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The Galaxy Hosts and Large-Scale Environments of Short-Hard γ-ray Bursts

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ABSTRACT

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The rapid succession of discovery of short–duration hard–spectrum 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, like a burst of coincident gravitational radiation or a Li-Paczyński *mini-supernova*, 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 the locations of short GRBs could begin to yield fundamental clues about their nature. We present the first 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 of a neutron star–black hole binary. The fourth event, in contrast, occurred within a dwarf galaxy with a star formation rate exceeding 0.5 $M_\odot\,\mathrm{yr}^{-1}$. 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, gamma-ray bursts: individual: 050509b, 050709, 050724, 050813

1. Introduction

The nature of the progenitors of short-duration, hard spectrum, gamma-ray bursts (Kouveliotou *et al.* 1993) (GRBs) 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, Kulkarni & Djorgovski 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-II 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.* 2005; Fox *et al.* 2005; Burrows *et al.* 2005; Morris *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.* 2005). 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.* 2005) 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. 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.

In this Letter, 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, 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 dataset 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 GRB 050509b and GRB 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. 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 milliarcsecond in each coordinate. We list the absolute positions of host galaxies for 050509b, 050709, and 050724 in Table 1. We also list the magnitudes of the galaxies determined from our imaging (converted to R-band magnitude

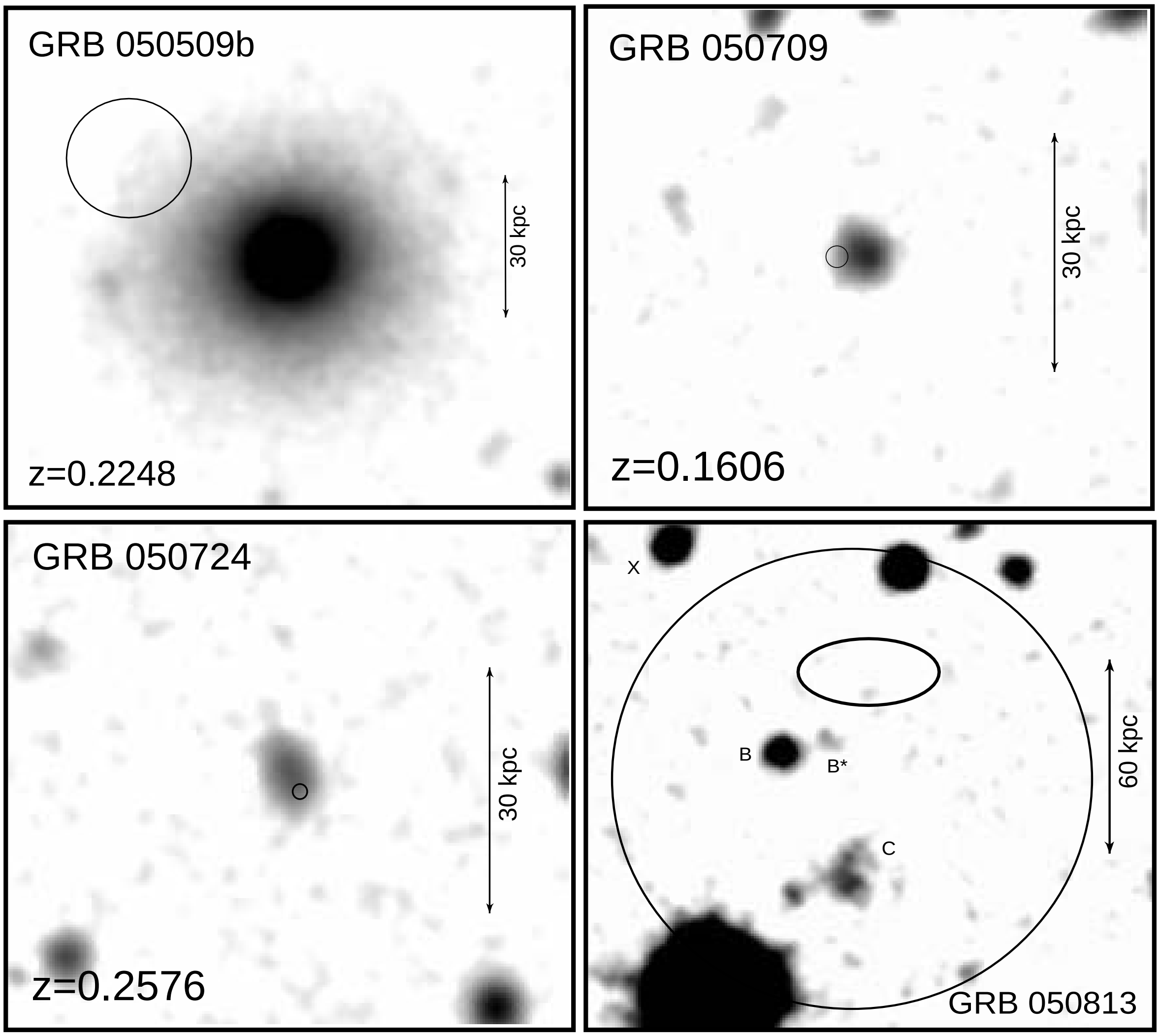

Fig. 1.— Optical light montage of four host galaxy regions of short-hard GRBs. The ellipses in each panel represent the astrometric position of the most accurate X-ray afterglow position reported with the exception of GRB 050813 (see text). In the case of GRB 050709 and GRB 050724 where optical afterglows 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.* 2005) 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.

for consistency) with the exception of GRB 050509b where we report the more accurate Sloan Digital Sky Survey r' photometry (Abazajian *et al.* 2005).

The ellipses in each panel represent the astrometric position of the most accurate X-ray afterglow position reported (68% confidence interval for GRB 050509b (Bloom *et al.* 2005); 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. The 90% containment radius previously reported for GRB 050813 (Morris *et al.* 2005) is shown as a large circle. We have re-analyzed the X-ray data using an optimized technique for faint transient (Bloom *et al.* 2005) and localized GRB 050813 to α(J2000) = $16^{\rm h}07^{\rm m}56^{\rm s}.953 \pm 0.20$ sec, δ(J2000) = $+11^{\rm d}14'56''60 \pm 1.45$ arcsec. The smaller ellipse 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 ($16^{\rm h}07^{\rm m}57^{\rm s}.393$ $+11^{\rm d}14'42''.79$ and $16^{\rm h}07^{\rm m}56^{\rm s}.850$ $+11^{\rm d}15'01''.12$) are likely foreground Galactic stars.

Spectroscopy of the host galaxies were acquired on a number of facilicities using various spectrometers available (Figure 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 $0.7''$ longslit and the 600line/mm 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 $1''$ longslit for $\lambda < 4500$Å and using the GMOS spectrometer on the Gemini-North telescope with a $0.75''$ slit (following astrometry based on a Magellan guide-camera image) and the R400 grating centered at 690nm 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 640nm. 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 [OII]. In the cases of GRB 050509b, GRB 050724, and GRB 050813, we do not detect any significant emission and we employ the SFR calibration of (Kennicut 1998) to place conservative upper limits on the current star formation rate (Table 1). In the host galaxies of GRB 050509b and GRB 050724, the absence of strong Hβ absorption also indicates that there has been no significant SFR over the past ≈ 1 Gyr.

In the case of GRB 050709, there are strong emission lines observed indicating significant ongoing star formation (Price, Roth & Fox 2005). We have estimated the SFR by first comparing the relative Hα and Hβ fluxes to measure the reddening along the sightline to the galaxy under the assumption of Case B recombination. We infer a reddening $E(B-V) = 0.4 \pm 0.1$ and deextinct the Hα emission to derive a luminosity $L_{\mathrm{H}\alpha} > 6 \times 10^{40}$ergs/s. We report this as a lower limit because (i) the slit does not encompass the entire galaxy and (ii) the Hα line is located on the atmospheric B-band. For our reported limit, we have applied only a conservative correction for the atmospheric absorption. The implied SFR is SFR $> 0.5 M_{\odot}\mathrm{yr}^{-1}$ (Kennicut 1998).

We present only the spectrum for galaxy B associated with GRB 050813 (Figure 1). Our spectrum of galaxy C shows a 4000Å 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 GRB050813 (Gladders *et al.* 2005). We have also obtained spectra of two bright galaxies near GRB 050724 (at positions $16^{\mathrm{h}}24^{\mathrm{m}}46^{\mathrm{s}}.739$ $-27^{\mathrm{d}}32'28''.90$ and $16^{\mathrm{h}}24^{\mathrm{m}}43^{\mathrm{s}}.344$ $-27^{\mathrm{d}}32'07''.21$) and did not find them to be at the same redshift as the host galaxy; we therefore have found no evidence that the GRB 050724 is a member of a galaxy cluster.

3. Discussion

Based on positions of the afterglows, two of four bursts (050509b and 050813) are associated with clusters of galaxies (Bloom *et al.* 2005; Gladders *et al.* 2005). Because only $\approx 10\%$ of the mass of the Universe is contained within clusters, this suggests that either 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.* 2005). 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 three bright galaxies near the X-ray afterglow position of GRB 050724 show them all to be 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

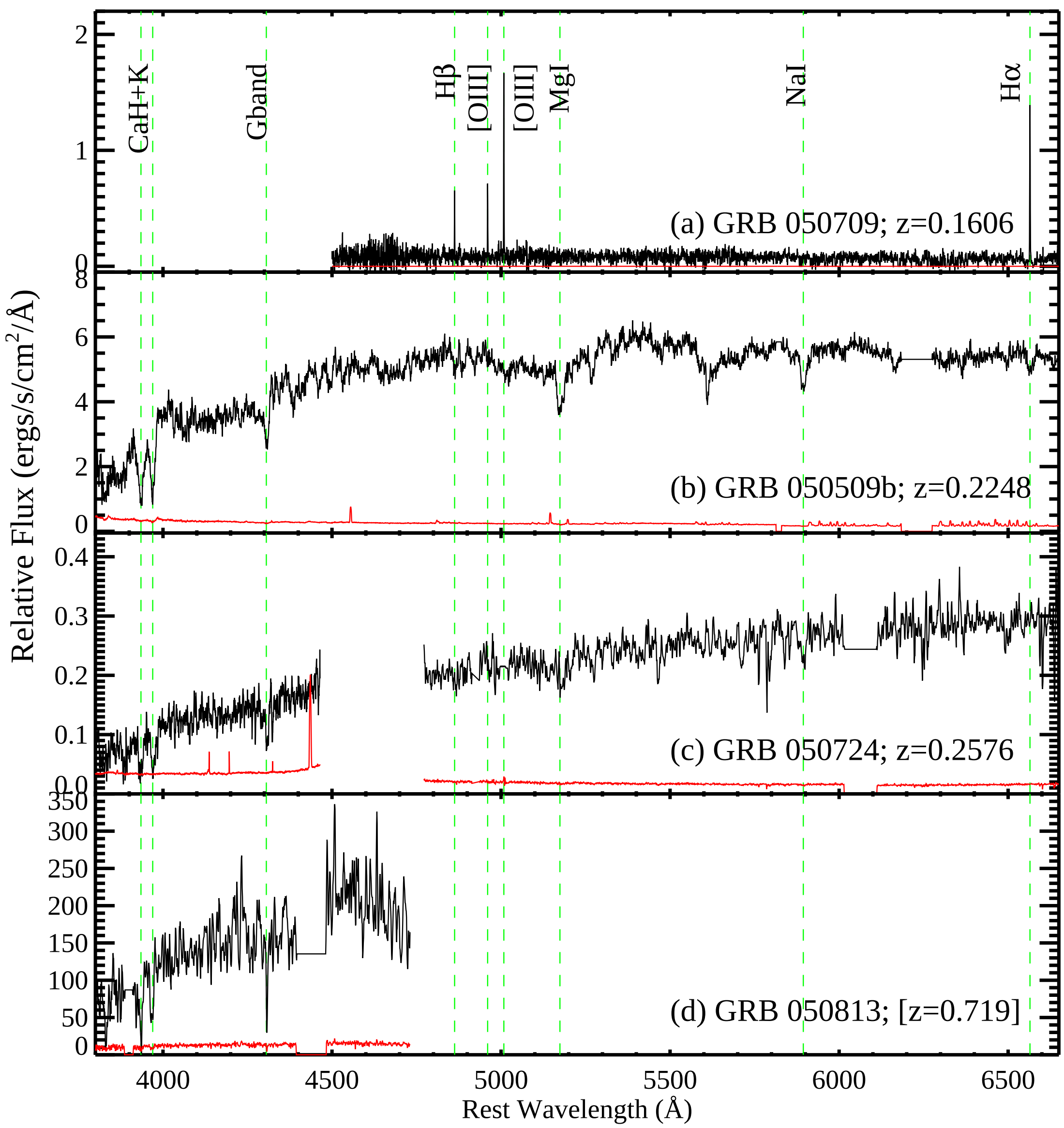

Fig. 2.— Optical spectroscopy for the host galaxies of short-hard GRBs. With the exception of GRB 050724, these data are the discovery spectra which established the redshift of the GRB event and also the physical properties of the galaxy host and/or environment. For GRB 050813, we show the spectrum for galaxy B.

show a significant preponderance to correlate with galaxy clusters.

We now turn to the putative galaxy hosts of short-hard GRBs. In three of four cases, the GRB has been plausibly associated with a galaxy to better than a 99% confidence level (Figure1). 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 (Figure 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 billion years ago. The host galaxy of GRB 050709 exhibits strong emission lines that indicate on-going star formation with a conservative lower limit of SFR $> 0.5 M_{\odot}\mathrm{yr}^{-1}$. These observations indicate that these short-hard GRBs occurred during the past $\sim$ 7 billion years 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, Hjorth & Gorosabel 2004). These host galaxies have small stellar masses and bluer colors than present-day spiral galaxies (Le Floc'h *et al.* 2003) (suggesting a low metallicity). 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 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 (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 do follow it. If we introduce a ~ 1 Gyr time delay from starburst to explosion, as expected from compact object mergers, the observed redshift distribution of these GRBs (i.e. 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.* 2005; Hjorth *et al.* 2005). Third, our measured offsets (Figure 1) of the short-hard GRBs from their putative hosts are compatible with predicted site of merging compact remnant progenitors (Fryer, Woosley & Hartmann 1999; Bloom, Sigurdsson & Pols 1999). Noteworthy, and somewhat counterintuitive, is that the albeit small offset of GRB 050724 (2.36 ± 0.90 kpc) is near the median predicted merger offset for such galaxies (Bloom, Sigurdsson & Pols 1999).

The identification of the host galaxies and redshifts finally fixes the isotropic-equivalent burst energies. Table 2 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 one order of magnitude, than their long counterparts, which typically release a total γ-ray energy of 5×10^{50} erg when collimation is taken into account. The total isotropic-equivalent energy in γ-rays, $E_{\gamma,\rm iso}$ appears to correlate with the burst duration, such that longer events are also more powerfulBerger *et al.* (2005). We find that $E_{\gamma,\rm iso} \propto T_{90}^{\psi}$ and $\psi \approx 3/2$ to 2. The total energies, durations, and the general behavior of the correlation between them are in rough agreement with the numerical modeling of GRB central engines arising from compact object mergers (Lee, Ramirez-Ruiz & Granot 2005; Oechslin & Janka 2005; Rosswog, Ramirez-Ruiz & Davies 2003).

Our fits to the available afterglow data indicate that the density in the circumburst medium is closer to that found in the interstellar ($n \approx 1$ cm^{-3}) rather than intergalactic medium ($n \approx 10^{-3}$ cm^{-3}). This might suggest a selection bias where short-hard GRBs that occur in a dense external medium have a brighter afterglow emission, and thus are more accurately localized (Bloom *et al.* 2005).

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 micro-physical parameters of relativistic shocks. As new redshifts, offsets and host galaxies of short-hard GRBs are gathered, the theories of the progenitors will undoubtably be honed. Still, owing to the largely featureless light of afterglow radiation, unless short-hard bursts are eventually found to be accompanied by tell-tale 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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REFERENCES

Abazajian, K. *et al.* 2005, AJ, 129, 1755.

Berger, E. 2005, GCN Circular 3801.

Berger, E. *et al.* 2005, astro-ph/0508115.

Bloom, J. S., Kulkarni, S. R., and Djorgovski, S. G. 2002, AJ, 123, 1111.

Bloom, J. S. *et al.* 2005, astro-ph/0505480.

Bloom, J. S., Sigurdsson, S., and Pols, O. R. 1999, MNRAS, 305, 763.

Bornancini, C. G. *et al.* 2004, ApJ, 614, 84.

Burrows, D. N. *et al.* 2005, GCN Circular 3697.

Butler, N. *et al.* 2005, GCN Circular 3570.

Christensen, L., Hjorth, J., and Gorosabel, J. 2004, A&A, 425, 913.

Covino, S. *et al.* 2005, GCN Circular 3665.

Eichler, D. *et al.* 1989, Nature, 340, 126.

Eisenstein, D. J., Hogg, D. W., and Padmanabhan, N. 2005, GRB Circular Network, 3418, 1.

Fox, D. B. *et al.* 2005, GCN Circular 3585.

Fryer, C. L., Woosley, S. E., and Hartmann, D. H. 1999, ApJ, 526, 152.

Gehrels, N. *et al.* 2005, astro-ph/0505630.

Gladders, M. *et al.* 2005, GCN Circular 3798.

Guetta, D. and Piran, T. 2005, A&A, 435, 421.

Hjorth, J. *et al.* 2005, ApJ, 630, L117.

Hurley, K. *et al.* 2002, ApJ, 567, 447.

Kennicut, R. C. 1998, Ann. Rev. Astr. Ap., 36, 131.

Kouveliotou, C. *et al.* 1993, ApJ (*Letters*), 413, 101.

Le Floc'h, E. *et al.* 2003, A&A, 400, 499.

Lee, W. H., Ramirez-Ruiz, E., and Granot, J. 2005, astro-ph/0506104.

Morris, D. C. *et al.* 2005, GCN Circular 3790.

Nakar, E. *et al.* 2005, astro-ph/0502148.

Oechslin, R. and Janka, H. . 2005, ArXiv Astrophysics e-prints.

Paczynski, B. 1986, ApJ (*Letters*), 308, L43.

Price, P. A., Roth, K., and Fox, D. W. 2005, GCN Circular 3605.

Reaves, G. 1953, PASP, 65, 242.

Rosswog, S., Ramirez-Ruiz, E., and Davies, M. B. 2003, MNRAS, 345, 1077.

Sato, G. *et al.* 2005, GCN Circular 3793.

Sheinis, A. I. *et al.* 2000, in Proc. SPIE Vol. 4008, p. 522-533, Optical and IR Telescope Instrumentation and Detectors, Masanori Iye; Alan F. Moorwood; Eds., 522.

Sollerman, J. *et al.* 2005, astro-ph/0506686.

van Dyk, S. D. 1992, AJ, 103, 1788.

Woosley, S. E. 1993, ApJ, 405, 273.

Table 1. Physical Properties of the Hosts of Short-Hard GRBs

GRB	α (J2000)	δ (J2000)	z	r^a (kpc)	R^b (mag)	L_B^c ($10^9 L_\odot$)	SFR^d ($M_\odot \mathrm{yr}^{-1}$)	Spectral Type
050509b	12:36:12.878	+28:58:58.95	0.2248 ± 0.0002	39 ± 13	16.8 ± 0.05	100	< 0.1	Elliptical
050709	23:01:26.849	−38:58:39.39	0.1606 ± 0.0001	3.5 ± 1.3	21.1 ± 0.2	1.5	> 0.5	Late-type dwarf
050724	16:24:44.381	−27:32:26.97	0.2576 ± 0.0004	2.4 ± 0.9	19.8 ± 0.3	8.5	< 0.05	Early-type
050813 (B)	16:07:57.200	+11:14:53.09	0.719 ± 0.001	...	23.43 ± 0.07	8	< 0.1	Elliptical
050813 (C)	16:07:57.008	+11:14:47.37	0.73 ± 0.01	...	22.57 ± 0.07	18	< 0.2	Elliptical
050813 (X)	16:07:57.509	+11:15:02.13	0.722 ± 0.001	...	22.75 ± 0.07	15	< 0.1	Elliptical

[a]Projected offset of the X-ray afterglow positions from the optical centraoid 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.

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

[c]The R-band magnitudes were converted to B-band luminosities by assuming standard colors for these spectral types, adopting the redshift listed in column 1, and adopting the standard cosmology $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and Hubble's constant $H_0 = 70 \mathrm{kms^{-1}Mpc^{-1}}$. The luminosities have not been corrected for Galactic extinction and are reported relative to the Solar B-band luminosity.

[d]Unextinguished star formation rate based on Hα and/or [OII] luminosity. Upper limits are 3σ.

Table 2. Inferred Burst Energetics and Durations

GRB	$E_{\gamma,\mathrm{iso}}$[erg][a]	$T_{90}/(1+z)$ [sec][b]
050509b	2.75×10^{48}	0.032
050709	2.29×10^{49}	0.060
050724	1.0×10^{50}	0.203
050813	1.7×10^{50}	0.349

[a]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.

[b]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).