The puzzling afterglow of GRB 050721: a rebrightening seen in the optical but not in the X-ray

BY L. ANGELO ANTONELLI 1,2,*, VINCENZO TESTA 1, PATRIZIA ROMANO 3, DAFNE GUETTA 1, KEN’ICHI TORII 4, VALERIO D’ ELIA 1, AND DANIELE MALESANI 5

1 INAF-Astronomical Observatory of Rome, via Frascati, 33, 00040 Monteporzio, Rome, Italy
2 ASI Science Data Centre, via Galileo Galilei, 00044 Frascati, Rome, Italy
3 INAF-Astronomical Observatory of Brera, via E. Bianchi, 46, Merate (LC), 23807, Italy
4 Osaka University, 1-1 Machikaneyama-cho, Toyonaka, Osaka 560-0043, Japan
5 International School for Advanced Studies, via Beirut 2-4, I-34014 Trieste, Italy

We present here the analysis of the early and late multiwavelength afterglow emission, as observed by Swift a small robotic telescope and very large telescope (VLT). We compare early observations with late afterglow observations obtained with Swift and the VLT and we observe an intense rebrightening in the optical band at about 1 day after the burst, which is not present in the X-ray band. The lack of detection in X-ray of such a strong rebrightening at lower energies may be described with a variable external density profile. In such a scenario, the combined X-ray and optical observations allow us to derive that the matter density located at \( \sim 10^{17} \) cm from the burst is approximately a factor of 10 higher than in the inner region. This is the first time in which a rebrightening has been observed in the optical afterglow of a gamma-ray burst that is clearly absent in the X-ray afterglow.

Keywords: gamma ray; gamma-ray bursts; individual GRB 0507211

1. Introduction

The Swift gamma-ray burst (GRB) explorer (Gehrels et al. 2004) is currently detecting two to three GRBs per week, distributing coordinates with very small uncertainties (few arcmin down to several arcsec) within a few seconds up to tens of seconds after the GRB event. The prompt Swift alerts also allow the immediate follow-up of GRBs with ground-based facilities. The European Southern Observatory (ESO) made its four very large telescope (VLT) units able to react to transient sources within just 8 min after the trigger through the rapid response mode (RRM) procedure. Thanks to Swift, we can now investigate the characteristics of the very early stages of the afterglow, when the physical properties of the fireball...
and the circumburst medium can be derived from the properties of the light curve. Moreover, early observations easily span a long dynamical range in the afterglow lifetime, so that a rich phenomenology can be observed.

2. GRB 050721: the prompt emission and the X-ray afterglow

On July 21 2005 at 04:29:14.3 UT, the burst alert telescope (BAT; Barthelmy et al. 2005) on board Swift detected and located a long, weak burst. The masked-weighted light curve of the prompt emission of GRB 050721 shows a FRED-like structure with a single large peak visible in the 15–100 keV energy band, but not at higher energies. The calculated $T_{90}$ (15–350 keV) is $39 \pm 2$ s (estimated error including systematics). The time-averaged spectrum is well described by a single power law with a photon index $1.81 \pm 0.08$. The fluence in the 15–350 keV band is $(5.05 \pm 0.25) \times 10^{53}$ erg cm$^{-2}$ (all the errors are quoted at the 90% confidence level; Fenimore et al. 2005).

Following the BAT trigger, Swift immediately (186 s after the burst) followed up this event with its narrow field instruments: the X-ray telescope (XRT; Burrows et al. 2005) and the UV optical telescope (UVOT, Roming et al. 2005). A previously unknown fading X-ray source was detected within the BAT error circle, while no evident optical counterparts were seen in the optical images obtained by UVOT. The X-ray afterglow was then monitored for about a week by Swift. The background-subtracted light curve extracted in the 0.2–10 keV energy band (figure 1), with the BAT trigger as origin of time, is well fitted with a broken power law $F(t) = Kt^{-a_1}$ for $t < t_b$ and $F(t) = Kt_b^{-a_1}(t/t_b)^{-a_2}$ for $t > t_b$, where $t_b$ is the time of the break, and slopes are $a_1 = 2.37 \pm 0.24$ and $a_2 = 1.20 \pm 0.04$, and a break at $t = 399^{+75}_{-35}$ s ($\chi^2_{\text{red}} = 1.39$; 52 d.f.). The late afterglow light curve is fitted by a simple power law $F(t) = Kt^{-a}$ with $a = 1.20^{+0.39}_{-0.42}$. The (0.3–10 keV) spectrum obtained during the first orbit is well fitted by an absorbed power law model, with the hydrogen column density (at $z = 0$) kept as a free parameter. The PC mode spectrum during the first orbit yields a photon index $\Gamma = 1.86^{+0.17}_{-0.16}$ and a column density $N_H = 3.25^{+0.71}_{-0.65} \times 10^{21}$ cm$^{-2}$, $\chi^2_{\text{red}} = 0.67$; 36 d.f. The observed count rate was $0.72 \pm 0.02$ cts s$^{-1}$ corresponding to an unabsorbed flux of $F_X(0.2–10 \text{ keV}) = 1.40 \times 10^{-10}$ ergs s$^{-1}$ cm$^{-2}$. The spectrum obtained by the sum of the last four observations is fitted by the same model yielding a best fit value of $\Gamma = 2.18^{+0.25}_{-0.22}$ and a column density consistent with the Galactic value ($\chi^2_{\text{red}} = 0.88$; 18 d.f.). The photon index of the late afterglow spectrum, compared with the early afterglow spectrum observed in the PC mode, shows a possible softening of the photon index by $\Delta \Gamma = 0.32 \pm 0.30$.

3. GRB 050721: the optical afterglow

The fast accurate localization obtained by Swift allowed a 0.3 m robotic telescope, located in New Mexico and operated from Osaka University, to detect the optical afterglow (OA) $\sim 369$ s after the trigger, at the level of $I_c \sim 15.6$ mag. The field was also observed by the MISTICI collaboration with the ESO-VLT UT2 telescope operated for the first time in RRM. The VLT observations started 25 min after the GRB and confirmed the presence of the OA within the XRT error circle. The optical afterglow was located at RA = 16$^h$53$^m$44$^s$.53,
December 28, 2005 (J2000), very close (1°.4) to a relatively bright star ($R_{ZK}17.4$) present in the USNO B1.0 catalog (U0616-0429150) (figure 2). The prompt identification of the OA allowed a very dense sampling of its light curve at early times, making it one of the best sampled light curves obtained so far. The observed light curve shows the typical fading behaviour for GRB afterglows well described by a simple power law ($F(t) = Kt^{-\alpha}$) with a slope $\alpha = 1.29 \pm 0.06$, which...

Figure 1. X-ray light curve of GRB 050721 afterglow in the 0.2–10 keV energy band. Empty squares and filled circles indicate WT and PC data, respectively. The curve is background-subtracted and the time is referred to the BAT trigger, 2005 July 21 at 04:29:14.28 UT. The solid line shows the best-fit broken power law. The last point is a $3-\sigma$ upper limit.

Figure 2. VLT images of the field of GRB 050721 obtained at two different epochs (a) UT 04:54:28 and (b) UT 05:30:45. Both the fading behavior of the optical transient and its proximity with the USNO star (U0616-0429150) are shown.

December = $-28^\circ22'51''.8$ (J2000), very close ($1''.4$) to a relatively bright star ($R=17.4$) present in the USNO B1.0 catalog (U0616-0429150) (figure 2). The prompt identification of the OA allowed a very dense sampling of its light curve at early times, making it one of the best sampled light curves obtained so far. The observed light curve shows the typical fading behaviour for GRB afterglows well described by a simple power law ($F(t) = Kt^{-\alpha}$) with a slope $\alpha = 1.29 \pm 0.06$, which...
is in good agreement with the X-ray slope during the same time-interval as shown in figure 3a. A late point, obtained at the end of the night (\( \sim 8000 \) s after the burst and \( \sim 6500 \) s after the first point), is well aligned along the early curve. The optical light curve is smoothly decaying and it does not show any significant flaring activity. GRB 050721 was also observed during the second night starting approximately 20 h after the burst and we found it approximately 1.8 mag brighter than the value predicted by extrapolating the first night dataset. Such a rebrightening was also observed in the following two observations, obtained at 45 and 69 h, respectively, after the burst. Moreover, if we consider these two points only, we obtain a power law decay with a steeper slope \((\alpha = 1.9 \pm 0.7)\), but still consistent with the previous one given the large error. A late deep observation (2.5 months later) did not reveal either an afterglow nor a host galaxy down to a limiting magnitude of \( R > 25.8 \) mag \((5\sigma)\). We can conclude that the observed flattening was not due to the emergence of the host galaxy, but that a rebrightening was present in the afterglow.

### 4. Discussion

The broadband spectral energy distribution (SED) and the early optical and X-ray decay indices of the afterglow of GRB 050721, are suggesting that both emissions result from the same component during the first hours after the GRB, but are possibly from different components at one day after the event.

The spectral and temporal properties of the afterglow of GRB 050721, during the first hours are consistent with a fireball expanding inside a uniform external medium \((\text{Sari et al. 1998})\), providing that, in the standard fireball model, the
The puzzling afterglow of GRB 050721

1239

electron cooling frequency lies blueward of the X-ray band. For a spectral index $\beta_{\text{ox}} \sim 0.80$, the predicted decay slope is $\alpha = 3\beta/2 \sim 1.2$, in very good agreement with the observed values both in the optical and in the X-ray band (their average being $\alpha = 1.23 \pm 0.03$). The inferred electron distribution index is computed as $p = 2\beta + 1 \sim 2.6$ or, alternatively, $p = 4\alpha/3 + 1 = 2.64 \pm 0.04$. Such value is not uncommon among GRB afterglows.

The situation changes substantially starting $\sim 1$ d after the GRB. At this time, the optical flux is significantly brighter than predicted by the early time decay and the optical spectrum is softer ($\beta_{\text{opt}} = 1.85 \pm 0.11$) than observed at earlier time, and steeper than usually observed in GRB afterglows. Both the flux and SED suggest that a new mechanism is powering the optical emission, leaving the X-ray region unaffected.

There are many possible explanations for such a bump in the optical light curve as largely discussed in Antonelli et al. (2006) (e.g. the emergence an underlying supernova, modifications in the afterglow physics like rebrightenings due to energy injection (like refreshed shock), fluctuations in the external medium, etc.). However, we find more plausible that it was due to fluctuations in the external medium. In such a case, we expect a bump in the optical light curve (but not in the X-ray one) when the fireball encounters regions with enhanced density $n$ (e.g. Lazzati et al. 2002). Such a density jump may be caused by winds termination shock, as proposed for the case of GRB 030329 by Huang et al. (2006). Nakar et al. (2003) have shown that the afterglow flux $F_{\nu}$ at different frequencies may be written in terms of the external density in a very simple way. Assuming the typical afterglow parameters, the synchrotron cooling frequency at 1 d from the burst is expected to be $\nu_c \sim 10^{15}$ Hz (just between the optical and X-ray band). Our data on the late X-ray afterglows of GRB 050721 cannot exclude (within uncertainties) both a steepening in the light curve ($\alpha = 1.20^{+0.39}_{-0.42}$) and a softening of the photon index ($\Delta \Gamma = 0.32 \pm 0.30$), that are compatible with the hypothesis that $\nu_c$ is shifted to energies lower than the X-ray band at this epoch. In such a case, the X-ray flux ($\nu > \nu_c$) is weakly dependent on the external medium density $n$, while the optical flux ($\nu < \nu_c$) is $F_{\nu} \propto n^{3/4}$ (Nakar et al. 2003). Since we see a rebrightening only in the optical band ($\nu < \nu_c$) and not in the X-ray band ($\nu > \nu_c$), we can conclude that this is evidence of fluctuations in the external medium. In particular, we can derive an estimate of the variation in the density from the fluctuations in the flux $n_2/n_1 \propto \left(F_{\nu}^{(2)} / F_{\nu}^{(1)}\right)^{4/3} \sim 10$.

References


Phil. Trans. R. Soc. A (2007)


