THE EARLY MULTICOLOR 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 minutes after the onset of the burst. The automatic identification of a bright afterglow with \( r' \sim 15.8 \text{ mag} \) triggered, for the first time, an observation sequence in the \( BVr' \) filters during the first hour after a GRB. Observations continued for \( \sim 1 \text{ day} \) 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 \( 1.2 \pm 0.1 \). We find evidence for a bump rising at \( t \sim 0.02 \text{ days} \) in all filters. From the spectrum and the light curve, we investigate different 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.

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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 interstellar medium (ISM) in the fireball scenario. For two bursts, an optical flash was detected simultaneously with the gamma rays: GRB 990123 and GRB 041219a. The former has been interpreted as the signature of a reverse shock (Akerlof et al. 1999), while for the latter a correlation between the gamma-ray and optical light curves seems to favor a common origin (Vestrand et al. 2005). These early afterglows show considerable variety; for example, in the case of GRB 030418 the optical emission was found to rise for the first 600 s, slowly vary for 1400 s, and then fade as a power law. This was interpreted as being due to variable extinction by the local circumburst medium (Rykoff et al. 2004). In the cases of 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 minutes after the GRB: at 0.5 and 2.7 minutes 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 the optical (Holland et al. 2003; Fynbo et al. 2005; de Ugarte Postigo et al. 2005), exhibited a number of bumps in its light curve, with all but the first being detected from radio to \( U \) band. Different interpretations have been suggested to explain the light curve’s features: Lazzati et al. (2002) modeled it using a variable density profile, most likely a uniform medium with clumps with density variations of order \( \Delta n/n \sim 10 \) and sizes of 10 cm. Other authors (Nakar et al. 2003; Björnsson 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 (the “patchy shell” model).

In this Letter, we report the robotic detection and automatic identification of GRB 050502a using the 2 m Liverpool Telescope (LT), located on La Palma, Canary Islands. These represent one of the first observations of a multicolor light curve in the first hour after a burst. In addition, we report on late follow-up observations performed with the LT and the 2 m Faulkes Telescope North (FTN), located on Maui, Hawaii; both are members of the RoboNet-1.0 consortium (Gomboc et al. 2005b).3

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2. OBSERVATIONS AND RESULTS

On 2005 May 2, the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) detected GRB 050502a at 02:13:57 UT and determined its position to be $\alpha = 13^\circ 29^\prime 45^\prime\prime.4$, $\delta = +42^\circ 40^\prime 26^\prime\prime.8$ (J2000) with an error radius of 2$^\prime$ (90% confidence level) (Götz et al. 2005). The GRB had a duration of 20 s. In the 20–200 keV band, it had a peak flux of $2 \times 10^{-7}$ ergs cm$^{-2}$ s$^{-1}$ and a fluence of $1.4 \times 10^{-6}$ ergs cm$^{-2}$ (Götz & Mereghetti 2005), thus ranking it among the faint-to-intermediate-fluence GRBs. The ROTSE-IIIb telescope started observing 23.3 s after the burst and detected a 14.3 mag (unfiltered) unknown fading source at $\alpha = 13^\circ 29^\prime 46^\prime\prime.3$, $\delta = +42^\circ 40^\prime 27^\prime\prime.7$ ($t = 98^\prime\prime.76$, $b = +72^\circ 61^\prime$) (Yost et al. 2005). Prochaska et al. (2005) acquired a spectrum with Keck I 3.5 hr after the GRB and identified a strong absorption feature, which they interpret as Si II $\lambda\lambda$ 1260 at redshift $z = 3.793$.

The LT responded robotically to the INTEGRAL alert and started observing 3 minutes after the GRB onset (2.5 minutes after the notice time). Independently of ROTSE-IIIb, it detected a bright fading source not present in the USNO-B1.0, 2MASS, or GSC 2.3 catalogs, with a position consistent with that of the optical transient (OT) from ROTSE-IIIb (Gomboc et al. 2005a). The automatic identification of the bright and rapidly fading OT by the LT GRB robotic pipeline (see Gomboc et al. 2005c for technical details) resulted in the automatic triggering of a multicolor imaging sequence that provided light curves in $BVr'i'z'$ filters from 3 minutes to 1 hr after the GRB onset. The robotic follow-up with the LT ended after the first hour. Subsequent follow-up observations were triggered manually on both the LT and FTN (Table 1). Magnitudes in $r'$ and $i'$ were calibrated using the Sloan Digital Sky Survey (SDSS) DR3 photometric database.$^4$ We obtained a consistent calibration using Landolt (1992) standard field stars for which Smith et al. (2002) provide an SDSS calibration. For the $B$ and $V$ filters, we calibrated with Landolt standard field stars. The zero points were stable during the night and fully consistent with the photometric values. This is also confirmed by the Carlsberg Meridian Telescope at La Palma.$^5$ Finally, we corrected for the air mass and Galactic extinction. The Galactic extinction toward GRB 050502a is low: $A_V = 0.03$ (Schlegel et al. 1998). We evaluated the extinction in the other filters following Cardelli et al. (1989): $A_{B} = 0.04$, $A_{V} = 0.03$, and $A_{R} = 0.02$. Magnitudes have been converted into flux densities $F_{\nu}$ (mJy) following Fukugita et al. (1995).

Figure 2 shows the multicolor light curve acquired by the LT during the first hour and the later points with both the LT and FTN. An achromatic bump rising at $t = 0.02$ days is evident. Fitting each light curve with a power law $F_{\nu} \propto t^{-\alpha}$, and excluding points between 0.02 and 0.2 days, we obtain power-law indices consistent across all bands: $\alpha_{B} = 1.20 \pm 0.04$, $\alpha_{V} = 1.16 \pm 0.06$, $\alpha_{R} = 1.19 \pm 0.04$, and $\alpha_{I} = 1.16 \pm 0.03$. By fitting only the $r'$ points obtained during the detection mode within 3.8 minutes of the GRB onset, we find 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 bump ($t = 0.004$ days), where no strong evidence for significant color change is observed (see Fig. 2), and at the bump ($t = 0.035$ days). Optical fluxes were obtained by interpolation. During the bump, a linear interpolation between consecutive points was 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 $t = 0.004$ days a Swift X-ray upper limit determined around 1.3 days (Hurkett et al. 2005), assuming a power-law decay, $F_{\nu} \propto t^{-\alpha_{\text{X}}}$, and two dif-

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$^4$ See [http://cas.sdss.org/astro/en/tools/chart/](http://cas.sdss.org/astro/en/tools/chart/).  
$^5$ See [http://www.ast.cam.ac.uk/~dwe/SRF/came_extinction.html](http://www.ast.cam.ac.uk/~dwe/SRF/came_extinction.html).
different slopes: (1) $\alpha_p = \alpha_{p(1)} = 1.45$ (Fig. 3, solid arrow) and (2) $\alpha_p = \alpha_{p(2)} = 0.95$ (Fig. 3, dashed arrow). The reasons for these choices are clarified in § 3. In case 1, the power-law index between the optical and X-rays must be $\beta_o > 0.7$; in case 2 it must be $\beta_o > 1.1$. 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 and 1.1 days 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 the bottom panel of the inset in Fig. 3), albeit not statistically significant: the flux ratio between the bump and the prebump epochs does not vary significantly for different optical bands (cf. also GRB 000301C; Masetti et al. 2000). Because of the high $z$, the Ly$\alpha$ forest suppresses both $B$- and $V$-band fluxes. This accounts for the unusually steep SED in the optical: by fitting all four points with a power law $F \propto r^{-\beta}$, the index is around $\beta = 2.8 \pm 0.8$ with a poor $\chi^2/\text{dof} = 116/2$. However, if we assume a standard value of $\beta = 0.8$ (see § 3), we find that the flux deficiency at high $r$ can be ascribed to the Ly$\alpha$ 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 $t \sim 0.02$ days is also supported by a brightening observed in the IR by Blake & Bloom (2005): initially, they observed a decay of 1.1 mag in the $J$ band between 47 and 94 minutes (corresponding to a power-law decay index of $\alpha = 1.5$, no error reported), followed by a brightening of $\Delta J \sim 0.1$ between 94 minutes (0.065 days) and 121 minutes (0.084 days). In addition to our measurements, Figure 2 also shows two unfiltered points from ROTSE-IIIb (Yost et al. 2005) and two other $R$-band measures reported by Mirabal et al. (2005), which we converted to $r'$ assuming $0.3 < R - I < 0.6$ (no uncertainty was reported, so we assumed the systematic 0.3 mag of the USNO-B1.0 catalog, as they calibrated with a USNO-B1.0 field star). In particular, the latter points seem to confirm the presence of the bump in $r'$, despite the large uncertainties. Durig (2005) reported unfiltered observations of the bump. Since the conversion of unfiltered to standard magnitudes requires some assumptions and implies large uncertainties, we are not as confident about the proper intercalibration of those converted magnitudes and our data as we are at earlier epochs, when the decay was simply monotonic. Therefore, lacking a comparison data set of unfiltered data covering both the monotonic early decay and the bump, we have not included Durig’s (2005) data in Figure 2.

Following Lazzati et al. (2002), if we interpret the bump as being due to density variations of the ISM, this is possible only if the observation occurred at a frequency $r = r_c$ (with $r_c$ the frequency of our optical bands) below the cooling break $r_c$ and above the peak synchrotron frequency $\nu_c$: $\nu_c < r < r_c$. In the following, we consider the two cases of a uniform ISM and a wind environment, respectively.

In the case of a 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 $r_c$ 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 $t < 1$ day, the only possibility is that $r < r_c$ at least until $t \sim 1$ day. The energy spectrum at frequencies $\nu < \nu_c$ is a power law with index $\beta = (p - 1)/2$, that is, $\beta = 0.8 \pm 0.05$. Figure 3 shows that this is consistent with our result. The cooling break $r_c$ must lie between the optical-band $r_c$ and the X-ray $r_{X}$: $r_c < r < r_{X}$. The power-law index of the spectrum between $r$ and $r_{X}$ is expected to be $\beta_{r_{X}} = p/2 = 1.3 \pm 0.05$. The X-ray power-law decay index, $\alpha_{r_{X}}$, is expected to be $\alpha_{r_{X}} = 3(p - 1)/4 (r > r_{X})$ and $\alpha_{r_{X}} = (3p - 2)/4$ after $r_{X}$ has crossed the X-ray band ($r < r_{X}$), thus experiencing a steepening of $\Delta \alpha_{r_{X}} = 0.25$. 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 \( \alpha_X = (3p - 2)/4 = 1.45 \). From Figure 3, as long as we assume the validity of the X-ray upper limit extrapolated back to \( t = 0.004 \) days assuming \( \alpha_X = 1.45 \) (solid arrow), we find that the shallowest power-law index allowed between the optical and X-rays is \( \beta_{\alpha m} > 0.7 \). Thus, this is consistent with a broken power law with power-law indices from 0.8 to 1.3. In summary, we conclude that the case of a uniform ISM is fully consistent with our observations.

In the case of a wind environment and \( p < 2 \), we must use the relation \( \alpha = (p + 8)/8 \) from Dai & Cheng (2001) for \( \nu_\alpha < \nu < \nu_{\alpha} \), which yields \( p = 1.6 \pm 0.8 \). The case of \( p > 2 \) is incompatible with the data: from the relation \( \alpha = (3p - 1)/4 \) by Chevalier & Li (1999), we derive \( p = 1.9 \pm 0.1 \). From \( \beta_{\alpha m} = (p - 1)/2 \) and \( \beta_{\alpha X} = p/2 \), holding for \( \nu_\alpha < \nu < \nu_{\alpha} \), respectively, we derive \( \beta_{\alpha m} = 0.3 \pm 0.4 \) and \( \beta_{\alpha X} = 0.8 \pm 0.4 \). Concerning the back-extrapolation of the X-ray upper limit, \( \alpha_X \) is expected to be \( \alpha_X = (p + 8)/(8/\nu_{\alpha}) \) and \( \alpha_X = (p + 6)/8 \) after \( \nu \) has crossed the X-ray band (\( \nu < \nu_{\alpha} \)), thus experiencing a steepening of \( \Delta \alpha_x = 0.25 \). For the same reason as in the previous case, it is reasonable to assume \( \alpha_X = (p + 6)/8 = 0.95 \) for most of the time. The consequent limit on the spectrum is \( \beta_{\alpha m} > 1.1 \) (Fig. 3, dashed arrow). This is compatible only with \( \beta_{\alpha X} \). Furthermore, \( \nu \) should be very close to the optical bands: this implies that during our observation, \( \nu \) should cross the optical bands, producing a slope change in the power-law decay of \( \Delta \alpha_x = 0.25 \), which is not observed. If we assume that \( \nu > \nu_{\alpha} \) for most of the time between \( t = 0.004 \) days and the epoch of the X-ray observation (~1.33 days), we derive the X-ray upper limit assuming \( \alpha_X = (p + 8)/8 = 1.2 \), yielding \( \beta_{\alpha m} > 0.9 \), which is not consistent with \( \beta_{\alpha m} = \beta_{\alpha X} = 0.3 \pm 0.4 \).

In contrast to GRBs 990123 and 021211, respectively, we find no evidence in the optical bands at the time of the bump (~0.1 mag, which however seems smaller than that observed by us in the optical. Moreover, according to Blake & Bloom the \( J \)-band rebrightening occurred between 0.065 and 0.084 days, later than the 0.02 days of the optical bands.

In conclusion, although the refreshed-shock scenario cannot be completely ruled out, because of 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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