A NEW POPULATION OF HIGH-REDSHIFT SHORT-DURATION GAMMA-RAY BURSTS

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ABSTRACT

The redshift distribution of the short-duration gamma-ray bursts (GRBs) is a crucial, but currently fragmentary, clue to the nature of their progenitors. Here we present optical observations of nine short GRBs obtained with Gemini, Magellan, and the *Hubble Space Telescope*. We detect the afterglows and host galaxies of two short bursts, and host galaxies for two additional bursts with known optical afterglow positions, and five with X-ray positions ($\lesssim 6''$ radius). In eight of the nine cases we find that the most probable host galaxies are faint, $R \approx 23–26.5$ mag, and are therefore starkly different from the first few short GRB hosts with $R \approx 17–22$ mag and $z \lesssim 0.5$. Indeed, we measure spectroscopic redshifts of $z \approx 0.4–1.1$ for the four brightest hosts. A comparison to large field galaxy samples, as well as the hosts of long GRBs and previous short GRBs, indicates that the fainter hosts likely reside at $z \gtrsim 1$. Our most conservative limit is that at least half of the five hosts without a known redshift reside at $z > 0.7$ (97% confidence level), suggesting that about $\frac{1}{3}$ to $\frac{2}{3}$ of all short GRBs originate at higher redshifts than previously determined. This has two important implications: (1) we constrain the acceptable age distributions to a wide lognormal ($\sigma \gtrsim 1$) with $\tau_* \sim 4–8$ Gyr, or to a power law, $P(\tau) \propto \tau^n$, with $-1 \lesssim n \lesssim 0$; and (2) the inferred isotropic energies, $E_{\gamma,\mathrm{iso}} \sim 10^{50}–10^{52}$ ergs, are significantly larger than $\sim 10^{48}–10^{49}$ ergs for the low-redshift, short GRBs, indicating a large spread in energy release or jet opening angles. Finally, we reiterate the importance of short GRBs as potential gravitational-wave sources and find a conservative detection rate with the advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) of $\sim 2–6$ yr^{-1}.

Subject headings: gamma rays: bursts

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1. INTRODUCTION

The redshift distribution of the short-duration GRBs serves as one of the primary clues to the nature of their progenitors. This is because distance measurements determine the energy budget and its dispersion, provide information on the progenitor age distribution and its relation to star formation, and allow us to estimate event rates for gravitational-wave detectors such as LIGO (in the context of neutron star–neutron star [NS-NS] and neutron star– black hole [NS-BH] progenitors). Initial observations suggested that short GRBs occur at significantly lower redshifts than long GRBs (for which $\langle z \rangle \sim 3$; e.g., Berger et al. 2005a; Jakobsson et al. 2006). In particular, GRBs 050724 and likely 050509b are associated with bright ($L \sim 2–4\ L^*$) elliptical galaxies at $z = 0.257$ and 0.226, respectively (Berger et al. 2005b; Gehrels et al. 2005; Bloom et al. 2006; Prochaska et al. 2006), while GRBs 050709 and 051221a were localized to star-forming galaxies at $z = 0.1606$ and 0.5465, respectively, with $L \sim 0.1–0.3\ L^*$ (Fox et al. 2005;

Hjorth et al. 2005; Covino et al. 2006; Soderberg et al. 2006). It has also been proposed that GRB 050911 occurred in a galaxy cluster at $z = 0.1646$ (Berger et al. 2007), that the old IPN burst GRB 790613 was associated with an elliptical galaxy at $z = 0.09$ (Gal-Yam et al. 2005), and that GRB 060502b was ejected from a bright galaxy at $z = 0.287$ (Bloom et al. 2007). These low redshifts have been used to argue for long progenitor lifetimes, $\gtrsim 4$ Gyr, and against a substantial population of short GRBs at high redshift (e.g., Guetta & Piran 2006; Nakar et al. 2006; Hopman et al. 2006). They also set the energy scale of short GRBs at $\sim 10^{48}–10^{49}$ ergs (e.g., Soderberg et al. 2006).

Despite these initial results, there is tentative evidence that some short GRBs may occur at higher redshifts. This includes the proposed association of GRB 050813 with a galaxy cluster at $z \sim 1.8$ (Berger 2006), a photometric redshift for GRB 060121 of $z \sim 1.7$ or ~ 4.6 based on the afterglow optical/near-IR spectral energy distribution (Levan et al. 2006; de Ugarte Postigo et al. 2006), and limits on galaxy brightness of $\gtrsim 19$ mag in error boxes of some

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TABLE 1
Short GRB Properties

GRB (1)	Date (UT) (2)	T_{90} (s) (3)	F_γ[a] (ergs cm^{-2}) (4)	R.A. (J2000.0) (5)	Decl. (J2000.0) (6)	Uncertainty (arcsec) (7)	OA? (8)	z (9)	R[b] (mag) (10)	L_B (L^*) (11)	Refs. (12)
051210..........	2005 Dec 10.240	1.27	$(8.1 \pm 1.4) \times 10^{-8}$	22 00 41.3	−57 36 48.2	4.2	N	≳1.4	23.80 ± 0.15	...	1
051227..........	2005 Dec 27.755	8.0[c]	$(2.3 \pm 0.3) \times 10^{-7}$	08 20 57.92	+31 55 30.4	3.5	Y	...	25.49 ± 0.15	...	2–4
060121..........	2006 Jan 21.934	1.97	$(4.7 \pm 0.4) \times 10^{-6}$	09 09 52.13	+45 39 44.9	3.7	Y	...	26.26 ± 0.30	...	5–6
060313..........	2006 Mar 13.008	0.70	$(1.1 \pm 0.1) \times 10^{-6}$	04 26 28.50	−10 50 40.2	4.0	Y	...	24.83 ± 0.20	...	7
060502b........	2006 May 2.726	0.09	$(4.0 \pm 0.5) \times 10^{-8}$	18 35 45.74	+52 37 52.5	4.4	N	...	25.83 ± 0.05	...	8–10
060801..........	2006 Aug 1.511	0.50	$(8.1 \pm 1.0) \times 10^{-8}$	14 12 01.31	+16 58 54.0	2.1	N	1.1304	22.97 ± 0.11	1	11–13
061006..........	2006 Oct 6.699	0.42[d]	$(1.4 \pm 0.1) \times 10^{-6}$	07 24 07.33	−79 11 55.8	2.2	Y	0.4377	22.65 ± 0.09	0.1	14–16
061210..........	2006 Dec 10.514	0.19[e]	$(1.1 \pm 0.2) \times 10^{-6}$	09 38 05.24	+15 37 16.5	3.4	N	0.4095	21.00 ± 0.02	1.5	17–19
061217..........	2006 Dec 17.153	0.21	$(4.6 \pm 0.8) \times 10^{-8}$	10 41 39.10	−21 07 26.9	6.0	N	0.8270	23.33 ± 0.07	0.5	20–21
050509b........	2005 May 9.167	0.04	$(9.5 \pm 2.5) \times 10^{-9}$	12 36 13.58	+28 59 01.3	9.3	N	0.226	16.75 ± 0.05	5	22–23
050709..........	2005 Jul 9.942	0.07	$(2.9 \pm 0.4) \times 10^{-7f}$	23 01 26.96	−38 58 39.5	0.4	Y	0.1606	21.05 ± 0.07	0.1	24–26
050724..........	2005 Jul 24.524	3.0[g]	$(3.9 \pm 1.0) \times 10^{-7}$	16 24 44.36	−27 32 27.5	0.5	Y	0.257	18.19 ± 0.03	1	27–29
051221a........	2005 Dec 21.077	1.40	$(1.2 \pm 0.1) \times 10^{-6}$	21 54 48.62	+16 53 27.2	0.2	Y	0.5465	21.81 ± 0.09	0.3	30–31

Notes.— Properties of the short GRBs discussed in this paper. Col. (1): GRB name. Col. (2): Localization date. Col. (3): Duration. Col. (4): Fluence. Cols. (5–7): Position of the X-ray afterglow, including uncertainty. Col. (8): Whether an optical afterglow was detected. Col. (9): Spectroscopic redshift. Col. (10): Host R-band magnitude, corrected for Galactic extinction (Schlegel et al. 1998). Col. (11): Rest-frame B-band luminosity. Col. (12): Relevant references. The four bursts at the bottom of the table are the low-redshift events previously identified. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Fluence is in the 15–150 keV energy band unless otherwise noted.
[b] Corrected for Galactic extinction (Schlegel et al. 1998).
[c] The burst is likely in the short-duration category, based on both the light-curve similarity to GRB 050724 with extended soft emission, and a negligible lag (Barthelmy et al. 2005a).
[d] This burst exhibits an extended soft tail with a duration of about 130 s (Krimm et al. 2006); detection with Konus-Wind indicates a 20–2000 keV fluence of 3.6×10^{-6} ergs cm^{-2} (Golenetskii et al. 2006).
[e] This burst exhibits an extended soft tail with a duration of about 85 s (Palmer et al. 2006).
[f] Fluence is in the 30–400 keV band.
[g] The light curve is dominated by a 0.25 s hard spectrum spike, with a BATSE duration of $T_{90} = 1.3$ s.

References.—(1) La Parola et al. 2006; (2) Hullinger et al. 2005; (3) Barthelmy et al. 2005a; (4) Beardmore et al. 2005; (5) Arimoto et al. 2006; (6) Mangano et al. 2006; (7) Roming et al. 2006; (8) Sato et al. 2006a; (9) Troja et al. 2006; (10) Bloom et al. 2007; (11) Sato et al. 2006a; (12) Sato et al. 2006b; (13) Butler 2006; (14) Krimm et al. 2006; (15) Golenetskii et al. 2006; (16) Troja et al. 2006; (17) Palmer et al. 2006; (18) Godet et al. 2006; (19) Racusin et al. 2006; (20) Parsons et al. 2006; (21) Evans et al. 2006; (22) Gehrels et al. 2005; (23) Bloom et al. 2006; (24) Villasenor et al. 2005; (25) Fox et al. 2005; (26) Hjorth et al. 2005; (27) Barthelmy et al. 2005b; (28) Berger et al. 2005b; (29) Grupe et al. 2006; (30) Burrows et al. 2006; (31) Soderberg et al. 2006.

poorly localized short bursts (typical size of 20 arcmin^2; Schaefer 2006). Determining with greater confidence whether a high-redshift population in fact exists, and how it relates to the low-redshift, short GRBs, remains an open issue, with implications for the burst energetics, progenitor lifetimes, and rate estimates.

Here we present optical observations of nine well-localized ($<6''$ radius) short GRBs discovered in the past year and find that eight are likely associated with faint galaxies, $R \sim 23-26.5$ mag (the remaining host has $R \approx 21$ mag). We show by comparison to the previously detected hosts (with $R \sim 17-22$ mag and $z \lesssim 0.5$), as well as to the hosts of long GRBs and large field galaxy samples, that these new host galaxies likely reside at $z \sim 1$. Indeed, we present spectroscopic redshifts for the four *brightest* hosts of $z \approx 0.4-1.1$. These observations establish for the first time that at least $\frac{1}{3}$ of all short GRBs originate at high redshift, and that some bursts produce $10^{50}-10^{52}$ ergs in their prompt emission, at least 2 orders of magnitude larger than the low-redshift short bursts. Most importantly, with this new high-redshift sample, we provide tighter constraints on the progenitor age distribution than previously possible and find that viable models include a wide lognormal distribution with $\tau_* \sim 4-8$ Gyr, or power-law distributions, $P(\tau) \propto \tau^n$, with $-1 \lesssim n \lesssim 0$.

2. OBSERVATIONS

The prompt emission properties and X-ray afterglow positions of the nine bursts discussed in this paper are provided in Table 1. The table also includes the properties of the four previous short bursts with measured redshifts. We consider here only events for

which X-ray or optical afterglow positions are available, providing positional uncertainties better than $6''$ radius and therefore a low probability of chance associations. We note that the prompt and X-ray afterglow properties of some of these bursts are discussed in detail in the published literature: GRB 051210 (La Parola et al. 2006), GRB 060121 (de Ugarte Postigo et al. 2006; Donaghy et al. 2006; Levan et al. 2006), GRB 060313 (Roming et al. 2006), and GRB 060502b (Bloom et al. 2007).

Before addressing the individual bursts, we note that in the context of the popular model of NS-NS or NS-BH binaries the progenitors may experience a kick, leading to mergers outside of the host galaxies. The range of offsets depends on the distributions of kick velocities, merger times, and host masses, but typical predicted values are $\sim 10-100$ kpc (Fryer et al. 1999; Belczynski et al. 2006). This translates to an angular distance of about $6''-60''$ at $z \approx 0.1$, or about $1.5''-15''$ at $z \gtrsim 0.7$. While kicks may provide an obstacle to secure associations when subarcsecond positions are not available, we stress that in the existing sample of short GRBs with secure associations, the offsets are all small— GRB 050709: 3.8 kpc (Fox et al. 2005); GRB 050724: 2.6 kpc (Berger et al. 2005b); and GRB 051221a: 0.8 kpc (Soderberg et al. 2006). In addition, as we show below, when precise optical positions are available for the new sample, the bursts invariably coincide at a high confidence level with faint galaxies. If these bursts were ejected from nearby galaxies there is no reason why they should always land on an unrelated galaxy. This, and the fact that not all progenitors are expected to experience a significant kick in the first place, indicates that kicks do not provide a significant
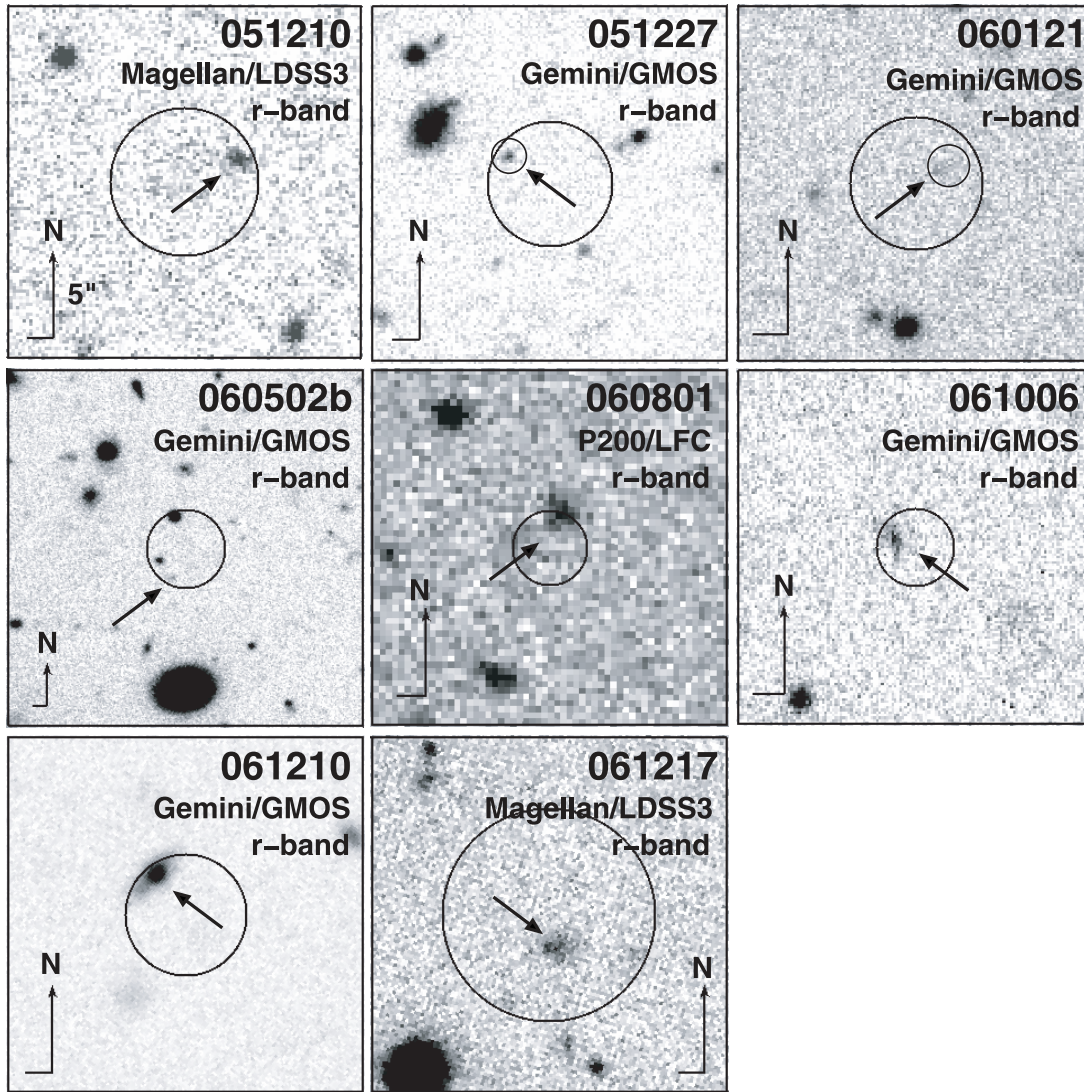
FIG. 1.—Ground-based images from Magellan and Gemini of several short GRB hosts. All images are 20″ on a side, with the exception of GRB 060502b, which is twice as large. The large circles mark the XRT error regions, while smaller circles mark the positions of the optical afterglows (when available). Arrows mark the positions of the hosts. For GRB 060502b, the bright galaxy to the south of the XRT position has been proposed as the host (Bloom et al. 2007), but we note that there is a faint galaxy within the XRT error circle (see also Bloom et al. 2007).

source of contamination. Below we provide an assessment of the brightest galaxies near each object and their associated probability of chance coincidence, compared to the faint galaxies coincident with the optical/X-ray afterglow positions.

Reduction of the Gemini data discussed below was performed using the GEMINI package in IRAF (for bias subtraction, flat-fielding, and frame co-addition). Magellan optical and near-IR observations were reduced using standard IRAF routines, including for the latter dark frame subtraction and fringe correction. Throughout the paper we use the standard cosmological parameters $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$.

2.1. GRB 051210

Optical observations of this burst were obtained with the Low Dispersion Survey Spectrograph (LDSS3) on the Magellan Clay 6.5 m telescope starting 19.4 hr after the burst for a total of 1200 s in the r band. These observations revealed a faint, extended object within the *Swift* X-Ray Telescope (XRT) error circle at R.A. = 22^{h}00^{m}40.93^s, decl. = $-57°36'47.1''$ (J2000.0; Bloom et al. 2005).

We obtained a deeper observation of this burst with the LDSS3 instrument on 2006 January 5 UT for a total exposure time of 1950 s in the r band. We detect the same extended object and measure its brightness to be $r_{AB} = 24.04 \pm 0.15$ mag in comparison to the Sloan Digital Sky Survey (SDSS) standard stars Feige 22 and G162-66; see Figure 1. No other sources are detected in the error circle to a 3 σ limit of $r_{AB} > 24.9$ mag. We further note that the nearest galaxies that are brighter than this putative host (with 21.6 and 20.4 mag) are located 23″ and 39″ from the center of the error circle, respectively (or, 115 and 195 kpc at $z \sim 0.3$–0.5). The expected number of such objects at these offsets is about 2 and 1.5, respectively (Beckwith et al. 2006). Thus, the large offsets and the order unity probability of chance coincidence suggest that they are not likely to be associated with the burst.

We further undertook spectroscopic observations[17] of the putative host with the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004) mounted on the Gemini-South 8 m telescope on

four consecutive nights, beginning on 2006 December 20.04 UT. A total of 9600 s were obtained using the nod-and-shuffle mode with the R400 grating at central wavelengths of 7250 and 7550 Å. The data were reduced using the GEMINI package in IRAF, while rectification and sky subtraction were performed using the method and software described in Kelson (2003). Wavelength calibration was performed using CuAr arc lamps, and air-to-vacuum and heliocentric corrections were applied. The final combined spectrum covers 5000–9500 Å at a resolution of about 7 Å. We detect weak continuum emission in each individual spectrum, but no clear emission or absorption features are detected in the combined spectrum. The lack of detectable [O II] $\lambda 3727$ emission (if the host is star-forming) indicates $z \gtrsim 1.55$, while the lack of a clear Balmer/4000 Å break (if the host is early-type) indicates $z \gtrsim 1.4$; we use the latter as a robust lower limit on the redshift.

2.2. GRB 051227

The optical afterglow was initially found in a pair of observations obtained 10.4 and 12.5 hr after the burst with the Very Large Telescope (VLT; Malesani et al. 2005). We contemporaneously observed the burst position with GMOS on the Gemini-North 8 m telescope, starting 13.9 hr after the burst for a total exposure time of 1500 s in the r band, and confirmed the presence of the optical source with $r_{AB} = 25.00 \pm 0.12$ mag. The position of the source is R.A. $= 08^h 20^m 58.11^s$, decl. $= +31°55'32.0''$ (J2000.0) with an uncertainty of $0.08''$ in each coordinate relative to the SDSS.

Additional observations with GMOS were obtained 38.6 and 62.4 hr after the burst for total exposures of 1500 and 1800 s, respectively, and confirmed that the object has faded between the first and second observations. The brightness of the object remains constant between the second and third observations, indicating the presence of the host galaxy. From the final observation, we measure for the host $r_{AB} = 25.78 \pm 0.15$ mag (Fig. 1). The positional offset between the afterglow and host is only $0.05'' \pm 0.02''$. The probability of chance coincidence at such a radius and brightness level is about 2×10^{-4}. We note that a brighter galaxy ($r_{AB} = 22.28 \pm 0.05$ mag) is located $4.6''$ away from the optical afterglow position, but its probability of chance coincidence is about 20% (Beckwith et al. 2006), significantly larger than for the underlying galaxy. Either way, the redshift of this galaxy is $z = 0.714$ (Foley et al. 2005), higher than for the previous short bursts.

2.3. GRB 060121

The optical afterglow was found by several groups starting 2 hr after the burst. Details are provided in de Ugarte Postigo et al. (2006) and Levan et al. (2006). These authors found that the afterglow has an unusually red $R - K$ color, suggestive of extinction and/or a Lyman break. The preferred redshift is $z \sim 1.7$ or ~ 4.6 (de Ugarte Postigo et al. 2006; Levan et al. 2006). In addition, Hubble Space Telescope (HST) observations with the Advanced Camera for Surveys (ACS) and the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) revealed an extended object coincident with the position of the afterglow with $F606W_{AB} = 27.0 \pm 0.3$ and $F160W_{AB} = 24.5 \pm 0.2$ mag (Levan et al. 2006).

We observed the position of the afterglow with GMOS on Gemini-North, starting on 2006 February 1.54 UT for a total exposure time of 1080 s in the r band, and 1050 s in i band. We detect the galaxy noted by Levan et al. (2006) and measure its brightness at $r_{AB} = 26.2 \pm 0.3$ mag and $i_{AB} > 25.9$ mag (3 σ) relative to several nearby stars with SDSS photometry (Cool et al. 2006; see Fig. 1).

In addition, we obtained the ACS and NICMOS data from the HST archive and processed the images using the MultiDrizzle routine (Fruchter & Hook 2002) in the STSDAS package of IRAF. The NICMOS images were first reprocessed with an improved dark frame created from the Hubble Ultra Deep Field (HUDF) using the IRAF task `calnica` in the NICMOS package. We measure for the host galaxy $F606W_{AB} = 27.2 \pm 0.3$ and $F160W_{AB} = 24.8 \pm 0.1$ mag, consistent with the values given by Levan et al. (2006). Images of the host are shown in Figure 2.

We note that our detection of the host in the r band ($\lambda_{eff} = 630$ nm) is about 1 mag brighter than the F606W flux ($\lambda_{eff} = 590$ nm). This is possibly indicative of a Lyman break at $\lambda \approx 610$ nm, or $z \approx 4$, in good agreement with the redshift estimated from the afterglow colors. At this redshift, the isotropic-equivalent energy is $E_{\gamma, iso} \approx 1.5 \times 10^{53}$ ergs, substantially larger than that of any other short GRB to date (see also de Ugarte Postigo et al. 2006).

Finally, for the nearby red galaxies noted by Levan et al. (2006; see Fig. 2), we measure, from our Gemini data and the NICMOS data, $(i - H)_{AB} > 2.7, >3.0, >2.1$, and >2.3 mag. From the ACS data we find a 3 σ limit of $V > 27.6$ mag in a $0.6''$ aperture, leading to colors of $(V - H)_{AB} > 4.4, >4.6, >3.8$, and >4.0 mag. The nearest of these red galaxies is located $8.7''$ away from the afterglow position, or about 70 kpc at $z \sim 1$. These galaxies represent an overdensity by about a factor of 20 (Levan et al. 2006), but the large separation likely indicates that they are not related to the burst. We note that even if they are related, they likely reside at $z > 1$ (Levan et al. 2006).

2.4. GRB 060313

The optical afterglow was discovered with the VLT, the Danish 1.5 m telescope, the Swift Ultraviolet/Optical Telescope (UVOT), and our Gemini observations (Levan & Hjorth 2006; Thoene et al. 2006; Schmidt et al. 2006; Schady & Pagani 2006). We observed the position of the burst with GMOS on Gemini-South, starting 71 minutes after the burst for a total of 1800 s in the r band. We clearly detect the afterglow with $r_{AB} = 19.99 \pm 0.02$ mag relative to several nearby USNO stars (the systematic uncertainty is 0.18 mag). Follow-up observations with GMOS were obtained 1.01 days (900 s exposure) and 2.02 days (1500 s exposure) after the burst, confirming that the source has faded to 22.47 ± 0.07 and 23.58 ± 0.14 mag, respectively; see Figure 3. Finally, we observed the afterglow position on 2006 March 22 UT (10 days after the burst) for a total exposure time of 1800 s, but did not detect the afterglow to a 3 σ limit of $r_{AB} > 24.7$ mag (Fig. 3). A faint galaxy is detected about $0.4''$ from the position of the afterglow in HST ACS observations with $F775W_{AB} = 26.2 \pm 0.2$ and $F475W_{AB} = 26.8 \pm 0.2$ mag (D. B. Fox et al. 2007, in preparation). The probability of chance coincidence is only 4×10^{-3} (Beckwith et al. 2006).

The nearest bright galaxy has $r_{AB} \approx 18.7$ mag and is located about $27''$ away (or about 80 kpc at $z \sim 0.2$) from the optical afterglow position. The probability of chance coincidence for this galaxy is about 0.06, significantly larger than for the faint galaxy. Moreover, the detection of a bright optical afterglow from this burst requires a circumburst density, $n \gtrsim 10^{-3}$ cm^{-3} (e.g., Soderberg et al. 2006), which is unlikely at such a large offset from the host galaxy, where we would expect densities similar to the intergalactic medium.[18] We therefore consider this galaxy to be a chance association.

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[18] If the burst occurred in a globular cluster associated with the nearby galaxy, the density may be sufficient to produce an afterglow.
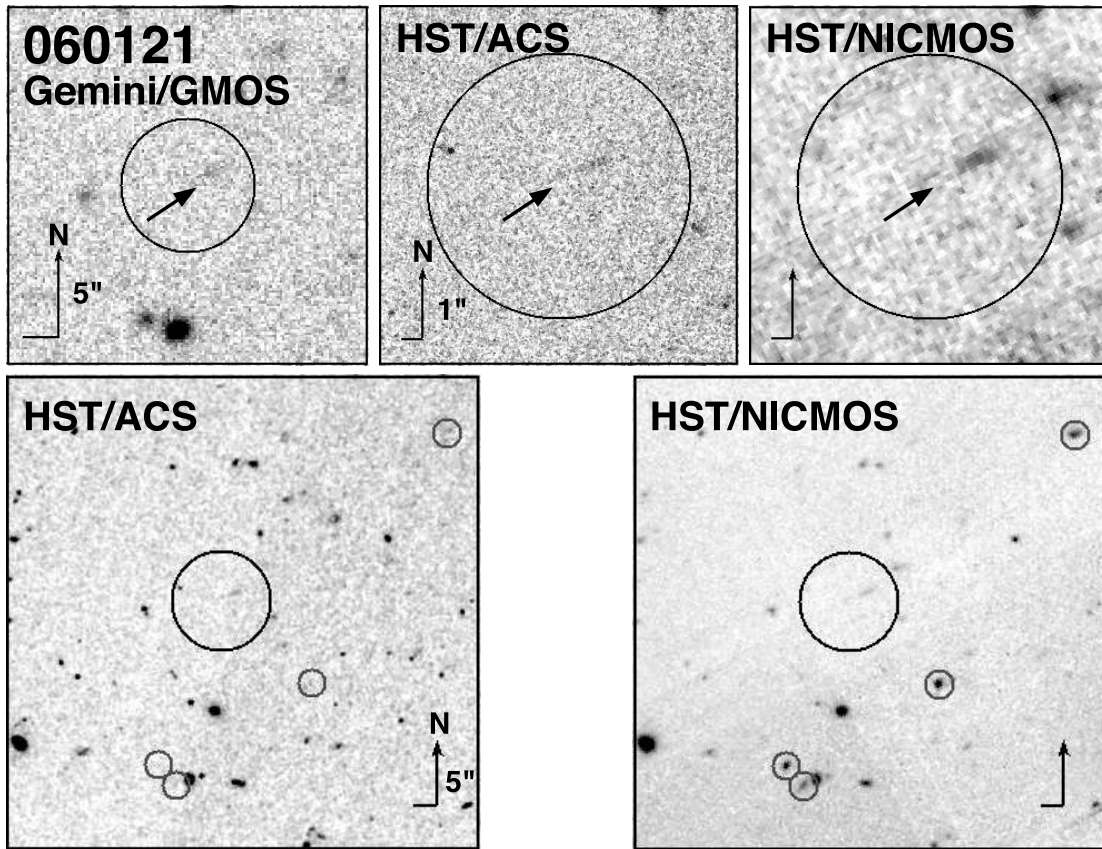
FIG. 2.—Gemini r-band and *HST* ACS F606W and NICMOS F160W observations of the host galaxy of GRB 060121. The black circles mark the XRT error region. The two bottom panels provide a larger view of the field, with four nearby very red galaxies marked by gray circles (see also Levan et al. (2006). [*See the electronic edition of the Journal for a color version of this figure.*]

Finally, we obtained from the European Southern Observatory archive VLT observations taken with the Infrared Spectrometer and Array Camera (ISAAC) on 2006 March 21.41 (K_s band; 1320 s), March 29.99 (J band; 800 s), and March 30.10 UT (H band; 650 s). No object is detected at the position of the afterglow to 3 σ limits of $K_{AB} > 22.9$ mag, $H_{AB} > 21.0$ mag, and $J_{AB} > 20.9$ mag relative to a nearby Two Micron All Sky Survey (2MASS) star.

2.5. GRB 060502b

Initial optical observations revealed a single object within the XRT error circle (Halpern & Mirabal 2006; Berger et al. 2006). We obtained spectroscopy of this object with GMOS on Gemini-North and showed that it is an M giant star (Berger et al. 2006). We further imaged the position of the burst with GMOS, starting

16.8 hr after the burst for a total exposure time of 1500 s in the r band. In addition to the star noted above, we detect a faint object within the XRT error circle with $r_{AB} = 23.95 \pm 0.13$ mag relative to USNO-B (with a systematic uncertainty of 0.35 mag). *HST* ACS observations reveal that this object has a stellar point-spread function and is hence unlikely to be the host (D. B. Fox et al. 2007, in preparation).

A second r-band observation with GMOS was obtained 40.8 hr after the burst for a total exposure time of 1500 s. Due to improved seeing conditions (0.5″ vs. 0.95″ in the first image), we detect an additional faint source, not clearly visible in our first epoch, for which we measure $r_{AB} = 25.22 \pm 0.18$ mag (with a systematic uncertainty of 0.4 mag); see Figure 1. This object was also noted by Bloom et al. (2007), who proposed instead that the host is a bright galaxy 17.5″ (or about 70 kpc) south of the XRT error
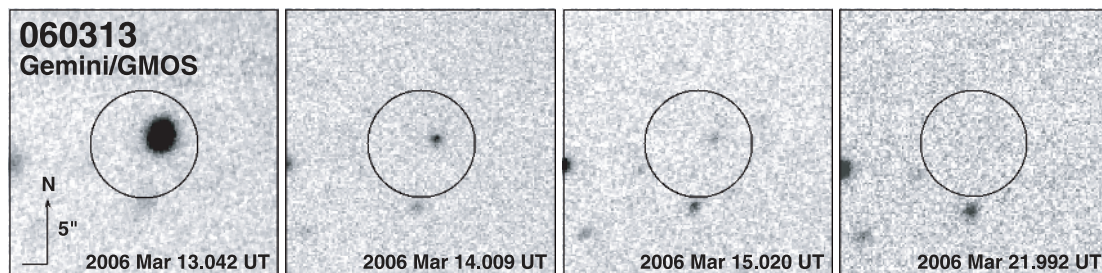

FIG. 3.—Gemini r-band observations of the afterglow of GRB 060313. The fading behavior is evident. No host galaxy is detected at the position of the afterglow 10 days after the burst, to a 3 σ limit of $r > 24.7$ mag. However, a faint galaxy is detected within 0.4″ of the afterglow position in *HST* ACS images with F775W(AB) = 26.2 ± 0.2 mag (D. B. Fox et al. 2007, in preparation). We note that the source ellipticity in the initial epoch is due to the image quality.
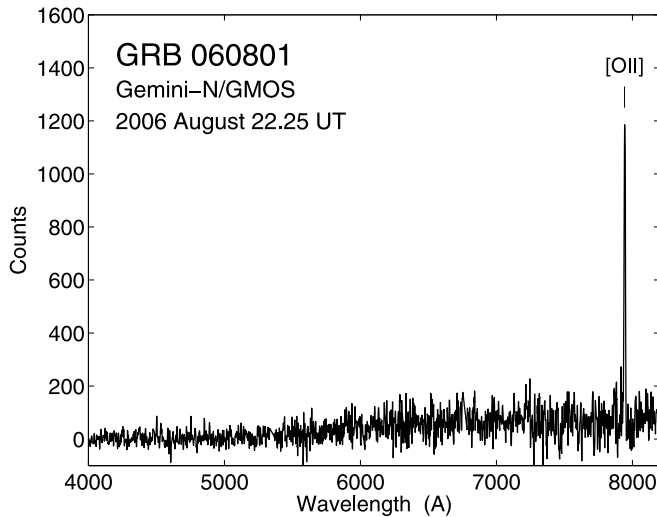
Fig. 4.—Gemini GMOS spectrum of the putative host galaxy of GRB 060801, smoothed with a 3 pixel boxcar. We detect a single bright emission line, which we identify as the [O II]λ3727 doublet at $z = 1.1304$.

circle (Fig. 1). In this scenario the large offset requires a progenitor kick of $v > 55$ km s^{-1} (Bloom et al. 2007). This proposed association is based on a probability of chance coincidence of about 0.03 (see § 3).

2.6. GRB 060801

Optical observations revealed four objects within the initial XRT error circle, ranging in brightness from $R \approx 22$ to 24.6 mag, of which none revealed any variability between 0.5 and 1.5 days after the burst (Castro-Tirado et al. 2006; Piranomonte et al. 2006a, 2006b). Only two of these sources are located within the revised XRT error circle, with $R = 23.7$ mag (source B) and 24.6 mag (source D), and extended morphologies (Piranomonte et al. 2006b). We obtained imaging observations of the burst with the Large Format Camera on the Hale 200 inch (5 m) telescope, starting 16.0 hr after the burst for a total exposure time of 1500 s in the r band. Photometry of the two extended sources relative to several nearby SDSS stars indicates $r_{AB} = 23.20 \pm 0.11$ and 24.1 ± 0.3 mag, respectively, somewhat brighter than the magnitude quoted in the GCN circular. We note that the nearest galaxies with significantly brighter magnitudes ($r_{AB} \approx 19.8$–20.5 mag) are located $40''$–$70''$ away from the XRT position. The probability of chance coincidence for these galaxies is of order unity.

We obtained spectroscopic observations of source B with GMOS on Gemini-North on 2006 August 22.25 UT, for a total exposure time of 1800 s with the R400 grating at a central wavelength of 6050 Å. The data were reduced using the GEMINI package in IRAF, while rectification and sky subtraction were performed using the method and software described in Kelson (2003). Wavelength calibration was performed using CuAr arc lamps, and air-to-vacuum and heliocentric corrections were applied. The spectrum covers 4000–8200 Å at a resolution of about 7 Å. We detect weak continuum emission and a single broad (FWHM ≈ 11 Å) emission line at a wavelength of 7943.19 Å, which we identify as the barely resolved [O II]λ3727 doublet at $z = 1.1304$ (Fig. 4). We note that all things being equal, source D, which is a factor of 2 fainter, is likely to reside at an even higher redshift.

At $z = 1.1304$, the putative host galaxy has an absolute magnitude $M_B \approx -21$ mag, or $L_B \approx L^*$, compared to the luminosity function of $z \sim 1.1$ galaxies in the DEEP2 survey (Willmer et al. 2006). In addition, the isotropic equivalent energy of the burst at this redshift is $E_{\gamma,\mathrm{iso}} = (2.7 \pm 0.3) \times 10^{50}$ ergs.

2.7. GRB 061006

Optical observations with the VLT revealed a single object within the XRT error circle of this burst, which faded by about 0.5 mag between 14.6 and 38.4 hr after the burst (Malesani et al. 2006a, 2006b). We observed the position of the afterglow with GMOS on Gemini-South, starting 3.6 days after the burst. A total of 900 and 1440 s were obtained in the i and r bands, respectively. We detect a faint, extended object coincident with the afterglow at R.A. = $07^h24^m07.75^s$, decl. = $-79°11'55.3''$ (J2000.0), with an uncertainty of about $0.16''$ relative to several nearby 2MASS stars (Fig. 1). Photometry of this object relative to USNO-B indicates $r_{AB} = 24.18 \pm 0.09$ mag (with a systematic uncertainty of 0.26 mag) and $i_{AB} = 23.11 \pm 0.09$ mag (with a systematic uncertainty of 0.30 mag). We note that there are no other significantly brighter galaxies within about $45''$ of the afterglow position.

In addition, we observed the position of this source with Persson's Auxiliary Nasmyth Infrared Camera (PANIC) on the Magellan Baade 6.5 m telescope on 2006 October 8.39 UT in Y band for a total of 960 s. We detect an extended source coincident with the optical position with $Y = 22.0 \pm 0.2$ mag using a Y-band zero point of 25.06 mag for PANIC, measured on 2006 August 21 (C. Burns 2006, private communication). We estimate the uncertainty in the zero point to be about 30%.

Finally, we obtained spectroscopic observations of the putative host galaxy with GMOS on Gemini-South on 2006 November 20.31 UT for a total exposure time of 3600 s using the nod-and-shuffle mode with the R400 grating at a central wavelength of 7200 Å. The data were reduced using the GEMINI package in IRAF, while rectification and sky subtraction were performed using the method and software described in Kelson (2003). Wavelength calibration was performed using CuAr arc lamps, and air-to-vacuum and heliocentric corrections were applied. The spectrum covers 4900–9200 Å at a resolution of about 7 Å. We detect weak continuum emission and several emission lines corresponding to [O II]λ3727, Hβ, [O III]λ4959, and [O III]λ5007 at $z = 0.4377 \pm 0.0002$ (Fig. 5).

At this redshift, the putative host galaxy has an absolute magnitude $M_B \approx -18.6$ mag, or $L_B \approx 0.1 L^*$, compared to the luminosity function of $z \sim 0.5$ galaxies in the DEEP2 survey (Willmer et al. 2006). In addition, the isotropic equivalent energy of the burst at this redshift is $E_{\gamma,\mathrm{iso}} = (6.9 \pm 0.5) \times 10^{50}$ ergs.

2.8. GRB 061210

We observed the BAT error circle with GMOS on Gemini-North on two separate occasions: 2.1 and 25.6 hr after the burst. Digital image subtraction using the ISIS software package (Alard & Lupton 1998) revealed no variable sources to a limit of $r_{AB} > 23.5$ mag at the time of the first observation. The subsequent detection of two X-ray sources within the BAT error circle (Godet et al. 2006) allowed us to propose candidate host galaxies, of which the brightest has $r_{AB} = 21.00 \pm 0.02$ mag and is located at R.A. = $09^h38^m05.36^s$, decl. = $+15°37'18.8''$ (J2000.0), with an uncertainty of about $0.25''$ relative to USNO-B (Fig. 1). The XRT source containing this galaxy eventually faded (Racusin et al. 2006), confirming that it is likely the host galaxy of GRB 061210. We note that the nearest galaxies that are brighter than the putative host (by about 1.8 mag) are located about $45''$ and $60''$ away from the X-ray afterglow position.

We obtained spectroscopic observations of the putative host with LDSS3 on the Magellan/Clay 6.5 m telescope on 2006 December
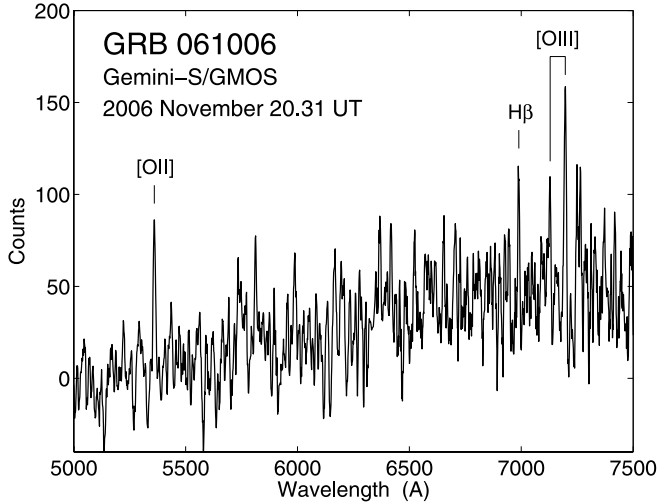
FIG. 5.—Gemini GMOS spectrum of the putative host galaxy of GRB 061006, smoothed with a 7 pixel boxcar. We detect several emission lines corresponding to [O II]λ3727, Hβ, [O III]λ4959, and [O III]λ5007 at $z = 0.4377 \pm 0.0002$.
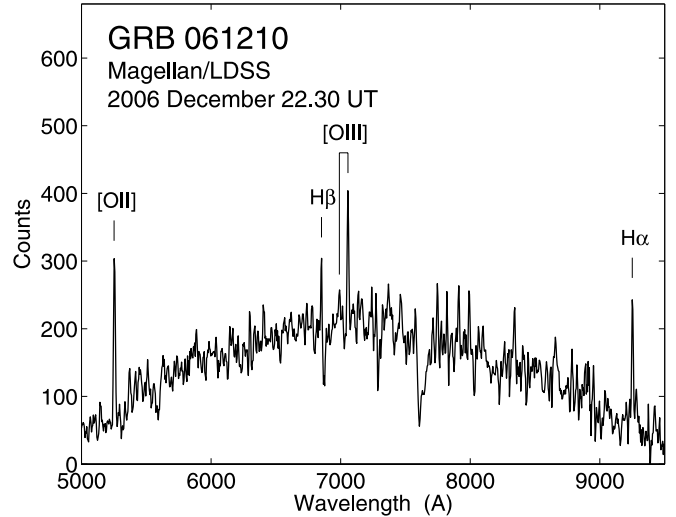

FIG. 6.—Magellan LDSS3 spectrum of the putative host galaxy of GRB 061210, smoothed with a 3 pixel boxcar. We detect several emission lines corresponding to [O II]λ3727, Hβ, [O III]λ4959, [O III]λ5007, and Hα at $z = 0.4095 \pm 0.0001$.

22.30 UT, for a total exposure time of 4400 s. The data were reduced using standard IRAF packages, while rectification and sky subtraction were performed using the method and software described in Kelson (2003). Wavelength calibration was performed using HeNeAr arc lamps, and air-to-vacuum and heliocentric corrections were applied. The spectrum covers 3500–9800 Å at a resolution of about 7 Å. We detect several emission lines corresponding to [O II]λ3727, Hβ, [O III]λ4959, [O III]λ5007, and Hα at $z = 0.4095 \pm 0.0001$ (Fig. 6).

At this redshift the putative host galaxy has an absolute magnitude $M_B \approx -20.4$ mag, or $L_B \approx 1.5\ L^*$, compared to the luminosity function of $z \sim 0.4$ galaxies in the DEEP2 survey (Willmer et al. 2006). In addition, the isotropic equivalent energy of the burst at this redshift is $E_{\gamma,\mathrm{iso}} = (4.6 \pm 0.8) \times 10^{50}$ ergs.

2.9. GRB 061217

We observed the XRT error circle of GRB 061217 (Evans et al. 2006) with LDSS3 on the Magellan 6.5 m telescope on 2006 December 21.36 UT for a total of 600 s in the r band. This led to the identification of an extended object with $r_{AB} = 23.33 \pm 0.07$ located at R.A. = $10^h 41^m 39.08^s$, decl. = $-21°07'28.7''$ (J2000.0), with an uncertainty of about $0.28''$ relative to USNO-B (Fig. 1). No brighter galaxies are detected within a radius of about $80''$.

We obtained spectroscopic observations of the putative host with LDSS3 on 2006 December 22.24 UT, for a total exposure time of 4100 s. The data were reduced using standard IRAF packages, while rectification and sky subtraction were performed using the method and software described in Kelson (2003). Wavelength calibration was performed using HeNeAr arc lamps, and air-to-vacuum and heliocentric corrections were applied. The spectrum covers 4500–9500 Å at a resolution of about 6 Å. We detect a single bright and resolved emission line, which we identify as the [O II]λ3727 doublet at $z = 0.8270$ (Fig. 7).

At this redshift the putative host galaxy has an absolute magnitude $M_B \approx -19.6$ mag, or $L_B \approx 0.5\ L^*$, compared to the luminosity function of $z \sim 0.8$ galaxies in the DEEP2 survey (Willmer et al. 2006). In addition, the isotropic equivalent energy of the burst at this redshift is $E_{\gamma,\mathrm{iso}} = (8.3 \pm 1.4) \times 10^{49}$ ergs.

3. A $z \sim 1$ HOST GALAXY POPULATION

In order to address the redshift distribution of the new short GRBs in a robust way, we consider, in addition to the full sample

of nine events, the subset of unambiguous short bursts: 051210, 060313, 060502b, 060801, 061006, 061210, and 061217. The remaining two bursts (051227 and 060121) are most likely in the short-duration category (Barthelmy et al. 2005a; Donaghy et al. 2006) but have formal T_{90} durations of $\gtrsim 2$ s. The discussion of host redshift likelihoods below applies to all events, but for the purpose of burst statistics we consider both samples separately where appropriate.

The observed magnitudes of the candidate host galaxies (with the exception of GRB 061210), corrected for Galactic extinction, range from $R = 22.6$ to 26.3 mag; see Table 1. The distribution of magnitudes for our sample, as well as the low-redshift hosts detected previously, is shown in Figure 8. Overall, the host magnitudes range up to $R \approx 17$ mag. The two brightest hosts (050509b and 050724) are elliptical galaxies and would stand out from the distribution even more if we considered their near-IR brightness. We find that the median host brightness is $\langle R \rangle = 23.0 \pm 0.8$ mag, nearly 2 mag brighter than the median value of $\langle R \rangle = 24.8 \pm 0.5$ mag for the hosts of long GRBs.

The most crucial point demonstrated in Figure 8 is that the four secure redshifts previously available ($z = 0.1606-0.5465$) belong to the four brightest host galaxies. This is not surprising given the relative ease of spectroscopic follow-up for galaxies with $R \lesssim 22$ mag. Similarly, the four redshifts presented in this paper, $z \approx 0.4-1.1$, belong to the next four brightest hosts, and the highest ones ($z = 0.827$ and 1.130) are measured for the hosts with $R \approx 23$ mag. Extending this trend to the rest of the faint host sample, we conclude that they most likely reside at $z \sim 1$ and beyond; see Figure 9.[19] In addition, we note that the new hosts with measured spectroscopic redshifts continue the trend that short GRBs occur in $\sim L^*$ galaxies (Table 1).

If on the other hand we were to argue that the faint hosts are located at a low redshift, $z \lesssim 0.5$, then the implied absolute magnitudes would be $M_B \gtrsim -17$ mag, or $L \lesssim 0.01\ L^*$. This is 10–100 times fainter than the previously detected low-redshift hosts, again pointing to a difference in the two host populations. We consider this possibility highly unlikely for two primary reasons.

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[19] We note that for GRB 060313 the limit on the redshift is $z \lesssim 1.7$, based on the detection of the afterglow in the UVOT UVW2 filter with $\lambda_{\mathrm{eff}} \approx 2000$ Å (Roming et al. 2006). For GRB 051210 the likely redshift is $z \gtrsim 1.4$ (§ 2.1).
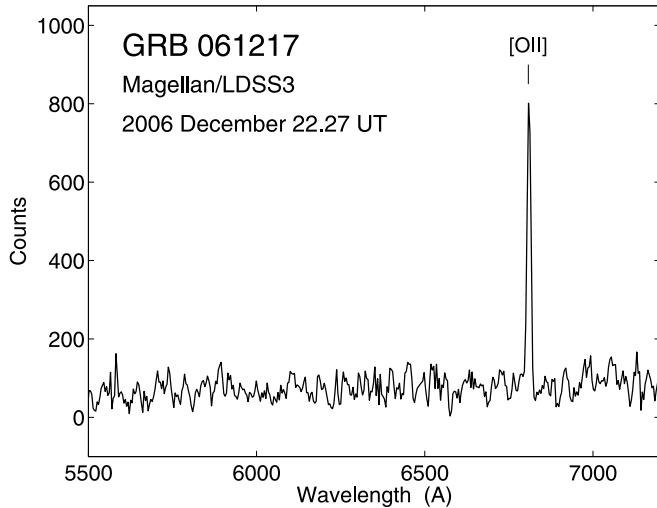
FIG. 7.—Magellan LDSS3 spectrum of the putative host galaxy of GRB 061217, smoothed with a 3 pixel boxcar. We detect a single bright emission line, which we identify as the [O II]λ3727 doublet at $z = 0.8270$.

First, the two faintest hosts for which we do have a spectroscopic redshift are located at $z = 0.827$ and 1.130 in L^* galaxies; the remaining five hosts are even fainter and are therefore likely to be at even higher redshifts (Table 1). Similarly, for GRB 060121 the probability that it is located at $z < 0.5$ is only 5×10^{-3}, based on the afterglow spectral energy distribution (de Ugarte Postigo et al. 2006), and GRB 051210 resides at $z \gtrsim 1.4$. Second, even in the sample of long GRBs, which *are* thought to be biased in favor of low-luminosity galaxies (Fruchter et al. 2006; Stanek et al. 2006), all galaxies with $R > 23$ mag are located at $z > 0.7$ (Fig. 9).

Our conclusion that the hosts are located at $z \sim 1$ is further supported by a comparison to large galaxy samples with spectroscopic and photometric redshifts (Cowie et al. 2004; Wirth et al. 2004; Coe et al. 2006). As shown in Figure 9, there is a clear trend of decreasing brightness with redshift, which is also seen in the
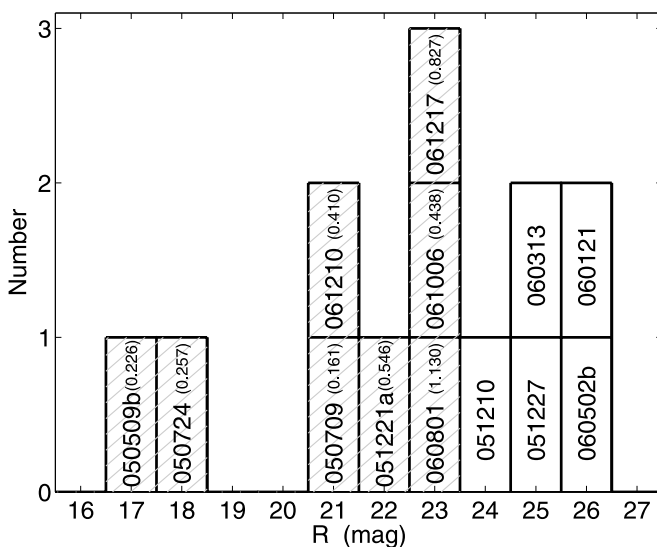

FIG. 8.—Histogram of observed R-band magnitudes for the host galaxies of short GRBs. Hatched bars mark the hosts for which we have a measured redshift. Clearly, the low-redshift hosts are at the bright end of the distribution, and their redshifts are therefore not representative of the entire sample. On the other hand, the hosts with $z > 1$ appear to be more representative of the faint hosts, suggesting that these galaxies are also located at $z \gtrsim 1$.
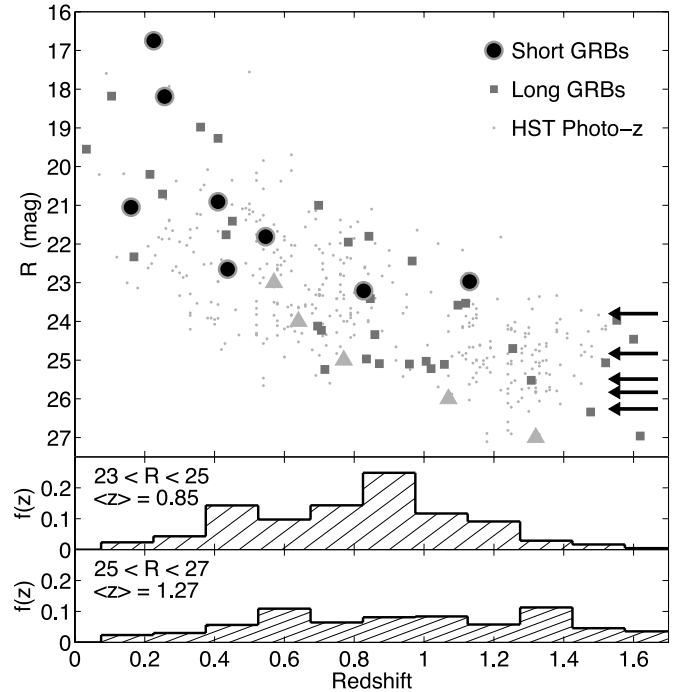

FIG. 9.—Host galaxy R magnitudes (corrected for Galactic extinction; Schlegel et al. 1998) plotted vs. redshift for short GRBs (*circles, arrows*), long GRBs (*squares*), and galaxies in the *HST* ACS Early Release Observation fields VV 29 (UGC 10214) and NGC 4676 (Benítez et al. 2004). In all samples, we observe a trend of increasing apparent magnitude with redshift. The triangles indicate the median redshift of a galaxy sample complete to the appropriate magnitude limit (Coe et al. 2006). For $R \gtrsim 26$ mag, appropriate for our sample, the median redshift is about 1.1. The bottom panels show the redshift distributions of galaxies in two magnitude bins from spectroscopic (23 mag $< R < 25$ mag; Cowie et al. 2004; Wirth et al. 2004) and photometric (25 mag $< R < 27$ mag; Coe et al. 2006) redshift surveys. The clear magnitude-redshift relation for short GRB hosts suggests that the faint host galaxies discussed in this paper are located at $z \sim 1$. [*See the electronic edition of the Journal for a color version of this figure.*]

sample of short GRBs with a measured redshift. As mentioned above, even the subset of long GRB hosts with $R > 23$ mag resides exclusively at $z > 0.7$. Similarly, the median redshift of galaxies with $23 < R < 25$ mag in the GOODS region is about 0.85 (Cowie et al. 2004; Wirth et al. 2004), while galaxies with $25 < R < 27$ mag in the HUDF have a median (photometric) redshift of about 1.3 (Coe et al. 2006). The HUDF sample also indicates that for a limiting magnitude of $R \approx 26$ mag, appropriate for our sample of faint short GRB hosts, the expected median redshift of a typical galaxy sample is about 1.1 (Coe et al. 2006). Making the reasonable assumption that the hosts without a measured redshift are drawn from the general population of galaxies, based on the various arguments provided above, we conclude that they likely reside at $z \gtrsim 1$.

To provide formal constraints, we note that in the GOODS and HUDF galaxy samples 70% of the galaxies with 23 mag $< R < 27$ mag are located at $z > 0.7$. For our sample of seven unambiguous short bursts, there is therefore a 97% probability that at least three reside at $z > 0.7$ (as confirmed by the measured spectroscopic redshifts). Considering the full sample of nine events, the corresponding number is four galaxies. For a limiting redshift of $z = 0.55$, corresponding to the highest redshift previously measured for a short GRB, the fraction of field galaxies with 23 mag $< R < 27$ mag above this redshift is 84%. Therefore, there is a 97% probability that four bursts in the unambiguous sample reside at $z > 0.55$, or five out of the full sample. Based on the secure host identifications, it appears that short GRB hosts

are drawn from the bright end of the galaxy luminosity function (Fig. 9). This implies that the inferred fraction at $z > 0.7$, or alternatively the inferred median redshift, is probably even higher than the values above.

Finally, we stress that four of the nine bursts have optical afterglow positions, making the host associations highly likely. In fact, taking a conservative positional uncertainty of $0.2''$ radius for these bursts, the probability of chance coincidence at $R = 23$ mag (26 mag) is only about 3.5×10^{-4} (3.5×10^{-3}) using the cumulative galaxy number counts in the HUDF and GOODS (Beckwith et al. 2006). The median brightness of these four hosts is $\langle R \rangle \approx 25.2$ mag, indicating that our inference of a high-redshift origin is robust. As noted above, with such low probabilities of chance coincidence the possibility that these bursts were instead ejected from nearby brighter galaxies is highly unlikely.

For the other five events, two of the putative hosts (051210 and 061210) are the only sources within the XRT error circle to the limit of our observations, while for GRBs 060502b, 060801, and 061217, there may be more than one galaxy within the error circle, but they are all *fainter* than our putative hosts (Fig. 1; see also Bloom et al. 2007). While the chance coincidence probability is high ($\sim 0.1-1$) for galaxies of similar or brighter magnitude within the XRT error circles, the lack of viable nearby bright alternatives for GRBs 051210, 060108, 061210, and 061217 (§ 2) indicates that our identified hosts are secure (or that the hosts are even fainter).

This leaves the host of GRB 060502b, which was proposed to be a bright galaxy $17.5''$ (or about 70 kpc) south of the XRT error circle (Fig. 1; Bloom et al. 2006a). In this scenario the large offset requires a progenitor kick of $v > 55$ km s^{-1} (Bloom et al. 2006a). This proposed association is based on both a probability of chance coincidence of about 3% for the putative bright host (compared to order unity for the faint galaxies *within* the XRT error circle), and its similarity to the hosts of GRBs 050509b and 050724. However, based on the sample presented here, we suggest that the ejection scenario is not required. First, GRBs 050724, 050709, and 051221a did not have substantial offsets from their hosts. Moreover, we show here that the bursts with precise optical afterglow positions are coincident with faint hosts. Thus, in none of the secure cases do we find evidence for a required offset. In fact, there is a 33% chance probability that 1 of the 13 bursts with positional accuracies better than $\sim 6''$ will be located within $17.5''$ of a bright galaxy as the one proposed by Bloom et al. (2007), given a single-trial probability of 3%. With such a high probability of chance coincidence, it cannot be convincingly argued that GRB 060502b was ejected from its host.

Second, as can be seen in Figure 8, the hosts of GRBs 050509b and 050724 do not appear to be representative of the general short GRB host population. We therefore argue that the coincidence of at least half of the short GRBs with galaxies fainter than $R \approx 23$ mag suggests that the host of GRB 060502b is most likely one of the faint galaxies within the XRT error circle. While there is a higher probability of chance coincidence for such faint galaxies, this association removes the need for a (model-dependent) progenitor kick. With the existence of the new sample of faint hosts, future evidence for significant offsets (and hence progenitor kicks) will have to rely on a large statistical sample rather than individual cases, or on a direct determination of the burst redshift from an absorption spectrum, which coincides with the redshift of an offset galaxy.

4. DISCUSSION

We present optical observations from Magellan, Gemini, and *HST* for nine short GRBs, of which four have subarcsecond po-

sitions from optical afterglow detections, and the rest are localized to better than a $6''$ radius based on the X-ray afterglow. We find that eight of the nine bursts appear to be associated with galaxies fainter than $R \approx 23$ mag (and the remaining with an $R = 21$ mag galaxy), in contrast to previous short GRBs that were associated with galaxies brighter than $R \approx 22$ mag at $z \lesssim 0.5$. This suggests that the new hosts reside at higher redshifts, and indeed our spectroscopic redshifts are in the range $z \approx 0.4-1.1$, with the two faintest hosts residing at the highest redshifts.

Using the conservative subset of unambiguous short bursts, we conclude at the 97% confidence level that at least three short GRBs from our sample originated at $z > 0.7$; for the full sample, the corresponding number is four. To this sample we can add GRB 050813, which is most likely associated with a galaxy cluster at $z \sim 1.8$ and is certainly located beyond $z = 0.72$ (Berger 2006; Prochaska et al. 2006). Thus, we conclude that in either the full or the unambiguous samples at least $\frac{1}{3}$ of the short bursts are located at $z > 0.7$, with an upper bound of about 60%. This conclusion is therefore completely robust against ambiguity about the nature of some of these short GRBs. We note that such a redshift distribution has been predicted in the context of NS-NS and NS-BH progenitors by Belczynski et al. (2006), with peak redshifts of $z \sim 1$ and ~ 1.5, respectively.

We now address the implications of our results for the age and energy distributions of short GRBs. Analysis of the redshift and luminosity distributions of the first few short GRBs led to the conclusion that the progenitors experience a long time delay prior to the GRB explosion (Guetta & Piran 2006; Nakar et al. 2006; Hopman et al. 2006). The favored models required a delay of $\gtrsim 4$ Gyr, or a power-law distribution $P(\tau) \propto \tau^n$, with $n \gtrsim -1/2$ (Nakar et al. 2006). In addition, Zheng & Ramirez-Ruiz (2007) found $n \gtrsim 3/2$ from the ratio of short GRBs in early- and late-type galaxies at low redshift. The discovery of a high-redshift population now implies that not all progenitors are several gigayears old. In the context of a single age distribution, and assuming a single power-law luminosity function, models with a lognormal age distribution are required to be broad ($\sigma \gtrsim 1$) and with a characteristic age of $\tau_* \sim 4-8$ Gyr (see, e.g., Fig. 3 of Nakar et al. 2006). Narrow lognormal distributions ($\sigma \sim 0.3$) cannot reproduce both the low- and high-redshift samples.

Models with a power-law distribution, on the other hand, are required to have $-1 \lesssim n \lesssim 0$. The lower bound predicts about 60% of all short GRBs at $z > 0.7$, consistent with our upper limit of $\sim 60\%$, while the upper bound on n predicts about 25% at $z > 0.7$, consistent with our minimum estimate of $\sim \frac{1}{3}$. A distribution with $n = 3/2$ (Zheng & Ramirez-Ruiz 2007) predicts less than 10% of the short GRBs at $z > 0.7$, in conflict with our findings of $\sim 30\%-60\%$. We note that the allowed range of n-values is still consistent with existing data on the relative fraction of short GRBs in cluster versus field early-type galaxies (Berger et al. 2007; Shin & Berger 2007). Additional spectroscopic redshifts are required for further refinement of the age distribution, but the new limits already suggest that the typical ages are shorter than previously deduced.

The existence of a population of short GRBs at $z \sim 1$ also indicates that the energy release of some events may be larger than previously suspected. For the bursts with spectroscopic redshifts presented in this paper, we find that the γ-ray fluences (Table 1) correspond to isotropic equivalent energies of $E_{\gamma,\mathrm{iso}} \sim 10^{50}-10^{51}$ ergs. For the remaining bursts, assuming $z = 1$, we find $E_{\gamma,\mathrm{iso}} \sim 10^{50}-10^{52}$ ergs, and possibly $\sim 10^{53}$ ergs for GRB 060121 if it is located at $z \sim 4$ (§ 2.3). This can be contrasted with $E_{\gamma,\mathrm{iso}} \approx$ few $\times 10^{48}$ ergs for GRBs 050509b, 050709, and 050724 (Berger et al. 2005b; Fox et al. 2005; Bloom et al. 2006), and a beaming-corrected $E_\gamma \approx 1.5 \times 10^{49}$ ergs for GRB 051221a

(Burrows et al. 2006; Soderberg et al. 2006). If beaming corrections are not significant, the inferred energies in excess of $\sim 10^{51}$ ergs are difficult to explain in models of $\nu\bar{\nu}$ annihilation (Rosswog & Ramirez-Ruiz 2002). This may point to energy extraction via magnetohydrodynamic processes (e.g., Blandford & Znajek 1977). On the other hand, if the true energy release of all short GRBs is about 10^{49} ergs, then the required jet opening angles for the high-redshift bursts are about $10°$. This is consistent with the opening angle inferred for GRB 051221a (Burrows et al. 2006; Soderberg et al. 2006).

Finally, we reiterate that there is growing interest in the possible detection of gravitational waves from short GRBs in the context of compact object mergers (Dalal et al. 2006; Nakar et al. 2006). This is partly because the detection of gravitational waves will provide insights about the underlying system (e.g., degree of beaming, masses of the constituents), while nondetection will rule out the binary merger model. Moreover, from the point of view of gravitational-wave detection of astrophysical sources, short GRBs provide a clean signal, thanks to directional and temporal information. At the current sensitivity of LIGO ($d \lesssim 20$ Mpc; Cutler & Thorne 2002), it is unlikely that short GRBs will be detected in the absence of significant beaming and a low-luminosity population (Nakar et al. 2006).

However, the order of magnitude increase in sensitivity for advanced LIGO should broaden the science reach dramatically. At the predicted advanced LIGO sensitivity, a binary with 1.4 $M_\odot$ constituents would be detectable out to ~ 520 Mpc (here we follow Dalal et al. 2006).[20] If short GRBs are beamed (Burrows et al. 2006; Soderberg et al. 2006), the three-station detectability increases to ~ 580 Mpc. In the optimal case of a face-on binary directly overhead, the maximum distance is ~ 1.3 Gpc ($z = 0.26$). We also note that the addition of a fourth observatory (e.g., AIGO[21]) would increase these values to 600, 675, and 1500 Mpc, respectively.

With the full sample of events found previously and presented in this paper, we find that at most $\frac{1}{3}$ of the short bursts are located within $z \lesssim 0.25$ (compared to $\frac{5}{8}$ found by Gal-Yam et al. [2005] and Nakar et al. [2006]). With the detectability distances quoted above, this leads to an expected event rate for advanced LIGO of about 6 yr^{-1}, using the Burst and Transient Source Experiment (BATSE) all-sky rate of 170 yr^{-1}. Alternatively, we note that of the rough observed rate of three bursts per year at $z < 0.3$, one (050709) is within the range of detectability of an advanced LIGO network. With a constant comoving density, this indicates that $\sim 10\%$ of the $z < 0.3$ bursts would be detectable, or an extrapolated all-sky rate of ~ 2 yr^{-1}. Thus, even with no additional correction factors for beaming and low-luminosity events, we find an expected advanced LIGO rate of ~ 2–6 yr^{-1}, indicating that simultaneous operations of this network and a γ-ray satellite are of crucial importance (see also Nakar et al. 2006).

The observations presented in this paper move us a step closer to an unbiased view of short GRBs. In the near term, additional spectroscopic redshifts for the faint host population are essential. In addition to confirming the distance scale of these galaxies, the spectra will also provide an indication of the host types (early vs. late), the age of the dominant stellar population, star formation rates, and possibly associations with galaxy clusters or groups (Berger et al. 2007; Shin & Berger 2007). This information, along with morphological classification from *HST* observations (D. B. Fox et al. 2007, in preparation), will allow us to refine the determination of progenitor ages (Gal-Yam et al. 2005; Shin & Berger 2007; Zheng & Ramirez-Ruiz 2007), as well as the distribution of energy release and the expected rate for future gravitational-wave experiments.

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[20] With the two LIGO observatories and the Virgo detector operational, the detection requires a signal-to-noise ratio S/N > 7, or each individual detector to have S/N > $7/\sqrt{3}$ = 4. Our maximum distance is for an average over all possible inclinations of the binary, and over all possible sky positions.

[21] See http://www.gravity.uwa.edu.au/docs/aigo_prospectus.pdf.

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