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The Early (<1 hr) Multi–Colour Afterglow of GRB 050502a with the 2-m Liverpool Telescope

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Abstract The 2-m robotic Liverpool Telescope automatically discovered the optical afterglow of the *INTEGRAL* gamma-ray burst GRB 050502a 3 min after the GRB onset. The automatic identification of a bright optical transient of $r' \sim 15.8$ triggered for the first time a multi–colour observation sequence in the $BVr'i'$ filters during the first hour after a GRB. All the four light curves are fitted by a simple power law with index of 1.2 ± 0.1. We also find evidence for an achromatic bump rising at $t \sim 0.02$ days. We investigate different scenarios compatible with the data. We find possible evidence for a uniform circumburst medium with clumps in density, as in the case of GRB 021004. The alternative case of a wind environment cannot be ruled out, although it can hardly account for our observations. The alternative interpretation of the bump, as the result of a refreshed shock, appears to be more problematic, although it cannot be ruled out either.

Key words: gamma-rays: bursts — techniques: photometric

1 INTRODUCTION

The number of Gamma-Ray Bursts (GRBs) with optical afterglow measurements within minutes of the gamma-ray emission is continuously increasing mainly thanks to the *Swift* mission (Gehrels et al. 2004). Apparently there is no standard behaviour for the early optical afterglow: for some GRBs, such as GRB 990123 (Akerlof et al. 1999) and GRB 041219a (Vestrand et al. 2005), an optical flash was detected simultaneously with the gamma-rays. In the cases of GRB 990123 and GRB 021211, the early light curve is described by a power law whose index varies from ~ -2 to ~ -1 a few min after the GRB (Holland et al. 2004).

GRB 021004 exhibited a first bump followed by others detected from radio to the U-band (e.g., de Ugarte Postigo et al. 2005). Alternative interpretations have been proposed to explain the bumps of GRB 021004. Lazzati et al. (2002) modelled it using a density variable profile. Alternatively, other works (Nakar et al. 2003; Björnsson et al. 2004; de Ugarte Postigo et al. 2005) model the bumps as due to the energy injection episodes through refreshed shocks. Nakar et al. (2003) show that the bumps could be also explained as due to a variable energy profile (patchy shell model).

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Here we report on the robotic detection of the optical afterglow of GRB 050502a performed by the 2-m Liverpool Telescope (LT) located in La Palma, Canary Islands: these observations represent one of the first examples of a multi–colour light curve in the first hour after a burst (Guidorzi et al. 2005). Furthermore, 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* consortium[1] (Gomboc et al. 2005a).

The results presented here are discussed in more detail by Guidorzi et al. (2005).

2 OBSERVATIONS

The 20-s long GRB 050502a was detected by *INTEGRAL* on 2005 May 2 at 02:13:57 UT and localised 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 earliest detection of the optical afterglow was by ROTSE–IIIb at 23.3 s after the GRB (Yost et al. 2006). They found a 14.3-mag unknown fading source at $\alpha =$13:29:46.3 and $\delta = +42:40:27.7$ (J2000).

The redshift was measured to be $z = 3.793$ by Prochaska et al. (2005).

The LT reacted robotically to the *INTEGRAL* notice and 3 min after the GRB onset (2.5 min after the notice time), independently of ROTSE-IIIb, detected a bright fading source not present in the USNO–B1.0, 2MASS and GSC23 catalogues, with a position consistent with that of ROTSE–IIIb (Gomboc et al. 2005b). The automatic detection of the LT GRB pipeline (Guidorzi et al. 2006) triggered the acquisition of the first early multi–colour light curve in the $BVr'i'$ filters from 3 min to 1 h after the GRB onset. The robotic follow–up with LT ended after the first hour.

See Guidorzi et al. (2005) for the description of the data reduction and of the photometric calibration.

3 DATA ANALYSIS

Figure 1 shows the multi–colour light curve acquired with LT during the first hour and the late points with both LT and FTN. A fit with a power–law ($F \propto t^{-\alpha}$) for each filter gives the following results: $\alpha_B = 1.20 \pm 0.04$, $\alpha_V = 1.16 \pm 0.06$, $\alpha_{r'} = 1.19 \pm 0.04$, $\alpha_{i'} = 1.16 \pm 0.03$. From the fit we excluded the time window 0.02 d$< t < 0.2$ d, in which there is evidence for a bump rising at $t \sim 0.02$ d.

Figure 2 shows the rest–frame Spectral Energy Distribution (SED) at two epochs: before the bump ($t = 0.004$ d) and at the bump ($t = 0.035$ d). Optical fluxes have been obtained by interpolation. We also used the X-ray upper limit by *Swift* around 1.3 d (Hurkett et al. 2005). We back-extrapolated this limit to $t = 0.004$ d assuming a power–law decay, $F_{\rm X} \propto t^{-\alpha_{\rm X}}$, in two cases: i) $\alpha_{\rm X} = \alpha_{\rm X}^{(1)} = 1.45$ (solid arrow in Fig. 2); ii) $\alpha_{\rm X} = \alpha_{\rm X}^{(2)} = 0.95$ (dashed arrow in Fig. 2). The reasons for these choices are clarified in Sec. 4. In case i) the power–law index between optical and X-rays must be: $\beta_{\rm OX} > 0.7$; in case ii) it must be: $\beta_{\rm OX} > 1.1$. However utmost care is required, as early X-ray afterglows can be characterised by a rapid decline followed by a shallower decay (Tagliaferri et al. 2005).

We do not find evidence for a significant colour change at the time of the bump, as shown by the bottom panel of the inset in Fig. 2: the flux ratio between the bump and the pre-bump epochs does not vary significantly for different optical bands.

If we assume a power-law spectrum, $F \propto \nu^{-\beta}$, with the value of $\beta = 0.8$ (see Sec. 4) in agreement with that found by Yost et al. (2006), the radiation deficiency in B and V is due to the Lyman-α forest (see the top panel of the Inset in Fig. 2). At $z = 3.793$ the Lyman α (1216 Å) falls at 5828 Å(observer frame), i.e. in the V band, while the Lyman edge (912 Å) falls at 4371 Å, i.e. in the B band.

4 DISCUSSION

Hereafter we discuss two environments: uniform ISM vs. wind environment. For a thorough discussion of the possible interpretations see Guidorzi et al. (2005).

If the bump is due to density variations of the ISM (either uniform or wind), it must be $\nu_{\rm m} < \nu_{\rm O} < \nu_{\rm c}$, where: $\nu_{\rm O}$ is the frequency of our optical bands, $\nu_{\rm c}$ is the cooling frequency, $\nu_{\rm m}$ is the peak synchrotron frequency (Lazzati et al. 2002; Sari et al. 1998).

For a uniform ISM, from our measure of $\alpha = 1.2 \pm 0.1$ we derive $p = 2.6 \pm 0.1$ ($\alpha = 3(p-1)/4$). Knowing p, we have information about the energy spectrum, $F \propto \nu^{-\beta}$ ($\nu_{\rm m} < \nu < \nu_{\rm c}$): $\beta = (p-1)/2$, i.e. $\beta = 0.8 \pm 0.05$, consistent with our result (Fig. 2). Since it is $\nu_{\rm O} < \nu_{\rm c} < \nu_{\rm X}$, the power–law index of

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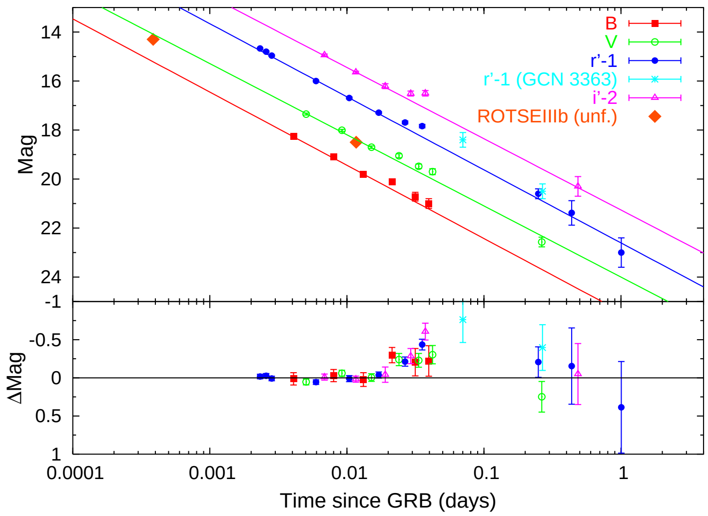

Fig. 1 *Top Panel*: Multi–colour light curve of GRB 050502a measured with the Liverpool and Faulkes North Telescopes. Also shown are the best-fit power laws: all of them are consistent with a power–law index of 1.2 ± 0.1 (see text). Two ROTSE–IIIb unfiltered points (Yost et al. 2006) and two r' points derived from Mirabal et al. (2005) are plotted as well. *Bottom Panel*: residuals with respect to the best-fitting power laws. From Guidorzi et al. (2005).

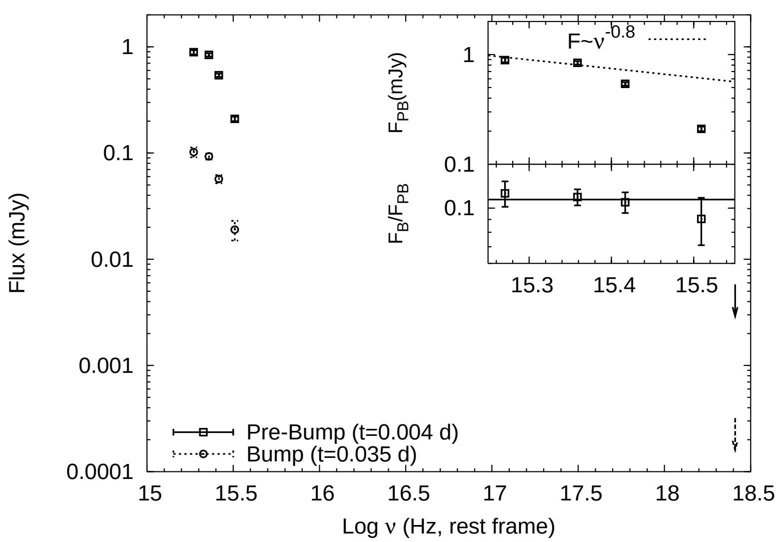

Fig. 2 Rest–frame SED at two epochs: $t = 0.004$ d (Pre-Bump) and $t = 0.035$ d (Bump). Optical points have been interpolated at the same epochs. The X-ray upper limit at $t = 0.004$ d (solid arrow) has been obtained by back-extrapolating the values provided by Hurkett et al. (2005), around ∼1.3 d, assuming 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 ν is due to the Lyman-α forest (see text). *Inset, bottom panel*: the flux ratio between the two epochs as a function of ν is consistent with a constant (weighted average of 0.108 ± 0.005, $\chi^2/dof = 1.2$) shown by the solid line. From Guidorzi et al. (2005).

the spectrum between $\nu_{\rm c}$ and $\nu_{\rm X}$, is expected to be $\beta_{\rm cX} = p/2 = 1.3 \pm 0.05$. The X-ray power–law decay index is expected to be $\alpha_{\rm X} = (3p-2)/4$ ($\nu_{\rm c} < \nu_{\rm X}$). Thus we back-extrapolate the X-ray upper limit to $t = 0.004$ d assuming $\alpha_{\rm X} = (3p-2)/4 = 1.45$ (solid arrow in Fig. 2). It follows that the power–law index between optical and X-rays must be $\beta_{\rm OX} > 0.7$, consistent with a broken power law with power–law indices from 0.8 to 1.3.

In the case of wind environment, for $\nu_{\rm m} < \nu < \nu_{\rm c}$ we obtain $p = 1.6 \pm 0.8$ from the relation $\alpha = (p+8)/8$ by Dai & Cheng (2001) valid for $p < 2$. From $\beta_{\rm mc} = (p-1)/2$ ($\nu_{\rm m} < \nu < \nu_{\rm c}$) and $\beta_{\rm cX} = p/2$ ($\nu_{\rm c} < \nu < \nu_{\rm X}$) we derive: $\beta_{\rm mc} = 0.3 \pm 0.4$ and $\beta_{\rm cX} = 0.8 \pm 0.4$. The back-extrapolation of the X-ray upper limit to $t = 0.004$ d assuming $\alpha_{\rm X} = (p+6)/8 = 0.95$ ($\nu_{\rm c} < \nu_{\rm X}$) translates into the following constraint: $\beta_{\rm OX} > 1.1$ (dashed arrow in Fig. 2), marginally in contradiction with both values of $\beta_{\rm mc} = 0.3 \pm 0.4$ and $\beta_{\rm cX} = 0.8 \pm 0.4$.

Notably, we do not find any evidence for a change in the slope of the light curve decay within the very first minutes of the GRB found in the cases of GRB 990123 and GRB 021211, interpreted as the transition between reverse and forward shocks. In the case of GRB 050502a the bump sets in at ∼6 min 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 thought to have taken place. It is sensible to infer that if a similar transition had occurred, we should have detected it before the bump. The lack of evidence for a reverse shock is also supported by the early ROTSE observations begun 44 s after the initial gamma-rays (Yost et al. 2006).

We cannot rule out the interpretation of the bump as the result of a refreshed shock catching up with the afterglow front shock, although it appears to be more problematic. According to the original refreshed-shocks scenario (Kumar & Piran 2000; Granot et al. 2003), the duration Δt of the bump is expected to be comparable with its start time: $\Delta t \approx t$. This is not the case of GRB 050502a, as it is $\Delta t \approx 0.2$ d and $t \sim 0.02$ d.

Finally, we note that Yost et al. (2006) interpreted the bump as the beginning of a steepening due to the crossing of $\nu_{\rm c}$ through the optical bands, with $\Delta\alpha$ consistent with 0.25. Although the post-bump steepening is proved by the late well-sampled MDM R-band observations from 97 to 470 min, the uncertainties affecting the ROTSE unfiltered measurements covering the bump make the bump less evident. Our R-band measurements indicate significant enhancements in all of the four optical filters and this cannot accounted for by the passage of the cooling frequency alone.

In conclusion, from the ROTSE and MDM observations reported by Yost et al. (2006), it is likely that the cooling frequency crossed the optical band soon after the bump explaining the late steepening. However, the bump has probably been produced by another mechanism, which we identify as density enhancements in a ISM, although a different environment, such as wind, or a different mechanism such as an energy injection episode cannot be completely ruled out.

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