THE EARLY (<1 HR) MULTI-COLOR AFTERGLOW OF GRB 050502A: POSSIBLE EVIDENCE FOR A UNIFORM MEDIUM WITH DENSITY CLUMPS

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ABSTRACT

The 2-m robotic Liverpool Telescope reacted promptly to the gamma–ray burst GRB 050502a discovered by INTEGRAL and started observing 3 min after the onset of the GRB. The automatic identification of a bright afterglow of \(t' \sim 15.8\) triggered for the first time an observation sequence in the \(BVr'i'\) filters during the first hour after a GRB. Observations continued for \(~1\) day using the RoboNet-1.0 network of 2-m robotic telescopes. The light curve in all filters can be described by a simple power law with index of 1.2 ± 0.1. We find evidence for a bump rising at \(t \sim 0.02\) days in all filters. From the spectrum and the light curve we investigate different interpretative scenarios and find possible evidence for a uniform circumburst medium with clumps in density, as in the case of GRB 021004. Other interpretations of such bumps, such as the effect of energy injection through refreshed shocks or the result of a variable energy profile, are less favored. The optical afterglow of GRB 050502a is likely to be the result of slow electron cooling with the optical bands lying between the synchrotron peak frequency and the cooling frequency.

Subject headings: gamma rays: bursts

1. INTRODUCTION

Although a considerable number of Gamma-Ray Bursts (GRBs) have detected optical counterparts, there are still few with optical afterglow measurements within minutes of the gamma rays: Figure 1 shows the early light curves (unfiltered, \(R\) and \(V\)) for all of these. The early afterglow is particularly interesting as it carries information about the immediate surroundings of the GRB progenitor, concerning either the circumburst medium or the interaction between shells and the ISM in the fireball scenario. For two GRBs, an optical flash was detected simultaneously with the gamma rays: GRB 990123 and GRB 021211, the early light curve is described by a power law whose index varies from \(\sim 2\) to \(\sim 1\) a few min after the GRB; at 0.5 min and 2.7 min in the rest frame, respectively (Holland et al. 2004). This has been interpreted as due to the transition between reverse and forward shocks.

GRB 021004, one of the best observed GRBs in optical (Holland et al. 2003; Fynbo et al. 2003; de Ugarte Postigo et al. 2005), exhibited a number of bumps in its light curve, with all but the first bump being detected from radio to \(U\) band. Different interpretations have been suggested to explain the light curve features: Lazzati et al. (2003) modeled it using a variable density profile, most likely a uniform medium with clumps with density variations of the order of \(\Delta n/n \sim 10^6\) cm. Other authors (Nakar et al. 2003; Birorsisson et al. 2004; de Ugarte Postigo et al. 2005) account for the bumps with episodes of energy injections when inner shells catch up with the afterglow shock at late times. In addition, Nakar et al. (2003) show that the bumps could be also explained by a variable energy profile that is angularly-dependent on jet structure ("patchy
shells model).

In this Letter, we report the robotic detection and automatic identification of GRB 050502a using the 2-m Liverpool Telescope (LT) located in La Palma, Canary Islands: these observations represent one of the first observations of a multi-color light curve in the first hour since the burst. In addition, we report on late follow-up observations performed with LT and the 2-m Faulkes Telescope North (FTN) located at Maui, Hawaii, both members of the RoboNet-1.0 consortium3 (Gomboc et al. 2005a).

2. OBSERVATIONS AND RESULTS

On 2005 May 02 INTEGRAL detected GRB 050502a at 02:13:57 UT and determined its position at \( \alpha = 13:29:45.4 \) and \( \delta = +42:40:26.8 \) (J2000) with an error radius of 2 arcmin (90\% C.L.) (Götz et al. 2005). The GRB had a duration of 20 s. In the 20–200 keV band it had a peak flux of \( 2 \times 10^{-7} \text{erg cm}^{-2} \text{s}^{-1} \) and a fluence of \( 1.4 \times 10^{-6} \text{erg cm}^{-2} \) (Götz & Mereghetti 2005), thus ranking among faint/intermediate fluence known fading source at \( 2005 \), thus ranking among faint/intermediate fluence.

The Galactic extinction following Cardelli et al. (1989):

\[ A_B = 0.04, A_V = 0.03 \text{ and } A_I = 0.02. \]

Magnitudes have been converted into flux densities \( F \) (mJy) following Fukugita et al. (1995).

Figure 4 shows the multi-color light curve acquired by the LT during the first hour and the later points with both LT and FTN. An achromatic bump rising at \( t \sim 0.02 \text{ d} \) is evident. Fitting each light curve with a power law of the form \( F \propto t^{-\alpha} \), and excluding points \( 0.02 < t < 0.2 \text{ d} \), we obtain power-law indices consistent across all bands: \( \alpha_B = 1.20 \pm 0.04, \alpha_V = 1.16 \pm 0.06, \alpha_I = 1.19 \pm 0.04, \alpha_r = 1.16 \pm 0.03 \). By fitting only the \( r' \) points obtained during the detection mode within 3.8 min of the GRB onset time, we get a power-law index of \( \alpha_r, \text{early} = 1.3 \pm 0.1 \), consistent with the slopes reported above.

Figure 3 shows the rest-frame Spectral Energy Distribution (SED) at two epochs: before the burst \( (t = 0.004 \text{ d}) \), where no strong evidence for significant color change is observed (see Fig. 2), and at the burst \( (t = 0.035 \text{ d}) \). Optical fluxes have been obtained by interpolation. During the burst, a linear interpolation between consecutive points has been adopted, considering that the variability timescales are much larger than the time difference between the pairs of data points used for interpolation. Moreover, we back-extrapolated to \( t = 0.004 \text{ d} \) a Swift X-ray upper limit determined around \( 1.3 \text{ d} \) (Hurkett et al. 2005), assuming a power-law decay, \( F_X \propto t^{-\alpha_X} \), and two different slopes: \( i) \alpha_X = 0.9 \) (solid arrow in Fig. 3); \( ii) \alpha_X = 0.5 \) (dashed arrow in Fig. 3). The reasons for these choices are clarified in Sec. 3. In case (i) the power-law index between optical and X-rays must be: \( \beta_{OX} > 0.7 \); in case (ii) it must be: \( \beta_{OX} > 1.1 \). However a word of caution is needed, particularly because we know from the Swift observation that during the first few hundred seconds the early X-ray afterglows can be characterized by a steep decline followed by a shallower decay (Tagliaferri et al. 2005).

The back-extrapolation for the radio upper limits provided by van der Horst et al. (2005) between 0.6 d and 1.1 d is much more difficult, given that in general the behavior of the early radio afterglow is likely to be very different from the optical one. Hereafter, we do not consider these radio limits.

We note a possible marginal reddening of the spectrum at the time of the bump (see bottom panel of the inset in Fig. 3), albeit not statistically significant: the flux ratio between the bump and the pre-bump epochs does not vary significantly for different optical bands (see also GRB 000301C, Masetti et al. 2000). Due to the high \( z \), the Lyman-\( \alpha \) forest suppresses both \( B \) and \( V \) band fluxes. This accounts for the unusually-steep SED in the optical: by fitting all the four points with a power law, \( F \propto \nu^{-\beta} \), the index is around \( \beta = 2.8 \pm 0.8 \) with a poor \( \chi^2 (\chi^2/\text{dof} = 116/2) \). However, if we assume a standard value of \( \beta = 0.8 \) (see Sec. 3), we find that the flux deficiency at high \( \nu \) can be ascribed to the Lyman-\( \alpha \) forest (see the top panel of the Inset in Fig. 3).

3. DISCUSSION

The reality of the bump we find in the light curve at \( t \sim 0.02 \text{ d} \) is also supported by a rebrightening observed in the IR (Blake & Bloom 2005): initially they observed a decay of 1.1 mag in the \( J \) band between 47 min and 94 min (corresponding to a power-law decay index of \( \alpha = 1.5 \), no error reported), followed by a rebrightening of \( \Delta J \sim 0.1 \) between 94 min (0.065 d) and 121 min (0.084 d). In addition to our measurements,
Following Lazatti et al. (2002), if we interpret the bump as due to density variations of the ISM, this is possible only if the observation occurred at a frequency $\nu = \nu_0$ (let $\nu_0$ be the frequency of our optical bands) below the cooling break $\nu_c$ and above the peak synchrotron frequency $\nu_{\text{pe}}$; $\nu_m < \nu < \nu_{\text{pe}}$. In the following we consider the two cases of uniform ISM and wind environment, respectively.

In the case of uniform ISM, the expected power–law index of the light curve is $\alpha = 3(p-1)/4$, where $p$ is the electron energy distribution index (Sari et al. 1998). From our measure of $\alpha = 1.2 \pm 0.1$ we derive $p = 2.6 \pm 0.1$. We also note that when $\nu_c$ crosses the optical band we should expect a steepening in the light curve of $\Delta \alpha = 0.25$. Since we do not find evidence for this before $t < 1$ d, the only possibility is that $\nu_c < \nu$, at least until $t \sim 1$ d. The energy spectrum at frequency $\nu_m < \nu < \nu_c$ is a power law with index $\beta = (p-1)/2$, i.e. $\beta = 0.8 \pm 0.05$. Figure 2 shows that this is consistent with our result. The cooling break $\nu_c$ must lie between the optical band $\nu_0$ and the X-ray $\nu_X$: $\nu_c < \nu_X < \nu_{\text{pe}}$. The power–law index of the spectrum between $\nu_c$ and $\nu_X$ is expected to be $\beta_X = p/2 = 1.3 \pm 0.05$. The X–ray power–law decay index, $\alpha_X$, is expected to be: $\alpha_X = 3(p-1)/4$ ($\nu_c > \nu_X$), $\alpha_X = (3p-2)/4$ after $\nu_c$ has crossed the X–ray band ($\nu_c < \nu_X$), thus experiencing a steepening of $\Delta \alpha_X = 0.25$. As this is expected to occur soon after the GRB, it is sensible to back-extrapolate the X–ray upper limit assuming for most of the time $t < 0.004$ d and the epoch of the X–ray observation ($\sim 1.33$ d), we derive the X–ray upper limit assuming $\alpha_X = (p+8)/8 = 1.2$, yielding $\beta_{OX} > 0.9$, which is not consistent with $\beta_{OX} = \beta_{m\nu c} = 0.3 \pm 0.4$.

In contrast to GRBs 990123 and 021211, we find no evidence for a change in the temporal slope within the first few minutes of the onset of GRB 050502a, ruling out a transition from reverse to forward shock emission at this time. In GRB 050502a the bump rises soon after the GRB in the rest-frame, to be compared with 0.5 min and 2.7 min of GRB 990123 and GRB 021211, respectively, when the above transition between reverse and forward shocks is supposed to occur. Should GRB 050502a have exhibited a similar transition, we should have detected it before the bump. We conclude that, despite the fact that a wind environment cannot be ruled out, the uniform ISM with clumps in density seems to better account for our observations.

The interpretation of the bump as the result of a refreshed shock catching up with the afterglow front shock seems more problematic, even if it cannot be ruled out. In fact, according to the original refreshed-shocks scenario (Kumar & Piran 2003; Granot et al. 2003), we should expect that the duration $\Delta t$ of the bump is comparable with its start time: $\Delta t \approx t$. In the case of GRB 050502a our measures and those by Mirabal et al. (2005) show that, in spite of the uncertainty, $\Delta t \approx 0.2$ d and $t \approx 0.02$ d. Following Kumar & Piran (2000), the impact between the two shells should produce a forward shock in the outer shell responsible for the bump and a reverse shock propagating in the inner shell. If $E_1$ and $E_2$ are the energy of the outer and inner shells, respectively, the increase in the emission due to the forward shock is expected to be $f = (1 + E_2/E_1)^{(p-3)/4}$. From Fig. 2 we measure a flux increase of $10^{25/2} \sim 1.6 (\Delta m \sim 0.5)$; from $p = 2.6$ we obtain $E_2/E_1 \sim 0.4$. The spectrum at the bump is expected to have two peaks: the lower $\nu$ peak is due to the reverse shock in the inner shell and its frequency should be $\sim 7 \nu_m^2 (E_2/E_1)^1 \approx 64 (\gamma_0/5)^2$ times lower than the peak frequency of the outer shell, i.e. $\nu_{\text{pe}}$, which we know is below the optical bands at the time of the bump ($\gamma_0$ is the Lorentz factor of the outer shell at the time of impact). The increase of emission at this frequency due to the inner shell is expected to be a factor $\sim 8 (\gamma_0/5)^{2/3} \approx 25 (\gamma_0/5)^{2/3}$. Thus, the bump should have been more evident at low frequency: $\nu_m^2/(\gamma_0/5)^2 < \nu_0$, i.e. IR or radio. Unfortunately, the lack of early radio observations prevents this prediction from being tested. In the $\beta$-band at $\sim 2$ min after the burst (Blake & Bloom 2005) report a rebrightening of $\sim 0.1$ mag, which however seems smaller than that observed by us in the op-
tical. Moreover, according to Blake & Bloom (2005) the J-band rebrightening occurs between 0.065 d and 0.084 d, i.e. later than 0.02 d of the optical bands.

In conclusion, although the refreshed-shock scenario cannot be completely ruled out due to the lack of early radio observations, our observations appear to be more difficult to reconcile with its predictions than with those of the variable density environment.

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Nakar, E., Piran, T., & Granot, J. 2003, New A, 8, 495
Fig. 1.— Early light curves (unfiltered, $R$ and $V$) for a set of GRBs with detections within minutes of the GRB. Grey triangles show the case of 050502a (filter $r'$) robotically detected and followed-up by the Liverpool Telescope. Data are taken from GCN circulars, except for GRB 030418 (Rycol et al. 2004) and GRB 041219a (Vestrand et al. 2005). Only the latter values are corrected for Galactic dust extinction, which was high in this case ($\Delta R = 4.9$).

Fig. 2.— Top Panel: Multi-color light curve of GRB 050502a measured with the Liverpool and the Faulkes North Telescopes. Also shown are the best-fit power laws; all of them are consistent with a power–law index of $1.2 \pm 0.1$ (see text). Two ROTSE–IIIb unfiltered points (Yost et al. 2005) and two $r'$ points derived from Mirabal et al. (2005) are plotted as well. Bottom Panel: residuals with respect to the best-fitting power laws.
Fig. 3.— Rest-frame SED at two epochs: $t = 0.004$ d (Pre-Bump) and $t = 0.035$ d (Bump). Optical points have been interpolated at the same epochs. The X-ray upper limit at $t = 0.004$ d (solid arrow) has been obtained by back-extrapolating the values provided by Hurkett et al. (2005), around $\sim 1.3$ d, assuming a power-law decay with index of $\alpha_X = 1.45$. Alternatively, the other X-ray upper limit at $t = 0.004$ d (dashed arrow) is obtained assuming $\alpha_X = 0.95$ (see text). *Inset, top panel:* close-up of the Pre-Bump optical points with the power law with $\beta = 0.8$ (dotted line). The flux deficiency at high $\nu$ is due to the Lyman-$\alpha$ forest (see text). *Inset, bottom panel:* flux ratio between the Bump and the Pre-Bump epochs as a function of $\nu$. All the ratios are consistent with a constant value (weighted average of $0.108 \pm 0.005$, $\chi^2$/dof = 1.2) shown by the solid line.
### Table 1. Optical Photometry for GRB 050502a with LT and FTN

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*aThis corresponds to the time delay with respect to the GRB trigger time, $t_0 = 0.09302$ UT.