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A PUTATIVE EARLY-TYPE HOST GALAXY FOR GRB 060502B: IMPLICATIONS FOR THE PROGENITORS OF SHORT-DURATION HARD-SPECTRUM BURSTS

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ABSTRACT

Starting with the first detection of an afterglow from a short-duration hard-spectrum γ-ray burst (SHB) by *Swift* last year, a growing body of evidence has suggested that SHBs are associated with an older and lower redshift galactic population than long-soft GRBs and, in a few cases, with large ($\gtrsim$10 kpc) projected offsets from the centers of their putative host galaxies. Here we present observations of the field of GRB 060502B, a SHB detected by *Swift* and localized by the X-Ray Telescope (XRT). We find a massive red galaxy at a redshift of $z = 0.287$ at an angular distance of 17.1″ from our revised XRT position. Using associative and probabilistic arguments, we suggest that this galaxy hosted the progenitor of GRB 060502B. If true, this offset would correspond to a physical displacement of 73 ± 19 kpc in projection, about twice the largest offset inferred for any SHB to date and almost an order of magnitude larger than a typical long-soft burst offset. Spectra and modeling of the star formation history of this possible host show it to have undergone a large ancient starburst. If the progenitor of GRB 060502B was formed in this starburst episode, the time of the GRB explosion since birth is $\tau \approx 1.3 \pm 0.2$ Gyr and the minimum kick velocity of the SHB progenitor is $v_{\rm kick,min} = 55 \pm 15$ km s^{-1}.

Subject headings: astrometry — galaxies: elliptical and lenticular, cD — gamma rays: bursts

1. INTRODUCTION

Since the seminal work of Kouveliotou et al. (1993) a consensus view has emerged that short-duration hard-spectrum GRBs (SHBs) arise from a separate physical population than long-duration soft-spectrum GRBs (LSBs). The populations are distinguished phenomenologically by an observed bimodality in the GRB duration distribution (Mazets et al. 1981; Norris et al. 1984) and an apparent corresponding bimodality in spectral hardness. While most LSB progenitors are now believed to be due to the death of massive stars, in the absence, until recently, of a successful detection of an afterglow or a host galaxy, the nature of the SHBs remained a mystery.

In 2005 May the *Swift* satellite detected and localized SHB 050509B and, for the first time, found a fading X-ray afterglow (Gehrels et al. 2005); this was the first SHB localized quickly ($\lesssim$10 s) and accurately (<100 arcsec^2). Ground-based follow-up observations led to the discovery of an early-type galaxy at a redshift of $z = 0.258$ approximately 10″ from the X-ray afterglow position (Bloom et al. 2006c). A chance association with such a galaxy was deemed unlikely even under conservative assumptions ($P <$ few percent) and stood in stark contrast with the lines of sight of LSBs, with which no association with an early-type galaxy was ever made. Both the nature of the burst itself (lacking any supernova signature; Hjorth et al. 2005a) and the location (in the halo of a red galaxy with very little star formation) suggested a progenitor of a very different nature from the purported progenitors of LSBs. In particular, these observations were in close agreement with predictions (Brandt & Podsiadlowski 1995; Bloom et al. 1999; Fryer et al. 1999) for the nature of the environment—particularly the offset from host galaxy and the type of the host associated with the merger of a degenerate binary (e.g., Narayan et al. 1992).

Further *Swift* and *HETE-2* detections of SHBs have continued to support this hypothesis, although SHBs are not universally at large offsets and are not always associated with early-type galaxies (see Bloom & Prochaska 2006 for a review). SHB 050724 (Berger et al. 2005; Prochaska et al. 2006; Gorosabel et al. 2006) and 050813 (Prochaska et al. 2006), like 050509B, were found to be in close association with old, red galaxies (see also Levan et al. 2006). SHB 050724 had optical and radio afterglow emission that pinpointed its location to be within its red host, making the association completely unambiguous, although the association of 050813 with any single host remains somewhat tentative. Not all hosts lack active star formation; SHB 050709 (Villasenor et al. 2005; Hjorth et al. 2005b; Fox et al. 2005; Covino et al. 2006) and 051221A (Soderberg et al. 2006) both had optical afterglows and were associated with galaxies with evidence for current star formation. However, despite the availability of both X-ray and optical afterglow locations, no nearby host has been successfully identified for either SHB 060121 or SHB 060313 (although see J. Hjorth et al. 2006, in preparation).

In this article we examine the field of Swift SHB 060502B (Troja et al. 2006b), and in § 2 we present imaging and spectroscopy of a bright red galaxy near the X-ray afterglow position. In § 3 we present evidence that supports the notion that the progenitor of SHB 060502B was born in that galaxy. Accepting this connection, we discuss the implications of the nature of the host and offset for the progenitors of SHBs. Although the association of this galaxy with the GRB is the most tenuous of SHB–host associations thus far proposed, we conclude in § 4 that there are both observational and theoretical motivations for accepting this association for this and (similarly configured) future SHBs. Some of our work on this GRB was given preliminarily in Bloom et al. (2006a); our results presented herein are consistent with, but supersede, that reference. Throughout this paper we assume $H_0 = 71\ h_{71}$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. SHB 060502b AND G^*

At 2006 May 2 17:24:41 UTC, the *Swift* Burst Alert Telescope triggered (Troja et al. 2006b) on a GRB consisting of a strong

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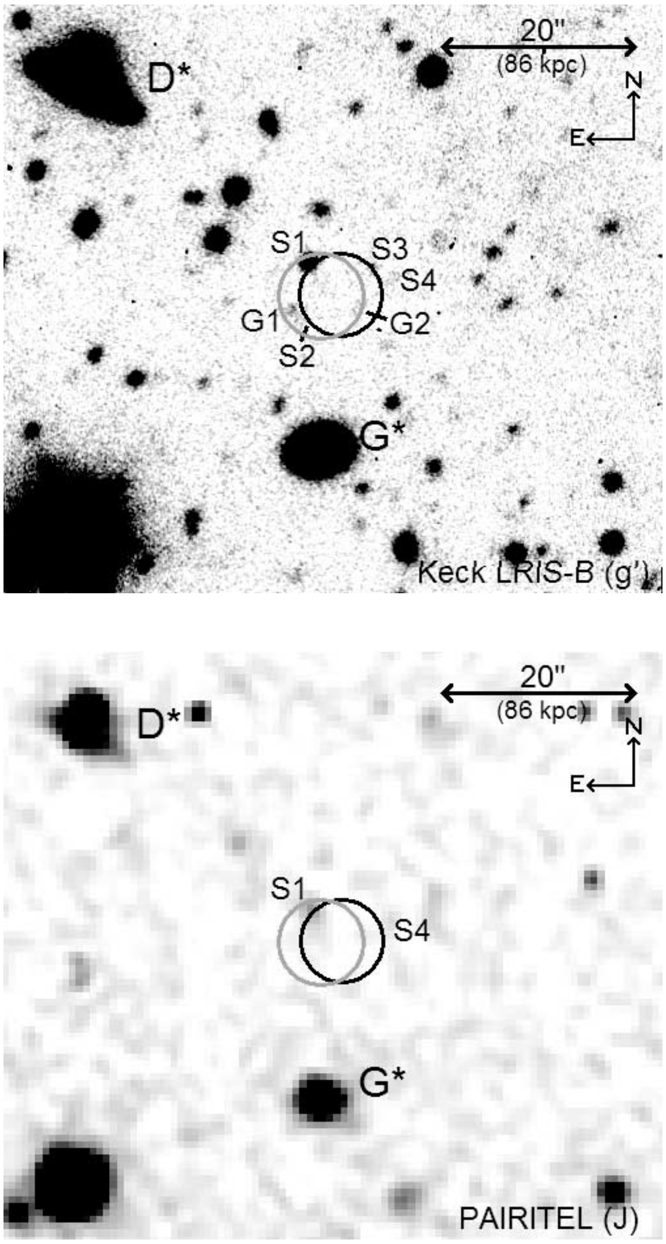

Fig. 1.—Finding chart of the field of GRB 060502b from Keck (g' band, *top*) and PAIRITEL (*J*-band, *bottom*). Noted are sources discussed in the literature and in this paper that are consistent with the *Swift* XRT error circle (*gray*; Troja et al. 2006a) and with our revised XRT error circle (*black*); S1 is a Galactic star. Also marked is G^*, which we identify as the putative host of 060502B. The position of G^* with respect to the USNO B1.0 catalog is $\alpha = 18^{\rm h}35^{\rm m}45.80^{\rm s}$, $\delta = +52°37'35.9''$ (J2000.0).

single spike with a FWHM of 40 ms and a possible second precursor spike; 90% of the total fluence arrived over a time span of 90 ± 20 ms (Sato et al. 2006), making it one of shortest GRBs localized by *Swift* (E. Troja 2006, private communication). The X-ray afterglow was localized to a final position of $\alpha = 18^{\rm h}35^{\rm m}45.74^{\rm s}$, $\delta = +52°37'52.47''$ (J2000.0) with a 4.4″ uncertainty radius (90% confidence; Troja et al. 2006a). Using seven X-ray persistent sources found within 10″ of eight sources in the Digitized Sky Survey (DSS) near the X-ray positions, we find a consistent position of $\alpha = 18^{\rm h}35^{\rm m}45.48^{\rm s}$, $\delta = +52°37'52.7''$ (J2000.0) with a 4.36″ uncertainty radius (90% confidence); this accounts for the small shift of the DSS astrometric frame to the (more precise)

TABLE 1

Photometry of the Putative Host of GRB 060502B

Filter	Magnitude	Instrument/Survey	Reference
B	19.7	USNO-A	1
B	20.40	APM-North	2
B	20.58	USNO-B	3
B	19.75	USNO-B	3
g'	20.290 ± 0.01	Keck-LRIS	4
R	18.6	USNO-A	2
R	18.62	USNO-B	3
R	18.21	USNO-B	3
R	18.06	APM-North	2
R	18.5	GSC2.2	5
R	18.711 ± 0.01	Keck-LRIS	4
I	17.77	USNO-B	3
J	17.16 ± 0.05	PAIRITEL	4
H	16.43 ± 0.05	PAIRITEL	4
K_s	15.23 ± 0.05	PAIRITEL	4

References.—(1) VizieR Online Data Catalog, 1252 (D. B. A. Monet et al. 1998); (2) VizieR Online Data Catalog, 1267 (R. G. McMahon et al. 2000); (3) Monet et al. 2003; (4) this work; (5) McLean et al. 2000.

2MASS frame.[5] Starting 74 s after the GRB, the Ultraviolet and Optical Telescope (UVOT) on board *Swift* obtained a deep unfiltered exposure of 100 s and found no optical afterglow candidate to a limiting magnitude of 19.1 mag (Troja et al. 2006b). Likewise, no optically variable counterpart was found in rapid ground-based imaging to $R < 20$ mag several minutes to hours after the GRB (Lipunov et al. 2006; Zhai et al. 2006; Kann et al. 2006; Takahashi et al. 2006; Meurs et al. 2006; Halpern & Mirabal 2006b). No variable optical counterpart was found in deep image differencing of r' Gemini Multiobject Spectrograph (GMOS) Gemini 8 m data taken at 0.7 and 1.7 days after the GRB (Price et al. 2006). Three sources in the refined *Swift* XRT error circle were identified, one of which was shown through spectroscopy to be a Galactic star (Berger et al. 2006; Halpern & Mirabal 2006a; Rumyantsev et al. 2006). Three additional sources are located in or near our modified XRT error circle.

2.1. *Imaging*

On 2006 May 30 UTC, using the Low-Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) on the Keck I 10 m telescope, we imaged the field of SHB 060502B in the *R* and g' filters for 300 and 330 s, respectively. The images were processed in the usual manner. We also observed the field from 2006 May 3 7:48:22 to 9:47:05 UTC with the 1.3 m Peters Automated Infrared Imaging Telescope (PAIRITEL; Bloom et al. 2006b). We reduced and stacked the images in *J*, *H*, and K_s band using the standard pipeline. A Keck and PAIRITEL finding chart of the field is presented in Figure 1. Astrometry was performed on all images relative to the USNO B1.0 catalog (Monet et al. 2003) with typical 1 σ rms relative to that catalog of 250 mas in each coordinate.

From the PAIRITEL imaging, we took note of an extended red source (G^*) to the south of the XRT position, at a position of $\alpha = 18^{\rm h}35^{\rm m}45.76^{\rm s}$, $\delta = +52°37'36.7''$ (J2000.0). Motivated by the inference of old galaxies at low redshift ($z \sim 0.2$) associated with some SHBs at large projected offsets (Bloom & Prochaska 2006), we investigated the nature of G^*. Photometry from the Keck data were performed using observations of the standard-star field

[5] An outline of the XRT reanalysis technique was presented in Butler & Bloom (2006). Details may be found in Butler (2006).

TABLE 2
Keck Photometry of Faint Objects in or Near the XRT Error Circle

Object	g' (mag)	R (mag)
S1	23.438 ± 0.03	21.756 ± 0.01
G1	25.937 ± 0.07	24.028 ± 0.06
S2	26.557 ± 0.12	26.049 ± 0.27
S3	26.561 ± 0.12	26.480 ± 0.52
S4	26.799 ± 0.15	26.219 ± 0.41
G2	27.944 ± 0.40	>26.5

PG 2213 (Landolt 1992). For G^*, we use a 6″ (radius) aperture, while a smaller aperture of 1.4″ was used for photometry of several fainter objects in and around the XRT error circle. PAIRITEL data were photometered relative to the 2MASS (Skrutskie et al. 2006) using a 6″ radius aperture to capture most of the flux of G^*. A summary of the photometry of this object is found in Table 1. Photometry of other objects in and around the XRT error circle is presented in Table 2.

We further investigate the nature of G^* by fitting different profiles to our Keck imaging of the galaxy using the software package GALFIT (Peng et al. 2002). Initially, we fit a bulge+disk model, modeling the galaxy as a sum of an exponential profile and a de Vaucouleurs profile. The de Vaucouleurs component was reduced to a point source by the fit, and the residuals were very large. The residuals for a fit with a single, general Sérsic profile were also unacceptable. A significantly better fit was obtained with a model of the sum of two general Sérsic profiles; the best fit for this model is an inner component with half-light radius $R_s = 0.56''$ and Sérsic index $n = 0.82$ (approximately exponential) and a very sharp, nearly box-car outer component with $R_s = 2.47''$ and $n = 0.12$. The residuals have a spiral arm appearance in g' band; these features are not detected in residual fits in the R-band image, suggestive of blue color and likely some star formation. The degree of concentration (low n of both fits) is surprising given the red color and small amount of star formation in this galaxy. However, we note that (1) this may be to some degree an overestimate of the concentration, which has been shown (Blanton et al. 2003) to be seeing dependent, and (2) while commonly associated in older literature only with slow-decaying profiles such as de Vaucouleurs ($n = 4$), large surveys have shown that old, red galaxies exhibit a wide range of profile indices from <1 up to 5 (Blanton et al. 2003), and concentrated profiles are not necessarily surprising.

2.2. *Spectroscopy*

On 2006 May 31 UTC, we obtained spectra of G^* using a 1.0″ slit at an angle of 15.7° east of north to also include the nearby faint galaxy "G1" in the slit. Several spectrophotometric standard stars were observed throughout the night at different air masses. Spectra of G^* were obtained at a median air mass of 1.37. At this angle and with this air mass, the differential slit losses are expected to be considerable, so we correct our resulting spectra using the broadband photometry as described above.

The spectrum of G^* (Fig. 2) exhibits prominent absorption features due to the Ca II H and K doublet and the hydrogen Balmer series, as well as a weak emission line due to [O II] at $z = 0.287$. These spectral signatures suggest that galaxy G^* is a poststarburst system with a small amount of on-going star formation.

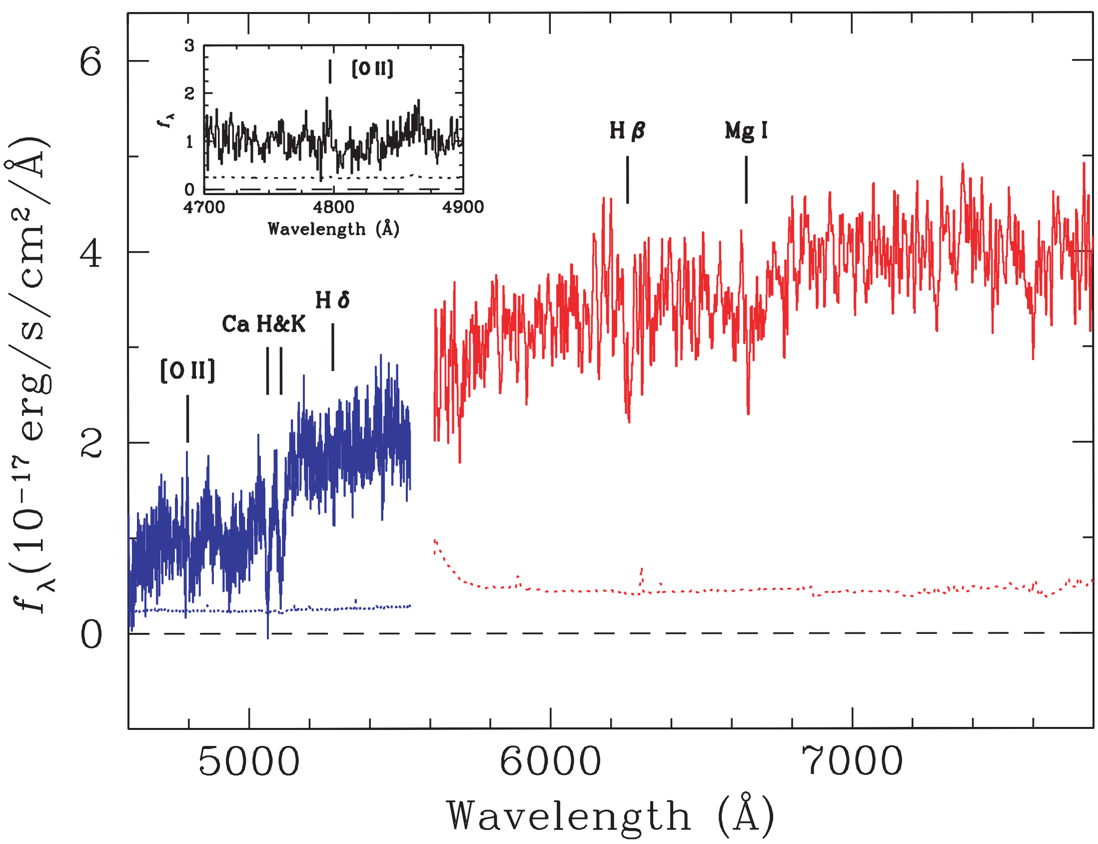

Fig. 2.—Observed Keck spectrum of G^* from the blue- and red-side chips of LRIS. A model for the rms noise is shown below the spectrum. Prominent absorption and emission features are labeled.

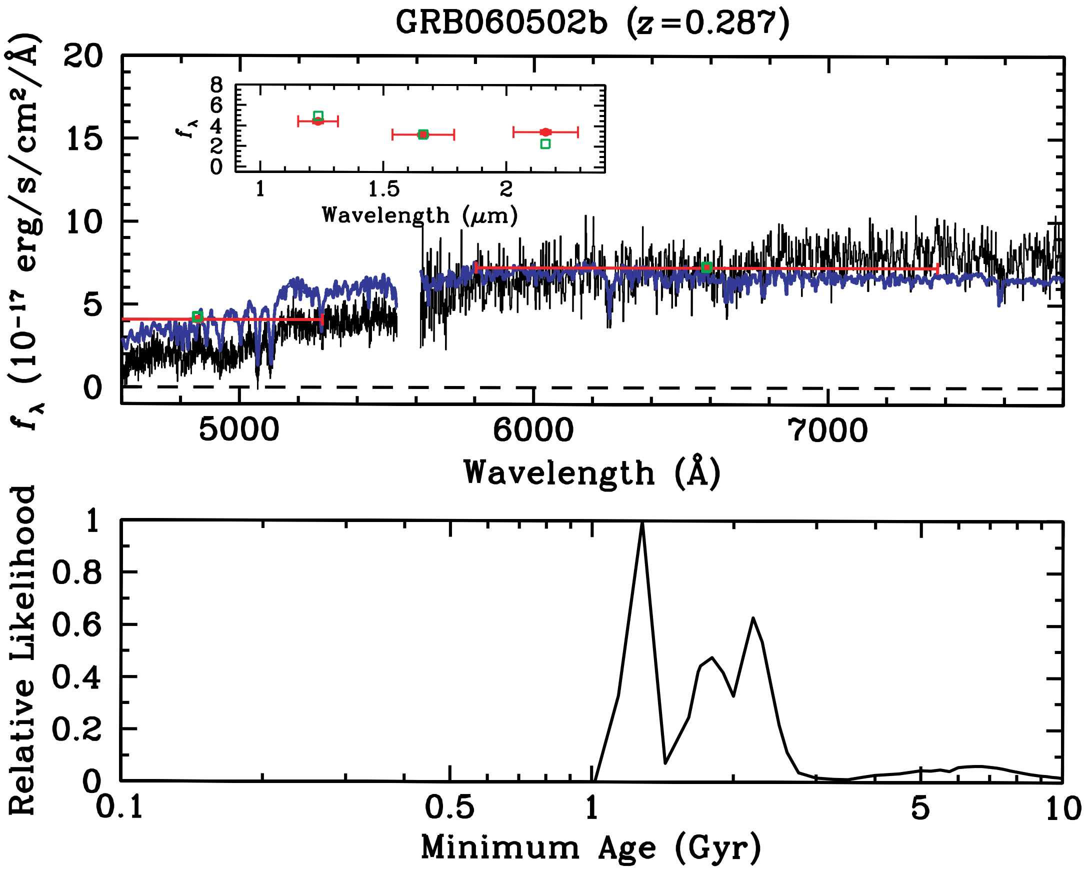

FIG. 3.—Model of the galaxy age and star formation history of G^*. *Top*: Model (*blue curve and green squares*) overplotted on the Keck spectrum (*black curve*) and broadband photometry (*red lines*) corrected for Galactic extinction of $A_V = 0.146$ mag (Schlegel et al. 1998). The inset is the near-IR photometry both observed and modeled. *Bottom*: Inferred star formation history from the model, indicating a recent starburst about 1.3 Gyr prior to the GRB explosion and some extended star formation activity prior.

To determine the on-going star formation rate, we measure an equivalent width of $W_{\rm obs} = 4.1 \pm 0.7$ Å for the [O II] line. Given a significant differential slit loss, we scale the spectral continuum to match the observed broadband flux in the g' band, AB(g') = 20.12 ± 0.03 (corrected for Galactic extinction), and estimate a total line flux of f([O II]) = $(2.3 \pm 0.4) \times 10^{-16}$ ergs s^{-1} cm^{-2}. At $z = 0.287$, the observed line flux corresponds to a total luminosity of L([O II]) = $(6.1 \pm 0.9) \times 10^{40}$ ergs s^{-1}. This indicates an on-going star formation rate of ~0.8 $M_\odot$ yr^{-1}, following the empirical relation of Kennicutt (1998), or 0.4 $M_\odot$ yr^{-1}, following Kewley et al. (2004) with no extinction correction for the observed L([O II]).

To constrain the underlying stellar population, we consider a suite of synthetic stellar population models generated using the Bruzual & Charlot (2003) spectral library. We adopt a Salpeter initial mass function with a range of metallicity from $\frac{1}{5}$ solar to solar and a range of star formation history from a single burst to an exponentially declining star formation rate of e-folding time 300 Myr. We include no dust in our synthetic spectra. Comparing the observed narrowband features and broadband photometry with model predictions allows us to constrain the stellar age in galaxy G^*. The results are presented in Figure 3, where the observed spectral energy distribution of the galaxy is shown in the top panel together with the best-fit model. The bottom panel of Figure 3 shows the likelihood distribution function versus stellar age, indicating that the last major episode of star formation occurred at ≈1.3 Gyr ago.

The velocity dispersion along the slit angle was 460 km s^{-1}, suggesting that G^* is a massive galaxy. The absolute K-band magnitude is $M_K \approx -23.3$ mag, implying it is 1.6 L_* for early-type galaxies (Kochanek et al. 2001). The best-fit stellar population and age suggest $M/L_K = 2.2$, leading to a total stellar mass of $7 \times 10^{11}\ h_{71}^{-2}\ M_\odot$. With a rest-frame equivalent width of Hδ $W_{\rm rest} = 2.9 \pm 0.5$ Å and [O II] $W_{\rm rest} = 3.2 \pm 0.5$ Å, the

TABLE 3
Gang of Three: The Inferred Properties of SHBs Associated with Early-Type Galaxies

SHB	z	$E_{{\rm iso},\gamma}$ (ergs)	$d_{\rm proj}$[a] (kpc)	References
050509b................	0.225	$(27 \pm 10) \times 10^{47}$	39 ± 13	Bloom et al. (2006c)
050724..................	0.258	1.0×10^{50}	2.4 ± 0.9	Prochaska et al. (2006)
060502b................	0.287	$(79 \pm 15) \times 10^{47}$	73 ± 19	This work

Note.—We do not include SHB 050813 owing to an uncertain redshift and uncertain association with a galaxy.
[a] Projected physical offset from putative host in units of h_{71}^{-1}.

classification of G^* is closest to "k," although it could be consistent with "k + a" (formerly part of the "E + A" class) (following Fig. 4 of Dressler et al. 1999).

3. G^* AS THE HOST OF SHB 060502B

We advance the hypothesis that G^* hosted the birth of the progenitor of SHB 060502B, which traveled an appreciable distance from its birth site before producing the GRB event. At a redshift of $z = 0.287$, the offset of the XRT position from the center of the galaxy ($17.05'' \pm 4.36''$) corresponds to $r = 73 \pm 19\ h_{71}^{-1}$ kpc in projection. With a fluence of $(4.0 \pm 0.5) \times 10^{-8}$ ergs cm^{-2}, the total energy release in γ-rays, assuming a unity k-correction, is $E_{\rm iso,\gamma} = (79 \pm 10) \times 10^{47}$ ergs. Our proposed association is based on both probabilistic and associative grounds. This is supported by a dynamical calculation in § 4.

3.1. *Probabilistic Arguments*

Even with the relatively large offset observed between GRB 060502B and G^*, the rarity of bright galaxies on the sky suggests an association. Based on our PAIRITEL photometry, the putative host G^* has an apparent magnitude of $K = 15.23$. The sky density of galaxies in the infrared at magnitudes $K < 18$ follows the approximate distribution $d\sigma/dm = 160 \times 10^{0.6(K-15)}$ mag^{-1} deg^{-2} (Kochanek et al. 2001). Integrating this distribution, we calculate a sky density of about 250 galaxies deg^{-2} of equal or greater brightness to G^*. The probability of a given GRB occurring by chance within the observed offset of $20''$ (using the far edge of the XRT error circle) from the center of such a galaxy is ≈ 0.025. Using the galaxy counts from the Calar Alto Deep Imaging Survey (Huang et al. 2001) we calculate similar probabilities with the R-band magnitude [$P(R < 18.5) \approx 0.03$] and B-band magnitude [$P(B < 20.5) \approx 0.05$]. These estimates do not consider host type or classification, the inclusion of which would generally serve to lower the probability. We address other galaxies as potential hosts in § 3.3.

3.2. *Associative Connection*

Probabilistic arguments aside, there are some heuristic arguments for the connection worth noting. Although not all SHBs have been associated with early-type galaxies, there is growing evidence from the small sample that SHBs are associated with older stars (Nakar et al. 2006; Prochaska et al. 2006; Guetta & Piran 2006; Zheng & Ramirez-Ruiz 2006), and likely with larger burst offsets from galaxies, than LSBs (Bloom & Prochaska 2006). Such a configuration is natural in the degenerate merger models; in particular, 75 kpc offsets from massive galaxies were predicted from ab initio binary evolution studies (Fryer et al. 1999; Bloom et al. 1999). As such, we contend that there is now a priori precedent to support our claim that G^* hosted the progenitor birth of SHB 060502B.

The G^*–SHB 060502B configuration shows some striking similarities with the other SHBs with putative early-type hosts (see Table 3). Not only would the redshift of $z = 0.287$ be remarkably similar to that of SHB 050509b and SHB 050724, but the inferred energy would be consistent with that of 050509b. Indeed, in energy, redshift, putative galaxy color and type, and offset scale, SHB 060502b finds a strong analog in SHB 050509b. Finally, we note that the weak X-ray afterglow and no detected optical afterglow would seem to indicate a low-density circumburst environment, as would be expected if the GRB originated far from the progenitor birth site.

3.3. *Consideration of Other Potential Hosts*

With such a large physical offset, the possibility remains that the association with the putative host is coincidental and in fact the GRB originates from a different source. Here we discuss a few alternative possibilities for the host galaxy of this GRB. While none of these possibilities can be strongly ruled out, we nevertheless consider them less likely as potential hosts than G^*, for various stated reasons.

The original XRT error circle contains two other optical sources, designated "G1" and "S2." Our refined XRT error circle, while generally consistent with the original XRT error circle, excludes both of these sources to 90% confidence. Nevertheless, as this does not completely eliminate the possibility of association (especially considering the possibility of ejection), we can ask whether or not the proximity of these sources to the XRT position suggests, on probabilistic grounds, that one of these objects is physically associated with the GRB. The extended object G1 (the brightest source and therefore the least likely to be coincident with the error circle by random chance) has a magnitude of $R \approx 24$; the integrated sky density for galaxies of equal or greater brightness is about 20 arcmin^{-2}. The probability of a chance association with such an object at this distance or less is ≈ 0.5—that is, a randomly placed XRT error circle of this size will be as close or closer to such a galaxy about half the time. The probabilities will be comparable or higher for S2 and several additional, fainter sources we identify in our imaging (S3, S4, and G2). So while association of the GRB with one of these faint sources cannot be ruled out, the large size of the XRT error circle simply does not allow this possibility to be strongly tested.

Visible on our LRIS imaging is a nearly edge-on spiral at a distance of $34''$ northwest of the center of the XRT error circle. Unfortunately, this galaxy is strongly blended with a bright Galactic star, so an accurate magnitude measurement is difficult, although the blended source has a combined magnitude of 15.56 in the 2MASS catalog, slightly fainter than G^*. Even making the conservative assumption that $K_{D^*} \approx K_{G^*}$, however, the probability of random association with an object of this magnitude at this distance is about a factor of 4 larger than for the association with G^*. So on probabilistic grounds, if we are to associate GRB 060502B with any object in Figure 1, G^* is by far the strongest candidate.

There are two additional objects visible at much greater angular distances from the GRB that suggest themselves as possible hosts on account of their unusual brightness. At a distance of $2.0'$ north of the XRT position is a bright spiral galaxy, visible in 2MASS with a magnitude of $K = 12.5$. Despite this large distance, the probability of "random" association in this case is ≈ 0.043, about twice that of association with G^*. Even more suggestively, at a distance of $6.9'$ is the bright galaxy UGC 11292, and with a magnitude of $K = 10.05$ (Kochanek et al. 2001), the probability of such a close random association is only 0.005 (less than our probability for G^*). Still, we tend to disfavor this hypothesis on theoretical grounds: at the measured redshift of this galaxy of $z = 0.0276$ (Kochanek et al. 2001), the physical offset between the galaxy center and the XRT position is 230 kpc. UGC 11292 is a very massive galaxy (at $M_K = -25.4$ it is probably several times as massive as G^*). Even with conservative assumptions about the galaxy mass and the position of the progenitor birthplace within it, a large kick ($v \gtrsim 500$ km s^{-1}) would be required to eject an object to this distance.[6] An intriguing alternative possibility might be that the GRB was ejected from a much smaller and much less notable host that itself is associated with UGC 11292. Perhaps

[6] To be sure, systemic kicks of >500 km s^{-1} are expected for compact object binaries (e.g., NS-NS or NS-BH binaries), but most systems in population synthesis studies receive lower velocity kicks ($v \approx 100$ km s^{-1}); thus, the *prior* expectation, in choosing between two possible kick velocities, would be weighted toward the smaller of the two inferred velocities.

the spiral galaxy mentioned above is a member of such an association; its gravitational potential well would be much more shallow and the offset would be only $\sim$70 kpc. This is within the range of predicted short-hard GRB offsets. However, although there is some evidence that some short-hard GRBs may originate from the local universe (Tanvir et al. 2005), no specific short GRB has yet been associated with any host with $z < 0.2$. Until the local population of short GRBs and their hosts (if real) has been better characterized or other low-probability chance associations with nearby galaxies are observed, this alternative hypothesis remains extremely speculative, and the a posteriori probability argument alone is not sufficient to consider UGC 11292 or its hypothetical group a likely host.

4. DISCUSSION AND CONCLUSIONS

The large offset from what we have argued is a plausible host, if true, holds important ramifications for both the sort of viable progenitors and where they are born. First, the large offset would seem to be at odds with the hypothesis of a degenerate binary origin in which systematic kicks are small (such as in globular clusters [GCs]; Grindlay et al. 2006). While the expected number density of GCs at 75 kpc is exceedingly small (e.g., Bekki et al. 2005), there certainly could be a GC at $z = 0.287$ in the XRT error circle (it would appear as faint red point source with magnitude $R \approx 29$, in principle observable with *HST* imaging). Alternatively, G^* could have undergone a major merger leaving behind a progenitor system at the XRT position. Second, if the progenitor was created during what appears to be the last starburst in the putative host, then the time since the zero-age main-sequence would be $\tau \approx 1.3 \pm 0.2$ Gyr (90% confidence). At the inferred offset, this would imply a minimum systemic kick velocity of $v_{\rm kick,min} = r/\tau \approx 55 \pm 14$ km s^{-1}. Such a kick velocity is comparable to the models for degenerate binaries (Fryer et al. 1999) and observations of Galactic double NS systems (Dewi et al. 2005). The kick could have been significantly larger, implying that the progenitor orbited about the host before the GRB event. Indeed, with the inferred stellar mass $7 \times 10^{11}\ M_\odot\ h_{71}^{-2}$ of the putative host, unless the progenitor was born on the outskirts of the host gravitational potential, the true $v_{\rm kick}$ would have to have been comparable to or greater than dispersion velocity of the host.

If the progenitor remains gravitationally bound to G^* then the systemic orbital velocity of progenitor spends most time near zero velocity, with its initial kinetic energy stored as gravitational potential. That is, we nominally expect an orbiting progenitor to produce a burst near the maximal distance from its host. Indeed, if all the energy is stored as potential, then for SHB 060502B the gravitational potential of the progenitor system is

$$\epsilon_{\rm pot} = \frac{GM_{G^*}}{d} \approx 6 \times 10^{14}\ {\rm ergs\ gm^{-1}} \left(\frac{M_{G^*}}{10^{12}\ M_\odot}\right)\left(\frac{d}{73\ {\rm kpc}}\right)^{-1}.$$

Upon birth, the kinetic energy per unit mass imparted to the progenitor must have been:

$$\epsilon_{\rm kin} = \frac{1}{2} v_{\rm kick}^2 \approx 1 \times 10^{14}\ {\rm ergs\ gm^{-1}} \left(\frac{v_{\rm kick}}{160\ {\rm km\ s^{-1}}}\right)^2.$$

Here we have taken the nominal velocity of the kick as the geometric mean of the dispersion velocity ($\approx$460 km s^{-1}) and $v_{\rm kick,min}$; that is, we assume $v_{\rm kick} = 160$ km s^{-1}. That $\epsilon_{\rm kin}$ is even within an order of magnitude of $\epsilon_{\rm pot}$ is either a remarkable coincidence[7] or, we suggest, indicative of support on dynamical grounds for the ejection hypothesis.

We end by acknowledging the difficulty of confirming, beyond reasonable doubt, our hypothesis that G^* hosted the birth of the progenitor of SHB 060205b. The progenitors of most LSBs, owing to their connection with massive stars, allowed for unambiguous associations with putative hosts—most with probability of chance alignment $P \lesssim 10^{-3}$ (Bloom et al. 2002). With SHB 060502b we have estimated under mildly conservative assumptions (i.e., without regard to host type) that the chance of a spurious assignment with G^* is $P \lesssim 10\%$. The $\epsilon_{\rm kin} \approx \epsilon_{\rm pot}$ argument and the similarity with GRB 050509b likely strengthen this particular association. Yet with SHBs, especially if the majority of progenitors are long-lived high-velocity degenerate mergers, the community must accept that an appreciable fraction of host assignments relative to LSBs will be spurious (Bloom et al. 1997). Of course absorption-line redshifts of SHB afterglows, one of the remaining observational goals of the field, will help to significantly cull the number density of viable hosts on the sky.

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[7] If the progenitor is a double neutron star with $M_{\rm prog} = 2.8\ M_\odot$, then the total respective energies are $E_{\rm pot} = M_{\rm prog}\epsilon_{\rm pot} = 3 \times 10^{48}$ ergs and $E_{\rm kin} = M_{\rm prog}\epsilon_{\rm kin} = 7 \times 10^{47}$ ergs. We can think of no progenitor model to explain why $E_{\rm kin}$ and $E_{\rm pot}$ is also comparable to $E_{{\rm iso},\gamma}$.

REFERENCES

Bekki, K., Beasley, M. A., Brodie, J. P., & Forbes, D. A. 2005, MNRAS, 363, 1211
Berger, E., Cenko, S. B., & Rau, A. 2006, GCN Circ. 5071
Berger, E., et al. 2005, Nature, 438, 988
Blanton, M. R., et al. 2003, ApJ, 594, 186
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002, AJ, 123, 1111
Bloom, J. S., Perley, D., Kocevski, D., Butler, N., Prochaska, J. X., & Chen, H. 2006a, GCN Circ. 5238
Bloom, J. S., & Prochaska, J. X. 2006, in AIP Conf. Ser. 836, ed. S. S. Holt, N. Gehrels, & J. A. Nousek (Melville: AIP), 473

Bloom, J. S., Sigurdsson, S., & Pols, O. R. 1999, MNRAS, 305, 763
Bloom, J. S., Starr, D. L., Blake, C. H., Skrutskie, M. F., & Falco, E. E. 2006b, in ASP Conf. Ser. 351, Astronomical Data Analysis Software and Systems XV, ed. D. P. C. Gabriel, C. Arviset, & E. Solano (San Francisco: ASP), 751
Bloom, J. S., Tanvir, N. R., & Wijers, R. A. M. J. 1997, preprint (astro-ph/9705098)
Bloom, J. S., et al. 2006c, ApJ, 638, 354
Brandt, N., & Podsiadlowski, P. 1995, MNRAS, 274, 461
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Butler, N., & Bloom, J. S. 2006, GCN Circ. 4500
Butler, N. R. 2006, ApJ, in press (astro-ph/0611031)
Covino, S., et al. 2006, A&A, 447, L5
Dewi, J. D. M., Podsiadlowski, P., & Pols, O. R. 2005, MNRAS, 363, L71
Dressler, A., Smail, I., Poggianti, B. M., Butcher, H., Couch, W. J., Ellis, R. S., & Oemler, A. J. 1999, ApJS, 122, 51
Fox, D. B., et al. 2005, Nature, 437, 845
Fryer, C. L., Woosley, S. E., & Hartmann, D. H. 1999, ApJ, 526, 152
Gehrels, N., et al. 2005, Nature, 437, 851
Gorosabel, J., et al. 2006, A&A, 450, 87
Grindlay, J., Portegies Zwart, S., & McMillan, S. 2006, Nature Phys., 2, 116
Guetta, D., & Piran, T. 2006, A&A, 453, 823
Halpern, J. P., & Mirabal, N. 2006a, GCN Circ. 5072
———. 2006b, GCN Circ. 5066
Hjorth, J., et al. 2005a, ApJ, 630, L117
———. 2005b, Nature, 437, 859
Huang, J.-S., et al. 2001, A&A, 368, 787
Kann, D. A., Klose, S., & Ferrero, P. 2006, GCN Circ. 5062
Kennicutt, R. C. 1998, ARA&A, 36, 189
Kewley, L. J., Geller, M. J., & Jansen, R. A. 2004, AJ, 127, 2002
Kochanek, C. S., et al. 2001, ApJ, 560, 566
Kouveliotou, C., Meegan, C. A., Fishman, G. J., Bhat, N. P., Briggs, M. S., Koshut, T. M., Paciesas, W. S., & Pendleton, G. N. 1993, ApJ, 413, L101
Landolt, A. U. 1992, AJ, 104, 372
Levan, A. J., et al. 2006, ApJ, 648, L9
Lipunov, V., et al. 2006, GCN Circ. 5056
Mazets, E. P., et al. 1981, Ap&SS, 80, 3
McLean, B. J., Greene, G. R., Lattanzi, M. G., & Pirenne, B. 2000, in ASP Conf. Ser. 216, Astronomical Data Analysis Software and Systems IX, ed. N. Manset, C. Veillet, & D. Crabtree (San Francisco: ASP), 145
Meurs, E. J. A., Vergani, S. D., O'Maoileidigh, C., Malesani, D., & Gualandi, R. 2006, GCN Circ. 5074
Monet, D. G. et al. 2003, AJ, 125, 984
Nakar, E., Gal-Yam, A., Piran, T., & Fox, D. B. 2006, ApJ, 640, 849
Narayan, R., Paczyński, B., & Piran, T. 1992, ApJ, 395, L83
Norris, J. P., Cline, T. L., Desai, U. D., & Teegarden, B. J. 1984, Nature, 308, 434
Oke, J. B. et al. 1995, PASP, 107, 375
Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2002, AJ, 124, 266
Price, P. A., Berger, E., Fox, D. B., Cenko, S. B., & Rau, A. 2006, GCN Circ. 5077
Prochaska, J. X., et al. 2006, ApJ, 642, 989
Rumyantsev, V., Karimov, R., Salyamov, R., Pavlenko, E., Efimov, Y., Pozanenko, A., & Ibrahimov, M. 2006, GCN Circ. 5184
Sato, G., et al. 2006, GCN Circ. 5064
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Soderberg, A. M., et al. 2006, ApJ, 650, 261
Takahashi, I. et al. 2006, GCN Circ. 5065
Tanvir, N. R., Chapman, R., Levan, A. J., & Priddey, R. S. 2005, Nature, 438, 991
Troja, E., Burrows, D. N., & Gehrels, N. 2006a, GCN Circ. 5093
Troja, E., et al. 2006b, GCN Circ. 5055
Villasenor, J. S., et al. 2005, Nature, 437, 855
Zhai, M., Qiu, Y. L., Wei, J. Y., Hu, J. Y., Deng, J. S., Wang, X. F., Huang, K. Y., & Urata, Y. 2006, GCN Circ. 5057
Zheng, Z., & Ramirez-Ruiz, E. 2006, ApJL, submitted (astro-ph/0601622)