The extreme, red afterglow of GRB 060923A: Distance or dust?

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ABSTRACT

Gamma-ray bursts are powerful probes of the early universe, but locating and identifying very distant GRBs remains challenging. We report here the discovery of the K-band afterglow of *Swift* GRB 060923A, imaged within the first hour post-burst, and the faintest so far found. It was not detected in any bluer bands to deep limits, making it a candidate very high redshift burst ($z \gtrsim 11$). However, our later-time optical imaging and spectroscopy reveal a faint galaxy coincident with the GRB position which, if it is the host, implies a more moderate redshift (most likely $z \lesssim 2.8$) and therefore that dust is the likely cause of the very red afterglow colour. This being the case, it is one of the few instances so far found of a GRB afterglow with high dust extinction.

Key words: gamma-rays: bursts; galaxies: high-redshift

1 INTRODUCTION

The immense luminosity of gamma-ray bursts (GRBs) means that in principle they could be observed to very high redshift (Lamb & Reichart 2000, e.g.). They are associated with massive stars (e.g. Hjorth et al. 2003), and there is accumulating evidence, albeit indirect, that they are preferentially (although not exclusively) found in lower-metallicity environments (e.g. Fynbo et al. 2003; Le Floc'h et al. 2003; Tanvir et al. 2004; Fruchter et al. 2006; Stanek et al. 2006). It therefore seems likely that GRBs will be produced even by the earliest generations of population II stars in the universe, and possibly by population III. This opens up the possibility that they could pinpoint the first luminous objects to form after the Big Bang (e.g. Bromm & Loeb 2006). Vari-

ous authors have attempted to model early star formation and infer a likely GRB rate as a function of cosmic time. Although there are many uncertainties in these models (which get larger as one attempts to push them earlier), they do predict that as many as ∼5–10% of *Swift* GRBs could be at $z > 5$ (e.g. Natarajan et al. 2005; Yoon, Langer, & Norman 2006; Bromm & Loeb 2006), in broad agreement with observational findings to date (Jakobsson et al. 2006a; Tanvir & Jakobsson 2007), and help make the case that occasional GRBs could be found at much higher redshifts.

Candidate high redshift bursts have normally been identified photometrically by a sharp break in the optical to near-infrared (nIR) spectral energy distribution (SED) of their afterglow light. The presence of a strong break in the afterglow spectrum is indicative of high opacity due to Lyα absorption from neutral hydrogen clouds in the early universe. Indeed this technique has already facilitated the iden-

tification of the high redshift afterglows of GRB 050814 (Jakobsson et al. 2006a) and GRB 050904 (Haislip et al. 2006), the latter of which was confirmed to be at $z = 6.3$ by a deep optical spectrum (Kawai et al. 2006). Recently, GRB 060927 was found at $z \approx 5.5$, and again its very red $R-I$ colour provided the first indication of extreme distance (Ruiz-Velasco et al. 2007).

However, the situation can at times be more complicated. Although GRB afterglows generally produce clean power-law spectra, they are subject to reddening from interstellar dust, the imprint of which can mimic the Lyα break. This is especially problematic if the SED is poorly sampled, as is often the case due to the difficulty of obtaining deep simultaneous multi-band optical and nIR photometry for many bursts, even when well placed for observation. Hence, there may be some degeneracy between a burst that lies at high redshift, and one that is highly reddened by intervening dust. A large proportion of star-formation in the high-redshift universe is thought to be heavily dust obscured (e.g. Chapman et al. 2005; Reddy et al. 2007), leading to the expectation that many GRBs, having short-lived progenitors, should occur in such regions. Rather surprisingly, in practice, examples of even moderately high extinction are rather rare (Klose et al. 2000; Levan et al. 2006a). This is a reflection of the fact that GRB hosts on the average seem to be less dusty than other populations of high-z star-forming galaxies (Le Floc'h et al. 2003; Tanvir et al. 2004; Le Floc'h et al. 2006), and probably also because GRBs destroy dust for considerable distances along our line-of-sight to them (e.g. Waxman & Draine 2000; Fruchter, Krolik, & Rhoads 2001; Savaglio, Fall, & Fiore 2003). The observational bias against discovering faint, dust reddened bursts is doubtless also a contributing factor at some level. Indeed, Fiore et al. (2007) have argued that the higher average excess hydrogen column (N_H) (and hence presumably obscuration) inferred in bright *Swift* bursts compared to BeppoSAX and HETE2, may be responsible for a dearth of $z < 2$ in the *Swift* sample with measured redshifts (see also Schady et al. 2007).

In any event, the potential of GRBs as high redshift probes has encouraged increasing efforts to obtain early nIR followup of afterglows. Many GRBs have had no optical afterglow found, but only in a few cases were searches deep and early enough to make them interesting. Here we present deep optical and nIR observations of the afterglow of GRB 060923A. The nIR observations uncovered a very faint K-band afterglow only an hour after the burst, which was not visible in subsequent J and H band imaging. Deep Gemini observations show that the afterglow was also very faint in the optical. We discuss possible explanations of this extreme colour in context of both a high redshift and high extinction origin for the burst.

2 OBSERVATIONS

2.1 *Swift* observations

GRB 060923A was discovered by *Swift* at 05:12:15 UT on 23rd September 2006 (Stamatikos et al. 2006). The burst was of the long-duration class with $T_{90} = 51 \pm 1$ s, and a photon index $\Gamma = 1.69 \pm 0.23$. The total fluence of the burst was $(8.7 \pm 1.3) \times 10^{-7}$ ergs cm^{-2} in the 15–150 keV band,
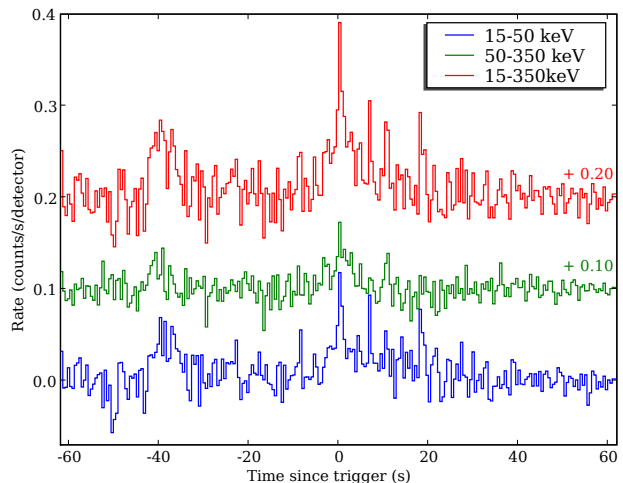

Figure 1. *Swift*/BAT light curve of the prompt emission, sampled at 0.5 s binning. The lower trace shows softer photon energies (15–50 keV), the middle trace harder (50–350 keV; displaced vertically by 0.1 counts s^{-1} detector^{-1} for clarity), and the top trace the sum (displaced by 0.2 counts s^{-1} detector^{-1}).

and peak photon flux in a 1 s bin was 1.3 ± 0.3 cm^{-2} s^{-1} (Tueller et al. 2006). The prompt gamma-ray light curve is shown in Fig. 1.

Observations with the *Swift* X-Ray Telescope (XRT) began after 81 seconds and revealed an X-ray afterglow at a location of $\alpha =$16:58:28.2, $\delta =$+12:21:40.0 (J2000) with uncertainty 6 arcsec (Conciatore et al. 2006). The X-ray afterglow initially declined rapidly with $\alpha = 2.7 \pm 0.3$ (following the convention for flux density, $F_\nu \propto t^{-\alpha} \nu^{-\beta}$; and 90% errors) and then entered a plateau phase for approximately 1 hour, finally settling into a shallower ($\alpha = 1.23 \pm 0.1$) decay. Fitting an absorbed power-law spectrum to the orbit 2 (1.2 to 1.9 hours post burst) and orbit 3 (2.8 to 3.4 hours) data we infer a spectral slope $\beta = 1.1 \pm 0.2$ (90% errors) and an effective column density of neutral hydrogen of $N_H = 14.5^{+3.9}_{-3.5} \times 10^{20}$ cm^{-2} (1σ errors and Milky Way abundance assumed), compared to a foreground estimated as $N_{H,Gal} = 4.52 \times 10^{20}$ cm^{-2} (Kalberla et al. 2005). No counterpart was seen with the UV-Optical Telescope (UVOT) to an unfiltered magnitude limit of about 18.5.

2.2 Optical and IR observations

Our first optical observations were obtained with the 2 m robotic Faulkes Telescope North (FTN) on Haleakala, starting 135 s post-burst and did not detect any counterpart to $R = 19.9$, in a 30 s exposure. Similarly, the SuperLOTIS group reported a limit of $R = 18.4$ in a 5×10 s exposure beginning at 41 s post-burst (Williams & Milne 2006). Longer FTN observations over the next hour found deeper limits of around $R = 22.2$.

We obtained our first K-band image at the 3.9 m United Kingdom Infrared Telescope (UKIRT) on Mauna Kea at 06:07 UT, approximately 55 minutes after the burst, which was followed with a set of multicolour (JHK) observations that began at 06:35 UT. These observations were

reduced via the ORAC-DR pipeline (see Cavanagh et al. 2003). Photometric calibration (also for the other nIR observations reported below) was performed relative to three 2MASS stars in the field. In these images we found a fading source in the K-band close to the X-ray centroid at position α =16:58:28.16, δ =+12:21:38.9 (J2000; astrometric calibration tied to NOMAD 1.0 stars and accurate to 0.25 arcsec in each coordinate), which was not visible in either the J or H band observations. At $K \approx 19.7$ within an hour of the burst, this is considerably fainter than previous afterglow detections in nIR estimated at the same epoch. For example, the faint, red afterglow of GRB 050215B was also only seen in K, but would have been $K \sim 19$ at 1 hour based on extrapolating back the later time decay curve (Levan et al. 2006b).

More optical observations were made at Gemini North on Mauna Kea beginning at 07:19 UT (2.1 hours post burst) in the Sloan r' and i' filters. The images were reduced using standard IRAF routines, and calibrated relative to a sequence of SDSS stars in the field (Adelman-McCarthy et al. 2006). Formally these data yielded no significant detection to deep limits, although there was marginal evidence of excess flux in the r' band. For such a faint afterglow, nIR spectroscopy was not a feasible option, and further information could only be gained from imaging. We therefore obtained additional observations of the burst position at the Very Large Telescope (VLT) on Cerro Paranal, in the optical using the FORS1 and FORS2 instruments and in the near-IR using ISAAC, over the following two nights. (The location of the burst was such that it was only observable above 30° altitude for about 90 minutes after the end of evening twilight for the northern observatories, and less in the south). The optical observations were again reduced via standard procedures using IRAF tools (in this case the SDSS sequence magnitudes were transformed to Cousins passbands via the equations of Lupton (2005)[1], to provide a better match to the filters used), while ISAAC observations were processed with *eclipse*[2]. These images provided a clearer detection of a faint, extended galaxy coincident with the afterglow position, the implications of which we discuss below. Finally we obtained, in better conditions, very late-time (>6 months post-burst) FORS2 R-band and ISAAC K-band images, and a 40 minute FORS1 optical spectrum, as part of the *Swift*/VLT Large Programme on GRB hosts (PI: J. Hjorth). The former of these confirmed the host detection at $R \approx 25.6$, but also showed the burst to have occurred on the optically brightest region of the galaxy. A very faint continuum trace was seen in the optical spectrum extending at least as blue as 4600 Å, but there were no indications of any significant emission lines. The two (early- and late-time) ISAAC K-band images each showed marginal (2σ) evidence of excess flux in an aperture centred on the afterglow location, and combining the two measures yields an estimated host magnitude of $K = 21.7 \pm 0.3$.

The discovery K-band image, and final VLT optical image showing the faint host, are shown in Fig. 2. A log of observations and photometry obtained by us at the afterglow position is shown in Table 1. These data-points and upper
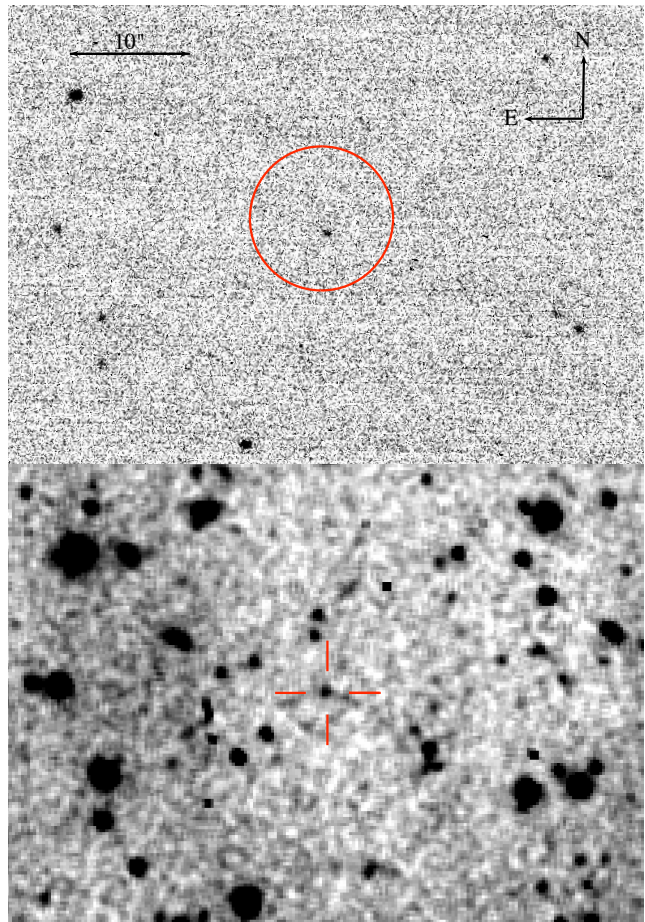
Figure 2. Upper: UKIRT/UFTI discovery image of the afterglow of GRB 060923A in the K-band within the (plotted) XRT error circle; Lower: final VLT/FORS2 R-band image (lightly smoothed), obtained 6 months post-burst, showing the faint, extended host galaxy at the same location. The crosshairs indicate exact position of afterglow, showing it to be coincident with the brightest region of the host.

limits in optical, infrared and X-ray are shown in Fig. 3, together with data for a number of other bursts, illustrating the range of typical afterglow luminosities.

In addition, the GRB location was also observed by Fox, Rau, & Ofek (2006) at Gemini North and Keck-I who found the afterglow to have a brightness of $K = 20.6$ at $\sim$ 2 hours after the burst. The implied power-law decay slope to this point from our first UKIRT observations is $\alpha \approx 1.3$, consistent with the decay observed in the X-ray. They also obtained a deep J-band limit of $J > 23.7$ at 90 minutes post burst, confirming that the afterglow was red even in nIR colours.

These limits certainly make GRB 060923A one of the optically darkest afterglows observed to date. Other bursts with famously deep non-detections include GRB 970828, which was undetected to $R = 23.8$ at 3.4 hours (Groot et al. 1998), and GRB 050412, with a limit estimated at $R = 24.9$ at 2.3 hours (Kosugi et al. 2005). In terms of the X-ray to optical spectral slope, $\beta_{RX} < 0.1$, it is also one of the most extreme bursts detected to date, requiring a significant spec-

Table 1. Log of our ground-based observations of GRB 060923A, and measured photometry.

Telescope/instrument	Δt (hours)	Filter/grism	Magnitude	Measured flux (μJy)
Faulkes-N/Hawkcam	0.037–0.050	R	R_c >19.9	4 ± 14
Faulkes-N/Hawkcam	0.037–0.20	R	R_c >21.0	2 ± 5
Faulkes-N/Hawkcam	0.037–0.99	R	R_c >22.2	0.5 ± 1.6
UKIRT/UFTI	0.92–1.25	K	$K = 19.7 \pm 0.1$	8.2 ± 0.8
UKIRT/UFTI	1.39–1.44	J	J >23.6	-1.6 ± 1.1
UKIRT/UFTI	1.46–1.50	H	H >20.6	2.1 ± 1.7
UKIRT/UFTI	1.50–1.55	K	K >20.1	1.6 ± 2.2
Gemini-N/GMOS	2.13	r′	r' >24.7	0.25 ± 0.11
Gemini-N/GMOS	2.33	i′	i' >24.7	0.15 ± 0.16
VLT-UT2(Kueyen)/FORS1	18.73	I	$I_c = 24.7 \pm 0.3$	0.26 ± 0.08
VLT-UT1(Antu)/ISAAC	18.47	K_s	$K = 21.6 \pm 0.4$	1.5 ± 0.6
VLT-UT1(Antu)/FORS2	42.54	R	$R_c = 25.5 \pm 0.2$	0.18 ± 0.04
VLT-UT1(Antu)/FORS2	4300	R	$R_c = 25.65 \pm 0.12$	0.16 ± 0.02
VLT-UT1(Antu)/ISAAC	4420	K_s	$K = 21.7 \pm 0.4$	1.3 ± 0.6
VLT-UT2(Kueyen)/FORS1	5160	300V		

Photometry of the afterglow of GRB 060923A, all calibrated relative to field stars (SDSS for optical and 2MASS for infrared). Δt is the time from 23 Sep 2006 05:12:15 UT (to the start of the observation, where a range is not given). We have not corrected for foreground dust extinction, which is estimated at only $A_V = 0.18$ (Schlegel, Finkbeiner, & Davis 1998), and therefore is essentially negligible given other uncertainties. The upper limits on magnitudes are 2σ. The early measurements were made in 0.9 arcsec diameter apertures for UKIRT images and 1.7 arcsec diameter apertures for the FTN images. Later time observations, where host galaxy flux may be expected to dominate, are made in 2 arcsec diameter apertures (centred on the afterglow location); this includes the brightest parts of the host, but may miss some lower surface brightness light. Formal flux measurements and 1σ uncertainties are reported also for non-detections. NB. see text for constraining observations by other authors.

tral break between X-ray and optical, and therefore "dark" by this criterion too (Jakobsson et al. 2004; Rol et al. 2005).

3   DISCUSSION

The extremely red colours of the afterglow implied by the non-detections in the optical suggest that the flux at wavelengths shortward of about 1.5 μm is significantly suppressed (see Fig. 4).

Relatively few GRB afterglows exhibit such red colours (Levan et al. 2006a). This is probably due to a combination of factors: for instance, GRBs are expected to destroy dust (especially the smaller grains) for many parsecs along the line of sight; and, despite increasingly effective nIR campaigns, there is still some selection bias against picking up the reddened afterglows. However, most importantly, studies of GRB host galaxies have found relatively few that exhibit signs of high dust content. For example, the number with detectable submm emission is below that expected based on the proportion of global star formation thought to take place in ultra-luminous dusty galaxies (Tanvir et al. 2004; Michałowski et al. 2007). Similarly mm observations at IRAM (e.g. Priddey et al. 2006) and mIR observations with *Spitzer* (Le Floc'h et al. 2006) also find that GRB hosts have relatively little emission on the average. A small number of GRBs have taken place in extremely red galaxies (EROs) at moderate redshifts, which is presumably indicative of dust reddening (e.g. GRB 030115, Levan et al. 2006a; GRB 020127, Berger et al. 2007), but even these cases are not massive dusty galaxies judged by their far-IR emission (Tanvir et al. 2004; Priddey et al. 2006).

The rare red afterglows are likely to be the result of

either extreme reddening or high redshift. We discuss each of these possibilities in relation to GRB 060923A below.

3.1   The high redshift scenario

As discussed above, highly reddened afterglows and dusty host galaxies are rare amongst GRBs observed to date. From Fig. 5 we see that the energetics of the burst are such that the prompt emission would not be extreme even if it originated at $z \gtrsim 10$. The afterglow is faint in all bands, consistent with a high-z interpretation. Similarly, the rest-frame duration of the prompt emission would have been about 5 s at such redshifts, quite reasonable for a long GRB.

Although the H band limit from our short UKIRT exposure is not very constraining, it is clear from Fig. 4 that in the absence of dust extinction, a redshift around $z = 11$ or greater is required to explain the red $J - K$ colour of the afterglow. As discussed below, however, the detection of a host galaxy in the optical rules out this possibility.

3.2   The high extinction scenario

The discovery of a host galaxy in the optical suggests a moderate redshift, and specifically the detection in our FORS1 spectrum of light down to $\lambda \approx 4600$ Å indicates $z \lesssim 2.8$, since above that redshift the Lyα forest should render invisible the already weak continuum trace (a harder upper bound $z < 4$ comes from the Lyman limit). In fact, the magnitude and colour of the galaxy are entirely typical of other long-duration GRB hosts (Le Floc'h et al. 2003). At first sight it may seem somewhat surprising that the host colour, $R_c - K < 4$, is not unusually red if the afterglow
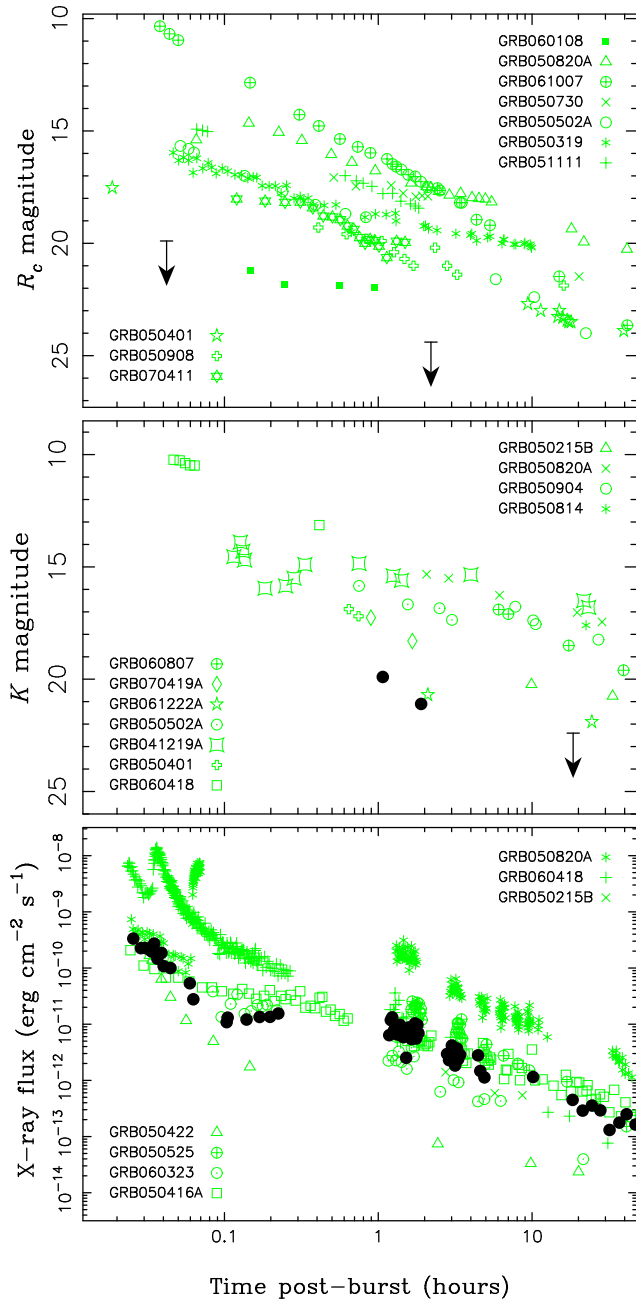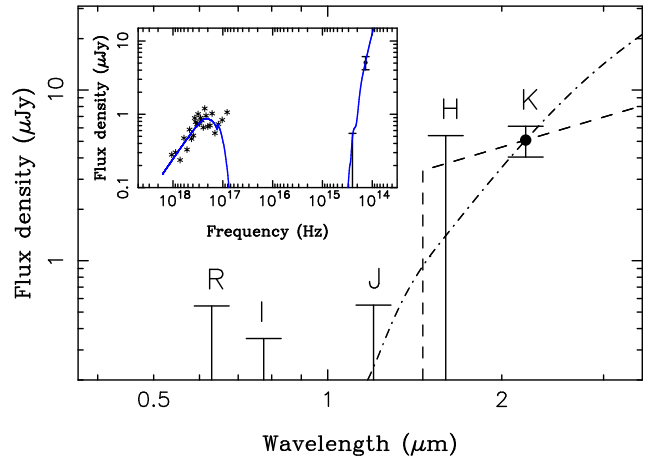
Figure 4. The spectral energy distribution of the afterglow of GRB 060923A as observed with UKIRT and Gemini. We have subtracted the host galaxy contribution, as estimated from the later time observations, and shifted the photometry to a common epoch of 90 minutes post-burst assuming a decay rate of $\alpha = 1.3$. Error ranges are 2σ. Also shown are two illustrative model SEDs: in each case we assume an intrinsic spectral slope of $F_\nu \propto \nu^{-1}$, then the dashed line uses $z = 11$ and no dust extinction, whereas the dot-dashed line is $z = 2$ and a high rest-frame extinction of $A_V = 3$ with a Pei (1992) SMC extinction law (usually the best fitting to GRB afterglows, e.g. Kann, Klose, & Zeh 2006; Schady et al. 2007). The inset panel shows an absorbed, broken power-law model ($z = 2.8$, $A_{V,\rm rest} = 2.6$) which fits both the X-ray and nIR-band data, as described in the text.

is highly reddened. This could be explained geometrically, for example if we are viewing the burst through an edge-on disk or it is embedded in an extended star-forming complex where either the dust is patchy and widely distributed, or its scale length is longer than can be destroyed by the prompt UV flash from the burst itself. Interestingly, low surface brightness "filaments" can be seen extending southeast and south-west of the bright knot for several arcseconds (Fig. 2, lower panel). This would be unusually large if it is all part of a single host, but might indicate a merger or interacting morphology. This in turn could have triggered star formation, some of it dust enshrouded, producing the bright knot and the GRB progenitor.

However, even prior to identification of the likely host, there were a number of reasons to doubt the very high redshift hypothesis. In particular, the significant excess column density above the Galactic foreground, inferred from the X-ray spectrum. At very high-z the rest-frame soft X-rays move out of the *Swift*/XRT bandpass, so even high columns in the host will produce little attenuation (presumably exacerbated by the low metallicity at early cosmic times). For example, in the sample of 55 *Swift* long-duration bursts with redshifts considered by Grupe et al. (2007), none of those above $z = 2.7$ showed such a high excess column as seen here. We should caution, however, that the reliability of column densities derived from evolving X-ray afterglow spectra has been questioned by Butler & Kocevski (2007). This could be particularly relevant if truly at high-z since time-dilation would mean the XRT was observing early in the rest-frame. However, the faintness and redness of the afterglow in the nIR bands, and the fact that the spectral slope between the
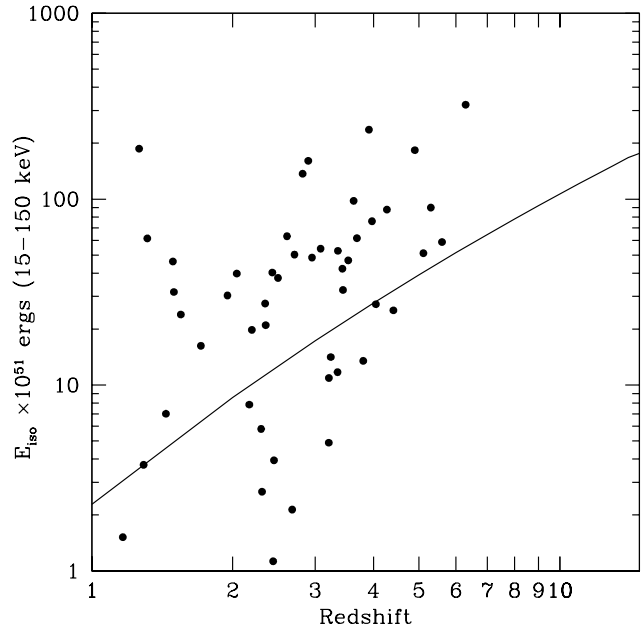

Figure 3. Afterglow light curves in the optical (R-band), near infrared (K-band) and X-ray (0.3–10 keV) for GRB 060923A in bold, compared to a set of other *Swift* GRB afterglows. These comparison light curves were chosen simply to illustrate the range in luminosity of typical *Swift* afterglows, which covers a band of width around 2 orders of magnitude in each case. Unfortunately, rather few bursts have dense coverage in both optical and nIR, and only GRB 050820A and GRB 050401 are included in all three panels. Note that error bars have been omitted for clarity. (Data taken from Blake et al. 2005; Cenko et al. 2006; Cenko & Fox 2006; Durig, McLarty, & Manning 2005; Evans et al. 2007; Guidorzi et al. 2005, 2007; Haislip et al. 2006; Huang et al. 2007; Jakobsson et al. 2006a; Kann et al. 2007; Levan et al. 2006b; Oates et al. 2006; Pandey et al. 2006; Rol, Tanvir, & Kerr 2007; Rykoff et al. 2005; Sharapov et al. 2005; Quimby et al. 2006; Watson et al. 2006; Yost et al. 2006).

Figure 5. The intrinsic isotropic energy of GRB 060923A as would be inferred from the observed 15–150 keV band fluence, as a function of assumed redshift (solid line). The locations of other *Swift* bursts with known redshifts (to September 2007) are shown as points. As can be seen, although the energy of GRB 060923A would be consistent with the bulk of the GRB population over a wide range of redshift it would not be overly energetic, even at $z = 10$–15. We assume a flat, Λ-dominated cosmology with $H_0 = 72$ km s^{-1}Mpc^{-1}, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$.

nIR and X-ray, $\beta_{KX} \approx 0.4$, also requires a strong spectral break, can all be explained most easily if there is significant dust attenuation even in K. We illustrate this further with the inset panel in Fig. 4, which shows a combined fit to the X-ray and nIR data. The model in this case is fixed at $z = 2.8$, and assumes SMC extinction law, metallicity and gas-to-dust ratio. The unabsorbed spectrum is a $F_\nu \propto \nu^{-1}$ power-law which breaks to $F_\nu \propto \nu^{-0.5}$. In fact this cooling break must be close to, or in the XRT band to provide a good simultaneous fit.

More generally, in Fig. 6 we show how several constraints on the afterglow properties would vary with assumed redshift. For simplicity, and to reduce the number of free parameters, we assume here an SMC dust extinction law and gas-to-dust ratio of $N_H/E(B-V) \approx 4.4 \times 10^{22}$ atoms cm^{-2} (Bouchet et al. 1985). The solid line shows the rest-frame extinction required to produce $J - K = 3.5$ from an intrinsic $F_\nu \propto \nu^{-1}$ afterglow spectrum (equivalent to $J - K \approx 1.7$, e.g. Gorosabel et al. 2002). In a rather model independent way, then, we can state that the afterglow should lie around this line or above it.

The shaded region shows the foreground-subtracted H I column density (the 1σ full range) derived by assuming the curvature of the X-ray spectrum is due to absorption by heavy elements (although we caution that columns inferred this way usually exceed that measured directly from Lyα absorption; Watson et al. 2007; Jakobsson et al. 2006b). For consistency we also assume SMC metallicity here, so whilst
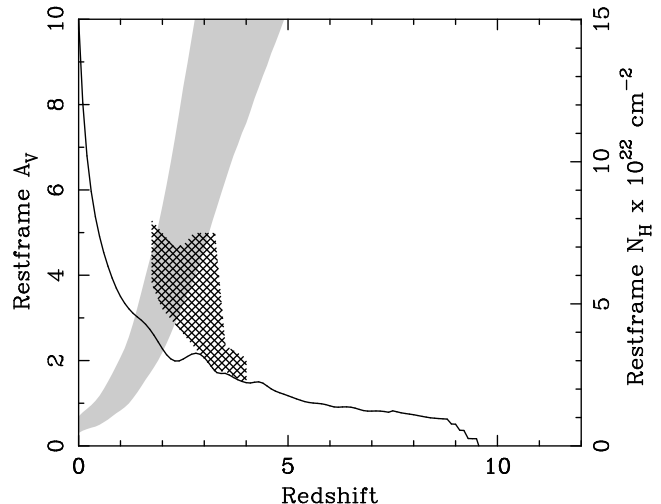

Figure 6. This plot shows various constraints on the combination of absorption and redshift, derived from the afterglow observations. As described in the text, the curve shows the required (minimum) rest frame extinction due to dust to explain the observed $J - K > 3.5$ colour of the afterglow of GRB 060923A. As with Fig. 4, we assume a Pei (1992) SMC extinction law, which should generally be appropriate for *Swift* bursts at moderate redshifts, although perhaps less so at $z > 6$ (e.g. Stratta et al. 2007). The expected H I column density corresponding to the A_V scale is shown on the right hand side. The shaded area then represents the N_H column (assuming SMC abundance $Z_{SMC}/Z_{MW} = 1/8$) inferred from the curvature of the X-ray spectrum. Finally, the hatched area shows the results of a combined model fit to the X-ray and K-band data. We fixed the Galactic foreground absorption and extinction at $N_{H,Gal} = 4.52 \times 10^{20}$ cm^{-2} (Kalberla et al. 2005) and $E(B - V)_{Gal} = 0.06$ (Schlegel, Finkbeiner, & Davis 1998) respectively.

the absolute scale may be wrong, the comparison of A_V and N_H should be valid.

Finally, the hatched region shows the results of model fitting to the combined X-ray and K-band data. Specifically, we extracted a *Swift*/XRT X-ray spectrum such that its observation log midpoint coincided with the time of the K band photometry. We fitted these together in count space (e.g. Starling et al. 2007) with models consisting of an absorbed power law or absorbed broken power law. A single power law is ruled out from the fits, unless the gas-to-dust ratio is very low. The broken power law high energy slope was fixed at a spectral index of $\beta = 1.0$ as found in fits to the X-ray spectrum alone. The lower energy slope was fixed at $\beta = 0.5$ as expected for a cooling break in the standard fireball model (Sari, Piran, & Narayan 1998). Below $z \approx 1.8$ the fit becomes unacceptably poor ($P < 2\%$ from a χ^2 test). The region shown is curtailed at the upper end at $z = 4$ based on the limits from the optical spectrum discussed below. The vertical extent of the region represents the 90% error range on A_V. We note that the hatched area is essentially consistent with the requirement of a reddened afterglow (above the solid curve). The part of the hatched region which does not coincide with the grey shaded band corresponds to best fitting models where the curvature of the X-ray spectrum is partly due to a cooling break, hence reducing the required absorption. In fact, the hardness ratio for the orbit 2 spec-

trum is consistent with that for orbit 3 and also for the combined spectrum beyond orbit 3, providing no evidence for a moving spectral break, but the statistics are too poor to make a firm statement.

We could, of course, have allowed more freedom in the model fitting, for example by not fixing the gas-to-dust ratio. However, allowing this to be a free parameter finds models with lower N_H column at a given extinction, whereas, for long GRB afterglows, the columns determined from X-rays are more often in excess of those determined from the reddening (e.g. Starling et al. 2007). A larger than expected cooling break ($\Delta\beta > 0.5$) could in principle reduce the required extinction, but then we would not explain the reddening of the afterglow. In any case, even with greater freedom it is hard to find any reasonable solution at $z < 1.5$.

We conclude that the burst likely occurred at $z \gtrsim 1.8$, which, combined with the constraint $z \lesssim 2.8$, requires $2 \lesssim A_V \lesssim 5$. This extinction would be high by typical GRB standards, but quite moderate compared to sight lines close the plane of a disk galaxy or through large dust-enshrouded star-forming regions.

We note that, whilst not common, optically dark bursts in blue galaxies at moderate redshifts, have been identified before, for example, GRB 970828 (Djorgovski et al. 2001), GRB 000210 (Gorosabel et al. 2003), GRB 051022 (Rol et al. 2007) and GRB 070306 (Jaunsen et al. 2008). Nevertheless, it remains odd that the location of the burst in this case places it within 0.2 arcsec, corresponding to at most a kiloparsec or two (at any plausible redshift), of the optically brightest part of the host. This strong spatial coincidence between burst position and the optically brightest regions of their hosts is seen in many other low-reddening long GRBs (Fruchter et al. 2006), and may be a consequence of the very short life-times of massive-star GRB progenitors, which do not move far from the star-forming region of their birth (Larsson et al. 2007). In the case of GRB 060923A, unless there is some separation along the line-of-sight, we require the dust-attenuated GRB to be close to a relatively unreddened region that dominates the optical light of the galaxy. A plausible geometry is one in which high optical-depth molecular clouds provide patchy obscuration of a large star-forming complex (cf. NGC 604 in M33 as a possible low-redshift analogue; Maíz-Apellániz, Pérez, & Mas-Hesse 2004), and the sight-line to the GRB happens to intersect one of these.

4 SUMMARY

There is great interest in GRBs with very red optical-nIR colours since they could be at very high redshift. GRB 060923A is arguably the most extreme example found to-date, being detected in the K-band, but with only deep limits in early observations in all bluer filters. If purely due to a Lyα break in the near-IR, this would indicate a redshift beyond $z \sim 11$. However, our later-time optical observations revealed a faint galaxy, presumably the host, at the same position, which must be at a more moderate redshift, probably $z \lesssim 2.8$ but certainly not above $z \approx 4$. The morphology of the host: a bright knot coincident with the GRB itself, and extended low surface brightness features may indicate a merger/interaction has produced this burst of star forma-

tion. A combined analysis of the X-ray and optical/nIR data suggest that the burst is also likely to have $z \gtrsim 1.8$ in order to reconcile the absorption required in both bands.

There is, of course, a slim chance that the GRB is coincident with an unrelated foreground galaxy. Following the analysis of Piro et al. (2002) we calculate a probability that the afterglow would be found coincident with an unrelated galaxy as bright as $R = 25.6$ to be about 3% – a small but non-negligible figure. However given the close alignment of the afterglow with the brightest knot of the galaxy, and that the colour and magnitude of the putative host are otherwise very plausible for a typical long-duration GRB, the conservative explanation remains that this is a case of dust rather than distance.

GRB 060923A nonetheless is likely to be representative of some proportion of the dark GRB population which optical surveys are biased against finding. It is therefore also a good example of the kind of interlopers which we must be able to reject in order to identify very high redshift GRBs. This study emphasises that early, deep photometry in a range of optical and nIR filters is essential to reliably identify candidates, and followup spectroscopy is highly desirable where possible.

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