A LATE, INFRARED FLASH FROM THE AFTERGLOW OF GRB 050319

KOSHY GEORGE, DIPANKAR P. K. BANERJEE, THYAGARAJAN CHANDRASEKHAR, AND NAGARHALLI M. ASHOK

Physical Research Laboratory, Navrangpura, Ahmedabad, Gujarat 380 009, India; koshy@prl.res.in, orion@prl.res.in, chandra@prl.res.in, ashok@prl.res.in

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ABSTRACT

We report the detection of a bright, near-infrared flash from the afterglow of gamma-ray burst GRB 050319, 6.15 hr 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, thus making it a unique event. We study the implications of its late timing in the context of current theoretical models for GRB afterglows.

Subject headings: gamma rays: bursts — infrared: general

1. INTRODUCTION

The observed properties of GRBs (gamma-ray bursts) and their afterglows are successfully explained by the internal-external shock model (Mészáros 2002; Piran 2005). In this framework, the afterglow arises from the 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 rarely been observed in the optical (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 2005), although 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 only the 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 that we establish this convincingly in § 2, but even then, given the novelty of the result, we present our observational detection with due caution. In § 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 2005 March 19, 09:31:18.44 UT, GRB 050319 triggered the Burst Alert Telescope on board the Swift gamma-ray satellite (Krimm et al. 2005). ROTSE-IIIb (Robotic Optical Transient Search Experiment) responded to GRB 050319 in 9.2 s, 27 s after the burst, and detected a 16 mag source that faded down to ~18 mag about 940 s after the burst (Rykoff et al. 2005). We became aware of the GRB only 6 hr after the outburst through the GRB Coordinate Network (GCN). Ongoing observations of the nova V574 Puppis were suspended, the GRB field was acquired, and an initial 20 s $J$-band (1.25 mm) image of the GRB field was immediately taken using the 1.2 m Mount Abu Infrared Telescope coupled with a 256 × 256 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 12.5 $\sigma$ above the background level

(Fig. 1). We then took 10 more frames in this position, each of 60 s duration (designated frames S1–S10). Subsequently, we dithered the field to three adjacent positions, again taking 10 exposures of 60 s 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 that was subtracted from the object image to give the sky-subtracted image. Since we had only two field stars, A and B, in the IRT frame, we could not get an astrometric position for the IRT—astrometry needs three 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 (we call these $\Delta x$ and $\Delta y$). 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, $\Delta x$ and $\Delta y$, with respect to A were known. Thus, we had four reference stars in the frame, thus enabling us to do the astrometry. The right ascension and declination of the IRT derived in this manner are $\alpha = 10^h16^m47^s66 \pm 0.02, \delta = +43^\circ32'55.6' \pm 0.5' (J2000)$, consistent with the Swift UV/Optical Telescope (UVOT) coordinates of $\alpha = 10^h16^m47^s76 \pm 0.03, \delta = +43^\circ32'54.9' \pm 0.5'$ (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 six stars around the IRT position. We find the mean right ascension and declination of these six stars to be $0^h42 (1 \sigma = 0.23$ east and $0^h37 (1 \sigma = 0.49$ south of their catalog values, respectively. The star closest to the IRT position has R.A. and decl. offsets of of $0^h2$ east and $0^h18$ south, respectively. If we take into account this systematic error, associated with a fairly large 1 $\sigma$ 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 and B by using the nova V574 Puppis field. The V574 Pup field is fairly crowded,1 and furthermore images of it were obtained in four dithered

1 See http://www.prl.res.in/~chandra for an image plus other related material.
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 and 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 ~6–8 pixels in x and y. Thus, a comparison of the differential magnitudes of the IRT and stars A and B with their closely juxtaposed Two Micron All Sky Survey (2MASS) counterparts in the V574 field should reasonably account for flat-fielding effects and should 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 $J = 12.56 \pm 0.03$ mag for star A and $13.98 \pm 0.05$ mag for star B, which are in reasonably good agreement with their 2MASS magnitudes of $12.466 \pm 0.018$ and $13.839 \pm 0.025$ mag, respectively. In addition, when the GRB field in Figure 1 was dithered northward, two other 2MASS stars appear in the field below stars 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 magnitudes are determined to be $10.85 \pm 0.03$ and $11.24 \pm 0.03$, respectively, which again compare well with their 2MASS J magnitudes of $10.827 \pm 0.017$ and $11.279 \pm 0.017$, respectively. Since the derived magnitudes of four field stars around the IRT match their 2MASS magnitudes fairly well, we 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 the J band due to the presence of a ninth-day Moon about 45° from the GRB position. This aspect has complicated the IR photometry. Our NICMOS3 detector has similar characteristics, pixel defects, and cosmetic artifacts to any other NICMOS3 detector used elsewhere. The detector is divided into four 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 the settling down of an array after reset (Rieke et al. 1993a, 1993b; see, e.g., Fig. 7 of Meixner et al. 1999) and a variability of the readout noise from pixel to pixel (see § 2.4 of Skinner et al. 1997 and Fig. 7 therein). A single column scan in the north-south 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 example, in IRAF, while using APHOT for aperture photometry, the background counts that are to be subtracted from the stellar counts within a circular aperture centered on the star are determined from the mean/background counts in an annulus positioned farther 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 a signal from the appropriate regions only. 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 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 (1) close to the array center or (2) 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 center 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

TABLE 1
LOG OF OBSERVATIONS

| Exp. Start* | Exp. Duration | Frame Designation | J Magnitude |
|-------------|---------------|------------------|-------------|
| 22151 ...   | 20            | D1               | 13.12 ± 0.08 |
| 22200 ...   | 60            | S1               | 14.55 ± 0.10 |
| 22261 ...   | 60            | S2               | 14.81 ± 0.20 |
| 22322 ...   | 60            | S3               | 14.79 ± 0.20 |
| 22383 ...   | 60            | S4               | 15.29 ± 0.28 |
| 22444 ...   | 60            | S5               | >15.5       |

* The exposure start time is relative to the Swift trigger of 2005 March 19 at 9.521789 UT.
The majority of the \( R \)-band data (filled circles) are from Wozniak et al. (2005), while the rest (triangles) are from GCN circulars (Quimby et al. 2005; Yoshioka et al. 2005; Torii 2005; Sharapov et al. 2005a, 2005b; Kiziloglu et al. 2005). The rapid fading of the IR flash may be seen here and also in the inset showing greater detail.

**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 light curve shown in Figure 2. To clearly demonstrate that the fading of the IRT is genuine, we compare its light curve with those of stars A and B in Figure 3. The light curves in Figure 3 are constructed from data from the first 11 frames. As can be seen, the light curves of stars A and B remain stable around their mean magnitudes within ±0.03 and ±0.05 mag, 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 hr after (Sharapov et al. 2005a) our observations, respectively. The closest reported \( V \)-band data are from the Swift UVOT (Boyd et al. 2005), 18,700 s after the burst, 1 hr prior to our observation. Thus, a flare with an \( \sim \)4 minute duration as recorded here could easily have been missed in the above optical observations even if it had occurred. A rapid brightness decline, on similar timescales as reported here, has been seen in the optical in GRB 990123 (Akerlof et al. 1999; a decline of 3 mag in \( \sim \)110 s; 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 \( \sim \)300 s). 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 mag occurring in \( \sim \)90 s. 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 2005) 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 that faded by 0.2 mag in \( \sim \)860 s (Price et al. 2003), while GRB 021004 was detected at 15.45 mag and showed a slow fading of \( \sim \)1.1 mag over 36 minutes (Fox et al. 2003). As can 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 (Johan et al. 2005), GRB 050319 is one of the farthest cosmological GRBs. Assuming a \( \Lambda \)CDM cosmology with \( H_0 = 71 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_m = 0.27 \), and \( \Omega_\Lambda = 0.73 \), the luminosity distance \( d_L \) is found to be 28.36 Gpc. An integrated fluence \( S = 8 \times 10^{-7} \) ergs cm\(^{-2}\) in the 15–350 keV
passband was measured by Swift (burst duration = 15 s) 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 the context of the shock model appears to be difficult. We consider various models of the energy release for GRBs.

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 to 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 hr after the prompt $\gamma$-ray emission, well after the afterglow is visible, and is therefore extremely unlikely to be caused by a reverse shock. Furthermore, 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 2005). 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, $\Delta t$ is also expected to be of the order of $t$ (Kumar & Piran 2000), but there is a severe mismatch in the timescales $\Delta t$ and $t$ here. Theoretical investigations have studied the effects of variations in the circumburst density on afterglow light curves. A fireball expanding into a wind with decreasing outward density, as in the wind from Wolf-Rayet stars that 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 than in a constant density medium. More importantly, light-curve variations caused by over/underdense 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 $\sim 4000$ s after outburst. It is shown that the relatively fast decays (e.g., the decline of $\sim 2.2$ mag in 10.5 hr 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 timescale 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 timescale 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 $10^{14}$–$10^{15}$ cm, and the echo of the initial GRB outburst from such a dust shell can produce variations in the GRB light curve on a timescale similar to what we observe here, i.e., hours after the burst (Morgan & Reichart 2005). In this context, we also note that optical observations by Wozniak et al. (2005) of the afterglow of this GRB show the emergence of an additional component about $10^{5}$ s after the burst, which the authors have attributed to forward-shock emission.

To summarize, we present evidence of an IR flash in GRB 050319 occurring $\sim 6.15$ hr after the $\gamma$-ray emission that shows a rapid fading of 2.2 mag 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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