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The nature of the progenitors of short duration, hard spectrum, gamma-ray bursts[1] (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[2,3] and the progenitors of long-duration GRBs[4], we suggest that the progenitors of short bursts can be meaningfully constrained by the environment in which the bursts occur. Here we present the discovery spectra of the galaxies that hosted three short-hard GRBs and the spectrum of a fourth host. The results indicate that these environments, both at the galaxy scale and galaxy-cluster scale, differ substantially from those of long-soft GRBs. The spatial offset of three bursts from old and massive galaxy hosts strongly favours an origin from the merger of compact stellar remnants, such as double neutron stars or a neutron-star black hole binary. The star-forming host of another GRB provides confirmation that, like supernovae of Type Ia, the progenitors of short-hard bursts are created in all galaxy types. This indicates a class of progenitors with a wide distribution of delay times between formation and explosion.

In the past four 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[5–8]. Furthermore, each of these GRBs has been localized by its afterglow X-ray emission to within a circle of radius $10''$ on the sky[9–12]. 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[13,14]. The discovery of GRB 050509b and a fading X-ray afterglow[5] led to the first redshift and host galaxy association[9] for a short-hard GRB, solving 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 study the population of host galaxies and large-scale environments, examine the energetics, and begin to constrain the nature of the progenitors.

Based on positions of the afterglows, two of four bursts (050509b and 050813) are associated with clusters of galaxies[9,15]. Because only ≈ 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 discovered and localized in cluster environments[9]. 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, disfavouring 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[16]. Therefore, more sensitive observations of the fields of both historical and new well-localized short-hard GRBs may be expected to 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 (Figure 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. In Figure 2, we present the discovery spectra of three short-hard host galaxies and a high-resolution spectrum of GRB 050709 which was previously identified[17]. Three bursts are associated with galaxies exhibiting characteristic 'early-type' spectra. The absence of observable Hα and [O II] emission constrains the unobscured star formation rates (SFR) in these galaxies to $\mathrm{SFR} < 0.2 M_{\odot}\mathrm{yr}^{-1}$ (Table 1), where $M_{\odot}$ is the mass of the Sun, 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 $\mathrm{SFR} > 0.5 M_{\odot}\mathrm{yr}^{-1}$. These observations clearly indicate that these short-hard GRBs occurred during the past ~ 7 billion years of the Universe 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 $\mathrm{SFRs} \approx 1 - 10 M_{\odot}\mathrm{yr}^{-1}$ [18]. The galaxies have small stellar masses and bluer colors than present-day spiral galaxies [19] (suggesting a low metallicity). We therefore 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 [20].

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[21]) is unviable 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[22,23]). 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 is consistent with the star-formation rate[24]. Second, the lack of an associated supernova for all four short-hard GRBs is strong evidence against a core–collapse origin. Third, our measured offsets (fig. 1) of the short-hard GRBs from their putative hosts are compatible with predicted site of merging compact remnant progenitors[25,26]. Noteworthy, and somewhat counterintuitive, is that the albeit small offset of GRB 050724 (2.36 $\pm$ 0.90 kpc) is near the median predicted merger offset for such galaxies[26].

The identification of the host galaxies and redshifts finally fixes the absolute 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 powerful[27]. 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[28]. 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[9].

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. 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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Physical Properties of the Hosts of Short-Hard GRBs

GRB	z	r^a (kpc)	R^b (mag)	L_B^c ($10^9 L_\odot$)	SFR^d ($M_\odot \mathrm{yr}^{-1}$)	Spectral Type
050509b	0.2248 ± 0.0002	39 ± 13	16.8 ± 0.05	20	< 0.1	Elliptical
050709	0.1606 ± 0.0001	3.5 ± 1.3	21.1 ± 0.2	0.4	> 0.5	Late-type dwarf
050724	0.2576 ± 0.0004	2.4 ± 0.9	19.8 ± 0.3	2	< 0.05	Early-type
050813 (B)	0.719 ± 0.001	...	23.43 ± 0.07	4	< 0.1	Elliptical
050813 (C)	0.73 ± 0.01	...	22.57 ± 0.07	10	< 0.2	Elliptical
050813 (X)	0.722 ± 0.001	...	22.75 ± 0.07	8	< 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 [4], which is required because offsets are a positive-definite quantity and not strickly 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[29]. For the galaxies associated with GRB 050813 we have measured i-band magnitudes and converted to R-band assuming $R - i = 0.99$ 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 $H_0 = 70 \mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$. The luminosities have not been corrected for Galactic extinction and are reported relative to the Solar B-band luminosity.

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

Inferred Burst Energetics and Durations

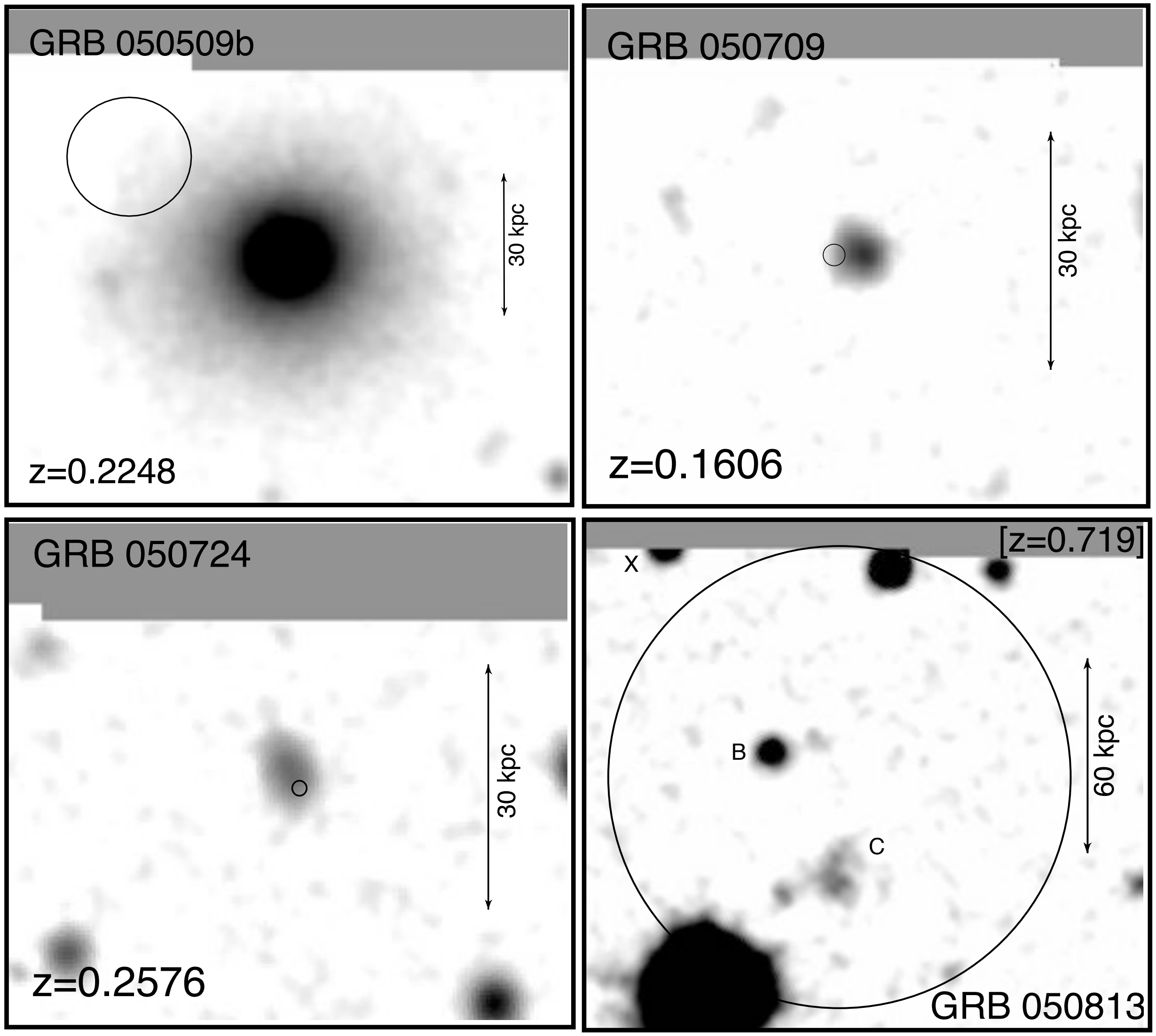
GRB	$E_{\gamma,\mathrm{iso}}$[erg] [a]	T$_{90}$/(1+z) [sec] [b]
050509b	2.75×10^{48}	0.032
050709	2.29×10^{49}	0.060
050724	1.0×10^{50}	0.203
050813	1.7×10^{50}	0.349

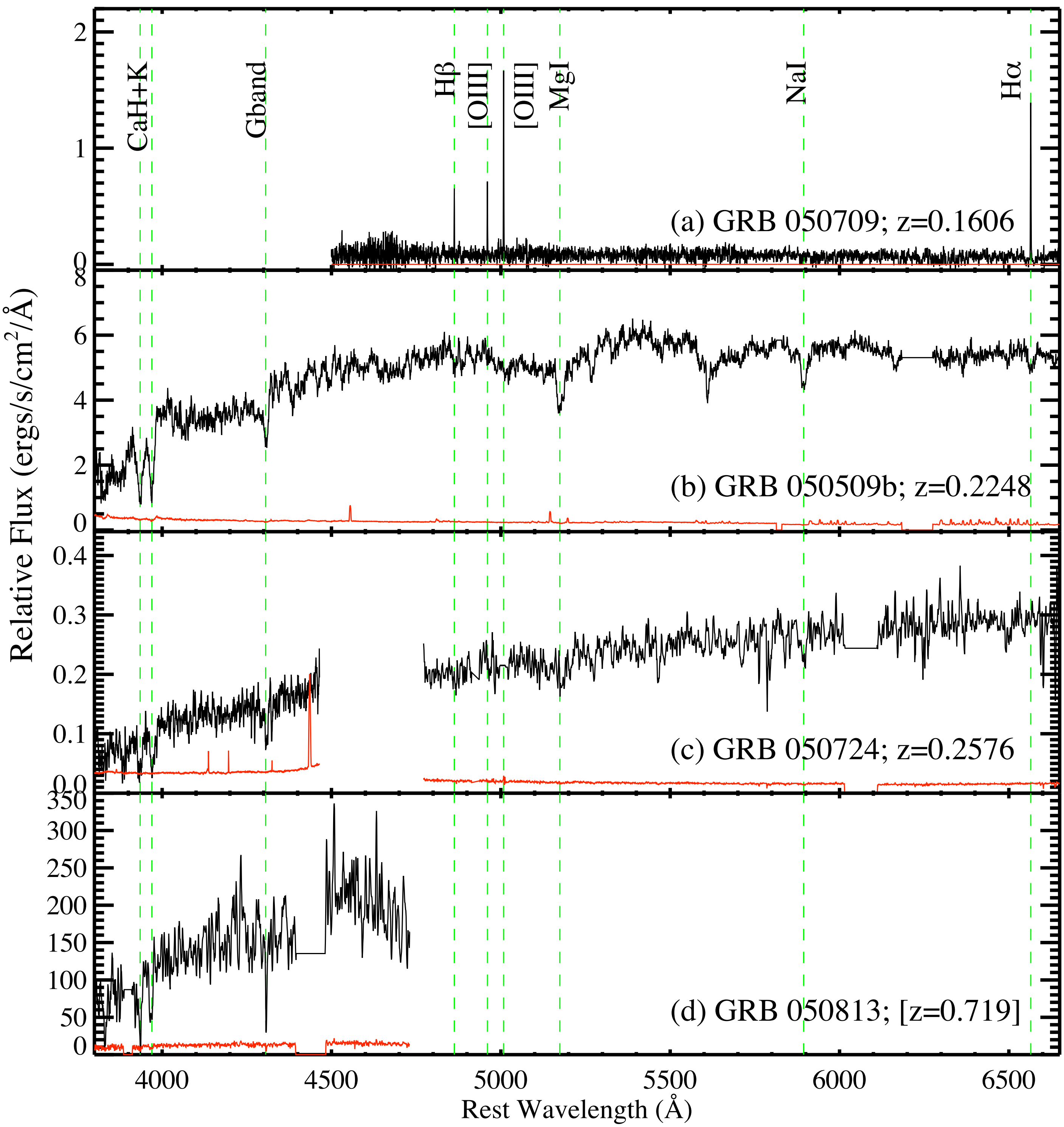
[a] Isotropic-equivalent energy $E_{\gamma,\mathrm{iso}}$, computed using the observed fluence and redshift under the assumption of a concordance cosmology with $\Omega_m = 0.29$, $\Omega_\Lambda = 0.71$ and Hubble's constant $H_0 = 70$ km s^{-1} Mpc^{-1}. While these energies are systematically lower 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[1].

Figure 1 Optical light montage of four host galaxy regions of short-hard GRBs. 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 [9] for which the chance of a spurious physical association with the burst is $\sim 10^{-3}$. Images were acquired on the Gemini North 8m Telescope (GRB 050724, i-band; GRB 050813) and Keck 10m Telescopes (GRB 050509b, R-band; GRB 050709, R-band) and processed in the usual manner. Processed images were registered to an absolute world coordinate system with typical 1 σ rms uncertainties of 150 milliarcsecond in each coordinate. We find the absolute positions of host galaxies for 050509b, 050709, and 050724 as α(J2000) = 12:36:12.878 δ(J2000) = +28:58:58.95, 23:01:26.849 −38:58:39.39, and 16:24:44.381 −27:32:26.97, respectively. The ellipses in each panel represent the astrometric position of the most accurate X-ray afterglow position reported (68% confidence interval for GRB 050509b[9]; 68% confidence interval for GRB 050709 [10]; 68% confidence interval for GRB 050724 [11]; and reflect the uncertainty in the astrometric tie between the X-ray and optical frame. The 90% containment radius previously reported for GRB 050813[12] is shown as a large circle. With the same data, using an optimized technique for faint transient localization[9], we have localized GRB 050813 to α(J2000) = 16:07:56.953 $\pm$ 0.20 sec, δ(J2000) = +11:14:56.60 $\pm$ 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. Adopting the redshift of the putative host or cluster redshift (GRB 050813) a projection scale is shown at right in each panel. The galaxies labeled in the panel GRB 050813 panel are referred to in figure 2. We note that galaxies X (16:07:57.509 +11:15:02.13; $i = 21.76 \pm 0.03$ mag), B (16:07:57.200 +11:14:53.09; $i = 22.44 \pm 0.04$), and C (16:07:57.008 +11:14:47.37; $i = 21.58 \pm 0.04$) show consistent, red colors that suggest a cluster membership[15]. The brightest objects at the edge of the large error circle (16:07:57.393 +11:14:42.79 and 16:07:56.850 +11:15:01.12) are likely foreground Galactic stars. 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.

Figure 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 properties of the galaxy host and/or environment. The data were acquired with the (a) Echellette Spectrometer and Imager on Keck II with a $1''$ slit in echellette mode; (b) the DEIMOS spectrometer on Keck II obtained through a $0.7''$ longslit using the 600line/mm grating; (c) the LRIS spectrometer on the Keck I telescope with the 600/4000 grism through a $1''$ longslit for the blue spectrum and the GMOS spectrometer on the Gemini-North telescope using a $0.75''$ slit (following astrometry based on a Magellan guide-camera image) and the R400 grating centered at 690nm for the red spectrum; and (d) the GMOS spectrometer using the identical setup as (c). The data were fluxed using spectrophotometric standards taken with the same instrumental setups. The absolute flux is uncertain, in particular, due to slit losses and is not corrected for reddening by the Milky Way. The redshifts of the galaxies were measured through fits to the spectral features indicated in the figure. We obtained spectra of two bright galaxies near GRB 050724 (at positions 16:24:46.739 -27:32:28.90 and 16:24:43.344 -27:32:07.21) and did not find them to be at the same redshift as the host galaxy; we therefore have found no evidence the GRB 050724 is a member of a galaxy cluster. Note that 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 [30]), 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[15].


GRB 050509b
30 kpc
z=0.2248
GRB 050709
30 kpc
z=0.1606
GRB 050724
30 kpc
z=0.2576
[z=0.719]
X
B
C
60 kpc
GRB 050813



CaH+K
Gband
Hβ
[OIII]
[OIII]
MgI
NaI
Hα
(a) GRB 050709; z=0.1606
(b) GRB 050509b; z=0.2248
(c) GRB 050724; z=0.2576
(d) GRB 050813; [z=0.719]
Relative Flux (ergs/s/cm²/Å)
Rest Wavelength (Å)