OPTICAL/INFRARED FLARES OF GRB 080129 FROM LATE INTERNAL SHOCKS

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ABSTRACT

Strong optical and near-infrared (NIR) flares were discovered in the afterglow of GRB 080129. Their temporal behaviors, the sudden emergence and the quick disappearance, are rather similar to those of many X-ray flares (for instance, the giant flare of GRB 050502B). We argue that the optical/NIR flares following GRB 080129 are a low-energy analogue of the X-ray flares and the most likely interpretation is the “late internal shock model.” In this model, both the very sharp decline and the very small ratio between the duration and the occurrence time of the optical/NIR flares in GRB 080129 can be naturally interpreted. The initial Lorentz factor of the flare outflow is found to be $\sim 30$, consistent with the constraint $\lesssim 120$ set by the forward shock afterglow modeling. Other possibilities, like the reverse shock emission or the radiation from the continued but weaker and weaker collision between the initial $\gamma$-ray burst outflow material, are disfavored.

Key words: gamma rays: bursts – radiation mechanisms: non-thermal

Online-only material: color figures

1. INTRODUCTION

GRB 080129 was triggered and located by the Swift Burst Alert Telescope (BAT) at 06:06:45 UT (Immler et al. 2008). The duration of prompt emission $T_{90}$ is 48 $\pm$ 10 s in the 15–350 keV band (Barthelmy et al. 2008). The time-averaged spectrum is best fitted by a simple power-law model, whose power-law index is $1.34 \pm 0.26$. The fluence in the 15–150 keV band is $8.9 \pm 1.4 \times 10^{-7}$ erg cm$^{-2}$ (Barthelmy et al. 2008). The BAT observations lasted until 320 s after the trigger, then slewed to another location of the sky. The X-ray telescope (XRT) and the UV–optical telescope (UVOT) started to point to GRB 080129 until $3.2 \times 10^3$ s after the trigger. A fading X-ray source was discovered and no emission was seen with UVOT. No flare was observed in the X-ray band since XRT started to observe (Holland 2008).

The optical/near-infrared (NIR) observations imaged by Gamma-Ray Burst Optical/Near-Infrared Detector (GROND) started immediately after the trigger (Greiner et al. 2009). The first images immediately revealed a strongly flaring source. Distinguished optical/NIR flares were observed with amplitude $\sim 3$ mag, duration of 80 s (FWHM, hereafter we define the FWHM as the observed variability timescale $\delta t$ in the flare), peaking at $t_{p} \sim 540$ s after the $\gamma$-ray burst (GRB) trigger. Their rise and decline can be well approximated by $t^{1/2}$ and $t^{-4}$, respectively. Thereafter, the afterglow brightness is continuously rising until 6000 s after the GRB. The optical spectroscopy suggests a redshift $z = 4.349$ for GRB 080129.

Greiner et al. (2009) interpreted the optical/NIR flares as the radiation of continued but weaker and weaker collisions between the material ejected during the prompt emission phase. In this work we do not follow their treatment for the following arguments. (1) In such a scenario, the NIR/optical flares emerge when the synchrotron self-absorption frequency drops below the observer’s frequencies. If correct, the NIR and optical flares should have an observable/significant time delay, that is the higher the observer’s frequency, the earlier the arrival time. However, we did not see such a delay in the data (Greiner et al. 2009; see also our Figure 1). (2) The NIR/optical flares appeared and then peaked at a time $t \sim 540 s \gg T_{90}$. If the IR/optical flares are indeed from the outflow material ejected during the prompt $\gamma$-ray emission phase, their declines are governed by the high-latitude emission and cannot be steeper than ($t - T_{90})^{-2+\beta} \approx t^{-2+\beta}$, again inconsistent with the data, where $\beta \lesssim p/2$ is the spectral index, and $p$ is the power-law index of the energy distribution of the shock-accelerated electrons (Kumar & Pannaitescu 2000; Fan & Wei 2005). This puzzle can be solved if the jet is so narrow that we have seen its edge, i.e., $\theta_j \lesssim 0.01(100/\Gamma_i)$, where $\theta_j$ is the half-opening angle and $\Gamma_i$ is the initial Lorentz factor of the outflow. However, such a possibility has been convincingly ruled out by the late-time afterglow observation because the jet break at $\sim 1.8 \times 10^4$ s suggests a $\theta_j \sim 0.076 \gg 1/\Gamma_i$ (Greiner et al. 2009). The latter argument applies to the reverse shock emission model as well. That is why we will not discuss such a possibility in this work either.

We note that the temporal behavior of the NIR/optical flares detected in GRB 080129 is quite similar to that of X-ray flares observed in a good fraction of Swift GRB afterglows (e.g., Guetta et al. 2006; Chincarini et al. 2007). For comparison purpose, we replotted both the giant X-ray flare following GRB 050502B (Burrows et al. 2005) and the NIR flares in GRB 080129 in Figure 1. The physical parameters are summarized in Table 1 and the similarities are evident. Motivated by these similarities we suggest that the NIR flares detected in GRB 080129 should have the same origin of the flares observed in the X-ray afterglows, i.e., the NIR flares should be powered by the so-called late internal shocks too (Fan & Wei 2005; Burrows et al. 2005; Zhang et al. 2006). Such a model was thought to have been ruled out by the request of a very large initial Lorentz factor ($\Gamma_i \sim 800$) of the flare outflow (Greiner et al. 2009). We will show in this work that $\Gamma_i \sim$ tens, a typical value taken in the X-ray flare modeling (Fan & Wei 2005), is large enough to reproduce the data and is consistent with the upper limit ($\lesssim 120$) set by the forward shock optical afterglow modeling of GRB 080129.

This work is arranged as follows. In Section 2, we briefly introduce the late internal shock model and then discuss the identity of two independent constraints that are widely used to rule out other possibilities. In Section 3, we apply the late
internal shock model to the IR flares following GRB 080129. We summarize our results with some discussions in Section 4.

2. THE LATE INTERNAL SHOCK MODEL

In the standard fireball model, the GRB prompt emission is powered by the interaction of shells with different Lorentz factors in the relativistic outflow launched by the central engine, i.e., the internal shock model (Paczynski & Xu 1994; Rees & Mészáros 1994) while the afterglow is believed to be the external forward shock emission (Piran 1999). However, since the launch of Swift satellite, energetic X-ray flares have been detected in about half of the GRBs afterglows. The temporal behavior of most X-ray flares share some similarities with the prompt soft $\gamma$-ray emission and cannot be interpreted by the external forward shock model (see Mészáros 2006; Zhang 2007 for recent reviews). The most likely interpretation is the so-called late internal shocks model, in which the GRB central engine restarts after the prompt emission phase and launches unsteady outflow. The underlying physical processes are less clear. Among the various models put forward for a review (Zhang 2007) the collision between the fast and slow material of the new outflow can power strong flares peaking in the X-ray or far-ultraviolet band. The duration of these flares ($\delta t$) is determined by the re-activity process of the central engine and can be much shorter than the occurrence time of the flares. On the other hand, since the ejection time ($\sim t_{\text{ej}}$) of the last main pulse of the flare is close to $t_p$, the net flux of the high-latitude emission of the pulses can be approximated by $(t_p - t_{\text{ej}})^{-\left(2+\beta\right)}$, which can be much steeper than $t^{-\left(2+\beta\right)}$. So the late internal shock model can naturally account for the main characters, the sudden emergence and then a rapid drop, of the X-ray flares detected so far. For the emission of the external shocks, it is well known that (1) $\delta t/t$ has to be in order of 1 or larger (Nakar & Piran 2003); (2) the decline cannot be steeper than $t^{-\left(2+\beta\right)}$ unless the edge of the GRB ejecta is visible. This is because the GRB outflow is curving and emission from high latitude (relative to the observer) will reach us at later times and give rise to a decline shallower than $t^{-\left(2+\beta\right)}$ (Fenimore et al. 1996; Kumar & Panaitescu 2000). Usually, these two limitations have been taken as independent evidences for the late internal shock model (e.g., Chincarini et al. 2007). Below we show that they are highly relevant and even identical.\(^1\)

As shown in Figure 2, $f_p$ is the maximum flux at the peaking time $t_p$ in the flare, $t_1$ and $t_2$ are the time at which the flux is half of $f_p$ in the rising and decaying light curves, respectively. The FWHM time is therefore $\delta t \equiv t_2 - t_1$. Before and after $t_p$, the light curves are approximated by $t^{\alpha_1}$ and $t^{-\alpha_2}$, respectively.

\(^1\) Fan et al. (2008a) pointed this out in a proceeding paper but did not prove it.
respectively. It is straightforward to see that \( \delta t / t_f \sim 1 \) and
\( \delta t / t_p \sim 1 \) respectively. The rising power-law index \( \alpha_1 \) is taken as 2, 4, 6, 8, 10, 12, and 14, respectively. The horizontal dot line represents \( \alpha_1 = 2 + \beta = 3.25 \), where we take \( \beta = p / 2 = 1.25 \), while the vertical dot line represents \( \delta t / t_p = 1 \).

(A color version of this figure is available in the online journal.)

3. PHYSICAL PARAMETERS AND THE SYNCHROTRON RADIATION OF GRB 080129 IN LATE INTERNAL SHOCK MODEL

We assume that the Lorentz factors of the ejected material in the restarting outflow are highly variable, and take \( \Gamma_s \sim 10 \) and \( \Gamma_f \sim 100 \) as the typical Lorentz factor of the slow and fast shells, respectively. The masses of the fast and slow shells are taken as \( m_f \lesssim m_s \). In the late internal shock model, the inner fast shell will catch up with the outer slow shell at the radius \( \sim 2 \Gamma_f^2 c \delta t / (1 + z) \) (where \( \delta t_i \) is taken as the observed typical variability timescale of one pulse in GRB 080129 optical/ NIR flare), and internal shock are generated. The merged shell’s Lorentz factor is \( \Gamma_i \approx \sqrt{\Gamma_s \Gamma_f} \sim 30 \) (Piran 1999), and the Lorentz factor of the internal shock can be estimated as \( \gamma_{sh} \approx (\sqrt{\Gamma_s / \Gamma_f} + \sqrt{\Gamma_f / \Gamma_s}) / 2 \).

Adopting the cosmological parameters \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_M = 0.3 \), and \( \Omega_{\Lambda} = 0.7 \), we have a luminosity distance \( D_L = 1.2 \times 10^{22} \text{ cm} \) for GRB 080129 at a redshift \( z = 4.35 \). The observed maximum flux of the flare in GRB 080129 is about \( \sim 0.5 \text{ mJy (NIR)} \) and \( \sim 0.3 \text{ mJy (optical)} \), respectively (Greiner et al. 2009). Assuming an efficiency factor of the optical flare \( \epsilon \sim 0.1 \), the total luminosity of the flare outflow can be estimated by \( L_{\text{m}} \sim 3 \times 10^{48} \text{ erg s}^{-1} \). This luminosity implies that the fallback accretion rate is about \( \sim 10^{-5} \) to \( 10^{-3} \) times that of the GRB prompt accretion, if the efficiency factor of converting the accretion energy into the kinetic energy of the outflow is nearly a constant (MacFadyen et al. 2001).

The variability timescale \( \delta t_i \) of GRB080129’s optical flare is significantly longer than that of the prompt emission. Here, we take \( \delta t_i \sim 30 \text{ s} \), as suggested by the smoothness of the flare light curves. The typical radius of the late internal shock is \( R_{\text{int}} \sim 2 \Gamma_i^2 c \delta t_i / (1 + z) \approx 3.4 \times 10^{14} \Gamma_i^2 1.5 \delta t_i 1.5 \text{ cm} \). In this work, we take the convenience \( Q_s = Q / 10^6 \) in units of cgs except with specific notation. Below, following Fan & Wei (2005), we show that with the parameters \( \Gamma_i \sim 30 \), \( L_{\text{m}} \sim 3 \times 10^{48} \text{ erg s}^{-1} \), \( \epsilon_e = 0.4 \), \( \epsilon_B = 0.05 \), and \( \delta t_i = 30 \text{ s} \), the flare data can be reasonably reproduced.

We first investigate the interaction between the inner fast shell and the outer slower one. The comoving number density of the electrons is \( n_e \sim L_{\text{m}} / (4 \pi c T_e^2 m_e c^3) \approx 4.6 \times 10^7 L_{\text{m},48.5} \Gamma_i^{-3} \delta t_i^{-1} \text{ cm}^{-3} \), where \( m_p \) is the rest mass of the proton. The thermal energy density of the shocked material is \( \epsilon_e = 4 \gamma_{sh} (\gamma_{sh} - 1) m_p c^2 \) (Blandford & McKee 1976). So, the strength of magnetic field can be estimated as

\[
B \approx (8 \pi \epsilon_B e \text{e})^{1/2} \approx 6 \times 10^2 G_{\text{e},1.3}^{1/2} \left( \gamma_{sh}^{1/2} \delta t_i^{-1} \right) \Gamma_i^{-1} \delta t_i^{-1} \Gamma_i^{-3} \delta t_i^{-1} \text{ cm}^{-3}.
\]

As usual, we assume that in the shock front the accelerated electrons take an energy distribution \( d\epsilon_e / d\epsilon_e \propto \epsilon_e^{p-1} \) for \( \epsilon_e > \gamma_{sh} m_e \), where \( \gamma_{e,m} = \epsilon_e (\gamma_{sh} - 1)(p - 2) m_p / (p - 1) m_e \) is the minimum Lorentz factor of the shocked electrons (Sari et al. 1998), and \( m_e \) is the rest mass of an electron. Here for GRB 080129, we take \( p = 2.5 \). We can get the observed typical frequency of the synchrotron radiation

\[
\nu_m = \nu_{\text{e,m}} \gamma_{e,m} \Gamma B / [2(1 + z) \pi m_e c] \approx 3.7 \times 10^{14} \text{ Hz} \epsilon_{-0.4}^{1/2} \epsilon_{\text{e},1.3}^{1/2} \left( \gamma_{sh}^{1/2} \delta t_i^{-1} \right) \Gamma_i^{-3} \delta t_i^{-1} \Gamma_i^{-3} \delta t_i^{-1} \text{ cm}^{-3}.
\]

where \( q_e \) is the charge of the electron.

The cooling Lorentz factor is estimated by \( \nu_c \approx 7.7 \times 10^8 (1 + z) / (\Gamma B^2 \delta t_i) \). So, the cooling frequency is (Sari et al. 1998)

\[
\nu_c = \nu_{\text{e,c}} \gamma_{e,c} B / [2(1 + z) \pi m_e c] \approx 1 \times 10^{21} \text{ Hz} \epsilon_{\text{e},1.3}^{3/2} \epsilon_{\text{e},1.3}^{1/2} \left( \gamma_{sh}^{1/2} \delta t_i^{-1} \right) \Gamma_i^{-3/2} \delta t_i^{-3/2} \Gamma_i^{-3/2} \delta t_i^{-1} \Gamma_i^{-3/2} \delta t_i^{-1} \text{ cm}^{-3}.
\]

The synchrotron self-absorption frequency can be estimated as

\[
\nu_a \approx 0.1 \times 10^{14} \text{ Hz} \epsilon_{\text{e},1.3}^{1/4} \epsilon_{\text{e},1.3}^{5/4} \left( \gamma_{sh} - 1 \right) \gamma_{sh}^{1/2} \Gamma_i^{-3/2} \delta t_i^{-1} \Gamma_i^{-3/2} \delta t_i^{-1} \Gamma_i^{-3/2} \delta t_i^{-1} \text{ cm}^{-3}.
\]
The maximum spectral flux of the synchrotron radiation is
\[ F_{\nu_{\text{max}}} \approx 3.3 \Phi_0 (1 + z) N_e c^2 \sigma T_B (32 \pi^2 q_d D_\gamma^2) \], where \( N_e \) is the total number of emitting electrons, \( N_e = L_{\text{ob}} / [(1 + z) \Gamma_0 m_p c^2] \), with \( \delta \) is the observed typical variability timescale of the total flare, and \( \Phi_0 \) is a function of \( p \). For \( p = 2.5 \), we have \( \Phi_0 \approx 0.6 \) (Wijers & Galama 1999). For \( \nu_c < \nu_m < \nu_{\text{opt}} \), the predicted flux is (Sari et al. 1998)
\[ F_{\nu} = F_{\nu_{\text{max}}} (\nu / \nu_c)^{-1/2} \sim 5 \times 10^{-4} \text{Jy} \left( \nu / (3 \times 10^{14} \text{Hz}) \right)^{-1/2} \times \left( \frac{q_{\text{sh}}}{2} \right)^{-1/2} \left( \frac{q_{\text{sh}}}{1} \right)^{-1/4} \left( \frac{\Gamma_0}{3} \right)^{-3/4} \left( \frac{N_e}{10^{57}} \right)^{1/2} \left( \frac{D_{\text{L,29}}}{10^{29}} \right)^{-2}. \]

(6)

Taking \( \nu_{\text{NIR}} = 3 \times 10^{14} \text{Hz} \), we have \( F_{\nu_{\text{opt}}} \approx 0.5 \text{mJy} \), consistent with the observation of GRB 080129’s flare in the NIR band.

In the optical and X-ray band satisfying \( \nu_c < \nu_a < \nu_{\text{opt}} \), the flux can be estimated as
\[ F_{\nu} = F_{\nu_{\text{opt}}} (\nu / \nu_{\text{opt}})^{-1/2} (\nu_{\text{opt}} / \nu_{\text{NIR}})^{-p/2} \] (Sari et al. 1998). Taking \( \nu_{\text{opt}} = 5 \times 10^{14} \text{Hz} \) for the optical band and \( 2 \times 10^{17} \text{Hz} \) for the X-ray band, we have \( F_{\nu_{\text{opt}}} \sim 0.3 \text{mJy} \) and \( F_{\nu_{\text{NIR}}} \sim 1.7 \times 10^{-4} \text{mJy} \), respectively. Approximately, the optical peak flux of the flare is \( 0.3 \text{mJy} \), as inferred from Figure 1 of Greiner et al. (2009). So, our result is consistent with the optical data too. In the X-ray band, no observation was carried out for \( t \leq 3.2 \times 10^3 \text{s} \). So, it is impossible to test our predication in the X-ray band.

4. DISCUSSION

In \( 10^3 - 10^5 \text{s} \) after the trigger of GRBs, bright X-ray flares have been well detected in a good fraction of Swift GRB X-ray afterglows (Falcone et al. 2007; Chincarini et al. 2007). However, for many X-ray flares the peak energy is unknown and the upper limit is about 0.2 keV. Fan & Piran (2006) speculated that some X-ray flares actually peaked in the UV/optical band and thus should be classified as UV/optical flares. However, before 2008 people had not detected a canonical optical flare with plenty of data. The best candidate of UV/optical afterglow data of GRB 080129 (Greiner et al. 2009).

The optical/NIR flares following GRB 080129 have very sharp decline (\( \alpha_2 \gg 2 + \beta \)) and very small \( \delta t / t_p (\approx 0.15) \), similar to that of the giant X-ray flare following GRB 050502B. These two characters rule out the possibility of being the reverse shock emission or being the radiation of the continued but weaker and weaker collision between the outflow material ejected during the prompt emission phase. Instead, these optical/NIR flares can be attributed to the re-activity of the central engine, as the X-ray flares detected in a good fraction of Swift GRB X-ray afterglows. In the framework of late internal shock model, with reasonable physical parameters (in particular \( \Gamma_1 \sim \text{tens} \)) we calculate the synchrotron radiation. The typical frequency is just in the NIR band and the flux estimated in the NIR and optical bands are also consistent with the observations (see Section 3 for details). We conclude that the flares in GRB 080129 peaking in the NIR/optical band are a low-energy analogue of the X-ray flares, confirming the speculation of Fan & Piran (2006).

The identification of a low-energy analogue of the X-ray flares in the optical/IR band also helps the people to diagnose the physical composition of the outflow launched by the re-activity of the central engine. Fan et al. (2008b) showed that polarimetry of the flares is highly needed to achieve such a goal. Technically, the optical polarimetry is much more plausible than the X-ray polarimetry at present (Covino et al. 1999).

In this work, we also show that the two constraints \( \alpha_2 \gg 2 + \beta \) (i.e., the decline constraint) and \( \delta t / t_p \ll 1 \), widely/separately used to support the “central engine origin” of the afterglow emission, are highly relevant and even identical (see Section 2 for details) for the flares. The decline constraint may be more general. For example, the very sharp drop detected in the X-ray afterglow of GRBs 070110 (Troja et al. 2007), 060413, 060522, 060607A, and 080330 (Zhang 2009) is in support of a central engine origin though the constraint \( \delta t / t_p \ll 1 \) is unsatisfied.

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REFERENCES

Barthelmy, S. D., et al. 2008, GCN Circ. 7235
Blandford, R. D., & McKee, C. F. 1976, Phys. Fluids, 19, 1130
Boër, M., et al. 2006, ApJ, 638, L71
Burrows, D. N., et al. 2005, Science, 309, 1833
Chincarini, G., et al. 2007, ApJ, 671, 1903
Covino, S., et al. 1999, A&A, 348, L1
Falcone, A. D., et al. 2007, ApJ, 671, 1921
Fan, Y. Z., & Piran, T. 2006, MNRAS, 370, L24
Fan, Y. Z., Piran, T., & Wei, D. M. 2008a, in AIP Conf. Proc. 968, Astrophysics of Compact Objects, ed. Y.-F. Yuan, X.-D. Li, & D. Lai (Melville: AIP), 32
Fan, Y. Z., & Wei, D. M. 2005, MNRAS, 364, L42
Fan, Y. Z., Xu, D., & Wei, D. M. 2008b, MNRAS, 387, 92
Fenimore, E. E., Madras, C. D., & Nayakshin, S. 1996, ApJ, 473, 998
Greiner, J., et al. 2009, ApJ, 693, 1912
Guetta, D., et al. 2006, Nuovo Cimento B, 121, 1061
Holland, S. T. 2008, GCN Circ. 7227
Immler, S., et al. 2008, GCN Circ. 7226
Kumar, P., & Panaitescu, A. 2000, ApJ, 541, L51
MacFadyen, A. I., Woosley, S. E., & Herger, A. 2001, ApJ, 550, 410
Mészáros, P. 2006, Rep. Prog. Phys., 69, 2259
Nakar, E., & Piran, T. 2003, ApJ, 598, 400
Paczynski, B., & Xu, G. H. 1994, ApJ, 427, 708
Piran, T. 1999, Phys. Rep., 314, 575
Rees, M. J., & Mészáros, P. 1994, ApJ, 430, L93
Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
Troja, E., et al. 2007, ApJ, 665, 599
Wei, D. M., Yan, T., & Fan, Y. Z. 2006, ApJ, 636, L69
Wijers, R. A. M. J., & Galama, T. J. 1999, ApJ, 523, 177
Zhang, B. 2007, Chinese J. Astron. Astrophys., 7, 1
Zhang, X. H. 2009, Res. Astron. Astrophys., 9, 213
Zhang, B., et al. 2006, ApJ, 642, 354