IS THE LINE-LIKE OPTICAL AFTERGLOW SED OF GRB 050709 DUE TO A FLARE?

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ABSTRACT

Recently, Jin et al. reanalyzed the optical observation data of GRB 050709 and reported a line-like spectral energy distribution (SED) component observed by the Very Large Telescope at $t \sim 2.5$ days after the trigger of the burst, which had been interpreted as a broadened line signal arising from a macronova dominated by an iron group. In this work, we show that an optical flare origin of such a peculiar optical SED is still possible. Interestingly, even in such a model, an “unusual” origin of the late-time long-lasting *Hubble Space Telescope* F814W-band emission is still needed and a macronova/kilonova is the natural interpretation.

Key words: gamma-ray burst: individual (GRB 050709) – radiation mechanisms: non-thermal

1. INTRODUCTION

Gamma-ray bursts (GRBs) are short flashes of γ-rays from outer space. In general, GRBs can be divided into two distinct sub-groups based on the time duration distribution of the prompt soft gamma-ray emission (Kouveliotou et al. 1993). One group, with a typical duration of $\sim 20$ s, has been named the “long GRBs.” The other group, with a much shorter duration of $< 2$ s, has been called the “short GRBs” (sGRBs). Except for a few outliers that have been called the long-short or hybrid GRBs, the nearby long GRBs were found to be associated with bright supernovae (Kumar & Zhang 2015) and hence from the collapse of massive stars. In contrast, no bright supernova emission has been detected in the afterglow of sGRBs and hybrid GRBs. Such a fact has been taken as one of the most compelling pieces of evidence for the compact binary merger origin of these events (Berger 2014).

Though no luminous supernovae in the afterglow of sGRBs and hybrid GRBs have been detected so far, the searches for much weaker and softer near-infrared/optical transients powered by the radioactive decay of r-process material synthesized in ejecta launched during the mergers, i.e., the so-called Li-Paczynski macronovae/kilonovae (Li & Paczynski 1998; Kulkarni 2005; Metzger et al. 2010) have attracted wider and wider attention. In comparing with the remarkable progresses made on numerical simulation in these few years (e.g., Roberts et al. 2011; Korobkin et al. 2012; Barnes & Kasen 2013; Kasen et al. 2013; Piran et al. 2013; Tanaka & Hotokezaka 2013; Grossman et al. 2014; Lippuner & Roberts 2015), the macronova/kilonova sample increases rather slowly. In 2013 the first macronova/kilonova candidate, mainly based on one single *Hubble Space Telescope* (HST) F160W-band detection, was identified in sGRB 130603B (Berger et al. 2013; Tanvir et al. 2013). In 2015, the joint re-analysis of the Very Large Telescope (VLT) and HST afterglow data of the hybrid GRB 060614, a burst famous for sharing some characters of both long and sGRBs, revealed strong evidence for the presence of a macronova/kilonova component (Yang et al. 2015). Further examination of the afterglow allowed some authors to derive a tentative macronova light curve (Jin et al. 2015). Very recently, Jin et al. (2016) reanalyzed the VLT and *HST* afterglow data of sGRB 050709. Together with the Danish 1.5 m telescope optical afterglow data (Hjorth et al. 2005), Jin et al. (2016) showed that the optical signal, interpreted as the afterglow, is actually dominated by the macronova/kilonova component at $t > 2.5$ days and such a component is rather similar to that identified in hybrid GRB 060614. Note that sGRB 050709 was the first short event with an identified optical counterpart; the successful identification of a macronova/kilonova emission component in the optical data implies that macronova/kilonova is common in merger-originated (either double neutron star merger or neutron star and black hole merger) events. The statistical study of the nearby short and hybrid GRBs with sufficient optical afterglow observations to hunt for macronova/kilonova indeed provides strong support to such a possibility (Jin et al. 2016). Though these progresses are intriguing and encouraging, the “peculiar” VLT $I/R/V$ afterglow emission measured at $t \sim 2.5$ days is still to be better understood. The peculiarity is that the $R$-band flux is significantly larger than the $I$-band and $V$-band fluxes, which is unexpected in the afterglow emission. Jin et al. (2016) hypothesized that such a signal is due to a wind-macronova since a strong line feature can be produced by a macronova dominated by the iron group (Kasen et al. 2013). If correct, it reveals the nature of the composition of the sub-relativistic outflow. However, we noticed that the VLT $I/R/V$ measurements were carried out individually. The different measure times actually left more freedom for the theoretical interpretation, which is the focus of this work.

This work is organized as follows. In Section 2, we show that the result of the VLT $I/R/V$ measurements at $t \sim 2.5$ days is indeed inconsistent with the regular afterglow model. We discuss in Section 3 an optical flare model to interpret the peculiar VLT optical spectral energy distribution (SED) and in Section 4 we discuss whether in this case a macronova component is still needed or not. We summarize the results with some discussions in Section 5.

2. THE LINE-LIKE VLT $I/R/V$ SED

The optical counterpart was first detected by the Danish 1.5 m telescope, a series of observations were made but only the first two epochs of $R$-band observations at one day and two days after the burst detected the counterpart (Hjorth et al. 2005). It is notable that Covino et al. (2006) reported the VLT detection of the sGRB 050709 counterpart in $R$ and $V$ bands and an upper limit in the $I$ band. They are a sequence of
observations taken in about half an hour; the first six 100 s exposures are in the $I$ band, then the six 60 s exposures are in the $V$ band, and finally one 20 s and five 60 s exposures are in the $R$ band. Thanks to the more suitable choice of the now available reference frame of the $I$-band data analysis, the very recent re-analysis by Jin et al. (2016) found a significant $I$-band detection. Later, three more epochs of observations were conducted; however, no significant signs of an optical counterpart were detected. The detection of the afterglow in $I/R/V$ bands in a short time interval by VLT on 2005 July 12 can be directly used to build the SED without any correction, as shown in Figure 1. In the regular forward shock model, the long-lasting afterglow emission is attributed to the synchrotron radiation of the electrons accelerated in the shock front and the spectrum is well understood (Sari et al. 1998). Usually the optical afterglow spectrum is power-law-like. However, when we try to fit the VLT SED by a power law, the best fit yields a reduced $\chi^2$ of $\sim 12.4$ (see the yellow dashed line in Figure 1), which is too large to be acceptable. A thermal spectral fit yields a reduced $\chi^2$ of $\sim 10$, which is not acceptable either (see the blue dashed line in Figure 1). Such facts strongly suggest that the VLT optical emission is irregular and a specific model is crucially needed (see also Jin et al. 2016), which is the focus of the rest of this work. $HST$ also took three epochs of F814-band observations within a month after the burst, all clearly detected the counterpart. Later, two more epochs of observation were made, but the counterpart has faded away (Fox et al. 2005).

3. AN OPTICAL FLARE MODEL FOR THE LINE-LIKE VLT SED

In Jin et al. (2016), the peculiar VLT optical afterglow data has been attributed to the intrinsic spectrum of a single radiation component. In view of the fact that the VLT observations in $I$, $R$, and $V$ bands were carried out in a time interval rather than “fully simultaneously,” in this work, we consider an alternative possibility in which the data may be interpreted assuming an optical flare, with a flux comparable to the “afterglow” component, which appeared after the VLT $I$-band measurement but before the $R$-band measurement on 2015 July 12th. It is worth noting that distinct optical flares in the late afterglow of GRBs had been well detected (e.g., Greiner et al. 2009), which had been interpreted as the central engine re-activity (e.g., Gao 2009). In such a scenario, the peculiar VLT optical SED is not intrinsic but an observation bias, the idea is explained in detail as the following. The time interval of the VLT observations on 2005 July 12 is about half an hour, which is much shorter than the measurement time of $t \sim 2.5$ days. Hence, in such a short time interval, the forward shock afterglow emission can be taken as stable and the emission in $V/R/I$ bands is denoted as $f_{V,fs}$, $f_{R,fs}$, $f_{I,fs}$, respectively. If there was an optical flare taking place after the $I$-band measurement but before the $V$- and $R$-band measurements, the contribution of the flare emission in the recorded $V/R/I$ fluxes are $f_{V,fl}$, $f_{R,fl}$, $f_{I,fl}$, respectively. For illustration, one can consider the specific scenario of $f_{V,fl} \approx 2f_{V,fs}$ and $f_{R,fs} \approx f_{R,fl}$. For the forward shock emission, it is well known that $f_{I,fs} \approx (\nu_{R}/\nu_{I})^\beta f_{R,fs} \approx 1.2f_{R,fs}$ and $f_{V,fl} \approx (\nu_{R}/\nu_{V})^\beta f_{R,fs} \approx 0.85f_{R,fs}$, where $\nu_{R}$ and $\nu_{I}$ are the $R$- and $I$-band frequencies, respectively, and $\beta \sim 1$. The “recorded” $I/R/V$ flux ratios are $\sim 1.2:2:1.3$, significantly different from the intrinsic SED and may account for our observation, though both the intrinsic spectra of the afterglow and the flare are power laws. If by chance $f_{V,fl} = 0$ (i.e., the optical flare took place after the observations in $I/V$ bands), the “recorded” SED will be a more distinct broadened “line.” Though, in this work, we focus on the interpretation of the line-like VLT SED of GRB 050709; for illustration in Figure 2, we show in various conditions what will happen in the SED measurement based on the photometric data collected separately in a few bands. Clearly, the observed SED could be very peculiar in comparison to that of the regular afterglow spectrum.

In the current case, the most direct evidence for presence of an optical flare could be the identification of significant flux variability in $R$ and $V$ bands. For such a purpose, we have analyzed the VLT $I/R/V$ band data of GRB 050709 measured on 2005 July 12. The analysis is the same as in Jin et al. (2016), except in this work, we analyze each individual exposure before combine them into a single image in each band. The results are plotted in Figure 3. It is worth noting that one $V$-band and one $R$-band exposure have been discarded because of their poor quality. For the exposures in $V$ band, the resulting signal-to-noise is not high enough to reliably check the possible evolution. The signal-to-noise of the $R$-band exposures is better; however, one can claim that there is neither distinct flux variability nor stable flux.

Below we focus on a more specific scenario and try to fit the observation data. As usual, we assume that the afterglow flux drops with time as $\propto t^{-\alpha_3}$ and there was an optical flare appearing at $t_0$ and peaking at $t_p$. The increase of the optical flare is assumed to be $\propto (t - t_0)^{\beta_0}$. The decrease of the optical flare is assumed to be $\propto (t - t_0)^{\beta_3}$. It is worth noting that due to the so-called high latitude emission, the optical decline index $\alpha_3$ cannot be larger than $2 + \beta_0$ (i.e., $\alpha_3 \leq 2 + \beta_0$), where $\beta_0$ is the spectral index in the optical band (Fenimore et al. 1996; Kumar & Panaitescu 2001). For the current potential optical flare, $\beta_0$ is essentially unknown and we simply assume that $\beta_0 \approx 1$ and $\alpha_3 \approx 3$. 

![Figure 1. SED of the afterglow of sGRB 050709 measured by VLT on 2005 July 12, the data are taken from Jin et al. (2016). The best fit with a power law is $\nu^{-0.04}$, or with a thermal spectra is temperature $T = 7339$ K. Both fits are too poor to be acceptable.](image)
We therefore fit the $R$-band data with the following empirical functions:

$$F_R = \begin{cases} F_1 t^{\alpha_1}, & 0 < t < t_0; \\ F_1 t^{\alpha_1} + F_2 (t - t_0)^{\beta_1}, & t_0 < t < t_p; \\ F_1 t^{\alpha_1} + F_3 (t - t_0)^{-3}, & t > t_p. \end{cases}$$

To include the contribution of the VLT $I$/$V$ band data, we convert such emission into $R$ band with an optical spectrum $F_\nu \propto \nu^{\beta_1}$ (here, $\beta_1 = (\alpha_1 + 1)/2$). The fit to these data yields

**Table 1**

| Parameter | $\alpha_1$ | $\alpha_2$ | $\beta_1$ | $t_p$ (s) | $t_0$ (s) |
|-----------|------------|------------|------------|-----------|-----------|
| Value     | -2.38      | 2.52       | -0.689     | 213550.8s | 212683s   |

**Figure 2.** Diagrammatic sketch to show possible peculiar SEDs yielded in the superposition of an optical flare with the forward shock afterglow emission. Here $a'$–$f'$ are the SEDs corresponding to the light curves $a$–$f$, respectively.

**Figure 3.** Optical observations of GRB 050709 on 2005 July 12. Note that each exposure has been analyzed individually.
the physical parameters reported in Table 1, and the results are shown in the insert of Figure 4. These parameters are typical in comparison to other optical flares in GRB afterglows (Li et al. 2012).

4. IS THE MACRONOVA EMISSION STILL NEEDED?

So far, we have shown that the line-like SED measured by VLT on 2005 July 12 may be attributed to the superposition of an afterglow component with an optical flare. One would then ask whether a macronova is still needed or not in such a scenario. For such a purpose, we subtract the $I$-band/$F814W$-band "afterglow" emission, based on the $R$-band decay $F_R \propto t^{-2.38}$ and an optical spectrum $f_\nu \propto \nu^{-0.69}$. Interestingly, we have found out that the $HST$ $F814W$-band data is significantly in excess of such an "afterglow" component, favoring the presence of a macronova in a wide time interval (from $t \sim 5$ days to 19 days after the GRB trigger), see Figure 4.

5. DISCUSSION

The flares are believed to be produced by late activity of the GRB central engine (e.g., Fan et al. 2005; Zhang et al. 2006), i.e., the GRB central engine restarted possibly due to the fallback accretion. One is obliged to accept a more complicated afterglow picture, namely, that the observed afterglow emission is a superposition of the traditional external shock afterglow and an afterglow related to the late central engine activity (e.g., Zhang et al. 2006). If an optical flare opportunistically occurs during the observations, a very unusual SED is measured. We discuss six different SEDs when an optical flare is observed at a different time using three different bands, results are compatible with a line-like structure, or an absorption line or even a rising power law (see Figure 2 for illustration).

The three VLT $I/R/V$-band observations of GRB 050709 afterglow on 2005 July 12 constitutes a peculiar SED, which has been interpreted as a broad-line-like spectrum from an iron-group-element-dominated macronova (Jin et al. 2016), which could arise from an accretion disk wind (Metzger et al. 2009) in which the heavier r-process elements are depleted because strong neutrino irradiation from a remnant neutron star or the accretion torus can increase the electron fraction of the disk material. Alternatively, as shown in this work, the SED could be due to a flare during the observation. It is hard to distinguishing between these two possibilities due to the limitation of the observations, but both models favor a macronova component that was dominant in the time range between 6 and 19 days. Future detection of a similar SED or another type of SED built in Section 3 may strengthen one of these possibilities. Furthermore, having better timing and wavelength coverage can help, for example, splitting one-round filter shift into more, or making multi-band observation simultaneously. However, to be more reliable, we suggest splitting one-round filter shift into two-round, or better if a multi-band (for example $I/R/V$) camera, which can make the observations simultaneously on an 8 m telescope. In the future, for similar sources ($R \sim 24$ mag), spectra can be directly derived from the ELT-class (European Extremely Large Telescope) telescopes, which may finally solve this puzzle. An interesting possibility is that the sub-relativistic neutron-rich ejecta from the compact object mergers may have heavy or lighter composition in different directions and the resulting signal may be a combination of macronova resulting from those (e.g., Metzger & Fernández 2014; Kasen et al. 2015). Spectroscopic information for these faint signals could allow for a better understanding of the phenomena, and be useful for understanding the formation of heavy elements via a neutron star binary merger.

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