THE FAINT AFTERGLOW AND HOST GALAXY OF THE SHORT-HARD GRB 060121

A.J. Levan1,2, N. R. Tanvir3, A.S. Fruchter4, E. Rol5, J.P.U. Fynbo6, J. Hjorth5, G. Williams6, E. Bergeron4, D. Bersier5, M. Bremer5, T. Grav6, P. Jakobsson5, K. Nilsson10, E. Olszewski5, R.S. Priddey3, D. Rafferty7, J. Rihotsky2

ABSTRACT

We present optical and X-ray observations of the afterglow and host galaxy of the short-hard GRB 060121. The faint R-band afterglow is seen to decline as $t^{-0.66\pm0.09}$ while the X-ray falls as $t^{-1.18\pm0.04}$, indicating the presence of the cooling break between the two frequencies. However, the R-band afterglow is very faint compared to the predicted extrapolation of the X-ray afterglow to the optical regime (specifically, $\beta_{OX} \sim 0.2$), while the K-band is consistent with this extrapolation ($\beta_{KX} \sim 0.6$), demonstrating suppression of the optical flux. Late time HST observations place stringent limits on the afterglow R-band flux implying a break in the R-band lightcurve. They also show that the burst occurred at the edge of a faint red galaxy which most likely lies at a significantly higher redshift than the previous optically identified short-duration bursts. Several neighboring galaxies also have very red colors that are similarly suggestive of higher redshift. We consider possible explanations for the faintness and color of the burst. Our preferred model is that the burst occurred at moderately high redshift and was significantly obscured; however, it is also possible that the burst lies at $z > 4.5$ in which case the faintness of the R-band afterglow could be attributed to the Lyman-break. We discuss the implications that either scenario would have for the nature of the progenitors of short bursts.

Subject headings: gamma-rays: bursts

1. INTRODUCTION

The nature of the distinct subset of $\gamma$-ray bursts (GRBs) with short-durations of $<2$ s has seen rapid progress over the past year, following the discovery of the first X-ray afterglow to GRB 050509B (Gehrels et al. 2005; Bloom et al. 2006). A number of other afterglows have been discovered subsequently at X-ray, optical and radio wavelengths (e.g. Hjorth et al. 2005a; Fox et al. 2005; Berger et al. 2005; Soderberg et al. 2006). These observations show that typically short bursts have fainter afterglows than those of long duration bursts, lie at lower redshift (usually, it seems, $z < 1$), and are associated with galaxies of all types, including those with no sign of ongoing star formation (Gehrels et al. 2005; Berger et al. 2005). The latter fact indicates a significant delay between the formation of the progenitor stars, and the creation of the GRB. Indeed, in no case has any sign of supernova emission been seen (e.g. Hjorth et al. 2005b). These characteristics contrast markedly with those of long bursts which originate in star forming host galaxies (e.g. Fruchter et al. 1999; Christensen et al. 2004) at higher redshift (Jakobsson et al. 2006) and are now known to be associated with the core-collapse of massive stars (e.g. Hjorth et al. 2003). The preferred model for the short-duration bursts has thus become that the majority of them come from either neutron star - neutron star (NS-NS) or neutron star - black hole (NS-BH) mergers (e.g. Eichler et al. 1992; Davies, Levan & King 2005; Lee, Ramirez-Ruiz & Granot 2005), although other mechanisms which produce GRBs in populations of all ages (e.g. Usov 1992; Dermer & Atrey 2006; Levan et al. 2006a) remain possible given the paucity of observational constraints so far.

Here we present optical and X-ray observations of GRB 060121. This short-hard burst was discovered by the High Energy Transient Explorer (HETE-2) and is only the fourth to have a well-studied optical afterglow. The afterglow of GRB 060121 is approximately a magnitude fainter than the other examples at similar times. In previous cases a bright host galaxy was readily identified under the optical transient; however in the case of GRB 060121 this is not the case. In fact, deep Hubble Space Telescope (HST) observations, reported below, were necessary to locate a faint, red galaxy at the location of the optical afterglow.

2. OBSERVATIONS

GRB 060121 was detected by HETE-2 on 2006 January 21, 22:24:54.5 UT and was localised by the Soft X-ray camera (SXC) (Prigozhin et al. 2006). It was
identified as a short, $t_{90} < 2$ s, and spectrally hard burst with a peak in its $\nu f_\nu$ spectrum at $120 \pm 7$ keV (Boer et al. 2006). Swift performed target of opportunity observations of GRB 060121, beginning at 2006 January 22 01:21:37 UT. Observations with the X-ray telescope (XRT) revealed a relatively bright X-ray afterglow (Mangano et al. 2006).

2.1. The Optical Afterglow

Our first observations of GRB 060121 were taken with the Nordic Optical Telescope (NOT) using ALFOSC, starting at 2 hours post-burst. Subsequent observations were obtained with the 90prime imager (Williams et al. 2004) on the Steward Observatory 2.3-m Bok Telescope and at the Wisconsin Indiana Yale NOAO telescope (WIYN). All of these observations were reduced in the standard fashion within IRAF. A log of the observations is shown in Table 1.

| Date       | UT        | $\Delta t$ (hours) | Telescope | Band   | Magnitude |
|------------|-----------|--------------------|-----------|--------|-----------|
| 2006-01-22 | 00:23:53  | 1.98               | NOT       | R      | 22.65 ± 0.21 |
| 2006-01-22 | 01:00:21  | 2.59               | NOT       | I      | 21.96 ± 0.30 |
| 2006-01-22 | 04:02:45  | 5.63               | Bok 2.3m  | R      | 23.79 ± 0.19 |
| 2006-01-22 | 04:52:06  | 6.48               | Bok 2.3m  | B      | > 24.0 |
| 2006-01-22 | 05:40:29  | 7.25               | Bok 2.3m  | R      | 23.72 ± 0.15 |
| 2006-01-22 | 09:41:39  | 11.27              | Bok 2.3m  | R      | 23.44 ± 0.25 |
| 2006-01-22 | 11:32:15  | 13.12              | WIYN      | R      | 23.75 ± 0.20 |
| 2006-01-23 | 07:58:22  | 33.56              | WIYN      | R      | 24.91 ± 0.16 |

**Note.** — Photometry of the afterglow of GRB 060121 obtained at the NOT, the Bok 2.3m, and the WIYN. Magnitudes are not corrected for the small Galactic extinction ($A_R = 0.044$).

Fig. 1.— R-band (top) and X-ray (0.2-10 keV - bottom) lightcurves of GRB 060121, fitted with single power-law decay indices as shown and discussed sections 2.1 & 2.2.

2.2. The X-ray afterglow

Swift XRT data were reduced using the FTOOL xrtpipeline. The light curve and spectrum were extracted using xselect, where data from the first 3 orbits have been filtered on grade 0 to counter any pile-up. Later orbits use the default filtering. A circular extraction region of radius of 71'' was employed for the first 3 orbits where the source was relatively bright, while a 47'' radius circle was used for later orbits. The background was estimated using extraction regions around the source, and has been dynamically subtracted for the light curve and spectrum. For both the light curve and the spectrum, 20 counts were grouped together per bin.

The X-ray light curve (Figure 1 - lower panel) has been modelled with a single power law, resulting in a fit with $\chi^2$/DOF = 28.92/27 and a power law decay index of $\alpha = -1.18 \pm 0.04$. The data is consistent with a monotonic evolution out to ~10 days since the burst, ruling out any jet break occurring before this time. Unfortunately no X-ray data exists for the period covering the possible optical flare. Thus we cannot rule out a flare in the X-ray data, in which the underlying decay was unaffected. However, since the X-ray light curve continues as a single power law, energy injection, as seen in GRB 051221 (Soderberg et al. 2006) can be ruled out.

The data used for the spectrum were obtained from the first 3 orbits where the X-ray afterglow was bright. The spectrum can be fit with an absorbed power law, with $\chi^2$/DOF = 8.11/14. The resulting photon index is $\Gamma = 2.33_{-0.26}^{+0.46}$ and the absorbing column density $N_H = 1.31_{-0.24}^{+0.46} \times 10^{21}$ cm$^{-2}$. The estimated Galactic absorption in this direction is $1.7 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990). Some interdependence is seen between $N_H$ and $\Gamma$, however this is insufficient to explain the observed excess $N_H$. We therefore conclude that GRB 060121 exhibits significant X-ray absorption above the Galactic value. This absorption estimate assumes zero
redshift. At higher redshift the rest-frame absorption may be substantially larger.

2.3. HST observations

GRB 060121 was observed with HST on February 27th 2006. Observations were obtained with both NICMOS/F160W and ACS/WFC/F606W. A total of 4608 s of observations were obtained using NICMOS and 4400 s using ACS. Astrometry was performed between the ground based observations of GRB 060121 and the ACS observations, and subsequently the NICMOS observations. Using 10 point sources in common to each image we were able to obtain a registration of the afterglow position on the ACS images accurate to 0.1'' (1σ).

Inspection of this location reveals a faint galaxy in the F606W image (F606W(AB) = 27.0 ± 0.3) and a somewhat brighter galaxy in the F160W observations (F160W(AB) = 24.5 ± 0.2). Interestingly the centroid of the galaxy in the F160W observations is offset ∼ 0.3'' west of the centroid in the F606W observations. This indicates either a color gradient within the host, or some continuing contribution from the afterglow. Further F160W observations will be necessary to distinguish between these possibilities. Furthermore there are five extremely red objects (EROs) in the field which are exceptionally faint (and low surface brightness) or undetected with ACS, but relatively bright in F160W. Some of these are exceptionally red (F606WF606W(AB) − F160W(AB) > 4), and would fall amongst the reddest galaxies observed in GOODS with R − Ks > 4.35 (AB), a population which comprises only ∼ 20% of the total number of EROs (Moustakas et al. 2004). Galaxies as red as this have an areal density on the sky of 0.41 ± 0.05 arcmin$^{-2}$ (Gilbank et al. 2004) and thus in our observed field of only 0.5 arcmin$^2$ they are overdense by a factor of 20, although it should be noted that EROs tend to be highly clustered. These objects may either represent a highly reddened population at moderate redshift (∼ 2) or could lie at very high redshift (z ∼ 5), although in the latter case they would be significantly brighter than typical Lyman break galaxies at comparable redshift (e.g. Lehnert & Bremer 2003).

The afterglow of GRB 060121 exhibits a bright X-ray afterglow, but is very faint in the optical (R ∼ 23 only 2 hours after the burst). The optical afterglow is somewhat fainter than previously reported optical afterglows of short duration bursts (e.g. Hjorth et al. 2005a; Soderberg et al. 2006). In fact, the observed optical to X-ray spectral slope is flatter than expected for the fireball model ($\beta_{OX}$ = 0.2), rendering GRB 060121 a dark burst as defined by Jakobsson et al. (2004). Indeed the direct extrapolation of the X-ray flux into the optical window using the technique of Rol et al. (2005) also places the R-band magnitude significantly fainter than its expected level. However the value of $\beta_{KX}$ = 0.6 is broadly consistent with the extrapolation of the X-rays to the K-band assuming that the cooling break lies between the two frequencies. Indeed the X-ray and optical lightcurves, shown in Figure 1 demonstrate a slower decay in the optical than the X-ray and are also consistent with the presence of the cooling break between the two frequencies. These parameters (with exception of the $\beta_{OX}$ which is discussed below) are consistent with those that would be expected from a $p = 2.2$ afterglow model.

The extrapolation of the optical lightcurve to late times is above the limit obtained via the HST observations and indicates that a temporal break has occurred. There is no break in the X-ray lightcurve out to 10 days post-burst, however optical monitoring ceased after 1.5 days. If the break in the R-band is due to the jet-break then it would have occurred > 10 days after the burst and the required slope would be $\alpha > 1.7$. For generic ambient medium parameters at $z = 3$ (see below) this would correspond to a beaming angle of > 7 degrees. However, if this break were the cooling break then it could have occurred in the R-band and been unobserved in the X-ray. If it occurred at the time of the final R-band observations then the late time slope is only constrained to be $\alpha > 1.1$, consistent with the X-ray slope, and thus with the motion of the cooling break. However, the value of $\beta_{KX}$ ∼ 0.6 indicates that the cooling break lies close to the X-ray band at ∼ 30 hours, and thus it is unlikely to reach the R-band until very late times.

A natural explanation of the SED is that the R-band afterglow is extinguished due to the presence of dust in the host galaxy. This would be supported by the red R − K color and the high column density measured directly from the X-ray spectrum. The X-ray and (to a lesser extent) K-band observations are largely unaffected by the presence of dust, while the R-band (or rest frame B or UV depending on $z$) exhibits the strongest signature of extinction. The location of GRB 060121 on a possibly edge-on galaxy, in which significant dust extinction could occur through the disk lends some support to this theory. Although the GRB does not lie near the centroid of the galaxy it does apparently lie along the major-axis of the galaxy, consistent with an origin in the disk.

The currently most popular model for (most) short-GRBs is that they originate from compact binary (NS-NS or NS-BH) mergers. At formation a neutron star receives a significant natal kick (e.g Arzoumanian et al. 2002); thus, NS-NS binaries are expected to be kicked from their birthplace at significant velocities (several hundred km s$^{-1}$). Their merger time is governed by the gravitational radiation timescale and can span a wide range of times from $10^6$ − $10^{10}$ years (e.g. Burgay et al. 2003).
However, even at the shorter end of this range the NS-NS binary would have travelled > 100 pc from its birth site, and out of the region of star formation in which it formed. Indeed, with a large kick and long inspiral time, the host galaxy might then be one of the many other galaxies in the field. It is unlikely that the faint R-band magnitude of the burst was caused by its being in the IGM – both the K-band and X-ray were reasonably bright.

An alternative explanation for the faint R-band afterglow is that the burst lies at significantly higher redshift (z ∼ 5). In this case the low value of β_{OX} would be explained by the Lyman-α break lying within the R-band, while the K-band would be unaffected and would lie on the extrapolation of the X-ray afterglow (as is observed). However, in this case we might expect to observe a stronger break between the R and I-bands which. For example GRB 000131 at z = 4.5 had R-I = 1.2 (Andersen et al. 2000) and GRB 050814 at z = 5.3 had R-I ∼ 2.5 (Jakobsson et al. 2006) while the measured colour of GRB 060121 (extrapolating I to the same epoch as our first R-band observation) is R-I = 0.90 ±0.36. This value has a large error due to the low signal to noise in our images and in fact is consistent with the colour of GRB 000131 (although also with a typical ν^−1 spectrum). A higher redshift, comparable to that of GRB 050814 is apparently ruled out, although z ∼ 4.5 certainly remains plausible.

Further observations of the host galaxy, especially in the I-band will be helpful in distinguishing between a strong break due to Lyman-α and gradual reddening.

Finally it is also important to consider whether GRB 060121 could in fact be due to a collapsar. Although its spectrum is moderately hard the duration of ∼ 2 s puts it within a region of the BATSE hardness-duration plot that contains an admixture of long, short, and possibly intermediate duration bursts (Horvath et al. 2005). Indeed, some classical long duration bursts have rest frame durations of <2 s (e.g. GRB 000301C Jensen et al. 2000; GRB/XRF 050416 Sakamoto et al. 2006; GRB 060206 Fynbo et al. 2006). However, if at z ∼ 3, then the rest-frame duration of GRB 060121 becomes < 0.7 s, while at lower redshift its host is significantly redder than the typical colors of long burst hosts (Christensen et al. 2004). Making a collapsar origin less plausible in this case.

4. CONCLUSIONS

We have presented deep optical and X-ray observations of the short-hard GRB 060121. These observations demonstrate that both the afterglow and host galaxy of GRB 060121 are significantly fainter and redder than previously optically-detected short bursts.

We believe the most likely explanation of its properties is that GRB 060121 lies at higher redshift than previously observed short bursts, z > 2, and probably is furthermore extinguished. If this is a compact binary merger then significant dust extinction is surprising since it would be expected that the binaries should receive significant natal kicks. Thus in this case either the binary received very little kick, or (by chance) its line of sight passed through an intervening galaxy.

Interestingly, GRB 060121 lies rather closer, in the hardness-duration sense, to the typical short-burst as seen by BATSE than the other well-localised short bursts studied to date. GRBs 050709 and 050724, in particular, were all very much at the spectrally soft end of that distribution (Hjorth et al. 2005a). This raises the question as to whether a significant proportion of the bursts classified by BATSE as short could in fact be a much higher redshift population than those seen recently by Swift and HETE-2. If so, then the width of the luminosity function of short bursts would be much wider than has previously been considered (e.g. Piran & Guetta 2005), with consequent implications for progenitor models.

ACKNOWLEDGEMENTS

We thank Jochen Heidt and Caroline Villforth for assistance with our NOT observations. A.J.L, NRT & ER are supported by PPARC. The Dark Cosmology Centre is funded by the Danish National Research Foundation. Based in part on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with program 10870. This research was supported in part by the National Science Foundation under Grant No. PHY99-07949.

REFERENCES

Andersen, M. I., et al. 2000, A&A, 364, L54
Arzoumanian, Z., Chernoff, D. F., & Cordes, J. M. 2002, ApJ, 568, 289
Berger, E., et al. 2005, Nature, 438, 988
Bloom, J. S., et al. 2006, ApJ, 638, 354
Boer, M., et al. 2006, GCN 4502
Burgay, M., et al. 2003, Nature, 426, 531
Christensen, L., Hjorth, J., & Gorosabel, J. 2004, A&A, 425, 913
Davies, M. B., Levan, A. J., & King, A. R. 2005, MNRAS, 356, 54
Dermer, C. D., & Atoyan, A. 2006, ApJ, submitted, astro-ph/0601142
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Eichler, D., Livio, M., Piran, T., & Schramm, D. N. 1989, Nature, 340, 126
Fox, D. B., et al. 2005, Nature, 437, 847
Fruchter, A. S., et al. 1999, ApJ, 519, L13
Fynbo, J. P. U., et al. 2006, A&A, submitted, astro-ph/0602444
Gilbank, D. G., Smail, I., Ivison, R. J., & Paczynski, C. 2003, MNRAS, 346, 1125
Hearty, F., et al. 2006, GCN 4604
Hjorth, J., et al. 2005a, Nature, 437, 859
Hjorth, J., et al. 2005b, ApJL, 630, L117
Hjorth, J., et al. 2003, Nature, 423, 847
Horváth, I., Balázs, L. G., Bagoly, Z., Ryde, F., & Mészáros, A. 2006, A&A, 447, 23
Jakobsson, P., Hjorth, J., Fynbo, J. P. U., Watson, D., Pedersen, K., Björnsson, G., & Gorosabel, J. 2004, ApJ, 617, L21
Jakobsson, P., et al. 2006, A&A, 447, 897
Jensen, B. L., et al. 2001, A&A, 370, 909
Jester, S., et al. 2005, AJ, 130, 873
Lee, W. H., Ramirez-Ruiz, E., & Granot, J. 2005, ApJ, 630, L165
Lehnert, M. D., & Bremer, M. 2003, ApJ, 593, 639
Levan, A. J., Tanvir, N. R., Fynbo, J., Hjorth, J., Fruchter, A., Grav, T., & Nilsson, K. 2006b, GR Coordinates Network, 4562
Levan, A. J., Wynn, G. A., Chapman, R., Davies, M. B., King, A. R., Priddey, R. S., & Tanvir, N. R. 2006a, MNRAS, in press, astro-ph/0601332
Malesani, D., Antonelli, L. A., Covino, S., Palazzi, E., Andreuzzi, G., & Tessini, G. 2006, GCN 4561
Mangano, V., La Parola, V., Mineo, T., Tagliaferri, G., Romano, P., O’Brien, P., & Burrows, D. N. 2006, GCN 4560
Moustakas, L. A., et al. 2004, ApJ, 609, L131
Piran, T., & Guetta, D. 2006, astro-ph/0602208.
Prigozhin, G., et al. 2006, GCN 4551
Rol, E., Wijers, R. A. M. J., Kouveliotou, C., Kaper, L., & Kaneko, Y. 2005, ApJ, 624, 868
Sakamoto, T., et al. 2006, ApJ, 636, L73
Soderberg, A. M., et al. 2006, ApJ, submitted, astro-ph/0601455

Usov, V. V. 1992, Nature, 357, 472
Williams, G. G., Olszewski, E., Lesser, M. P., & Burge, J. H. 2004, Proc. SPIE, 5492, 787