m_e c^2, \]  
where \( t_{\infty} \) and \( t'_{\infty} \) are the starting and ending times of the magnetic reconnection, \( f_e \) is the fraction of accelerated electrons within the reconnection area, \( n_e(\gamma, R) \propto R^{-2} \) is the number density of electrons in the bulk frame, and \( \delta E_{\gamma'}_{\text{inj}} \) is the dissipated energy for a single magnetic reconnection, which could be estimated as
\[ \delta E_{\gamma'}_{\text{inj}} = \frac{\sigma_0 - 1}{\sigma_0} \int_{t'_{\infty}}^{t'_{\infty}} B'/R_0^2 \left( \frac{L'(t')^2}{8\pi} \nu_{\gamma} d\nu' \right), \]  
where \( t'_{\infty} \) is the starting time. Considering both the expansion and reconnection effects, similar to the bulk magnetic field strength, here we assume a general evolution form for \( L'/R_0^2 \):
\[ L'(R) = L'_{0} \frac{R}{R_0} \left( \frac{R}{R_0} \right)^{-1}, \]  
where \( L'_{0} \) is the initial size of magnetic reconnection.

As seen by the observer, the radiation from each minijet is given by
\[ P_{\nu} = D_{1}D_{2}P_{\nu}' \]  
As suggested by Zhang & Zhang (2014), here we use a Gaussian shape to simulate each single pulse in the light curve. For a given time interval in the observer frame \((t_1, t_2)\), the time-resolved spectrum is given by
\[ P_{\nu}(\nu) = \sum_{n=1}^{N_{\text{time}}} P_{\nu}(\nu, t). \]  
For one ICMART event, the peak time of the light curve corresponds to the total duration of the cascade process, which
could be estimated as

\[ T_p \sim \frac{R_i}{2 \Gamma_i c} \sim 1.5 s \times \left( \frac{n_g}{10} \right) \left( \frac{\Gamma_0}{200} \right)^{-1} \left( \frac{L_i}{10^{11} \text{ cm}} \right)^{-1} \left( \frac{v_{\text{in}}}{10^9 \text{ cm s}^{-1}} \right)^{-1}. \] (18)

We assume an abrupt cessation of the cascade process, so that the number of new minijets drops to 0. The light curve after \( T_p \) is therefore contributed by the high-latitude emission from other minijets not along the line of sight due to the delay caused by the curvature effect.

### 3. Results

In order to justify whether the ICMART model could generate the Band spectrum and the observed \( E_p \) evolution patterns, we first run a series of simulations for one ICMART event with initial setup: \( M_{\text{bulk}} \in \mathcal{U}(3.5 \times 10^{-9}, 3.5 \times 10^{-6}) \), \( R_0 = 10^{18} \text{ cm} \), \( L_i = 1.2 \times 10^{11} \text{ cm} \), \( v_{\text{in}} = 3 \times 10^9 \text{ cm s}^{-1} \), \( n_g \in \mathcal{U}(13, 17) \), \( \Gamma_0 \in \mathcal{U}(100, 300) \), \( \sigma_0 \in \mathcal{U}(5, 50) \), \( k \in \mathcal{U}(5 \times 10^{-8}, 5 \times 10^{-2}) \), \( p \in \mathcal{U}(2.3, 2.8) \), \( f_e \in \mathcal{U}(0.001, 1) \), \( b \in \mathcal{U}(1.50) \), \( l \in \mathcal{U}(0, 1) \), \( \theta \in \mathcal{U}(0, 2/\Gamma_0) \), and \( \phi \in \mathcal{U}(0, \pi/2) \), where \( \mathcal{U} \) refers to a uniform distribution. In Figures 1 to 6 we plot the simulation results for selected situations that are relevant for illustrating the main conclusions, which can be summarized in the following sections.

#### 3.1. Light Curve

In our simulation, each ICMART event would produce highly variable light curves, which can be decomposed into the superposition of an underlying slow component and a more rapid fast component. The fast component is related to the individual locally Doppler-boosted mini-emitters, while the slow component is caused by the superposition of emission from all the minijets in the emission region. The duration of each minijet pulse and the total duration of the light curve are essentially determined by the parameters related to the number and scale of magnetic reconnection, e.g., \( L_i \), \( l \), \( v_{\text{in}} \), and \( n_g \).

Our results are basically consistent with the previous simulation results from Zhang & Zhang (2014). It is worth pointing out that Zhang & Zhang (2014) did not invoke any real radiation process for each minijet, so they have not discussed the evolution effect of the magnetic field and the scale of magnetic reconnection. Therefore, we find that if the evolution of the magnetic reconnection scale is not introduced (i.e., \( l = 0 \)), the radiation contributed by a single minijet in the early stage would be much larger than that in the late stage, due to the magnetic field decaying. Consequently, some short spikes (with flux equivalent to or even larger than the main peak) would show up in the early stage of the light curve as shown in Figure 1. This phenomenon will disappear after introducing the evolution of reconnection scale with radius (e.g., \( l > 0.2 \)).

#### 3.2. Spectrum

For most cases, the spectrum produced by ICMART events would behave as a broken power law, which could be well fitted with the Band function. For example, we plot the time-resolved spectrum at 1 and 3 s (in the observer frame) for one simulation\(^3\) in Figure 2(a), in a narrower bandpass from 3 keV to 3 MeV. In the example, the best-fit parameters for the Band function at 1 s/3 s are \( \alpha = -1.05 \pm 1.1 \), \( \beta = -2.32 \pm 2.23 \), and \( E_p = 550 \pm 330 \text{ keV} \), which are all typical values as suggested by the observations (Preece et al. 2000). This result is understandable since the observed spectrum is mainly shaped by the minijets that beam toward the observer, while as proven by Uhm & Zhang (2014), the radiation spectrum from minijets with \( \theta = 0 \) and \( \phi = 0 \) is very close to the Band function (see Figure 2 for an example). The simulated spectrum may be slightly broader than the spectrum of a single reconnection, which should be caused by the contributions from off-axis minijets. However, the overall trend of the spectrum will not deviate too much from the Band spectrum.

Under the free combination of initial parameters, the \( E_p \) value of the simulated spectrum would be distributed over a very wide range, much wider than the typical distribution from GRB observations (e.g., 3 keV to 3 MeV for the current sample; Demianski et al. 2017). In order to satisfy 3 keV < \( E_p < 3 \) MeV, a certain degeneracy is required between the initial parameters. For instance, since \( E_p \) is essentially proportional to \( \Gamma_0 B_{\text{e,m}}^2 \gamma_{\text{e,m}}^2 \) (Tavani 1996), the values of \( M_{\text{bulk}}, \sigma_0, \Gamma_0, R_0, k \) need to cooperate to make the magnetic field in the emission region \( B_{\text{e,m}}^2 \) in the range \( 10^{-8} \text{ G} \); on the other hand, the values of \( \sigma_0 \) and \( f_e \) need to cooperate to make the minimum injected electron Lorentz factor \( \gamma_{\text{e,m}} \) in the range \( 10^3 \text{–}10^5 \). Otherwise, \( E_p \) would be either higher (if \( B_{\text{e,m}}^2 \) and/or \( \gamma_{\text{e,m}} \) are too big) or lower (if \( B_{\text{e,m}}^2 \) and/or \( \gamma_{\text{e,m}} \) are too small) than the typical range of the GRB \( E_p \) distribution (see Figures 3(a) and (b) for an example). Moreover, if the magnetic field in the

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\(^3\) Here we would like to note that due to the randomness of \( \theta \) and \( \phi \), for a given parameter combination, different simulations may give a slightly different GRB light curve and spectrum, but the conclusions we show below are robust because the number of minijets is large enough to smooth out the main random effects.
radiation area is too small, the electrons would be cooled insufficiently, so the spectrum may deviate from the Band shape (see Figure 3 for an example).

For a Band-shape simulated spectrum, the higher value of spectral index ($\beta$) is mainly determined by the index of the injected electron energy distribution ($p$), while the lower-energy value of spectral index ($\alpha$) is essentially determined by the value of $B_{e}^0$ and its speed of evolution, which is reflected by the value of $b$ (see Figure 4 for examples). When $B_{e}^0$ is smaller than 1000 G and $b$ is larger than 30, $\alpha$ could be around $-1$ or even smaller, which is the typical value for current GRB observations. Otherwise, if $B_{e}^0$ is too high or $b$ is too small, $\alpha$
and the magnetic ICMART events. The physical parameters for each ICMART event are listed in Table 1.

\( E_p \) decreases throughout the whole event, even during the rising phase of the slow component, as shown in Figure 5. This is mainly because \( E_p \propto B_f^2 \) and the magnetic field decreases with radius (and hence time) as the shell expands in space. Our result is consistent with previous works (Uhm & Zhang 2016; Uhm et al. 2018), in which emission is from a single large region with decaying magnetic field.

However, it is interesting to note that a GRB light curve is usually composed of multiple ICMART events that are fundamentally driven by the erratic activity of the GRB central engine. In this case, one broad component in real data is not necessarily generated by just one ICMART event. In Figure 5(b), we show an example light curve that is generated by the superposition of three independent ICMART events. The physical parameters for each ICMART event are listed in Table 1. Basically, by adjusting the parameters, we make the flux of the three events increase in turn over time. If the absolute value of \( E_p \) is positively correlated with flux, which seems to be supported by GRB observations (e.g., Amati/Yonetoku relations, Amati et al. 2002; Yonetoku et al. 2004), the \( E_p \) evolution related to the overall light curve could be disguised as the intensity-tracking pattern, namely \( E_p \) increases during the rising phase of the broad pulse and decreases during the falling phase.

If our interpretation is correct, this may explain why both types of \( E_p \) behavior are observed in individual GRB pulses. Furthermore, for one particular GRB whose light curve consists of multiple broad pulses, the \( E_p \) evolution for each broad pulse could be randomly a hard-to-soft pattern or an intensity-tracking pattern. This could naturally explain why mixed \( E_p \) evolution patterns can coexist in the same burst, with a variety of combined patterns (Lu et al. 2012). For better illustration, we use the simulation results in Figure 5 as templates to simulate the \( E_p \) evolution and show that GRBs produced by multiple ICMART events could

1. have all pulses (including the first one) showing intensity-tracking behavior (see Figure 6(a));
2. have the first pulse showing a clear hard-to-soft evolution, while the rest of the pulses show tracking behavior (see Figure 6(b));
3. have the first pulse showing a nice tracking behavior, but the later pulses showing a clear hard-to-soft evolution (see Figure 6(c));
4. have an overall hard-to-soft evolution (see Figure 6(d));
5. have two patterns appear alternately (see Figures 6(e) and (f)).

It is notable that all these patterns have already been observed in the current GRB sample (Lu et al. 2012).

### 4. Conclusion and Discussion

The prompt emission of GRBs is still a mystery. The main uncertainty is the composition of the outflow, Poynting flux-dominated or matter-dominated, which essentially determines the mechanisms of energy dissipation, particle acceleration, and radiation. Putting together all the observational evidence, including the properties of the light curve, the nature of the spectrum, and the coordination between the spectrum and the light curve (e.g., the correlation between \( E_p \) and flux), may help to solve the problem.

In this work, we have developed a numerical code to simulate the prompt emission light curves, time-resolved spectrum, and \( E_p \) evolution patterns for GRBs produced by the ICMART model. Our simulation results could be summarized as follows.

![Simulated light curves](image1)

**Figure 5.** (a) Simulated \( E_p \) evolution of one ICMART event, with other parameters being the same as those in Figure 2. (b) Simulated \( E_p \) evolution of multiple ICMART events. The physical parameters for each ICMART event are listed in Table 1.

### Table 1

Parameters for Multiple ICMART Events Taken in the Simulation of Figure 5(b)

| \( M_{bulk} (M_{\odot}) \) | \( f_e \) | \( k \) | \( n_g \) | \( \sigma_0 \) | \( \Gamma_0 \) | \( p \) | \( b \) | \( l \) | Start Time (s) |
|-----------------|-------|------|------|--------|--------|------|------|------|----------------|
| \( 3 	imes 10^{-10} \) | 1.0 | \( 5 \times 10^{-4} \) | 15 | 8 | 200 | 2.8 | 30 | 0.7 | 0.0 |
| \( 3 \times 10^{-9} \) | 0.3 | \( 1.5 \times 10^{-5} \) | 15 | 8 | 200 | 2.8 | 30 | 0.2 | 0.7 |
| \( 3 \times 10^{-8} \) | 0.1 | \( 5 \times 10^{-7} \) | 15 | 8 | 200 | 2.8 | 30 | 0.2 | 1.3 |
1. The ICMART model could produce highly variable light curves, which can be decomposed into the superposition of an underlying slow component and a more rapid fast component. Such a result is consistent with previous simulations (Zhang & Zhang 2014) and the observational facts (Gao et al. 2012).

2. The ICMART model could produce a Band-shaped spectrum, whose parameters ($E_p, \alpha, \beta$) could follow the typical distribution from GRB observations, as long as the magnetic field and the electron acceleration process in the emission region are under appropriate conditions.

3. For one ICMART event, the evolution of the spectral peak $E_p$ is always a hard-to-soft pattern. But if one individual broad pulse in the GRB light curve is composed of multiple ICMART events, the $E_p$ evolution related to the overall light curve could be disguised as the intensity-tracking pattern. Therefore, mixed $E_p$ evolution patterns can coexist in the same burst, with a variety of combined patterns.

Our results show that the ICMART model can explain the main characteristics of the GRB light curve and spectrum, making it a very competitive model to produce GRB prompt emission. However, to interpret GRB observations in great detail, the ICMART model still faces some difficulties, which are worth pointing out.

In principle, the total energy and magnetic field strength carried by the shell of an ICMART event can vary randomly over a wide range. However, in order to produce GRBs from ICMART events, it is required that for all magnetic reconnection processes, there is a preferred range for the magnetic field and the electron acceleration process in the emission region. Detailed numerical simulations of magnetic reconnection and particle acceleration processes are needed to address whether the range of $B_e$ and $\gamma_{e,m}$ demanded by the model could be achieved. One possibility is that the magnetic reconnection process is so intense that there is an upper limit on the strength of $B_e$ (e.g., smaller than $10^4$ G). It is worth noticing that for most GRBs, $B_e$ cannot reach this upper limit, but needs to be lower than 100 G and needs to decay very rapidly (down 1–2 orders of magnitude) during the radiation process, otherwise the lower-energy index $\alpha$ for the majority of GRBs would be distributed around $-1.5$ (entering the deep fast cooling regime), instead of around $-1$ as suggested by the observations.

It is possible that in some ICMART event, $B_e$ is even lower than 10 G. For these cases, $E_p$ of the spectrum would shift into the soft X-ray band. This might be the physical origin of the phenomenon known as “X-ray flashes” (XRFs), which are generally believed not to be a different population from GRBs, but rather the natural extension of GRBs to the softer, less luminous regime (Sakamoto et al. 2008). An accumulated sample of more XRFs in the future with sky survey detectors in the X-ray band (e.g., Einstein Probe; Yuan et al. 2018) would help to justify this hypothesis.

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![Simulation for different $E_p$ evolution patterns by taking results in Figures 5(a) and (b) as templates: (a) overall intensity-tracking; (b) first hard-to-soft then intensity-tracking; (c) first intensity-tracking then hard-to-soft; (d) overall hard-to-soft; (e), (f) two patterns appear alternately. The gray lines represent the light curves and the red spots represent the $E_p$ value.](image)
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