A LATE, INFRARED FLASH FROM THE AFTHERGLOW OF GRB 050319

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ABSTRACT

We report the detection of a bright, near-infrared flash from the afterglow of GRB 050319, 6.15 hours after the burst. The IR flash faded rapidly from J=13.12 mag. to J>15.5 mag. in about 4 minutes. There are no reported simultaneous observations at other wavelengths making it an unique event. We study the implications of its late timing in the context of current theoretical models for GRB afterglows.

Subject headings: gamma ray: bursts — infrared: general

1. INTRODUCTION

The observed properties of GRBs (gamma ray bursts) and their afterglows are successfully explained by the internal-external shocks model (Meszaros 2002; Piran 2004). In this frame-work the afterglow arises from energy dissipation of the relativistic flow from the GRB as it is slowed down by the surrounding circumburst matter. The optical light curve of the afterglow generally decays slowly following a power law (or a broken power law). However, in some instances, a rapid flash is observed to occur contemporaneously with the GRB proper. Such a prompt flash has been observed in the optical rarely (Akerlof et al. 1999; Li et al. 2003; Vestrand et al. 2005) while the first infrared flash was detected only recently (Blake et al. 2005). Such prompt emission could be caused by a reverse shock occurring from the interaction of the outflow with the circumburst matter (Piran 2004) though internal shocks have also been invoked to consistently explain prompt emission (Vestrand et al. 2005; Blake et al. 2005). So far, there has been no detection of a late flash from a GRB. Here, we report the detection of such a late flash from GRB 050319 (George et al. 2005) which furthermore is the only second IR flash to be ever detected from a GRB. Since the origin of such a late flash is not easily explained by current theories of GRB afterglows, it becomes important to first establish the validity of the detection. We believe we establish this convincingly in Section 2 but even then - given the novelty of the result - present our observational detection with due caution. In Section 3, we discuss the implications of the late timing of the present IR flash in the context of the fireball model.

2. OBSERVATIONS AND DATA REDUCTION

On 19 March 2005, 09:31:18.44 UT, GRB 050319 triggered the Burst Alert Telescope on board the Swift gamma-ray satellite (Krimm et al. 2005). ROTSE-IIB (Robotic Optical Transient Search Experiment) responded to GRB 050319 in 9.2s, 27s after the burst and detected a 16 mag. source which faded down to ∼ 18 magnitude about 940 seconds after the burst (Rykoff et al. 2005). We became aware of the GRB only 6 hours after the outburst through the Gamma-Ray Burst Coordinate Network (GCN). Ongoing observations of the nova V574 Puppis were suspended, the GRB field was acquired and an initial 20s J band (1.25 μm) image of the GRB field was immediately taken using the 1.2 meter Mt. Abu Infrared Telescope coupled with a 256x256 HgCdTe (NICMOS3) array near-IR imager/spectrograph. In this frame, which we designate as D1 in Table 1, the IR transient (IRT) is significantly detected at 12.5σ above the background level (Figure 1). We then took 10 more frames in this position each of 60s duration (designated frames S1 to S10). Subsequently we dithered the field to three adjacent positions, again taking 10 exposures of 60s each at each dithered position. Thus the J band observations spanned ∼ 40 minutes. The log of the observations is given in Table 1. The dithered frames were median-combined to generate the sky frame which was subtracted from the object image to give the sky subtracted image. Since we had only 2 field stars A and B in the IRF frame, we could not get an astrometric position for the IRT - astrometry needs 3 or more stars - directly on this frame. We first measured the pixel-offsets of the IRT with respect to star A which is more centrally located than B (call these Δx and Δy). Subsequently, we took the first set of dithered frames - just after the IRT detection - in which we had moved the field South by ∼ 60". In these dithered frames, four field stars appeared (two were A and B; the other two stars are discussed further in the following paragraph). Although the IRT was absent in these frames as it had faded, we could reliably allocate an apparent x,y position to it since its offsets, Δx and Δy, with respect to A were known. Thus we had four reference stars in the frame permitting astrometry to be done. The RA and Dec. of the IRT, derived in this manner are α = 10:16:47.66 ± 0.02, δ = +43:32:55.6 ± 0.6 (J2000) consistent with the Swift UVOT co-ordinates of α = 10:16:47.76 ± 0.03, δ = +43:32:54.9 ± 0.5 (Boyd et al. 2005). The total systematic error in the derived IRT position, arising from the above approach, was estimated by applying the same techniques to the V574 Pup nova field being studied prior to the IRT detection. Here, we used the same number of reference stars in similar x, y positions as in the IRT analysis, included offsets for the dithered nova frames, and calculated the coordinates of 6 stars around the IRT position. We find the mean RA and Dec of these 6 stars to be 0.42" (1σ = 0.23") east and 0.37" (1σ = 0.49") south of their catalog values respectively. The star closest to the IRT position has RA & Dec offsets of 0.26"E and 0.18"S respectively. If we take into account this systematic error, associated with a fairly large 1σ error, the derived IRT coordinates continue to be consistent with the UVOT position.

In the absence of a good sky flat, we have adopted a slightly different approach to correct for the effects of flat-fielding on the measured counts of the IRT and stars A & B by using the nova V574 Puppis field. The V574 Pup field is fairly

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TABLE 1
LOG OF OBSERVATIONS.

<table>
<thead>
<tr>
<th>Exposure Start</th>
<th>Exposure duration</th>
<th>Frame designation</th>
<th>J Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>22151(+ 6.15328 hours)</td>
<td>20</td>
<td>D1</td>
<td>13.12 ± 0.08</td>
</tr>
<tr>
<td>22200</td>
<td>60</td>
<td>S1</td>
<td>14.55 ± 0.10</td>
</tr>
<tr>
<td>22261</td>
<td>60</td>
<td>S2</td>
<td>14.81 ± 0.20</td>
</tr>
<tr>
<td>22322</td>
<td>60</td>
<td>S3</td>
<td>14.79 ± 0.20</td>
</tr>
<tr>
<td>22383</td>
<td>60</td>
<td>S4</td>
<td>15.29 ± 0.28</td>
</tr>
<tr>
<td>22444</td>
<td>60</td>
<td>S5</td>
<td>&gt;15.5</td>
</tr>
</tbody>
</table>

*Exp. start is relative to the Swift trigger of 2005 March at 9.521789 UT

2 see www.prl.res.in/~chandra for an image plus other related material.

crowded\(^2\) and furthermore images of it were obtained in 4 dithered positions. Thus in at least one or more of these dithered images of the V574 Pup field, we could get a star (or stars) of this field to be sufficiently close in array (x,y) coordinates to the (x,y) coordinates of the IRT or stars A & B. We assume, that the response of the array (i.e. its flat-field response) will be reasonably similar over regions of the array separated by small amounts of ~ 6 to 8 pixels in x and y. Thus a comparison of the differential magnitudes of the IRT and stars A & B with their closely-juxtaposed 2MASS counterparts in the V574 field, should reasonably account for flatfielding effects and lead to correct J magnitude estimates for the IRT and stars A and B. In effect, we are using not one but several stars of the nova field to act as calibrators. This should ensure internal consistency and also reduce the scope for any major error in the derived magnitudes of the objects of interest. In this manner we obtain \( J = 12.56 ± 0.03 \) mag. for star A and 13.98 ± 0.05 mag. for star B which are in reasonably good agreement with their 2MASS magnitudes of 12.466 ± 0.018 and 13.839 ± 0.025 mags, respectively. In addition when the GRB field in Figure 1 was dithered northwards, two other 2MASS stars appear in the field below A and B. These also are found to have closely-juxtaposed counterparts in the V574 Pup field. Proceeding in a similar manner as above, their \( J \) band mags. are determined to be 10.85 ± 0.03 and 11.24 ± 0.03 respectively which again compare well with their 2MASS \( J \) magnitudes of 10.827 ± 0.017 and 11.279 ± 0.017 respectively. Since the derived mags. of 4 field stars around the IRT match their 2MASS magnitudes fairly well, we would thus believe that our derived magnitudes for the IRT are accurate.

Our observations were carried out under clear sky conditions. However the sky was bright in \( J \) band due to the presence of a ninth day moon about 45\(^{\circ}\) from the GRB position. This aspect has complicated the IR photometry. Our NICMOS3 detector has similar characteristics, pixel defects and other cosmetic artifacts as any other NICMOS3 detector used elsewhere. The detector is divided into 4 quadrants and unlike in an optical CCD, each quadrant is addressed separately during readout. The read noise and dark counts vary from quadrant to quadrant. Strips and shading effects across the quadrants do exist as seen in some of the frames in Figure 1. But we note that similar artifacts are seen in other NICMOS detectors and that these could be understood in terms of settling down of array after reset (Rieke at al. 1993 a,b; Meixner et al. 1999; e.g refer Figure 7 of Meixner et al. 1999) and a variability of the read-out noise from pixel to pixel (refer Section 2.4 of Skinner et al. 1997 and Figure 7 therein). A single column scan in the N-S direction of the array across the IRT position shows that the IRT signal clearly stands out, well above the background fluctuations due to shading patterns in the array. These artifacts do not in fact affect the registration of a stellar image but can affect the aperture photometry. For e.g. in IRAF, while using APPHOT for aperture photometry, the background counts to be subtracted from the stellar counts within a circular aperture centered on the star, is determined from the mean/median background counts in an annulus positioned further away from the star. In case the annulus should fall on areas with contrasting background counts, the mean background count can be wrongly estimated. We have taken care to avoid this error, especially in the case of the IRT in frames 1 and 2 of Figure 1 - in which an annulus is likely to sample varying backgrounds around the IRT because of shading - in the following way. Using the software IMPRO32, we have manually positioned a box aperture and obtained the counts around the IRT or in the background as the case may be, while being extremely careful that the box includes signal only from the appropriate regions. Thus we are certain that we have determined the signal counts on the IRT and stars A and B with sufficient accuracy. In this context, we also point out that the (x,y) centroid of the IRT is measured to be at (126,133) pixels on the array. Thus in the direction of the array columns, in which the shading exists, the IRT is considerably off by 5 pixels off from the nearest quadrant edge (located at 128 pixels). This enables a 10 pixel square box-aperture to be positioned satisfactorily enough (around the IRT or the background) without including regions of varying intensity, which arise from shading, within the box.

Is it possible that the IRT registration is an artifact of an unknown nature that arises by virtue of it either being (i) close to the array center or (ii) due to charge trapping? Both possibilities appear unlikely. Regarding the first point, as mentioned before, the (x,y) location of the IRT is not really coincident with the array centre at (128,128) but fairly well displaced from it. Also, from the survey of the literature on NICMOS3 array characteristics and behavior, we have not encountered mention of any detector-related effect that causes a stellar-like artifact to be created near the array center. Amplifier-glow, when the amplifiers are switched on during readout, is known to occur in NICMOS3 arrays but this is always seen at the 4 corners of the array where the amplifiers are located, never from near the center. Regarding the second point of charge trapping, prior to the acquisition of the IRT afterglow a nearby field was imaged with an exposure of 10 seconds in which there was no object in the subsequent position of the IRT. Hence it can be discounted that the recorded image of the IRT is due to memory effects caused by charge trapping from previous images at the pixel position of the IRT. We have also carefully examined a faint bar-shaped artifact, seen in the frames of Figure 1, which is located in the top, left corner of the images and runs in the N-E to S-W direction. We note that a single column scan across its brightest position does not show significantly excessive counts over the bar compared to the average background counts over the column. Further this artifact does not extend to the IRT position and we thus believe it does not affect the detection. We have therefore carefully analysed all possible factors that can affect the images of Figure 1 and feel that we have established that the IRT detection is secure.
Infrared studies of GRB 050319

3. RESULTS AND DISCUSSION

A rapid dimming of the IRT is seen in the images of Figure 1. This fast fading is also depicted in the lightcurve shown in Figure 2. To clearly demonstrate that the fading of the IRT is genuine we compare its lightcurve with those of stars A and B in Figure 3. The lightcurves in Figure 3 uses data from the first 11 frames. As can be seen, the lightcurves of stars A and B remain stable around their mean magnitudes within ± 0.03 and ± 0.05 mags respectively whereas the IRT fades. It is difficult to say whether an optical equivalent of the IR flash occurred because there are no reported, concurrent observations - the closest R band optical data being 2.19 before (Yoshioka et al. 2005) and 1.84 hours after (Sharapov et al. 2005) our observations respectively. The closest reported V band data is from SWIFT,UVOT (Boyd et al. 2005), 18700 seconds after the burst, one hour prior to our observation. Thus a flare with ~ 4 minute duration as we are recording here could easily have been missed in the above optical observations even if it had occurred. A rapid brightness decline, on similar time scales as reported here, has been seen in the optical in GRB 990123 (Akerlof et al. 1999; a decline of 3 mags. in ~ 110 seconds; but note that GRB 990123 was detected in both the rising and declining phases) and in GRB 021211 (Li et al. 2003; a 2 mag. drop in brightness in ~ 300 seconds). In the IR the first detection of a flash was reported only very recently for GRB 041219 (Blake et al. 2005). This IR flash, occurring 7.2 minutes after the gamma-ray trigger, shows a source that brightens and fades rapidly in the JHK bands - the total variability of 2.2 mags occurring in ~ 90 seconds. GRB 041219 however shows further complexities in its light curve with a rebrightening taking place 20 minutes after the trigger. It is worth mentioning two other cases that are discussed (Piran 2004) in the context of optical flashes, more because of the strong or early optical emission detected from them viz. GRB 021004 and GRB 030329. GRB 030329 had a very bright 12 mag. afterglow which faded by 0.2 mag in ~ 860 seconds (Price et al. 2003) while GRB 021004 was detected at 15.45 mag. and showed a slow fading of ~ 1.1 mag over 36 minutes (Fox et al. 2003). As may be seen, the decline in the afterglow brightness of these GRBs is much slower than that seen in an optical flash proper.

At a redshift of z = 3.24 (Johan et al. 2005), GRB 050319 is one of the farthest cosmological GRBs. Assuming a Lambda cosmology with $H_0 = 71 \text{ km/s/Mpc}$, $\Omega_M = 0.27$ and $\Omega_A = 0.73$ the luminosity distance $d_L$ is found to be 28.36 Gpc. An integrated fluence $S = 8 \times 10^{-7} \text{ erg/cm}^2$ in the 15-350 KeV passband was measured by Swift (burst duration = 15s) for...
this GRB (Krimm et al. 2005). For such a value of $S$, the isotropic energy release for GRB 050319, calculated using $E_{\gamma,iso} = 4\pi d_L^2 S/(1+z)$, is found to be $1.8 \times 10^{52}$ ergs which is typical of the energy release for GRBs.

The interpretation of the observed IR flash in context of the shocks model appears to be difficult. We consider various mechanisms that can explain fluctuations in the afterglow light curves viz. reverse shocks, variations in the density profile of the circumburst material and refreshed shocks. The $\gamma$-ray emission in GRBs is believed to originate from internal shocks when different 'shells' in a relativistic outflow from the compact central source collide with each other. The afterglow is produced by the interaction of this relativistic expanding flow with the circumburst material. A reverse shock, originating from this interaction, is predicted to occur contemporaneous with the prompt $\gamma$-ray emission and give rise to a strong optical flash. Such a reverse shock is invoked to explain (Nakar & Piran 2005) the prompt optical flash seen for example in GRB 990123. However, in our case, the flash occurs 6 hours after the prompt $\gamma$-ray emission, well after the afterglow is visible, and is therefore extremely unlikely to be caused by a reverse shock. Further, generalized arguments - applicable to a reverse shock also - indicate that the duration of an observed variation (as in a flash or rebrightening) should be similar to the time elapsed after the burst (Piran 2004). Since this is not the case here, a reverse shock is an unlikely cause for the observed IRT. Refreshed shocks are caused when slow shells in the ejecta catch up with the decelerating afterglow shock at later times causing a rebrightening of the afterglow light curve. For such refreshed shocks too, $\Delta t$ is expected to be of the order of $t$ (Kumar & Piran 2000). But there is a severe mismatch in the time-scales $\Delta t$ and $t$ here. Theoretical investigations have studied the effects of variations in the circumburst density on afterglow lightcurves. A fireball expanding into a wind with decreasing, outward density, as in the wind from WR stars which are considered potential progenitors of a GRB in the collapsar model (Woosley 1993), does not cause abrupt light-curve changes but rather leads to a steeper decline in the light curve (Chevalier & Li 1999) vis-à-vis expected that in a constant density medium. More importantly, light-curve variations caused by over/under-dense regions in the circumburst material have been simulated (Nakar & Piran 2003) for a variety of density profiles and specifically applied to GRB 021004 which showed a steep decay after a rebrightening at $\sim 4000s$ after outburst. It is shown that the relatively fast decays (for e.g. the decline of $\sim 2.2$ mags. in 10.5 hours seen in GRB 021004 subsequent to its rebrightening) cannot be reproduced by any reasonable, realistic, spherically-symmetric density variation in the circumburst matter. Thus in the present case, where the variability time-scale of the IR flash is several orders smaller than in GRB 021004, the difficulty in invoking density variations for causing the IR flash would become even more magnified. The most likely cause for the flash, as suggested for GRB 021004 also (Nakar & Piran 2003), could be the presence of angular structures in the ejecta or within the external circumburst matter. Such smaller structures could reduce the angular smoothing time-scale and hence reduce the duration of a fluctuation. But detailed models are needed to confirm this. Alternatively it needs to be assessed whether a dust echo around the progenitor can produce the characteristics of the observed flash. As has been pointed out recently, WC stars possess dust shells at typically $10^{14} - 10^{15}$ cms, and the echo of the initial GRB outburst from such a dust shell can produce variations in the GRB lightcurve on a timescale similar to what we observe here i.e. hours after the burst (Moran & Reichart 2005). In this context we also note optical observations of the afterglow of this GRB shows the emergence of an additional component about $10^4$ seconds after the burst (Wozniak et al 2005) which the authors have attributed to forward shock emission.

To summarise, we present evidence for an IR flash in GRB 050319 occurring $\sim 6.15$ hours after the $\gamma$-ray emission which shows a rapid fading of 2.2 mags. in $\sim 4$ minutes. Since a late flash is unexpected, efforts have been made to demonstrate convincingly that the detection is beyond observational errors. The present results could be suggestive of a new aspect about GRB afterglows that is yet to be understood.

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