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THE GALAXY HOSTS AND LARGE-SCALE ENVIRONMENTS OF SHORT-HARD GAMMA-RAY BURSTS

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ABSTRACT

The rapid succession of discoveries of short-duration hard-spectrum gamma-ray bursts (GRBs) has led to unprecedented insights into the energetics of the explosion and nature of the progenitors. Yet short of the detection of a smoking gun, such as a burst of coincident gravitational radiation or a Li-Paczyński minisupernova, it is unlikely that a definitive claim can be made for the progenitors. As was the case with long-duration soft-spectrum GRBs, however, the expectation is that a systematic study of the hosts and locations of short GRBs could begin to yield fundamental clues as to their nature. We present an aggregate study of the host galaxies of short-duration hard-spectrum GRBs. In particular, we present the Gemini-North and Keck discovery spectra of the galaxies that hosted three short GRBs and a moderate-resolution ($R \approx 6000$) spectrum of a fourth host. We find that these short-hard GRBs originate in a variety of low-redshift ($z < 1$) environments that differ substantially from those of long-soft GRBs, both on individual galaxy scales and on galaxy-cluster scales. Specifically, three of the bursts are found to be associated with old and massive galaxies with no current ($<0.1\ M_\odot\ \mathrm{yr}^{-1}$) or recent star formation. Two of these galaxies are located within a cluster environment. These observations support an origin from the merger of compact stellar remnants, such as double neutron stars or a neutron star–black hole binary. The fourth event, in contrast, occurred within a dwarf galaxy with a star formation rate exceeding $0.3\ M_\odot\ \mathrm{yr}^{-1}$. Therefore, it appears that like supernovae of Type Ia, the progenitors of short-hard bursts are created in all galaxy types, suggesting a corresponding class with a wide distribution of delay times between formation and explosion.

Subject headings: gamma rays: bursts — stars: formation — stars: neutron

1. INTRODUCTION

The nature of the progenitors of short-duration, hard-spectrum gamma-ray bursts (GRBs; Kouveliotou et al. 1993) has remained a mystery. Even with the recent localizations of four short-hard GRBs, no transient emission has been found at long wavelengths that directly constrains the progenitor nature. Instead, as was the case in studying the different morphological subclasses of supernovae (Reaves 1953; van Dyk 1992) and the progenitors of long-duration GRBs (Bloom et al. 2002), here we argue that the progenitors of short bursts can be meaningfully constrained by the environment in which the bursts occur.

In the past several months, the *Swift* and *HETE-2* satellites have discovered four GRBs whose short duration ($t < 2$ s) and spectral hardness place them within the short-hard GRB classification (Gehrels et al. 2005; Butler et al. 2005; Covino et al. 2005; Sato et al. 2005). Furthermore, each of these GRBs has been localized by its afterglow X-ray emission to within a circle of radius 10″ on the sky (Bloom et al. 2006; Fox et al. 2005; Burrows et al. 2005; Morris et al. 2005; Barthelmy et al. 2005). Although previous missions reported hundreds of short-hard GRBs, none of these were promptly localized to less than a few arcminutes and so a counterpart association at other wavelengths proved elusive (Hurley et al. 2002; Nakar et al. 2006). The discovery of GRB 050509b and a fading X-ray afterglow (Gehrels et al. 2005) led to the first redshift and host galaxy association (Bloom et al. 2006) for a short-hard GRB, providing unique insights for the long-standing mystery over the distance scale and energetics for at least some members of this class. Two subsequent bursts (GRB 050709 and GRB 050724) exhibited optical and radio afterglows (Hjorth et al. 2005b; Berger et al. 2005) that enabled subarcsecond localization. The four events now localized offer an opportunity to (1) study the population of host galaxies and large-scale environments, (2) examine the burst energetics, and (3) further constrain the nature of the progenitors.

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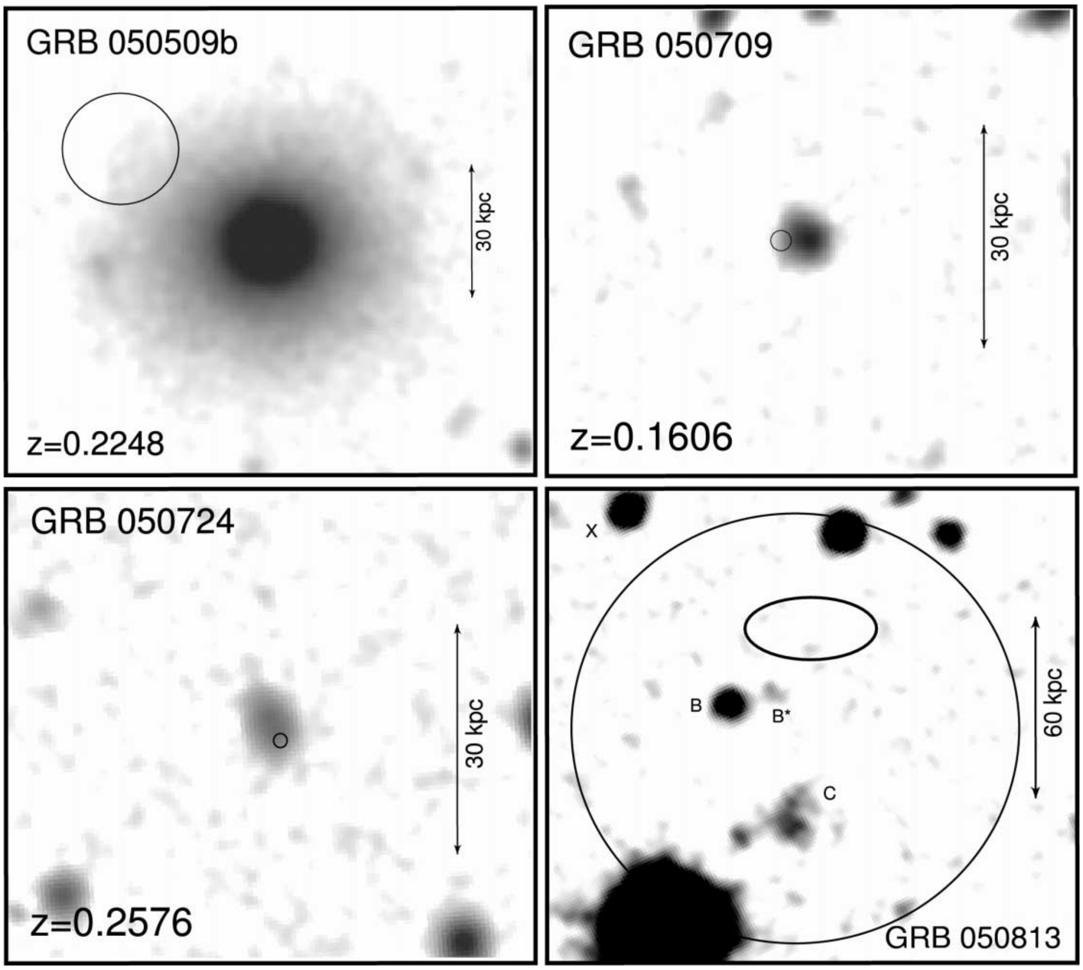

Fig. 1.—Optical light montage of four host galaxy regions of short-hard GRBs. The ellipses in each panel represent the astrometric position of the most accurate X-ray afterglow position reported with the exception of GRB 050813 (see text). In the case of GRB 050709 and GRB 050724, where optical afterglows were detected, the GRB is projected to within 2″ from the center of a galaxy with apparent magnitude $R < 19.5$ mag. The likelihood of a chance association between these afterglows and the putative host galaxies is less than 10^{-4} per event, given the covering fraction of such objects on the sky. Similarly, the error circle containing GRB 050509b encompasses a single bright galaxy, which is the putative host galaxy (Bloom et al. 2006), for which the chance of a spurious physical association with the burst is $\sim 10^{-3}$. Adopting the redshift of the putative host or cluster redshift (GRB 050813), a projection scale is shown at right in each panel. All images were smoothed with a Gaussian of 1.4–1.6 pixels to enhance the contrast between detected objects and sky noise. North is up, and east is to the left.

In this paper we present imaging and discovery spectra of the galaxies hosting the short-hard GRBs 050509b, 050724, and 050813. Based on these data, we report on their redshift, luminosity, spectral type, age, metallicity, and star formation rates. We also present a high-resolution spectrum ($R \equiv \lambda/\Delta\lambda \sim 6000$) of the host of the short-hard GRB 050709 and discuss its spectral properties and star formation characteristics. We draw comparisons to the larger data set of galaxies hosting long-soft GRBs and discuss the implications for the progenitor origin of short-hard GRBs.

2. OBSERVATIONS AND ANALYSIS

Optical images of the fields surrounding GRB 050724 and GRB 050813 were obtained using the Gemini Multi-Object Spectrograph (GMOS) on the Gemini-North Telescope with the i' filter. Optical images of the fields surrounding GRBs 050509b and 050709 were obtained using the Echellette Spectrometer and Imager (Sheinis et al. 2000) on the Keck II Telescope with the R filter. All imaging data were taken under photometric conditions and were processed using standard IRAF tasks.[19] Photometric solutions were derived from either a standard field taken during the night or from comparisons with USNO stars found in the science field. Figure 1 presents regions surrounding the localized position of each short-hard GRB. The processed images were registered to an absolute world coordinate system with typical 1 σ rms uncertainties of 150 mas in each coordinate. We list the absolute positions of host galaxies for GRBs 050509b, 050709, and 050724 in Table 1. We also list the magnitudes of the galaxies determined from our imaging (converted to R-band magnitude for consistency) with the exception of GRB 050509b, for which we report the more accurate Sloan Digital Sky Survey r' photometry (Abazajian et al. 2005).

The ellipses in each panel of Figure 1 represent the astrometric position of the most accurate X-ray afterglow position reported (68% confidence interval for GRB 050509b, Bloom et al. 2006; 68% confidence interval for GRB 050709, Fox et al. 2005; 68% confidence interval for GRB 050724, Burrows et al. 2005) and reflect the uncertainty in the astrometric tie between the X-ray and optical frame. A discussion of the differences between the various determinations of the GRB 050509b X-Ray Telescope (XRT) afterglow position has been discussed elsewhere (Bloom et al. 2006; Pedersen et al. 2006). The 90% containment radius previously reported for GRB 050813 (Morris

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TABLE 1
Physical Characteristics of Short-Hard GRBs and their Putative Host Galaxies

Property	050509b	050709	050724	050813(B)	050813(C)	050813(X)
$T_{90}/[1+z]$ (s)[a]	0.032	0.060	0.20	0.35	0.35	0.35
$E_{\gamma,\mathrm{iso}}$(ergs)[b]	2.75×10^{48}	2.29×10^{49}	1.0×10^{50}	1.7×10^{50}	1.7×10^{50}	1.7×10^{50}
R.A. (J2000)	12 36 12.878	23 01 26.849	16 24 44.381	16 07 57.200	16 07 57.008	16 07 57.509
Decl. (J2000)	+28 58 58.95	−38 58 39.39	−27 32 26.97	+11 14 53.09	+11 14 47.37	+11 15 02.13
z_{gal}	0.2248 ± 0.0002	0.1606 ± 0.0001	0.2576 ± 0.0004	0.719 ± 0.001	0.73 ± 0.01	0.722 ± 0.001
r (kpc)[c]	39 ± 13	3.5 ± 1.3	2.4 ± 0.9	...	...	...
R (mag)[d]	16.8 ± 0.05	21.1 ± 0.2	19.8 ± 0.3	23.43 ± 0.07	22.57 ± 0.07	22.75 ± 0.07
L_B (10^9 $L_\odot$)[e]	100	1.5	8.5	8	18	15
SFR ($M_\odot$ yr^{-1})[f]	<0.1	>0.3	<0.05	<0.1	<0.2	<0.1
Metallicity ($Z/Z_\odot$)[g]	1	0.25	0.2	1	...	1
Minimum Age (Gyr)	3	...	8	...	...	...
Spectral Type	Elliptical	Late-type dwarf	Early-type	Elliptical	Elliptical	Elliptical

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Source rest-frame duration, measured in T_{90}, the time when 90% of the total fluence of the GRB is accumulated, beginning after 5% of the fluence has been accumulated (Kouveliotou et al. 1993). Values were reported by the *Swift* and *HETE-2* Teams (Hurkett et al. 2005 ; Boer et al. 2005; Krimm et al. 2005; Sato et al. 2005; Gehrels et al. 2005; Villasenor et al. 2005; Barthelmy et al. 2005).

[b] Isotropic-equivalent energy $E_{\gamma,\mathrm{iso}}$, computed using the observed fluence and redshift under the assumption of a concordance cosmology with $\Omega_m = 0.29$, $\Omega_\Lambda = 0.71$, and Hubble's constant $H_0 = 70$ km s^{-1} Mpc^{-1}. While these energies are systematically lower than for long-soft GRBs, we note that with the energy range covered by *Swift* (15–350 keV) and the spectral properties of the prompt emission, the derived values should be considered lower limits.

[c] Projected offset of the X-ray afterglow positions from the optical centroid of the respective host galaxies. The quoted error is an approximation to the uncertainty of the most likely offset r, following Appendix B of Bloom et al. (2002), which is required because offsets are a positive-definite quantity and not strictly Gaussian. In general, $r \pm \sigma_r$ does not contain 68% of the probability distribution function.

[d] R-band magnitudes. We convert the Sloan Digital Sky Survey r magnitude for 050509b (Eisenstein et al. 2005). For the galaxies associated with GRB 050813, we have measured i-band magnitudes and converted them to R band, assuming $R - i = 0.99$ mag, appropriate for an elliptical galaxy at $z = 0.7$.

[e] The R-band magnitudes were converted to B-band luminosities by assuming standard colors for these spectral types, adopting the redshift listed in the z_{gal} row, and adopting the standard cosmology. The luminosities have not been corrected for Galactic extinction and are reported relative to the Solar B-band luminosity.

[f] Unextinguished star formation rate based on Hα and/or [O II] luminosity. Upper limits are 3 σ.

[g] Based on template fits to the galaxy spectra except for GRB 050709, where we estimate (O/H) from the [N II]/Hα ratio (Pettini & Pagel 2004). The uncertainty in these values is <30%.

et al. 2005) is shown as a large circle in the bottom right panel of Figure 1. We have reanalyzed the X-ray data using an optimized technique for a faint transient (Bloom et al. 2006) and localized GRB 050813 to $\alpha(J2000) = 16^{\mathrm{h}}07^{\mathrm{m}}56\overset{\mathrm{s}}{.}953 \pm 0\overset{\mathrm{s}}{.}20$, $\delta(J2000) = +11^\circ 14' 56\overset{''}{.}60 \pm 1\overset{''}{.}45$. The smaller ellipse in the bottom right panel shows this 68% containment radius. This localization makes the host identification of "B" or even the fainter "B$_*$" more likely over galaxy "C." We note that galaxies X, B, and C show consistent red colors that suggest a cluster membership (Gladders et al. 2005). The brightest objects at the edge of the large error circle ($16^{\mathrm{h}}07^{\mathrm{m}}57\overset{\mathrm{s}}{.}393$, $+11^\circ 14' 42\overset{''}{.}79$ and $16^{\mathrm{h}}07^{\mathrm{m}}56\overset{\mathrm{s}}{.}850$, $+11^\circ 15' 01\overset{''}{.}12$) are likely foreground Galactic stars.

Spectroscopy of the host galaxies were acquired on a number of facilities with several spectrometers (Fig. 2). Optical spectra of the host for GRB 050709 were obtained using the Echellette Spectrometer and Imager on Keck II with a 1″ slit in echellette mode. Optical spectra of the host for GRB 050509b were obtained using the DEIMOS spectrometer on Keck II with a $0\overset{''}{.}7$ long slit and the 600 line mm^{-1} grating. Optical spectra of the host for GRB 050724 were obtained using the LRIS spectrometer on the Keck I telescope with the 600/4000 grism through a 1″ long slit for $\lambda < 4500$ Å and using the GMOS spectrometer on the Gemini-North telescope with a $0\overset{''}{.}75$ slit (following astrometry based on a Magellan guide camera image) and the R400 grating centered at 690 nm providing spectra with $\lambda > 4700$ Å. Optical spectra of galaxies B, C, and X in the field surrounding GRB 050813 were obtained using the GMOS spectrometer with the same instrumental setup that was applied for the host GRB 050724, except centered at 640 nm. The data were fluxed using spectrophotometric standards taken with the same instrumental setups. The absolute flux is an underestimate, however, due to slit losses and reddening by the Milky Way.

The redshifts of the galaxies were measured through fits to the spectral features indicated in the figure. Based on these redshifts, we have measured or constrained the star formation rate (SFR) for these galaxies by measuring the luminosity of Hα and/or [O II]. In the cases of GRBs 050509b, 050724, and 050813, we do not detect any significant emission, and we employ the SFR calibration of Kennicutt (1998) to place conservative upper limits on the current star formation rate (Table 1). In the host galaxies of GRBs 050509b and 050724, the absence of strong Hβ absorption also indicates that there has been no significant SFR over the past ≈1 Gyr. The SFR values reported by other works in the literature consistent with our measurements (Gehrels et al. 2005; Berger et al. 2005; Gorosabel et al. 2006).

In the case of GRB 050709, there are strong emission lines observed, indicating significant ongoing star formation (Price et al. 2005; Fox et al. 2005). We have estimated the SFR by first comparing the relative Hα and Hβ fluxes to measure the reddening along the sight line to the galaxy under the assumption of case B recombination. We infer a reddening $E(B-V) > 0.4$, assuming a Milky Way extinction curve, and de-extinct the Hα emission (a factor of 2 correction) to derive a luminosity $L_{\mathrm{H}\alpha} > 4 \times 10^{40}$ ergs s^{-1}. We report this as a lower limit because (1) we have applied only a conservative correction to the Hα flux due to the B-band absorption, and (2) the slit does not encompass the entire galaxy. Using the Kennicutt (1998) empirical relation, we derive a lower limit to the SFR, SFR > 0.3 $M_\odot$ yr^{-1}, in reasonable agreement with other estimates (Fox et al. 2005; Covino et al. 2006; Hjorth et al. 2005b). We do not, however, confirm the absorption features at Hα and Hβ reported by Covino et al. (2006) and have no sensitive age constraint for this galaxy.

We present only the spectrum for galaxy B associated with GRB 050813 (Fig. 1). Our spectrum of galaxy C shows a 4000 Å

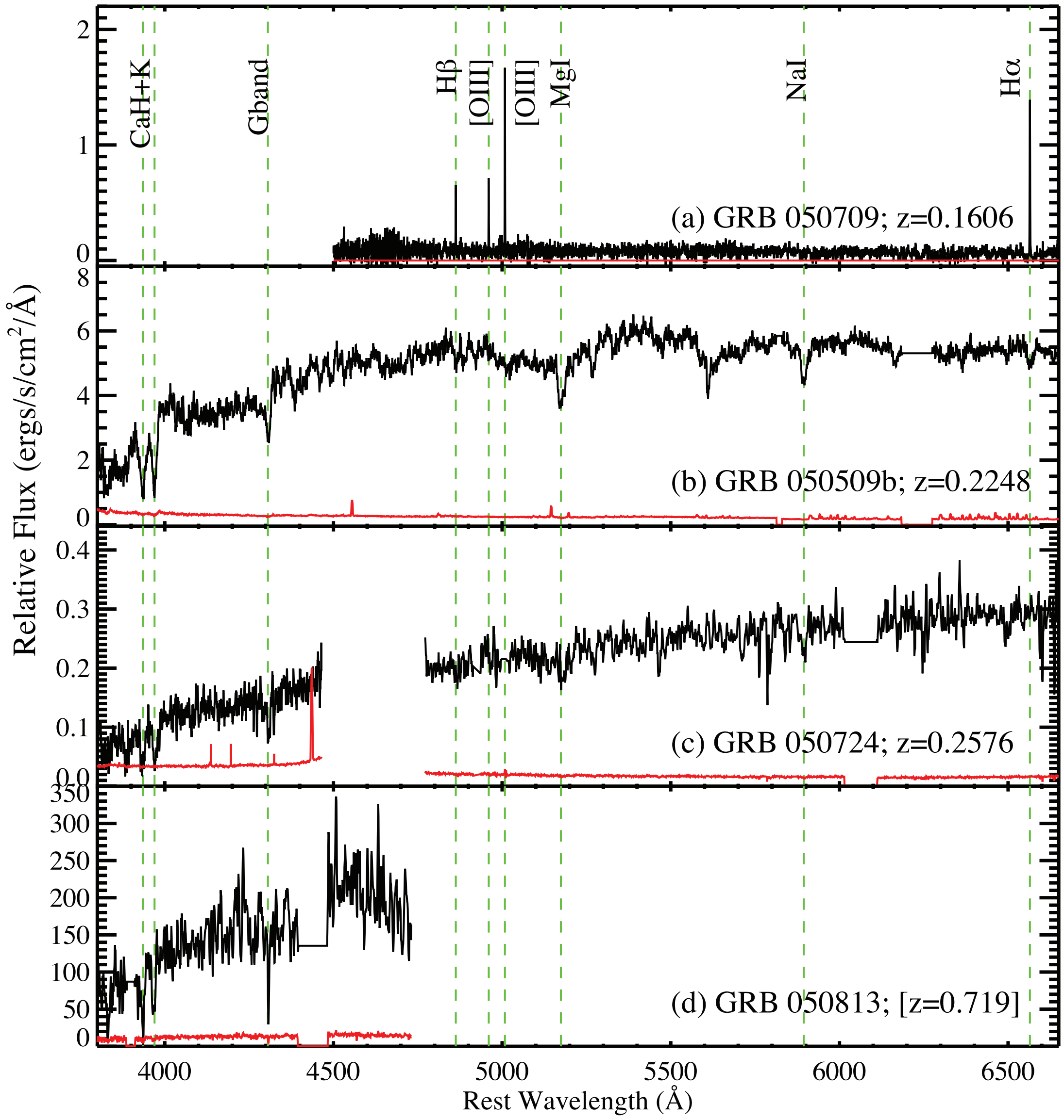

Fig. 2.—Optical spectroscopy for the host galaxies of short-hard GRBs. With the exception of GRB 050709, these data are the discovery spectra that established the redshift of the GRB event and also the physical properties of the galaxy host and/or environment. For GRB 050813, we show the spectrum for galaxy B.

break consistent with $z = 0.73$ and no significant emission lines, galaxy X shows absorption features indicating $z = 0.722$ (see also Berger 2005), and we have no redshift constraint for galaxy B_* ($i = 24.2 \pm 0.1$). The small projected distance between these sources ($\approx$40–100 h_{70}^{-1} kpc) and large velocity difference ($\Delta v = 690$–3000 km s^{-1}) strongly support the cluster nature of the progenitor environment for GRB 050813 (Gladders et al. 2005). We have also obtained spectra of two bright galaxies near GRB 050724 at positions $16^{\rm h}24^{\rm m}46\overset{\rm s}{.}739$, $-27°32'28\overset{''}{.}90$ and $16^{\rm h}24^{\rm m}43\overset{\rm s}{.}344$, $-27°32'07\overset{''}{.}21$. The latter galaxy has a redshift $z = 0.316$, based in Hβ and Hα emission. The former galaxy shows no absorption or emission features consistent with $z = 0.2576$, and its spectrum suggests a redshift $z > 0.4$. We therefore have found no evidence that GRB 050724 is located within a galaxy cluster.

We have constrained the age and metallicity of each early-type galaxy by performing least-squares fits to the galaxy spectrum with a suite of idealized templates (Bruzual & Charlot 2003). For the templates, we adopted a Salpeter initial mass function and considered a range of metallicity from 0.2 to 1 $Z_\odot$, as well as different star formation histories, ranging from a single burst model to an exponentially declining SFR with an e-folding time of 0.3 Gyr. None of the galaxy spectra are well matched by the burst model. The analysis places tight constraints (<30% uncertainty) on the metallicity of each galaxy, but the inferred age is more uncertain, especially because it is sensitive to the reddening assumed. With the exception of GRB 050724, for which we correct for Galactic extinction [$E(B-V) = 0.61$, Schlegel et al. 1998], we assume no reddening. To be conservative, we report minimum ages for the galaxies (Table 1). The values compare favorably with other estimates for GRB 050724 (Gorosabel et al. 2006), but our results contradict the young age for GRB 050509b reported by Castro-Tirado et al. (2005). Note that the galaxy spectra associated with GRB 050813 do not have sufficient spectral coverage to provide a meaningful age constraint. Finally, we estimate the metallicity for the galaxy associated with GRB 050709 from the measured [N II] λ6583 flux relative to Hα using the empirical calibration given by Pettini & Pagel (2004). We measure $\log([\text{N II}]/\text{H}\alpha) = -1.3 \pm 0.1$, which implies $\log(\text{O/H}) = 8.16 \pm 0.06$, comparable to the low metallicities observed in long-soft GRB host galaxies (e.g., Prochaska et al. 2004).

3. DISCUSSION

Based on positions of the afterglows, two of the four bursts (050509b and 050813) are very likely associated with clusters of galaxies (Bloom et al. 2006; Gladders et al. 2005). Because only ≈10% of the mass of the universe is contained within massive clusters, this suggests either that galaxies in clusters preferentially produce progenitors of short-hard GRBs or that short-hard bursts are preferentially more likely to be localized in cluster environments (Bloom et al. 2006). We have examined the *Swift* X-ray Telescope data of the fields of the other two GRBs (050709 and 050724) and found no conclusive evidence for diffuse hot gas associated with massive clusters. Furthermore, a spectroscopic study of two bright galaxies near the X-ray afterglow position of GRB 050724 show them at different redshifts, disfavoring a cluster origin for that burst. The cluster environments of at least two short-hard GRBs contrast strikingly with the observation that no well-localized long-soft GRB has yet been associated with a cluster (Bornancini et al. 2004). Therefore, more sensitive observations of the fields of both historical and new well-localized short-hard GRBs may be expected to show that a significant preponderance of them correlate with galaxy clusters.

We now turn to the putative galaxy hosts of short-hard GRBs. In three of the four cases, the GRB has been plausibly associated with a galaxy to better than a 99% confidence level (Fig. 1). In the fourth case (050813), there are two galaxies located in the error circle with comparable magnitude, and one may associate the event with either of these. Three of the bursts are associated with galaxies exhibiting characteristic early-type spectra (Fig. 2). The absence of observable Hα and [O II] emission constrains the unobscured star formation rates (SFR) in these galaxies to SFR $< 0.2\ M_\odot\ \mathrm{yr}^{-1}$, and the lack of Balmer absorption lines implies that the last significant star forming event occurred >1 Gyr ago. The host galaxy of GRB 050709 exhibits strong emission lines that indicate ongoing star formation with a conservative lower limit of SFR $> 0.3\ M_\odot\ \mathrm{yr}^{-1}$. These observations indicate that these short-hard GRBs occurred during the past ∼7 Gyr of the universe ($z < 1$) in galaxies with diverse physical characteristics.

In contrast to what is found for short-hard GRBs, all of the confirmed long-soft GRB host galaxies are actively forming stars with integrated, unobscured SFRs $\approx$ 1–10 $M_\odot\ \mathrm{yr}^{-1}$ (Christensen et al. 2004). These host galaxies have small stellar masses and bluer colors than present-day spiral galaxies (suggesting a low metallicity; Le Floc'h et al. 2003). The ages implied for the long-soft GRBs are estimated to be <0.2 Gyr (Christensen et al. 2004), which is significantly younger than the minimum ages derived for the early-type galaxies in our sample (Table 1). We conclude that the host galaxies of short-hard GRBs, and by extension the progenitors, are not drawn from the same parent population of long-soft GRBs. And although long-soft GRBs are observed to significantly higher redshift than the current short-hard GRB sample, one reaches the same conclusions when restricting samples to low-z, long-soft GRB hosts (Sollerman et al. 2005).

The identification of three galaxies without current star formation argues that the accepted progenitor model of long-soft GRBs (the collapse of a massive star; Woosley 1993) is not tenable as a source for the short-hard GRBs. Instead, the observations lend support to theories in which the progenitors of short-hard GRBs are merging compact binaries, e.g., neutron stars or black holes (Paczynski 1986; Eichler et al. 1989). This inference is supported through several channels. First, the redshift distribution of these short-hard bursts is inconsistent with a bursting rate that traces the star formation rate in the universe, unlike long-soft GRBs, which at least crudely follow it. If we introduce a ∼1 Gyr time delay in the host rest frame from starburst to explosion, as expected from compact object mergers, the observed redshift distribution of these GRBs (assuming they are representative of short-hard GRBs in general) is consistent with the star formation rate (Guetta & Piran 2005). Second, the lack of an associated supernova for all four short-hard GRBs is strong evidence against a core-collapse origin (Bloom et al. 2006; Hjorth et al. 2005a). Third, our measured offsets (Fig. 1) of the short-hard GRBs from their putative hosts are compatible with predicted sites of merging compact remnant progenitors (Fryer et al. 1999; Bloom et al. 1999). This includes the small offset of GRB 050724 (2.36 ± 0.90 kpc), which is near the median-predicted merger offset for such galaxies (Bloom et al. 1999).

The identification of the host galaxies and redshifts fixes the isotropic-equivalent burst energies. Table 1 shows the inferred isotropic energy release in prompt γ-ray emission, along with its duration in the source rest frames. These events suggest that short-hard GRBs are less energetic, typically by more than 1 order of magnitude, than their long counterparts, which typically release a total γ-ray energy of 5×10^{50} ergs, when collimation is taken into account. The total isotropic-equivalent energy in γ-rays, $E_{\gamma,\mathrm{iso}}$, appears to correlate with the burst duration, such that longer events are also more powerful (Berger et al. 2005). We find that $E_{\gamma,\mathrm{iso}} \propto T_{90}^{\psi}$ and $\psi \approx 1.5-2$. The total energies, durations, and general behavior of the correlation between GRBs are in rough agreement with the numerical modeling of GRB central engines arising from compact object mergers (Lee et al. 2005; Oechslin & Janka 2006; Rosswog et al. 2003).

The association of short-hard GRBs with both star-forming galaxies and with ellipticals dominated by old stellar populations is analogous to type Ia SNe. It indicates a class of progenitors with a wide distribution of delay times between formation and explosion, with a tail probably extending to many Gyr. Similarly, just as core-collapse supernovae are discovered almost exclusively in late-time star-forming galaxies, so too are long-soft GRBs. The detailed physics of the progenitors of supernovae is inferred through the time evolution of metals and ionic species revealed by spectroscopic observations. However, the progenitors of GRBs are essentially masked by afterglow emission, largely featureless synchrotron light, which reveals little more than the basic energetics and microphysical parameters of relativistic shocks. As new redshifts, offsets, and host galaxies of short-hard GRBs are gathered, the theories of the progenitors will undoubtedly be honed. Still, owing to the largely featureless light of afterglow radiation, unless short-hard bursts are eventually found to be accompanied by telltale emission features like the supernovae of long-duration GRBs, the only definitive understanding of the progenitors will come with the observations of concurrent gravitational radiation or neutrino signals arising from the dense, opaque central engine.

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