The radiative efficiency of relativistic jet and wind: A case study of GRB 070110

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29 July 2016

ABSTRACT

A rapidly spinning, strongly magnetized neutron star is invoked as the central engine for some Gamma-ray bursts (GRBs), especially, the “internal plateau” feature of X-ray afterglow. However, for these “internal plateau” GRBs, how to produce their prompt emission remains an open question. Two different physical process have been proposed in the literature, (1) a new-born neutron star is surrounded by a hyper-accreting and neutrino cooling disk, the GRB jet can be powered by neutrino annihilation aligning the spin axis; (2) a differentially rotating millisecond pulsar was formed due to different angular velocity between the interior core and outer shell parts of the neutron star, which can power an episodic GRB jet. In this paper, by analyzing the data of one peculiar GRB 070110 (with internal plateau), we try to test which model being favored. By deriving the physical parameters of magnetar with observational data, the parameter regime for initial period ($P_0$) and surface polar cap magnetic field ($B_p$) of the central NS are (0.96 ∼ 1.2) ms and (2.4 ∼ 3.7) × 10^{14} G, respectively. The radiative efficiency of prompt emission is about $\eta_\gamma$ ∼ 6%. However, the radiative efficiency of internal plateau ($\eta_X$) is larger than 31% assuming the $M_{\text{NS}}$ ∼ 1.4$M_\odot$ and $P_0$ ∼ 1.2 ms. The clear difference between the radiation efficiencies of prompt emission and internal plateau implies that they maybe originated from different components (e.g. prompt emission from the relativistic jet powered by neutrino annihilation, while the internal plateau from the magnetic outflow wind).

Key words: star: gamma-ray burst - star: magnetar - radiation mechanisms: non-thermal

1 INTRODUCTION

Gamma-ray bursts (GRBs) are the most luminous events ever known in the universe by far. Traditionally, the relativistic fireball model is proposed to interpret the observational phenomenon of GRBs (Mészáros 2002; Zhang & Mészáros 2004; Kumar & Zhang 2015). Within this scenario, the observed prompt gamma-ray emission is explained by the internal shocks (Mészáros & Rees 1993). Despite its attractive features, the internal shock model is suffered with some severe problems, such as inefficiency problem (Kumar & Zhang 2015 for a review). Alternatively, if the outflow is dominated by Poynting flux, significant magnetic energy is dissipated to produce non-thermal emission, a fraction of the dissipated energy is converted to kinetic energy (Zhang & Yan 2011). After the internal dissipation, the deceleration of the jet by the ambient medium excites a long term external shock with synchrotron emission which powers the broad band afterglow emission (Mészáros & Rees 1997; Sari, Piran & Narayan 1998; Zhang et al. 2006; Gao et al. 2013). In Swift era, the shallow decay (or plateau) segment is usually seen in the XRT light curves (Liang et al. 2007), and the widely discussed model for this component is energy injection into the external forward shock either from an long lasting central engine or from an ejecta with a wide distribution of Lorentz factors (Zhang et al. 2006; Nousek et al. 2006; Panaitescu et al. 2006). On the other hand, in rare cases, X-ray plateaus of long GRBs can be followed by a very steep decay (e.g. $t^{-\alpha}$; GRB 070110, Troja et al. 2007; L"{u} & Zhang 2014[i], and in some short GRBs as well (Rowlinson et al. 2010, 2013; Lü et al. 2015), which called an

\footnote{Throughout the paper, we use the convention $f \propto t^{-\alpha} \nu^{-\beta}$ for temporal and spectral power law models.}
“internal plateau” (Lyons et al. 2010). This is more difficult to be explained by standard external afterglow fireball model, and an internal dissipation process need to be invoked (Fan & Xu 2006). From theoretical point of view, such behavior could be naturally explained when a rapidly spinning, strongly magnetized neutron star called “millisecond magnetar” being invoked as the central engine of GRB (Dai & Lu 1998a; Zhang & Mészáros 2001; Gao & Fan 2006; Metzger et al. 2008), and the internal plateau feature is also “Smoking Gun” signature for magnetar collapsing into black hole (Kumar & Zhang 2015 for review).

Previous work have shown that rapidly spinning, strongly magnetized NS could produce both prompt emission and later plateau of afterglow with proper parameters (Usov et al. 1992). Under this framework, two different physical process are proposed to produce GRB jet. One is that a new-born neutron star surrounded by hyper-accreting and neutrino cooling disk, which is similar to disk cooling of black hole central engine via neutrino annihilation (Zhang & Dai 2008, 2009; Lei et al. 2009, 2013), but the structure of a hyper-accretion disk may be different. Zhang & Dai (2008, 2009) divide the disk of neutron star into two regions (e.g. inner and outer disks), and studied physical properties of disk structure. The GRB hot jet can be powered by neutrino annihilation following the spin axis. Later, the magnetar would release its rotation energy via magnetic dipole radiation to produce the observational plateau in X-ray afterglow. Alternative, a differentially rotating millisecond pulsar was suggested to produce the observational plateau in X-ray afterglow. However, if a normal decay is followed the plateau, it can not be confident to show that the shallow decay is originated from the internal dissipation of magnetar spin-down (Panaitescu et al. 2006). In order to find out the magnetar signature, which typically invokes a shallow decay phase (or plateau) followed by a steeper decay segment (steeper than \( t^{-3} \)). One requires three independent criteria to define our sample. First, it displays an “internal plateau”. Second, after the sharp decay following with plateau, another power-law component is appeared with decay index less than 1.5, which is contributed by the external shock emission. Third, the redshift of the burst need to be measured, in order to estimate the gamma-ray energy and kinetic energy. We systematically process the XRT data of more than 1250 GRBs observed between 2005 January and 2016 March. Only GRB 070110, with duration \( T_{90} \approx 88 \) s, is satisfied with those three requirements in our entire sample. We next perform a temporal fit to the plateau behavior of GRB 070110 with a smooth broken power law

\[
F = F_0 \left( \frac{t}{t_b} \right)^{\omega_1} + \left( \frac{t}{t_b} \right)^{\omega_2} \nu^{-1/\omega},
\]

where the break time, \( t_b \), \( \omega_1 \), \( \omega_2 \) are decay indices, respectively, and \( \nu \) describes the sharpness of the break. The larger the \( \omega \) parameter, the sharper the break. We also collect the optical observational data from Troja et al. (2007). Both X-ray and optical light curve are shown in Figure 1, and fitting result is presented in Table 1.

Another two important parameters are the isotropic gamma-ray energy \( (E_{\gamma, \text{iso}}) \) and kinetic energy \( (E_{K, \text{iso}}) \). \( E_{\gamma, \text{iso}} \) was measured from the observation fluence and distance, read as

\[
E_{\gamma, \text{iso}} = 4\pi k D_L^2 S_\gamma (1+z)^{-1} = (3.09 \pm 2.51) \times 10^{52} \text{ erg}
\]

where \( z = 2.352 \) is the redshift, \( D_L \) is the luminosity distance, \( S_\gamma = (1.8 \pm 0.2) \times 10^{-6} \text{ erg cm}^{-2} \) is gamma-ray fluence in BAT band, and \( k \) is the k-correction factor from the observed band to \( 10^{-4} \text{ keV} \) in the burst rest frame (e.g. Bloom et al. 2001). More details, please refer to Li & Zhang (2014). The \( E_{K, \text{iso}} \) is isotropic kinetic energy of the fireball. It could be estimated by standard forward afterglow model (Sari, Piran & Narayan 1998; Fan & Piran 2006). For the late time X-ray afterglow data (\( t > 5 \times 10^{4} \) s), one has decay slope \( \alpha_3 \approx 0.82 \), and the spectral index \( \beta_X \sim 1.12 \) in

\[
\frac{\alpha_1}{\alpha_2} = \frac{(2-\alpha_1)}{(2-\alpha_2)}
\]

So far, more than 120 GRBs have been observed with shallow (or plateau) decay segment in the X-ray afterglow. However, if a normal decay is followed the plateau, it can not be confident to show that the shallow decay is originated from the internal dissipation of magnetar spin-down (Panaitescu et al. 2006). In order to find out the magnetar signature, which typically invokes a shallow decay phase (or plateau) followed by a steeper decay segment (steeper than \( t^{-3} \)). One requires three independent criteria to define our sample. First, it displays an “internal plateau”. Second, after the sharp decay following with plateau, another power-law component is appeared with decay index less than 1.5, which is contributed by the external shock emission. Third, the redshift of the burst need to be measured, in order to estimate the gamma-ray energy and kinetic energy. We systematically process the XRT data of more than 1250 GRBs observed between 2005 January and 2016 March. Only GRB 070110, with duration \( T_{90} \approx 88 \) s, is satisfied with those three requirements in our entire sample. We next perform a temporal fit to the plateau behavior of GRB 070110 with a smooth broken power law

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the normal decay segment. Approximately, they are satisfied $2\alpha_3 \approx 3\alpha_3 - 1$ in the spectral regime $\nu > \text{max}(\nu_a, \nu_b)$, where $\nu_a$ and $\nu_b$ are the typical and cooling frequencies of synchrotron radiation, respectively. Following the equations and methods of Yost et al (2003), the flux was recorded in XRT (0.3 keV - 10 keV) as,

$$\text{Flux} = 1.2 \times 10^{-12} \text{erg} \ s^{-1} \ cm^{-2} \ (1 + \frac{z}{2})^{1/2} D_L^{1/2},$$

in this calculation, the Compton parameter ($Y$) is assigned to a typical value $Y = 1$. Combine with the observational data, one obtain $E_{K,\text{iso}} \sim 5 \times 10^{53}$ erg, the physical parameters of forward shock model are shown in Table 1, and the fitting result is presented in Figure 1.

3 PROMPT EMISSION AND RADIATIVE EFFICIENCY OF GRB 070110

3.1 Physical parameters of magnetar for GRB 070110

Since the internal plateau of GRB 070110 was explained by invoking magnetic dipole radiation of spin-down magnetar central engine. In this section, we use data to derive relevant physical magnetar parameters of GRB 070110 (e.g. the initial spin period $P_0$ and the surface polar cap magnetic field $B_p$).

The energy reservoir is the total rotational energy of the millisecond magnetar, which reads

$$E_{\text{rot}} = \frac{1}{2} I \Omega_0^2 \simeq 2 \times 10^{52} \text{erg} \ M_{1.4} R_{2.3}^2 P_{0.3}^{-2},$$

where $I$ is the moment of inertia, $\Omega_0 = 2\pi/P_0$ is the initial angular frequency of the neutron star, $M_{1.4} = M/1.4M_\odot$, $R$ is radius of NS, and the convention $Q = 10^7 Q_x$ is adopted in cgs units for all other parameters throughout the paper. Assuming that the magnetar with initial spin period $P_0$ is being spun down by a magnetic dipole with surface polar cap magnetic field $B_p$, the characteristic spin-down luminosity and spin-down time scale are

$$L_0 = 1.0 \times 10^{49} \text{erg} \ s^{-1} (B_{p,15}^2 P_{0.3}^{-4} R_6^6)$$

and

$$\tau = 2.05 \times 10^3 \text{s} \ (I_{14} B_{p,15}^{-2} P_{0.3}^{-2} R_6^{-6})$$

The internal plateau energy of GRB 070110 from internal dissipation ($E_{\text{pla}}$) is calculated based on the lightcurve fitting result and redshift information, read as

$$E_{\text{X,iso,pla}} = \int_{t_s}^{t_b} \frac{L_{\text{pla}}}{1 + z} dt = \int_{t_s}^{t_b} F_{\nu} d\nu d\Omega$$

where $t_s$ and $t_b$ is the starting and end time of internal plateau. Here, we adopt $t_s = 0$. Actually, the starting time is not effect the result too much because $t_s$ is much less than $t_b$.

On the other hand, two additional constraints are required to be satisfied in this situation. Firstly, the spin-down luminosity of magnetar should be brighter than observational internal plateau luminosity of GRB 070110 if internal plateau emission is contributed from magnetic dipole radiation, namely $L_0 > L_{\text{pla}}$. Another one is that spin-down time scale is larger than duration of internal plateau (maybe collapse time of magnetar into black hole), $\tau > t_b$. Use those two constraints with lower limit of initial period NS survived, the region of initial period and surface polar cap magnetic field of NS are $(0.96 \sim 1.2)\text{ ms}$ and $(2.4 \sim 3.7) \times 10^{14} G$, respectively. The result is shown in Figure 2 (gray region).

3.2 Radiative efficiency of relativistic jet and wind

One interesting question is that what is the radiative efficiency of GRB 070110 for prompt emission and internal plateau within the GRB jet produced by neutrino annihilation scenario. The GRB radiation efficiency of prompt emission is defined as (Lloyd-Ronning & Zhang 2004)

$$\eta_\gamma = \frac{E_{\gamma,\text{iso}}}{E_{\gamma} + E_{K,\text{iso}}} = \frac{E_{\gamma}}{E_{\gamma} + E_{K}}$$

where $E_{\gamma,\text{iso}} \sim (3.09 \pm 2.51) \times 10^{52}$ erg and $E_{K,\text{iso}} \sim 5 \times 10^{53}$ erg. One has $\eta_\gamma \sim (6 \pm 4)\%$.

Another radiative efficiency is from internal dissipation of internal plateau, which is defined as the ratio between internal plateau energy and total magnetic dipole radiation energy of magnetar ($E_m$), read as

$$\eta_X = \frac{E_{\text{X,iso,pla}}}{E_m}.$$  

It reflects how efficient the internal dissipation converts the total magnetic dipole energy into radiation during the X-ray internal plateau phase. The total magnetic dipole radiation energy $E_m$ should be less than $E_{\text{rot}}$, namely $E_m < E_{\text{rot}}$, one can get the lower limit of efficiency of internal plateau $\eta_X > 31\%$ for $M_{\text{NS}} \sim 1.4 M_\odot$ and $P_0 \sim 1.2$ ms.

The clear difference between the radiation efficiencies of prompt emission and internal plateau implies that they may be originated from different components, e.g. prompt emission from the relativistic jet powered by neutrino annihilation, while the internal plateau from the magnetic outflow wind.

4 CONCLUSIONS AND DISCUSSION

An internal dissipation process of magnetar with Poynting-flux dominated outflow was invoked to interpret internal plateau phase of GRB afterglows. We suggest that comparing the radiation efficiency of prompt emission and internal plateau phase could help to interpret the composition of GRB jet. We focus on analyzing the data of GRB 070110 which exhibits internal plateau feature following a normal decay. We firstly estimate the physical parameters of magnetar based on the observational feature of internal plateau, the parameter regime of initial period ($P_0$) and surface polar cap magnetic field ($B_p$) of NS are $(0.96 \sim 1.2)\text{ ms}$ and $(2.4 \sim 3.7) \times 10^{14} G$, respectively. In this case, the radiation efficiency of prompt emission would be $\eta_\gamma \sim (6 \pm 4)\%$ if the GRB jet was powered by neutrino annihilation. On the other hand, the lower limit of internal plateau radiative
efficiency is estimated as $\eta_{X} = 31\%$ with $M_{NS} \sim 1.4M_{\odot}$ and $P_{0} \sim 1.2$ ms.

Since the standard internal shock model and magnetic dissipation model for prompt emission predict lower and higher radiation efficiency, respectively (Kumar 1999; Panaitescu et al. 1999; Usov 1992; Zhang & Yan 2011). Also, it is wildly accepted that the internal plateau phase is from magnetar wind dissipation process, and the prompt emission radiation efficiency ($\eta_{r} \sim 6\%$) is much less than the minimum efficiency of internal plateau ($\eta_{X} = 31\%$), so that the prompt emission and later internal plateau of GRB 070110 may be from different origin, e.g., a new-born neutron star surrounded by a hyper-accreting disk generates the prompt emission, while the magnetic dipole dissipation is account for the later internal plateau.

One suspicion is that whether the neutrino annihilation of NS cooling can power the prompt emission of GRB 070110. If neutron star surrounded by a hyper-accreting model was accepted to power the GRB jet, the neutrino annihilation luminosity ($L_{\nu\nu}$) is contributed by neutrinos emitted from both disk and neutron star surface layer. Following Zhang & Dai (2009) method, there is no analytical solution of $L_{\nu\nu}$, but related to several parameters, e.g., accretion rate ($\dot{M}$), outflow index ($s$), viscosity ($\alpha$), energy parameter ($\varepsilon$) and efficiency factor to measure the surface emission ($\eta_{b}$). Therefore, we have to use numerical method to get the solution with right parameters to compare with observational prompt emission luminosity. Since $L_{\nu\nu}$ are not sensitively depending on the $\alpha$, $\varepsilon$ and $s$ (see Figure 7 and 8 in Zhang & Dai 2009), we fix the typical value of $\alpha = 0.1$, $\varepsilon = 0.5$ and $s = 0.2$. Assuming $\eta_{b} = 0.5$ and $\dot{M} = 0.03 M_{\odot} s^{-1}$, one has $L_{\nu\nu} \sim 3 \times 10^{48} \text{ erg s}^{-1}$. However, it is isotropic energy instead of true energy. Due to lack observation of jet break feature, one can estimate lower limit of the jet opening angle with the last observed point ($t_{j} \sim 25$ days) in X-ray afterglow, read as

$$
\theta_{j} = 0.057 \text{ rad} \left( \frac{t_{j}}{1 \text{ day}} \right)^{3/8} \left( \frac{1+z}{2} \right)^{-3/8} \nonumber \\
\times \left( \frac{E_{K, \text{iso}}}{10^{53} \text{ ergs}} \right)^{-1/8} \left( \frac{n}{0.1 \text{ cm}^{-3}} \right)^{-3/8} \nonumber \\
= 7.4^0 \quad (11)
$$

The prompt emission energy of GRB jet after beaming-corrected is

$$
E_{\gamma} = E_{\gamma, \text{iso}} \cdot f_{b} \simeq 2.5 \times 10^{50} \text{ erg} \quad (12)
$$

where $f_{b}$ is beaming factor of the GRB 070110

$$
f_{b} = 1 - \cos \theta_{j} \simeq (1/2) \theta_{j}^{2}, \quad (13)
$$

and the luminosity of prompt emission is $L_{\text{jet}} \sim E_{\gamma}/T_{90} \sim 2.8 \times 10^{48} \text{ erg s}^{-1}$. One has $L_{\nu\nu} > L_{\text{jet}}$ with typical value of parameters and $\dot{M} = 0.03 M_{\odot} s^{-1}$, namely, neutrino annihilation of NS can provide enough energy to power the GRB jet.

5 ACKNOWLEDGEMENTS

We acknowledge the use of the public data from the Swift data archive, and the UK Swift Science Data Center.

We thank Wei-Hua Lei for helpful comments and discussion. This work is supported by the National Basic Research Program (973 Programme) of China 2014CB845800, the National Natural Science Foundation of China (Grant No. 11533003), the One-Hundred-Talents Program of Guangxi colleges, Guangxi Science Foundation (grant No. 2013GXNSFFA019001), Scientific Research Foundation of GuangXi University (Grant No XGZ150299).

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Table 1. The fitting result of GRB 070110 lightcurve with smooth broken power-law and single power-law, and the parameters of standard external forward shock model.

| Parameters   | Value                        | Parameters | Value |
|--------------|------------------------------|------------|-------|
| $F_0$        | $(1.23\pm0.06)e^{-11}$ erg cm$^{-2}$ s$^{-1}$ | $\epsilon_c$ | 0.02  |
| $F_1$        | $(3.23\pm1.58)e^{-9}$ erg cm$^{-2}$ s$^{-1}$ | $\epsilon_b$ | $5e^{-4}$ |
| $\alpha_1$  | $0.10 \pm 0.07$              | $n$        | 5 cm$^{-3}$ |
| $\alpha_2$  | $8.7 \pm 0.8$                | $\Gamma$   | 90     |
| $\alpha_3$  | $-(0.82 \pm 0.04)$          | $p$        | 2.2    |
| $t_b$        | $20885 \pm 222$ s            | $E_{K,iso}$| $5e^{53}$ erg |

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