Afterglow upper limits for four short duration, hard spectrum gamma-ray bursts

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We present interplanetary network localization, spectral, and time history information for four short-duration, hard spectrum gamma-ray bursts, GRB000607, 001025B, 001204, and 010119. All of these events were followed up with sensitive radio and optical observations (the first and only such bursts to be followed up in the radio to date), but no detections were made, demonstrating that the short bursts do not have anomalously intense afterglows. We discuss the upper limits, and show that the lack of observable counterparts is consistent both with the hypothesis that the afterglow behavior of the short bursts is like that of the long duration bursts, many of which similarly have no detectable afterglows, as well as with the hypothesis that the short bursts have no detectable afterglows at all. Small number statistics do not allow a clear choice between these alternatives, but given the present detection rates of various missions, we show that progress can be expected in the near future.

Subject headings: gamma-rays: bursts

1. Introduction

It has been recognized for two decades that the time histories of cosmic gamma-ray bursts appear to fall into at least two distinct morphological categories, namely the short duration ($\approx 0.2$ s) bursts, comprising about 25% of the total, and the long duration ($\approx 20$ s) bursts, comprising about 75% (Mazets et al. 1981; Dezalay et al. 1992; Norris et al. 1984; Hurley et al. 1992; Kouveliotou et al. 1993; Norris et al. 2000). The energy spectra of these two classes of bursts are different: the short bursts tend to have harder spectra, while the long bursts tend to have softer spectra (Kouveliotou et al. 1993; Dezalay et al. 1992).
There is also some evidence that their number-intensity distributions differ (Belli, 1997; Tavani 1998). However, the two classes appear to have identical spatial (Kouveliotou et al. 1993) and V/V_max (Schmidt 2001) distributions. Radio and/or optical counterparts have now been identified for a total of about 30 bursts, and spectroscopic redshifts measured for about 15 of them, but all of them belong to the long duration class. Thus, one of the remaining GRB mysteries is the question of whether the origins of the long and short bursts are substantially different from one another.

Over the period 1999 December - 2001 February, the 3rd Interplanetary Network (IPN) contained two distant interplanetary spacecraft, *Ulysses* and NEAR (the Near Earth Asteroid Rendezvous mission). With the near-Earth spacecraft *BeppoSAX* and Wind (among others), the IPN detected and precisely localized over 100 bursts. (Prior to 1999 December, and after 2001 February, the IPN had only one distant spacecraft, *Ulysses*, and produced mainly annuli of location.) Fifty-six error boxes were produced rapidly and accurately enough to merit rapid circulation via the GRB Coordinates Network (GCN) circulars, and of these fifty-six, 34 were searched in the radio, optical, and/or X-ray ranges for counterparts. Of the 34 events which were followed up, four were short duration, hard spectrum bursts with small error boxes. The IPN localizes bursts by triangulation, or arrival-time analysis, and in general it derives the smallest error boxes for the short bursts, since the error box size is directly related to the accuracy with which the time histories from different spacecraft can be cross-correlated. A more complete description of the method may be found in Hurley et al. (1999a,b). We report here on these events and the results of the follow-up searches. This is the first, and to date the only time that radio observations have been carried out for this type of burst. In the optical band, the *Robotic Optical Transient Search Experiment* (ROTSE-I) has conducted rapid follow-up observations of three short bursts and obtained magnitude lower limits of \( \approx 13–15 \) for them (Kehoe et al. 2001); however no deep searches for long-lived optical afterglows have been carried out up to now.

2. Gamma-Ray Observations

Table 1 gives the dates and times of the four bursts, their peak fluxes and fluences from Konus-Wind measurements, the time interval over which the peak flux was measured, the spacecraft which observed them and references to the GCN circulars where they were announced; the delay between the burst and the issuance of the circulars is also given, and comments indicate any special circumstances surrounding the events. The *BeppoSAX* GRBM did not observe GRB000607 due to an SAA passage, and was Earth-occulted for GRB0001025B. Figure 1 displays their time histories. It is clear from these figures that the
four events fall into the short-duration category. The fact that all four bursts were detected as strong events by the NEAR X-Ray/Gamma-Ray Spectrometer (XGRS) further demonstrates that they have hard energy spectra, because this experiment has a lower energy threshold $\gtrsim 150$ keV. The Konus energy spectra, shown in figure 2, also show this clearly. Instrument references for the IPN experiments may be found in Hurley et al. (1992 - *Ulysses* GRB), Aptekar et al. (1995 - Konus-Wind), Goldsten et al. (1997), McClanahan et al. (1999) and Trombka et al. (1999 - NEAR-XGRS) and Feroci et al. (1997), Amati et al. (1997), and Frontera et al. (1997 - *BeppoSAX* GRBM).

In table 2, the preliminary and final error box areas are given, as well as the final error box coordinates; the first pair of coordinates gives the error box center, and the following four pairs, the corners. In three cases, as noted, the final error box is not completely contained within the preliminary one, due to a larger than usual difference between the preliminary and final *Ulysses* ephemerides. This had a minor effect on the observations reported here. In those cases where just three spacecraft observed the burst, the ambiguity between the two triangulated localizations was resolved by the ability of the Konus-Wind experiment to determine the ecliptic latitude of the burst.

3. **Follow-up observations**

Attempts were made to detect the optical, infrared, and radio counterparts to these four bursts; however, no X-ray follow-up observations could be conducted. Although a *BeppoSAX* target of opportunity program was in place, in 3 cases the sources did not satisfy the pointing constraints, while in the fourth, the delay in deriving the error box was too long, making the detection of a fading source unlikely. (We note that one other event, GRB991004, whose duration was $\sim 3.2$ s, has been followed up in X-ray observations (in’t Zand et al. 2000); however, this burst could belong to either the short or the long class with roughly equal probabilities.) Table 3 summarizes the optical and IR observations of the final error boxes. For each burst, this table gives, in chronological order, the observatory, the instrument, the delay between the burst and the observation, the band, the limiting magnitude, the Galactic extinction in the band of observation from Schlegel et al. (1998) for the low latitude events, the reference to the observation of the *initial* error box, and any appropriate comments. (E.g., “65% covered” means that only 65% of the final error box was observed.) The observations of three of the bursts were compromised by their proximity to the Sun or Galactic plane. Further details of the *Nordic Optical Telescope* (NOT) observation of GRB010119 may be found in Gorosabel et al. (2001). Table 4 similarly summarizes the radio observations, all of which were carried out with the VLA and covered the entire areas of all the final error
boxes.

4. Discussion

We now consider the question of whether the radio and optical counterpart searches were rapid and sensitive enough to have detected counterparts to these bursts. In the standard fireball model of the long GRBs (e.g. Wijers, Rees, and Meszaros 1997), gamma-radiation is produced by internal shocks in the expanding fireball, while the short- and long-wavelength afterglows are generated when relativistically expanding matter undergoes external shocks on an ISM which surrounds the source. There is no correlation, either in theory or in practice, between the duration of a burst and the decay rate of its afterglow. Therefore, in the following, we take as our working hypothesis that the afterglows of the short bursts are like those of the long bursts, and make no attempt to scale them.

Between 1997 and 2001, a total of 74 optical and/or IR searches have been carried out for the counterparts to long duration GRBs, as reported in the literature. Of them, 50 were unsuccessful and 24 were successful. In figure 3, we have characterized these observations by two parameters: the delay in hours between the burst and the observation, and the detection or upper limit R magnitude. (In some cases, no R band magnitudes were reported; these events are not plotted.) In the same figure, we have similarly characterized and plotted the upper limits for the four short bursts reported in table 3. In those cases where extinction is important, the value of the extinction has been subtracted from the R magnitude upper limit. For GRB001025B we have converted the I band upper limits to R using I-R=0.18, a value which is typical of optical afterglows.

In the same period, as reported in the literature, 14 unsuccessful attempts and 18 successful attempts have been made to detect the radio counterparts of long GRBs. Most of these observations were carried out by the VLA at frequencies of 4.86 and 8.5 GHz. Detections of the radio counterparts to the long bursts generally occurred at 8.5 GHz or higher frequencies, while the searches for the short burst counterparts have taken place at 1.43 and 4.86 GHz; at these lower frequencies, the fluxes of the long bursts tend to be weaker due to synchrotron self-absorption, but it is not known whether this would similarly affect the observations of the radio counterparts of the short bursts. In figure 4, we have again characterized each observation by two parameters: the delay in hours between the burst and the observation, and the detection or upper limit flux in mJy at 8.5 GHz. (In some cases, no 8.5 GHz observations were reported; these events are not plotted.) We have also plotted the upper limits for the fluxes of the four short bursts reported in table 4, by assuming a spectral index of -1.5 and converting the observed upper limits to frequencies of 8.5 GHz.
Thus the upper limits at 1.43 GHz are increased by a factor of 14.5, and those at 4.86 GHz are increased by a factor of 2.3.

Figure 3 demonstrates that the searches for optical and IR counterparts of the short bursts were generally fast enough and sensitive enough to have detected counterparts, if we assume that their behavior resembles that of the long bursts. That is, counterparts have been detected at roughly the same or later times and/or roughly at the same or more intense fluxes in each case. Figure 4 similarly shows that 3 out of the 4 radio searches were fast and sensitive enough to have detected counterparts. From this we can make a rough prediction of the results expected from these searches by calculating a “success rate” for counterpart searches. In the optical, this is $24/74 \sim 32\%$, but this number should be considered an upper limit, since some unsuccessful attempts may have gone unreported. In the radio, numerous unsuccessful attempts have definitely not been reported, and the actual success rate is $\sim 40\%$. Thus, ignoring possible correlations between the two success rates, we would have expected to find $\sim 4 \times 0.32$ or 1.3 optical counterparts and, taking into account that only 3 out of 4 of the radio searches were rapid and sensitive enough, $\sim 4 \times 0.75 \times 0.40$ or 1.2 radio counterparts to the four short bursts. These numbers are consistent with those actually found, namely 0 and 0, with Poisson probabilities $\sim 27$ and $30\%$, respectively. The results of this study are therefore consistent both with the working hypothesis that the counterparts of the short-duration, hard-spectrum GRBs behave like those of the long-duration, softer spectrum bursts, as well as with the hypothesis that the short-duration bursts have no observable counterparts at all. (For example, because the fluxes decay more rapidly than those of the long bursts; this is considered in Panaitescu et al. 2001.) Clearly though, the statistics of the small numbers involved, as well as the difficulties encountered in some of the optical observations, do not allow us to choose between these conclusions.

5. Conclusion

It has been proposed that extremely brief bursts (those with durations $<100$ ms) may be due to primordial black hole evaporations (Cline, Matthey and Otwinowski 1999); the events which we discuss in this paper have longer durations than this, and the following considerations therefore do not necessarily apply to them, if they indeed constitute a separate class. Virtually all bursts followed up in X-rays display X-ray afterglows (Costa 1999), but a large fraction of bursts do not display detectable long-wavelength afterglows. It is not known why this is the case, but possible explanations include sources at very high redshifts, obscured sources, and very tenuous circum-burster mediums. The ultimate source of energy for the initial explosion may be “collapsars” for the long duration bursts, and merging neutron stars.
for the short ones (MacFadyen and Woosley 1999; Ruffert and Janka 1999). Since a neutron star binary system can receive a large kick velocity and subsequently travel far from its host galaxy before merging (Fryer, Woosley, and Hartmann 1999), short bursts might be expected not to display long-wavelength afterglows, although they would still have X-ray afterglows (Kumar and Panaitescu 2000). Thus multi-wavelength afterglow observations hold the key to resolving the short GRB mystery. Even if the short bursts are devoid of long-wavelength afterglows, the detection of X-ray afterglows with *Chandra* or XMM will provide localizations which are precise enough for deep optical searches to test the host galaxy association.

Based on the present data, we can say that the short bursts do not display anomalously intense afterglows (which we would have detected), but we cannot distinguish the behavior of short bursts from that of the long bursts with no counterparts. However, the current interplanetary network, consisting of *Ulysses*, Mars Odyssey, Konus-Wind, and *BeppoSAX*, is at least as sensitive as the previous one to short bursts, and it will continue to operate for the next several years, as will HETE. Together they should provide the data needed to make progress. For example, after radio observations of about 12 short bursts have been carried out, the absence of counterparts would be significant at almost 3σ equivalent confidence, and would point to the conclusion that the afterglows of the short bursts in fact behave differently from those of the long bursts.

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Fig. 1.— The time histories of the four short bursts from Konus-Wind. The Earth-crossing times in seconds of day (UT) corresponding to time zero on the plots are 8690.4 s for GRB000607, 71366.9 for GRB001025B, 28870.3 s for GRB001204, and 37178.4 s for GRB010119. The dashed lines indicate the background levels.

Fig. 2.— The energy spectra of the four short bursts, from Konus-Wind. As this instrument has no spectral pre-memory, the spectra start at the trigger time.

Fig. 3.— Detections of GRB optical counterparts and upper limits. Each shaded dot represents an unsuccessful attempt to detect a GRB counterpart, plotted according to the upper limit to its R magnitude and the delay in hours between the burst and the observation. Each circle similarly represents a successful attempt. These points have been taken from the literature, and include IPN, BeppoSAX, and other bursts. The numbers 1, 2, 3, and 4 give the magnitude upper limits for the four short bursts (GRB000607, 001025B, 001204, and 010119 respectively) reported in table 3. For clarity, only the most constraining points are plotted.

Fig. 4.— Detections of GRB radio counterparts and upper limits. Each shaded dot represents an unsuccessful attempt to detect a GRB counterpart, plotted according to the upper limit to its 8.5 GHz flux and the delay in hours between the burst and the observation. Each circle similarly represents a successful attempt. These points have been taken from the literature, and include IPN, BeppoSAX, and other bursts. The numbers 1, 2, 3, and 4 give the 8.5 GHz flux upper limits for the four short bursts (GRB000607, 001025B, 001204, and 010119 respectively) reported in table 4. For clarity, only the most constraining points are plotted.
Table 1. *Four short duration, hard spectrum GRBs*

| Date (YYMMDD) | UT at Earth, s | Instruments or spacecraft | 15-5000 keV fluence, erg cm$^{-2}$ | 15-5000 keV peak flux, erg cm$^{-2}$ s$^{-1}$ | Time interval ms | Reference | Delay (h) | Comments |
|---------------|---------------|---------------------------|-----------------------------------|----------------------------------|-----------------|-----------|----------|----------|
| 000607        | 08690         | *Ulysses*, Konus, NEAR    | $5.3 \times 10^{-6}$              | $1.2 \times 10^{-4}$              | 8               | Hurley et al. 2000a | 19.1     | 35° from Sun |
| 001025B       | 71346         | *Ulysses*, Konus, NEAR    | $5.7 \times 10^{-6}$              | $2.2 \times 10^{-5}$              | 16              | Hurley et al. 2000b | 28.9     | b$^{11} \approx 4^\circ$ |
| 001204        | 28855         | *Ulysses*, Konus, BeppoSAX, NEAR | $2.0 \times 10^{-6}$ | $1.1 \times 10^{-5}$ | 48 | Hurley et al. 2000c,d | 65.3     |         |
| 010119        | 37178         | *Ulysses*, Konus, BeppoSAX, NEAR | $2.4 \times 10^{-6}$ | $3.5 \times 10^{-5}$ | 8 | Hurley et al. 2000e | 14.7     | b$^{11} \approx 5^\circ$ |
| Date       | Initial area, square arcminutes | Final area, square arcminutes | $\alpha_{2000}$     | $\delta_{2000}$     | Comments                                      |
|------------|---------------------------------|-------------------------------|---------------------|---------------------|-----------------------------------------------|
| 000607     | 30                              | 5.6                           | $2^h\ 33^m\ 59.30^s$ | $17^o\ 8'\ 30.94''$ | Final error box                               |
|            |                                 |                               | $2^h\ 34^m\ 6.88^s$   | $17^o\ 10'\ 56.20''$ | fully contained                               |
|            |                                 |                               | $2^h\ 33^m\ 47.28^s$   | $17^o\ 3'\ 8.00''$   | within initial one                            |
|            |                                 |                               | $2^h\ 34^m\ 11.34^s$   | $17^o\ 13'\ 54.01''$ |                                               |
|            |                                 |                               | $2^h\ 33^m\ 51.73^s$   | $17^o\ 6'\ 5.71''$   |                                               |
| 001025B    | 110                             | 24.5                          | $18^h\ 21^m\ 23.71^s$ | $-5^o\ 6'\ 23.91''$ | $\sim$ 3 square arcminutes                    |
|            |                                 |                               | $18^h\ 21^m\ 4.96^s$    | $-5^o\ 4'\ 20.34''$  | outside old error box                         |
|            |                                 |                               | $18^h\ 22^m\ 3.34^s$    | $-5^o\ 13'\ 22.26''$ |                                               |
|            |                                 |                               | $18^h\ 20^m\ 44.41^s$   | $-4^o\ 59'\ 28.15''$ |                                               |
|            |                                 |                               | $18^h\ 21^m\ 42.52^s$   | $-5^o\ 8'\ 27.90''$  |                                               |
| 001204     | 18                              | 6                             | $2^h\ 41^m\ 11.94^s$   | $12^o\ 52'\ 54.3''$  | $\sim$ 1.3 square arcminutes                  |
|            |                                 |                               | $2^h\ 41^m\ 16.77^s$   | $12^o\ 52'\ 14.42''$ | outside old error box                         |
|            |                                 |                               | $2^h\ 41^m\ 0.39^s$     | $12^o\ 51'\ 56.06''$ |                                               |
|            |                                 |                               | $2^h\ 41^m\ 23.49^s$   | $12^o\ 53'\ 52.58''$ |                                               |
|            |                                 |                               | $2^h\ 41^m\ 7.11^s$     | $12^o\ 53'\ 34.19''$ |                                               |
| 010119     | 11                              | 3.3                           | $18^h\ 53^m\ 46.17^s$  | $11^o\ 59'\ 47.04''$ | $\sim$ 1.5 square arcminutes                  |
|            |                                 |                               | $18^h\ 53^m\ 36.00^s$  | $11^o\ 59'\ 31.43''$ | outside old error box                         |
|            |                                 |                               | $18^h\ 53^m\ 53.61^s$  | $12^o\ 00'\ 34.50''$ |                                               |
|            |                                 |                               | $18^h\ 53^m\ 39.81^s$  | $11^o\ 58'\ 59.57''$ |                                               |
|            |                                 |                               | $18^h\ 53^m\ 57.42^s$  | $12^o\ 00'\ 02.63''$ |                                               |
Table 3. **Optical observations**

| Date      | Observatory | Instrument | Delay, h | Band | Limiting Magnitude | Extinction | Reference                        | Comments                  |
|-----------|-------------|------------|----------|------|--------------------|------------|----------------------------------|--------------------------|
| 000607    | BOOTES-1    | 0.3 m      | 51       | R    | 16                 |            | Masetti et al. (2000)            | Near dawn; poor seeing   |
|           | ESO         | 1.54 m     | 56       | R    | 19.5\(^a\)         |            | Masetti et al. (2000)            | Near dawn; 65% coverage  |
| 001025B   | Super-LOTIS | 0.6 m      | 30       | unfiltered | 19.5            | 5          | Park et al. (2000)               |                          |
|           | Calar Alto  | 2.2 m      | 48       | I    | 20.5               | 2.9        | Castro-Tirado et al. (2000)      |                          |
|           | Calar Alto  | 2.2 m      | 71       | I    | 20.5               | 2.9        | Castro-Tirado et al. (2000)      |                          |
|           | Calar Alto  | 2.2 m      | 96       | I    | 20.5               | 2.9        | Castro-Tirado et al. (2000)      |                          |
|           | Super-LOTIS | 0.6 m      | 102      | unfiltered | 20.5            | 5          | Park et al. (2000)               |                          |
|           | Las Campanas| 40 in      | 109      | I    | 21.5               | 2.9        | ...                              |                          |
| 001204    | USNO        | 1.0 m      | 68       | R\(_c\) | 18               |            | ...                              | Heavy clouds, poor seeing|
|           | Mt. Stromlo | 50 in.     | 74       | R    | 20.1               |            | Price et al. (2000)              |                          |
|           | Mt. Stromlo | 50 in.     | 74       | V    | 20.5               |            | ...                              |                          |
|           | ESO         | NTT        | 115      | K\(_s\) | 20.0            |            | Vreeswijk and Rol (2000)         | 80% coverage             |
|           | ESO         | NTT        | 233      | K\(_s\) | 20.0            |            | Vreeswijk and Rol (2000)         | 80% coverage             |
| 010119    | NOT         | 2.6 m      | 20       | R    | 22.3               | 1.6        | Gorosabel et al. (2001)          |                          |
|           | Palomar     | 60 in.     | 27       | R    | 18\(^a\)           | 1.6        | Price and Bloom (2000)           | Poor seeing              |
|           | Nyrölä      | 0.4 m      | 42       | R    | 19.5               | 1.6        | Oksanen et al. (2001)            | Poor seeing;             |
|           | Palomar     | 60 in.     | 51       | R    | 21.5\(^a\)         | 1.6        | Price and Bloom (2000)           | 3 ″ seeing               |

\(^a\)Photometric calibration was performed using USNO-A2.0 stars
| Date       | Delay, h | Frequency, GHz | Limiting flux, mJy | Reference             |
|------------|----------|----------------|--------------------|-----------------------|
| 000607     | 36       | 1.43           | 0.5                | Frail et al. (2000)   |
| 36         | 4.86     | 0.37           |                    | Frail et al. (2000)   |
| 40         | 1.43     | 0.5            |                    | Frail et al. (2000)   |
| 40         | 4.86     | 0.37           |                    | Frail et al. (2000)   |
| 64         | 1.43     | 0.5            |                    | Frail et al. (2000)   |
| 64         | 4.86     | 0.37           |                    | Frail et al. (2000)   |
| 001025B    | 31       | 4.86           | 0.7                | Berger and Frail (2000a) |
| 001204     | 68       | 4.86           | 0.25               | Berger and Frail (2000b) |
| 010119     | 26       | 4.86           | 0.35               | Berger and Frail (2001) |
GRB 000607 0 - 0.064s

$9.7 \times 10^{-0.83} \exp(-E/1240 \text{ keV})$

Photons / cm$^2$ s keV

GRB 001025B 0 - 0.192s

$2.4 \times 10^{-0.85} \exp(-E/1400 \text{ keV})$

GRB 001204 0 - 0.128s

$110 \times 10^{-1.65} \exp(-E/4300 \text{ keV})$

GRB 010119 0 - 0.192s

$1.7 \times 10^{-0.59} \exp(-E/350 \text{ keV})$

GRB 010119 0 - 0.192s

$1.7 \times 10^{-0.59} \exp(-E/350 \text{ keV})$
