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AFTERGLOW UPPER LIMITS FOR FOUR SHORT-DURATION, HARD SPECTRUM GAMMA-RAY BURSTS[1]

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ABSTRACT

We present interplanetary network localization, spectral, and time history information for four short-duration, hard spectrum gamma-ray bursts, GRB 000607, GRB 001025B, GRB 001204, and GRB 010119. All of these events were followed up with sensitive radio and optical observations (the first and

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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 with both 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 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 heading: gamma rays: bursts

1. INTRODUCTION

It has been recognized for two decades that the time histories of cosmic gamma-ray bursts (GRBs) 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, Scargle, & Bonnell 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. 1996). 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 Third Interplanetary Network (IPN) contained two distant interplanetary spacecraft, *Ulysses* and the *Near Earth Asteroid Rendezvous* (*NEAR*) 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 56, 34 were searched in the radio, optical, and/or X-ray ranges for counterparts. Of the 34 events that 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, 1999b). 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 in seconds 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 that 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* Gamma-Ray Burst Monitor (GRBM) did not observe GRB 000607 because of a South Atlantic Anomaly passage and was Earth occulted for GRB 001025B. 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 (1992; *Ulysses* GRB), Aptekar et al. (1995; Konus-*Wind*), Goldsten et al. (1997), McClanahan et al. (1999), Trombka et al. (1999; *NEAR*-XGRS), 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

TABLE 1

FOUR SHORT-DURATION, HARD SPECTRUM GRBs

GRB	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*	5.3×10^{-6}	1.2×10^{-4}	8	Hurley et al. 2000c	19.1	35° from Sun
001025B...	71346	*Ulysses*, Konus, *NEAR*	5.7×10^{-6}	2.2×10^{-5}	16	Hurley et al. 2000d	28.9	$b \approx 4°$
001204	28855	*Ulysses*, Konus, *BeppoSAX*, *NEAR*	2.0×10^{-6}	1.1×10^{-5}	48	Hurley et al. 2000a, 2000b	65.3	
010119	37178	*Ulysses*, Konus, *BeppoSAX*, *NEAR*	2.4×10^{-6}	3.5×10^{-5}	8	Hurley et al. 2000e	14.7	b ≈ 5°

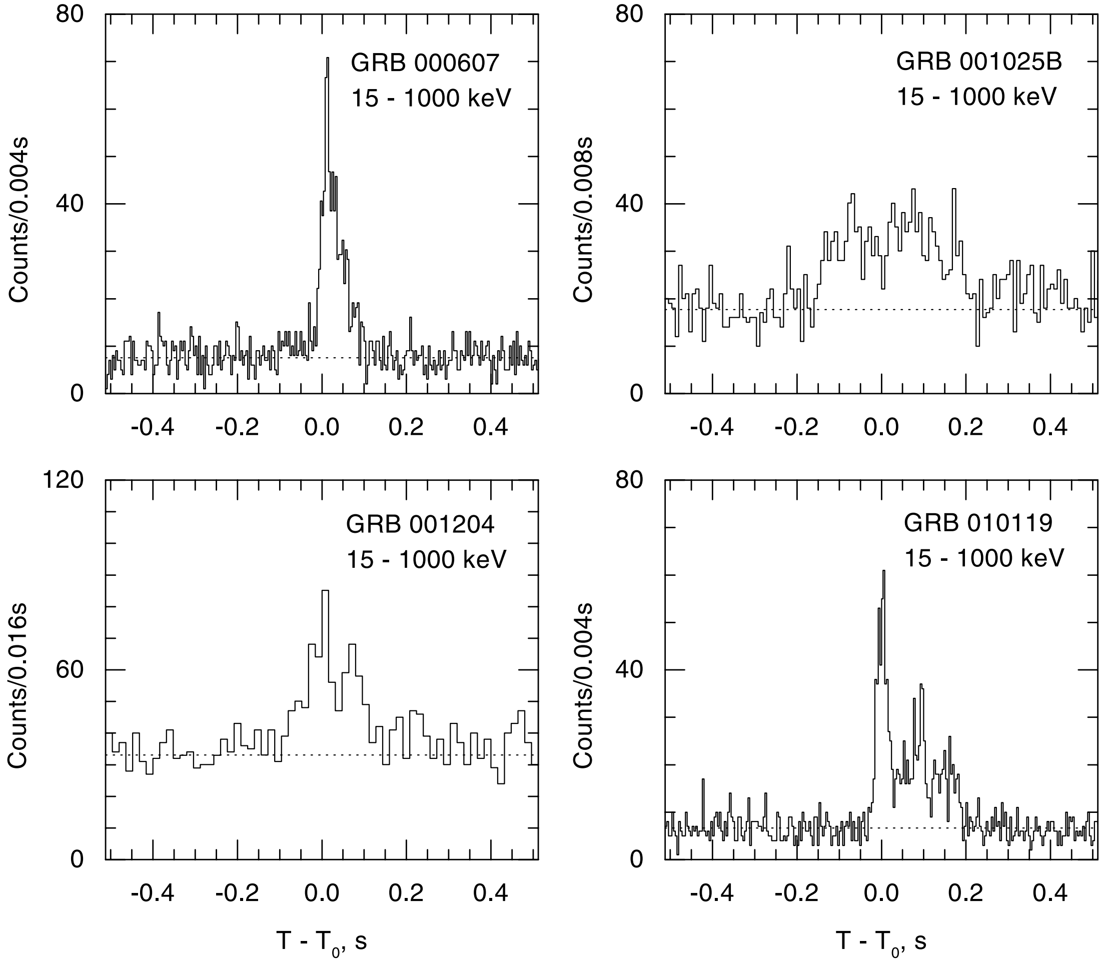

FIG. 1.—Time histories of the four short bursts from Konus-*Wind*. The Earth crossing times in seconds of day (UT) corresponding to time zero on the plots are 8690.4 s for GRB 000607, 71,366.9 for GRB 001025B, 28,870.3 s for GRB 001204, and 37,178.4 s for GRB 010119. The dashed lines indicate the background levels.

TABLE 2

ERROR BOXES

GRB	Initial Area (arcmin^2)	Final Area (arcmin^2)	$\alpha_{2000.0}$	$\delta_{2000.0}$	Comments
000607	30	5.6	2 33 59.30	17 8 30.94	Final error box
			2 34 6.88	17 10 56.20	fully contained
			2 33 47.28	17 3 8.00	within initial one
			2 34 11.34	17 13 54.01	
			2 33 51.73	17 6 5.71	
001025B......	110	24.5	18 21 23.71	−5 6 23.91	~3 square arcminutes
			18 21 4.96	−5 4 20.34	outside old
			18 22 3.34	−5 13 22.26	error box
			18 20 44.41	−4 59 28.15	
			18 21 42.52	−5 8 27.90	
001204	18	6	2 41 11.94	12 52 54.3	~1.3 square arcminutes
			2 41 16.77	12 52 14.42	outside old
			2 41 0.39	12 51 56.06	error box
			2 41 23.49	12 53 52.58	
			2 41 7.11	12 53 34.19	
010119	11	3.3	18 53 46.17	11 59 47.04	~1.5 square arcminutes
			18 53 36.00	11 59 31.43	outside old
			18 53 53.61	12 00 34.50	error box
			18 53 39.81	11 58 59.57	
			18 53 57.42	12 00 02.63	

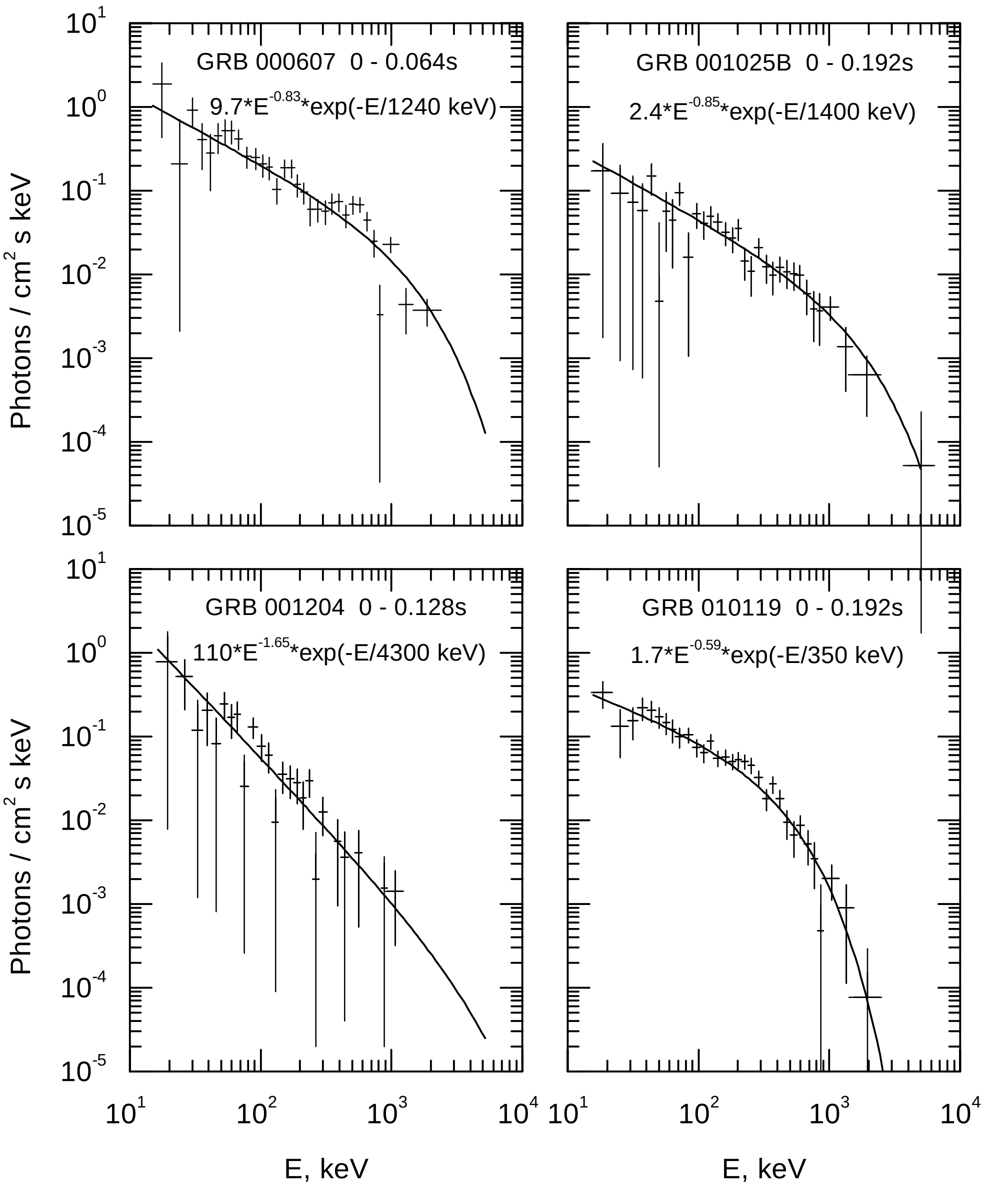

FIG. 2.—Energy spectra of the four short bursts from Konus-*Wind*. Since this instrument has no spectral prememory, the spectra start at the trigger time.

four pairs, the corners. In three cases, as noted, the final error box is not completely contained within the preliminary one because of 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 in which 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 three 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, GRB 991004, whose duration was ∼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 order of the columns, 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, Finkbeiner, & Davis (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 GRB 010119 may be found in Gorosabel et al. (2002). Table 4

TABLE 3

Optical observations

GRB	Observatory	Instrument	Delay (h)	Band	Limiting Magnitude (mag)	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, Alises, & Greiner (2000)	
	Las Campanas	40 inch	52	I	21.5	2.9	...	
	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 inch	109	I	21.5	2.9	...	
001204	USNO	1.0 m	68	R_c	18		...	Heavy clouds, poor seeing
	Mt. Stromlo	50 inch	74	R	20.1		Price, Axelrod, & Schmidt (2000)	
	Mt. Stromlo	50 inch	74	V	20.5		...	
	ESO	NTT	115	K_s	20.0		Vreeswijk & Rol (2000)	80% coverage
	ESO	NTT	233	K_s	20.0		Vreeswijk & Rol (2000)	80% coverage
010119	NOT	2.6 m	20	R	22.3	1.6	Gorosabel et al. (2001)	
	Palomar	60 inch	27	R	18[a]	1.6	Price, Morrison, & Bloom (2001)	Poor seeing
	Nyrölä	0.4 m	42	R	19.5	1.6	Oksanen et al. (2001)	Poor seeing
	Palomar	60 inch	51	R	21.5[a]	1.6	Price et al. (2001)	3″seeing

[a] Photometric calibration was performed using USNO-A2.0 stars.

similarly summarizes the radio observations, all of which were carried out with the Very Large Array (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 (see, e.g., Wijers, Rees, & 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 the interstellar medium that surrounds the source. There is no correlation, in either theory or practice, between the duration of a burst and the decay rate of its afterglow. Therefore, in the following discussion, 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.

TABLE 4

NRAO-VLA Observations

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 & Frail (2000a)
001204	68	4.86	0.25	Berger & Frail (2000b)
010119	26	4.86	0.35	Berger & Frail (2001)

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 in which extinction is important, the value of the extinction has been subtracted from the R-magnitude upper limit. For GRB 001025B, we have converted the I-band upper limits to R using $I - R = 0.18$, a value that 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 because of 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

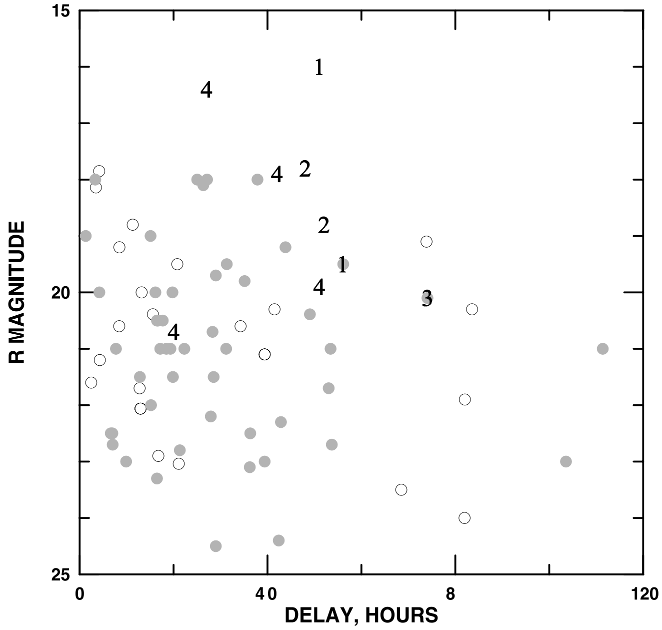

FIG. 3.—Detections of GRB optical counterparts and upper limits. Each shaded circle represents an unsuccessful attempt to detect a GRB counterpart, plotted according to the upper limit to its *R* magnitude and the delay in hours between the burst and the observation. Each open circle similarly represents 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 (GRB 000607, GRB 001025B, GRB 001204, and GRB 010119, respectively) reported in Table 3. For clarity, only the most constraining points are plotted.

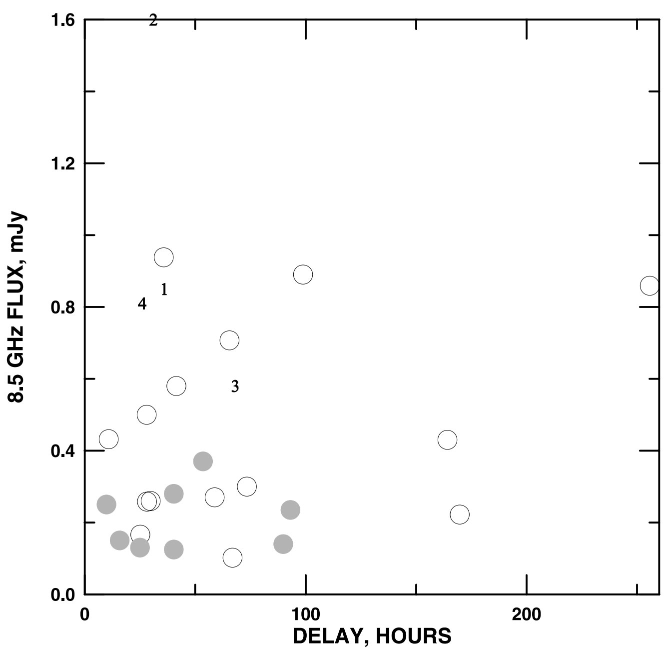

FIG. 4.—Detections of GRB radio counterparts and upper limits. Each shaded circle represents an unsuccessful attempt to detect a GRB counterpart, plotted according to the upper limit to its 8.5 GHz flux and the delay in hours between the burst and the observation. Each open circle similarly represents 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 (GRB 000607, GRB 001025B, GRB 001204, and GRB 010119, respectively) reported in Table 4. For clarity, only the most constraining points are plotted.

frequencies of 8.5 GHz. Thus, the upper limits at 1.43 Gz 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 three of the four 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 three of four 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 with both 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 the hypothesis that the short-duration bursts have no observable counterparts at all (e.g., because the fluxes decay more rapidly than those of the long bursts; this is considered in Panaitescu, Kumar, Narayan 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, & Otwinowski 1999); the events that 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 circumburster 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 & Woosley 1999; Ruffert & 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, & Hartmann 1999), short bursts might be expected not to display long-wavelength afterglows, although they would still have X-ray afterglows (Kumar & Panaitescu 2000). Thus, multiwavelength 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 that 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 the *High Energy Transient Explorer*. 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 3 σ 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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