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NEW IMAGING AND SPECTROSCOPY OF THE LOCATIONS OF SEVERAL SHORT-HARD GAMMA-RAY BURSTS

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ABSTRACT

The detection and characterization of the afterglow emission and host galaxies of short-hard gamma-ray bursts (SHBs) is one of the most exciting recent astronomical discoveries. In particular, indications that SHB progenitors belong to old stellar populations, in contrast to the long-soft GRBs, provide a strong clue about the physical nature of these systems. Definitive conclusions are currently limited by the small number of SHBs with known hosts available for study. Here, we present our investigation of SHBs previously localized by the interplanetary network (IPN). We show that the brightest galaxy within the error box of SHB 000607, at $z = 0.1405$, is the probable host galaxy of this event, expanding the sample of SHBs with known hosts and distances. We find a spatial association of the bright SHB 790613 and the cataloged position of the rich galaxy cluster Abell 1892. However, we are unable to verify the reality of this cluster via spectroscopy or multicolor imaging, and we conclude that this association may well be spurious. In addition, we rule out the existence of galaxy overdensities (down to $\approx$21 mag, i.e., $\approx 0.1\ L_*$ at $z = 0.2$) near the locations of two other SHBs and set a lower limit on their probable redshift. We combine our SHB sample with a complete sample of events discovered by the *Swift* and *HETE-2* missions and investigate the properties of the extended sample. We show that the progenitors of SHBs appear to be older than those of Type Ia SNe, on average, suggesting a typical lifetime of several Gyr. The low typical redshift of SHBs leads to a significant increase in the local SHB rate and bodes well for the detection of gravitational radiation from these events, should they result from compact binary mergers, with forthcoming facilities.

Subject heading: gamma rays: bursts

Online material: color figures

1. INTRODUCTION

The short-hard class of the gamma-ray burst (GRB) population (SHB; Kouveliotou et al. 1993; Nakar 2007) makes up a quarter of the entire GRB population observed by BATSE[2] with an all-sky detection rate of $\approx 170\ \mathrm{yr}^{-1}$ (Meegan et al. 1997). For many years, the failure to detect any afterglow emission associated with SHBs prevented rapid progress in this field. Still, population analysis of SHBs provided indirect clues about their typical distance. Namely, the almost isotropic sky distribution (Briggs et al. 1996; Balazs et al. 1998; Magliocchetti et al. 2003) and small value of $\langle V/V_{\max}\rangle$ (Katz & Canel 1996; Schmidt 2001; Guetta & Piran 2005) suggested a cosmological origin.

The long-expected breakthrough in this field has finally occurred following accurate localizations of SHBs by the *Swift*[3] and *HETE-2*[4] spacecraft. The discovery of the X-ray afterglow of GRB 050509b by the *Swift* X-ray Telescope (XRT; Gehrels et al. 2005) led to its

[1] Hubble Fellow.
[2] See http://www.batse.msfc.nasa.gov/batse/.
[3] See http://swift.gsfc.nasa.gov/docs/swift/swiftsc.html.
[4] See http://space.mit.edu/HETE/Welcome.html.

localization to within a few arcseconds, in close proximity to a bright elliptical galaxy, a member of a galaxy cluster at $z = 0.22$ (Bloom et al. 2006; Castro-Tirado et al. 2005a; Gehrels et al. 2005; Prochaska et al. 2006). Sensitive follow-up imaging of the XRT localization revealed many background galaxies within the error circle but no optical afterglow (Gehrels et al. 2005; Bloom et al. 2006; Hjorth et al. 2005a; Castro-Tirado et al. 2005a), and the lack of subarcsecond localization prohibits an unambiguous identification of the host galaxy of this SHB. However, a posteriori statistical arguments suggest that SHB 050509b was associated with the $z = 0.22$ system (Gehrels et al. 2005; Bloom et al. 2006; Eisenstein et al. 2005).

The precise localization of SHB 050709 by *HETE-2* (Butler et al. 2005) and the subsequent discovery of X-ray (Fox et al. 2005) and optical (Price et al. 2005; Hjorth et al. 2005b) afterglow emission pinpointed the location of this SHB to subarcsecond accuracy and led to the identification and detailed characterization of its host galaxy (Fox et al. 2005; Covino et al. 2006; Prochaska et al. 2006). This identification established that SHB 050709 is a relatively nearby event (at $z = 0.16$) and that its host is not an early-type galaxy, as suggested for 050509b, but rather a modestly star-forming galaxy with a star formation rate similar to that of Sb/c galaxies and a dominant population of middle-aged ($\sim$1 Gyr old) stars (Covino et al. 2006).

Shortly after, SHB 050724 was localized by *Swift* and turned out to have a rich afterglow spectrum, including X-ray (Romano et al. 2005; Fox et al. 2005), radio (Cameron & Frail 2005; Berger et al. 2005), and optical/IR (Gal-Yam et al. 2005; Berger et al. 2005; Castro-Tirado et al. 2005b; Cobb & Bailyn 2005; Wiersema et al. 2005). The afterglow detection led to the association of this burst with a red early-type galaxy (Berger et al. 2005; Prochaska et al. 2006) at $z = 0.257$. A few weeks later, SHB 050813 was localized by *Swift* and associated with a galaxy cluster at either $z = 0.722$ or $z = 1.8$ (Gladders et al. 2005; Berger 2005, 2006; Prochaska et al. 2006; M. Gladders et al., in preparation). These two events give further credence to the association of SHB 050509b with the nearby $z = 0.22$ cluster elliptical.

These observations suggest, when taken together, that a significant fraction of the progenitors of SHBs are drawn from old stellar populations and are therefore long-lived. This result establishes the physical difference between SHB progenitors and the short-lived, massive star progenitors of long-soft GRBs.

A few months before these exciting discoveries were made, the study of SHBs was briefly revitalized by a Galactic event: the unusually bright supergiant flare from a soft gamma-ray repeater (SGR 1806$-$20). The temporal structure and luminosity of this event indicated that it would have appeared as an SHB had it occurred in a nearby galaxy (Duncan 2001; Dar 2005; Nakar et al. 2006; Palmer et al. 2005; Hurley et al. 2005), and this possibility raised a flurry of speculation about the possible association of SHBs with extragalactic SGRs. In Nakar et al. (2006) we investigated this question by looking for bright host galaxies in the error boxes of well-localized SHBs, expected if these were indeed SGRs in nearby galaxies. This observational test had not been attempted previously. This work set lower limits on the distance and energy output of six SHBs and showed that only a small fraction of SHBs can in fact be extragalactic SGRs. The latter result was independently confirmed, using other approaches, by Palmer et al. (2005), Popov & Stern (2006), and Lazzati et al. (2005). These findings are consistent with results from the analysis of BATSE SHBs mentioned above, indicating a cosmological origin of SHBs.

Our mostly archival investigation has shown the wealth of information that can be extracted from few-square-arcminute error boxes of SHBs produced by the interplanetary network (IPN; Hurley et al. 2002a), especially when deep observations of the error boxes are obtained. Detailed exploration of the error boxes, especially in view of the breakthrough discoveries made during 2005 May–August, seems promising and timely. Here we report the results of this investigation.

2. OBSERVATIONS

We have compiled all the SHBs localized to within error boxes smaller than 10 arcmin^2 (3 σ) with absolute Galactic latitude $|b| > 20°$, ending up with five SHBs: 790613, 000607, 001204, 021201, and 020531. We have defined the following observational test to be carried out: we look for significant luminosity overdensities in the fields of interest in the *BVI* bands, either in the form of a single luminous galaxy or as an overdensity of many fainter galaxies. The initial search was based on imaging obtained with the robotic 60 inch (1.5 m) telescope at Palomar Observatory (P60; Cenko et al. 2006), with some additional images obtained using the Las Campanas 100 inch (2.5 m) du Pont telescope and the 200 inch (5 m) Hale telescope at Palomar Observatory (P200; in the Sloan Digital Sky Survey [SDSS] g and r bands). P60 imaging was reduced by the automated reduction pipeline (Cenko et al. 2006), including bias and flat-field correction and astrometric solution relative to USNO-B1 stars. Imaging from the 100 inch du Pont and 200 inch Hale telescopes was reduced using standard procedures within IRAF. A log of the observations is presented in Table 1.

We obtained spectra of bright galaxies, determined their redshifts, and included this additional information in our statistical analysis. Spectroscopy was conducted mainly using the Double Spectrograph (DBSP; Oke & Gunn 1982) mounted on the 200 inch telescope at Palomar Observatory on numerous occasions (Table 1) and reduced using the standard CCCP spectroscopic reduction pipeline (Gal-Yam et al. 2007). A single spectrum was obtained using the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) mounted on the 10 m Keck I telescope.

A reexamination of the afterglow search for SHB 020531 initially suggested the afterglow may have been detected but overlooked (see § 2.3.3). We have therefore systematically explored the galaxy population only in the remaining four SHBs, as described below, and excluded SHB 020531 from the statistical analysis performed. We return to this point in § 2.3.3.

2.1. *SHB 000607*

SHB 000607 was well localized by the IPN (error box area 5.6 arcmin^2; Hurley et al. 2002a). In our previous study of this event (Nakar et al. 2006) we identified a bright galaxy (000607-G1). This galaxy is the brightest galaxy in all the error boxes examined here. We also determined its redshift to be $z = 0.1405$ based on P200 spectroscopy (Fig. 1). In order to examine the probability of finding such a galaxy within the error box, we first calibrated its R-band magnitude using P60 observations of Landolt (1992) standard stars obtained during a photometric night. We then converted it to SDSS r and i magnitudes using synthetic photometry applied to the P200 spectrum, as described in Poznanski et al. (2002). We obtained $r = 17.9 \pm 0.1$ and $i = 17.3 \pm 0.1$.

We estimated the expected local density of galaxies using the Schechter function (Schechter 1976) fit to the SDSS luminosity function at $z \approx 0.1$ in the r and i bands from Blanton et al. (2003),

$$\phi(L > L_0) = \int_{L_0}^{\infty} \phi^*(L/L^*)^{\alpha} e^{-L/L^*}\, dL/L^*, \tag{1}$$

TABLE 1

JOURNAL OF OBSERVATIONS

SHB	Telescope	Instrument	Exposure	UT Date
		Photometry		
790613	P60	CCD	*B* (450 s), *V* (450 s), *I* (450 s)	2005 Aug 12
790613	P200	LFC	*g* (630 s), *r* (600 s)	2006 Mar 3
790613	P60	CCD	*g* (1800 s), *r* (1800 s), *i* (1800 s)	2008 Apr 23
000607	P60	CCD	*R* (720 s)	2005 Sep 28
001204	P60	CCD	*B* (450 s), *V* (450 s), *I* (450 s)	2005 Aug 11
	P60	CCD	*V* (1500 s), *R* (1500 s), *I* (900 s)	2005 Sep 28
	LCO100	Tek5	*V* (180 s), *I* (90 s)	2005 Sep 2
021201	P60	CCD	*B* (600 s), *V* (600 s), *I* (600 s)	2005 Sep 17
		Spectroscopy		
790613-G1	P200	DBSP	Red+blue (2700 s)	2006 Mar 4
790613-G2	P200	DBSP	Red+blue (2700 s)	2006 Mar 4
790613-G3	Keck I	LRIS	Red+blue (2400 s)	2006 Apr 22
790613-N1	P200	DBSP	Red+blue (1800 s)	2006 Mar 3
790613-N2	P200	DBSP	Red+blue (3600 s)	2006 May 3
790613-N3	P200	DBSP	Red+blue (3600 s)	2006 Jul 20
790613-N5	P200	DBSP	Red+blue (3600 s)	2006 Jul 20
000607-G1	P200	DBSP	Red+blue (900 s)	2005 Feb 6
001204-G1	P200	DBSP	Red+blue (2700 s)	2005 Aug 13
001204-G2	P200	DBSP	Red+blue (10800 s)	2005 Sep 9

NOTES.—P60: Palomar 60 inch robotic telescope. P200: Palomar 200 inch Hale telescope. LCO100: Las Campanas Observatory 100 inch du Pont telescope. Keck I: Keck I 10 m telescope. Spectroscopic observations with DBSP were obtained using the double-beam spectrograph with the 600 line grating on the blue side and 158 line grating on the red side, yielding a resolution of ≈1 and ≈5 Å, respectively. The Keck I LRIS spectrum was obtained using the 560 dichroic with 400 line grism/grating on the blue/red side, yielding a resolution of ≈5 Å.

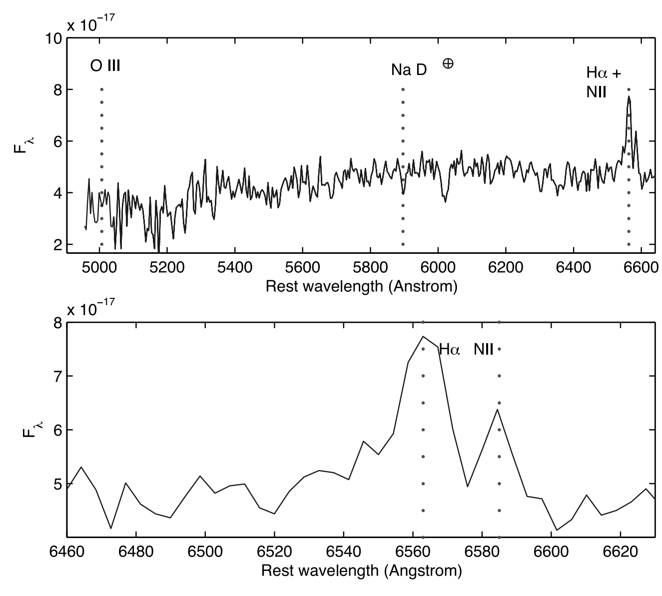

FIG. 1.—Spectrum of the bright galaxy 000607-G1, identified as the probable host of SHB 000607. We determine the redshift from Hα (6563 Å) and N II (6585 Å) in emission (see bottom panel for a detailed view) and Na D (5896 Å) in absorption. O III (5007 Å) is weak or absent. Telluric absorption is present near 6000 Å (*circled cross*). The spectral shape and emission-line strength indicate an early or intermediate spiral galaxy, perhaps of type Sb. Using the Kennicutt (1998) relation, we estimate a star formation rate of ≈0.3 $M_{\odot}$ yr^{-1} from the observed Hα luminosity. This is actually an upper limit, as the Hα line is contaminated by nearby N II (6550 Å) emission (*bottom*). The strength of the resolved N II line at 6585 Å suggests this contamination is small (<20%), but the low S/N and low resolution of the P200 spectrum preclude a more accurate determination. [*See the electronic edition of the Journal for a color version of this figure.*]

where $\phi_r^* = 5 \times 10^{-3}$ Mpc^{-3}, $M_r^* = -21.2$, and $\alpha_r = -1.05$ and $\phi_i^* = 5 \times 10^{-3}$ Mpc^{-3}, $M_i^* = -21.6$, and $\alpha_i = -1$ (we assume the standard cosmological model $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, and $h = 0.7$).

At $z = 0.1405$ (proper distance of 580 Mpc), $L_{000607\text{-G1}} \approx 1.3 \pm 0.1\ L_*$ (using the P200 spectrum for *k*-corrections) in both *r* and *i*. Thus, $\phi(L > L_{000607\text{-G1}}) \approx 6 \times 10^{-4}$ Mpc^{-3}, and within a distance of 580 Mpc there are about 5×10^5 galaxies that are as bright as or brighter than 000607-G1, implying an angular density of 3×10^{-3} arcmin^{-2}. Therefore, the probability of finding such a bright galaxy within the 5.6 arcmin^2 error box of GRB 000607 is ≈2%, while the probability of finding it anywhere within the four error boxes searched (a total angular area of 21 arcmin^2) is ≈7%. We find that the confidence level for association of this galaxy and GRB 000607 is 93%. Given the pitfalls of a posteriori statistics, we do not attempt to increase the statistical significance of the association by further examination of this galaxy in search of peculiar or noteworthy properties (colors, morphology, etc.). At a redshift of $z = 0.1405$, the total isotropic-equivalent energy emitted by this SHB would be 2×10^{49} erg (between 50 and 300 keV) and 2×10^{50} erg (between 0.15 and 5 MeV). The corresponding burst luminosity is $\approx 5 \times 10^{51}$ erg s^{-1} cm^{-2}.

The spectral shape and emission-line strength of 000607-G1 indicate an intermediate spiral galaxy, perhaps of type Sb. Using the Kennicutt (1998) relation we estimate a star formation rate of ≈0.3 $M_{\odot}$ yr^{-1} from the observed Hα luminosity, similar to that of the host galaxy of SHB 050709 (Fox et al. 2005).

2.2. *SHB 790613*

SHB 790613 was a short (∼48 ms) and hard GRB localized by the IPN to within an extremely small error box (in IPN standards; 0.7 arcmin^2; Barat et al. 1984, 1985). Figure 2 (*right*) shows an

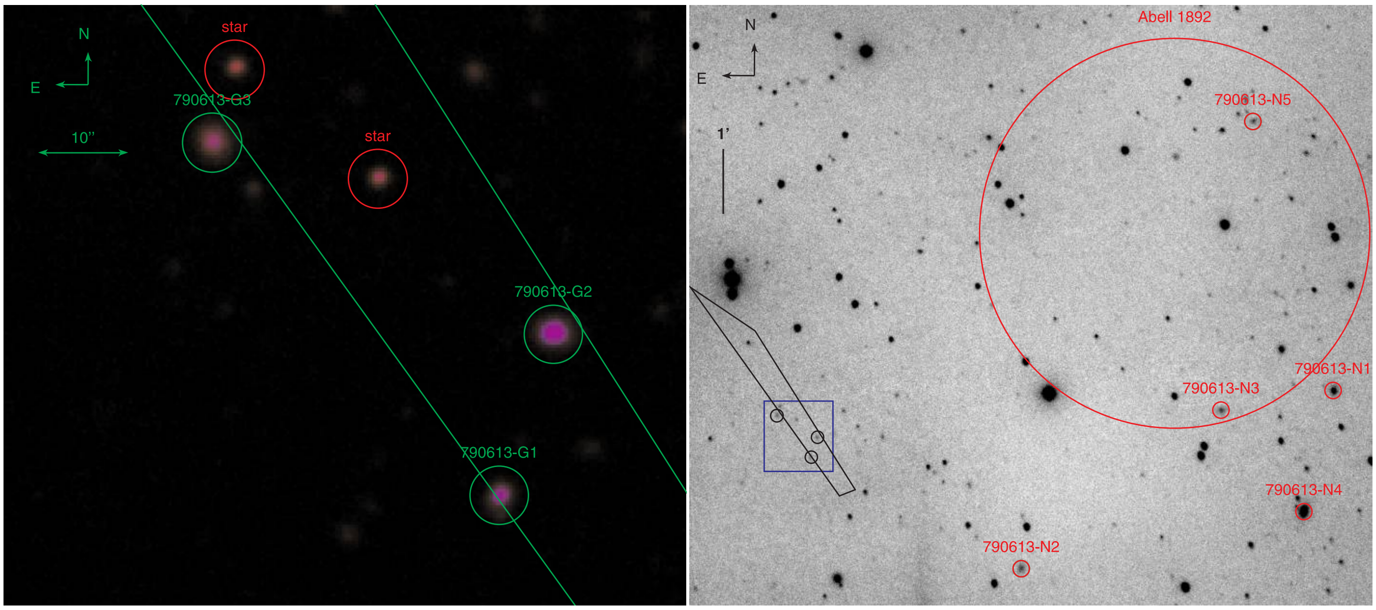

FIG. 2.—*Right*: P60 *I*-band image of the location of SHB 790613. The IPN error region is marked as a black polygon, and within it we mark the three detected galaxies in black circles. The cataloged location of Abell 1892 is marked with a large red circle, and the locations of nearby bright galaxies for which we have obtained spectroscopy are marked with small red circles. *Left*: Color image produced from our best-seeing *g*- and *r*-band frames from the Palomar 200 inch telescope of the center of the IPN error region (*purple square, right*). The image clearly shows the galaxies located within the IPN error region (*circled in green*) and two foreground stars (*circled in red*; these also have redder colors). The galaxies are well resolved compared to the stars, with measured PSFs which are at least 50% wider. The bright source in the northern part of the error region (*right*; it lies outside the boundaries of the left panel) also has a clear stellar PSF. The deeper 200 inch images reveal numerous fainter sources ($m_I > 21$), most likely fainter galaxies.

I-band image of the burst location obtained with P60. Three galaxies (790613-G1–790613-G3; black circles in Fig. 2, *right*; Table 2) are located within the IPN error region. All other objects brighter than our detection limit in P60 imaging ($m_I < 21$ mag) have stellar PSFs in our best images (seeing 1.4″; Fig. 2, *left*). As we show below, the galaxies are not physically related, and our observations therefore do not reveal a significant luminosity overdensity.

However, a query of the NED database[5] has shown that this burst occurred within 6.5′ of the cataloged center of a rich Abell galaxy cluster (Abell 1892, richness class $\Re = 1$; Abell 1958; Fig. 2, *right*). The Abell galaxy cluster catalog (Abell 1958) contains 2712 galaxy clusters, of which 1894 (≈70%) are considered to be rich ($\Re \geq 1$). The completeness of the catalog and the resulting sky density of clusters is a strong function of Galactic latitude. Abell (1958) reports ≈0.08 clusters deg^{-2} at Galactic latitude 40° (the Galactic latitude of SHB 790613 is 37.6°), of which ≈0.06 are expected to be rich. The chance probability of finding a rich cluster within 6.5′ (≈0.1°) from a random point in this latitude is therefore $P \approx \pi 0.1^2 \times 0.06 \approx 2 \times 10^{-3}$. We conclude that this association is significant, even considering that we have checked for a similar association (with negative results) in four other cases; but of course, the effects of a posteriori statistics are hard to quantify.

In order to determine the redshift of Abell 1892, since the cataloged value ($z = 0.09$; Struble & Rood 1999) is based on a single galaxy, we obtain additional spectroscopy of galaxies within the IPN error box and near the reported position of Abell 1892. We find that the three galaxies within the IPN region lie at discrepant redshifts in the range $0.247 < z < 0.432$ (Table 2) and are therefore unlikely to be related to Abell 1892. The galaxy 790613-N1 (LEDA 140268; reportedly a cluster member at $z = 0.09$) is found to actually be an early-type galaxy at $z = 0.19$. Other nearby bright galaxies (shown in Fig. 2 and reported in Table 2) lie at various other redshifts. Only two galaxies with late-type emission-line spectra (790613-N2 and 790613-N3, with redshifts $z = 0.0877$ and 0.0893, respectively) are possibly physically related. We therefore conclude that the redshift of Abell 1892 cannot be uniquely determined from the available data, and in fact, we cannot firmly establish that the galaxy overdensity cataloged by Abell represents a single physical system. Further, inspection of deep *gri* P60 imaging by one of us (M. G.) *fails* to show a prominent galaxy excess, as expected from a nearby, rich Abell cluster. The existence of a galaxy cluster at the cataloged location of Abell 1892 cannot be confirmed by our data, nor can we determine a likely distance for this burst.

If SHB 790613 is associated with a galaxy cluster, it must have occurred either in a faint cluster galaxy which lies within the error region and is below $M_I = 21$ or in intracluster space. This could happen if the progenitor of this SHB was a NS-NS merger (Eichler et al. 1989; Narayan et al. 1992); 1′ corresponds to ≈100 kpc at $z = 0.09$, which a neutron star (NS) binary with a modest initial kick velocity can travel before it merges. Alternatively, the progenitor might have belonged to the population of intergalactic stars accounting for 10%–20% of the stellar mass in galaxy clusters (e.g., Aguerri et al. 2005 and references therein). The detection of Type Ia supernovae (SNe Ia) resulting from this intergalactic population (Gal-Yam et al. 2003) shows that compact binaries (which are likely the progenitors of SNe Ia) can survive in this environment.

If SHB 790613 lies at a redshift of $z = 0.09$, the total isotropic-equivalent energy emitted by this SHB is 6×10^{49} erg (between 0.15 and 5 MeV). The burst luminosity is $\approx 1 \times 10^{51}$ erg s^{-1} cm^{-2}.

2.3. *Additional Bursts*

2.3.1. *SHB 001204*

SHB 001204 was localized by the IPN to within a 6 arcmin^2 error box (Hurley et al. 2002a). In our previous study of this event

[5] See http://nedwww.ipac.caltech.edu/.

TABLE 2
GALAXIES IN THE VICINITY OF SHB LOCATIONS

Galaxy	Coordinates (J2000.0) R.A.	Decl.	Magnitudes	Redshift	Comments
790613-G1	14 11 49.32	78 40 28.0	$I = 18.96 \pm 0.05$	0.270	
790613-G2	14 11 47.15	78 40 45.9	$I = 18.86 \pm 0.13$	0.247	
790613-G3	14 11 59.81	78 41 05.4	$I = 18.86 \pm 0.09$	0.432	
790613-N1	14 09 06.01	78 41 29.1	$I = 16.73 \pm 0.01$	0.197	LEDA 140268
790613-N2	14 10 43.65	78 38 45.0	$I = 17.28 \pm 0.01$	0.0877	
790613-N3	14 09 41.16	78 41 11.4	$I = 17.49 \pm 0.01$	0.0893	
790613-N4	14 09 15.45	78 39 37.4	$I = 15.45 \pm 0.01$	0.0583	2MASX J14091501+7839379, redshift via NED
790613-N5	14 09 30.51	78 45 38.9	$I = 17.94 \pm 0.01$	0.183	
000607-G1	02 33 48.50	17 03 59.5	$r = 17.9 \pm 0.1$	0.1405	
			$i = 17.3 \pm 0.1$		
001204-G1	02 41 04.36	12 52 39.2	$B = 19.97 \pm 0.07$	0.31	
			$V = 19.41 \pm 0.09$		
			$I = 19.78 \pm 0.07$		
001204-G2	02 41 14.74	12 52 29.6	$V = 20.41 \pm 0.3$	0.388	
			$I = 19.58 \pm 0.07$		
021201-G1	08 07 41.91	21 13 49.4	$g = 20.37 \pm 0.06$		SDSS J080741.91+211349.3 (galaxy)
			$r = 20.00 \pm 0.06$		
			$i = 19.78 \pm 0.08$		
			$z = 19.7 \pm 0.35$		
021201-M*	08 07 44.18	21 14 29.3	$g = 18.73 \pm 0.01$		SDSS J080744.18+211429.2 (red star)
			$r = 17.323 \pm 0.005$		
			$i = 15.846 \pm 0.004$		
			$z = 15.054 \pm 0.005$		

NOTES.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Astrometric solutions for all but the field of GRB 021201 were calculated automatically by the P60 reduction pipeline (Cenko et al. 2006) using USNO-B1 positions. Inspecting the scatter between the solutions derived for different images and bands, we find typical errors of order 0.05″ in right ascension and 0.2″ in declination. The absolute astrometric accuracy of the USNO-B grid is ≈0.25″ in each coordinate. Astrometry of objects in the field of GRB 021201 is from the SDSS DR4 and should be accurate to approximately 0.1″ in each coordinate. *BVI* magnitudes are calibrated against USNO-B1/ NOMAD *BVI* and are thus subject to a possible systematic zero-point offset. Our previous experience with such data (Nakar et al. 2006 and references therein) shows that this offset should typically be ≤0.2 mag. The errors given in the table are statistical only and accurately represent the uncertainty in the relative photometry within each field. SDSS *ri* magnitudes of 000607-G1 were calibrated using synthetic photometry and anchored to Landolt standards; see § 2.2 for details. SDSS magnitudes and errors of objects in the field of GRB 021201 are from the SDSS DR4.

(Nakar et al. 2006) we identified the brightest blue galaxy in this field, 001204-G1. We have since acquired P200 spectroscopy indicating that this galaxy is at $z = 0.310$ (Fig. 3). Finding a galaxy of this luminosity at this redshift in a random sky patch with an area similar to the SHB error box is not unexpected. P60 *BVI* imaging, as well as *VI* photometry obtained at the 100 inch du Pont telescope at Las Campanas Observatory, reveals additional galaxies within the error box (Fig. 4), five of them brighter than $r \approx 21$. P200 spectroscopy of the brightest of these (001204-G2; Fig. 4) indicates that it is at $z = 0.388$ (Fig. 5). In order to test whether this galaxy density is unique, we extract from the SDSS (Abazajian et al. 2005) a catalog of galaxies that covers ≈15 deg^2 from regions with Galactic extinction comparable to that in the direction of SHB 001204. We find that the average number of galaxies with $r < 21$ in a 6 arcmin^2 area is ≈6. We therefore conclude that the error box of SHB 001204 does not contain an uncommonly bright galaxy or a galaxy overdensity down to this limit.

Valuable information can also be extracted from a null detection. Based on the association of SHBs with an older stellar population (at least a few times 10^8 yr old), we can assume that the rate of SHBs follows either the blue or red luminosity, most of which is located within relatively bright galaxies. This is not the case for younger stellar populations traced by the UV light, a larger fraction of which is associated with intrinsically less luminous galaxies. As discussed in Nakar et al. (2006), this assumption implies that likely host galaxies should be more luminous than ≈0.33[0.02] L_* at 1[2] σ in these colors. The brightest galaxy for which we do not obtain a redshift in the error box of GRB

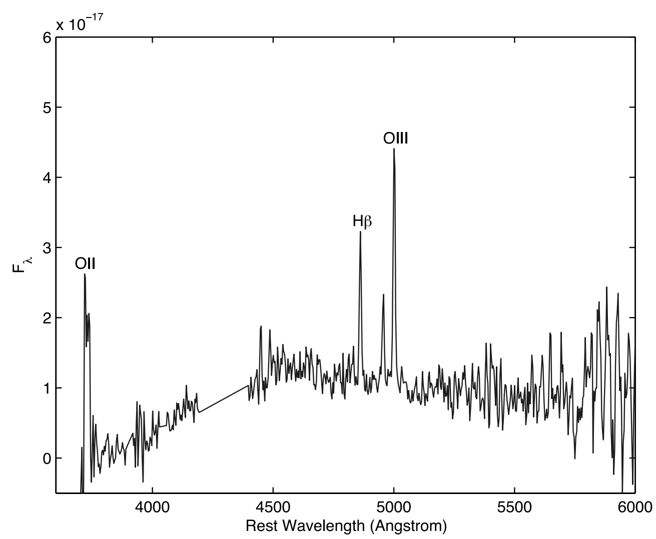

FIG. 3.—P200 spectrum of 001204-G1. Areas affected by strong sky-line residuals have been excised. Prominent emission lines (O III λλ5007+4959, Hβ, O II λ3727) indicate $z = 0.310$. The emission-line strength and overall shape are consistent with those of a late spiral (Sbc or similar). [*See the electronic edition of the Journal for a color version of this figure*.]

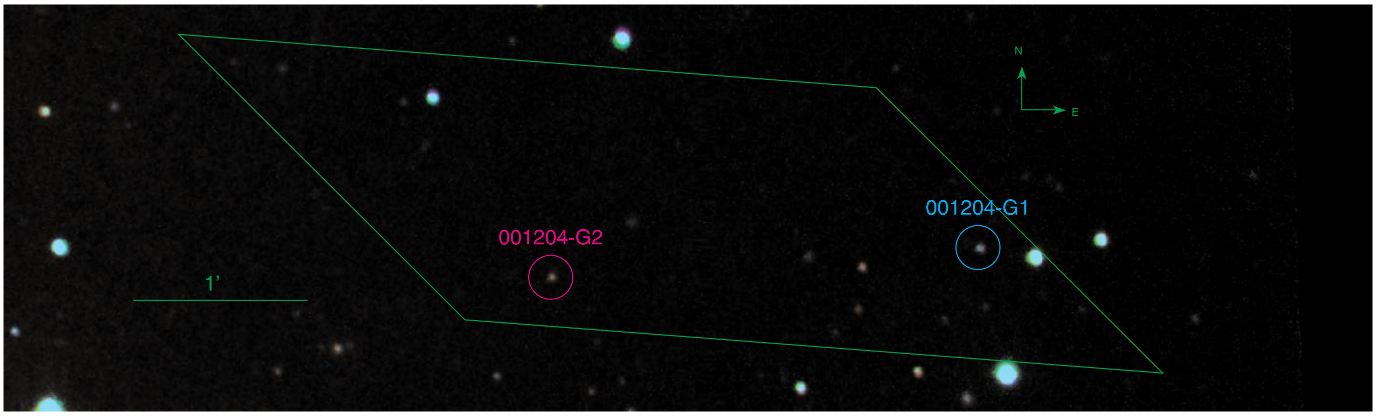

Fig. 4.—Color image of the IPN error box of SHB 001204 (*green*) made from LCO *VI* and P60 *R*-band imaging. The blue galaxy discussed by Nakar et al. (2006; 001204-G1; *cyan circle*) is at $z = 0.310$, while the brightest red galaxy in the field (001204-G2; *magenta circle*) is at $z = 0.388$ (Fig. 5). Additional galaxies are visible, but the density is not found to be significantly high compared to SDSS fields with similar properties (see text).

001204 has $r \approx 20.3$ corresponding to a minimal redshift of $z = 0.25[0.06]$ at $1[2]\ \sigma$, implying a lower limit on the isotropic bolometric energy release in γ-rays of $E_{\rm iso} = 5[0.25] \times 10^{50}$ erg.

2.3.2. *SHB 021201*

SHB 021201 has the largest error box in our sample; it was localized by the IPN to within 9 arcmin^2 (Hurley et al. 2002a). In our previous study of this event (Nakar et al. 2006) we identified what appeared to be a bright blue galaxy in a Palomar Observatory Sky Survey 2 (POSS 2) *B* plate of this field obtained in 1995 (Fig. 6). However, P200 spectroscopy of this source that we have since obtained indicates that it is an M star, and indeed, it appears to be pointlike in *R* and *I* POSS 2 plates obtained during 1997–1998, as it does on older plates from the USNO plate archive.[6] The extended appearance of this source is therefore either related to a plate defect or suggests that this star underwent an unusual ejection/illumination event around 1995.

There are no other bright galaxies in this error box, which is included in the SDSS Data Release 4 (DR4; released in 2005 July and not available during our previous analysis). The galaxy content of this error box is sparse even when compared to that of SHB 001204, and it is not consistent with a local overdensity of galaxies down to the SDSS limit. The brightest galaxy included in the SDSS database has $r = 20.25$, resulting in a lower limit similar to that obtained above for SHB 001204. Since both events have a similar energy output (Nakar et al. 2006), the lower limit on the energy release in γ-rays for SHB 021201 is $E_{\rm iso} = 5[0.25] \times 10^{50}$ erg (at $1[2]\ \sigma$) as well.

2.3.3. *SHB 020531*

This event was detected by *HETE-2* (Ricker et al. 2002), and its localization was improved several times by analysis of *HETE-2* data in conjunction with that of other spacecraft from the IPN

[6] See http://www.nofs.navy.mil/data/fchpix/.

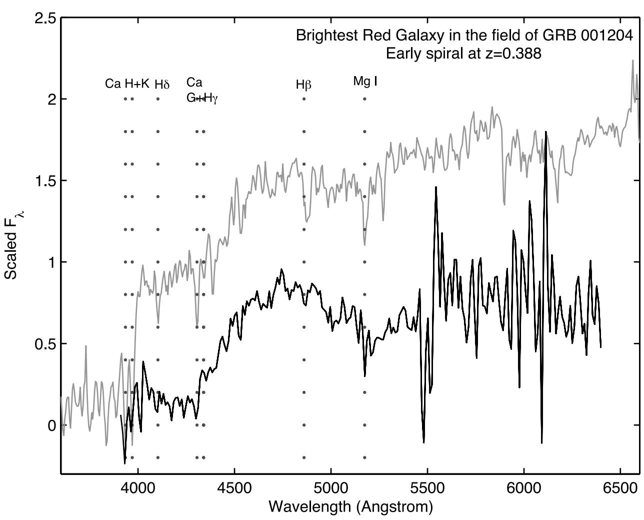

Fig. 5.—P200 spectrum of 001204-G2 (*black line*). We identify absorption lines of Ca (G, H, and K bands), H (Hδ, Hγ, and Hβ), and Mg i, indicating $z = 0.388$. Comparison with an Sa template spectrum from Kinney et al. 1996 (*gray line*) suggests this is an early spiral galaxy. [*See the electronic edition of the Journal for a color version of this figure*.]

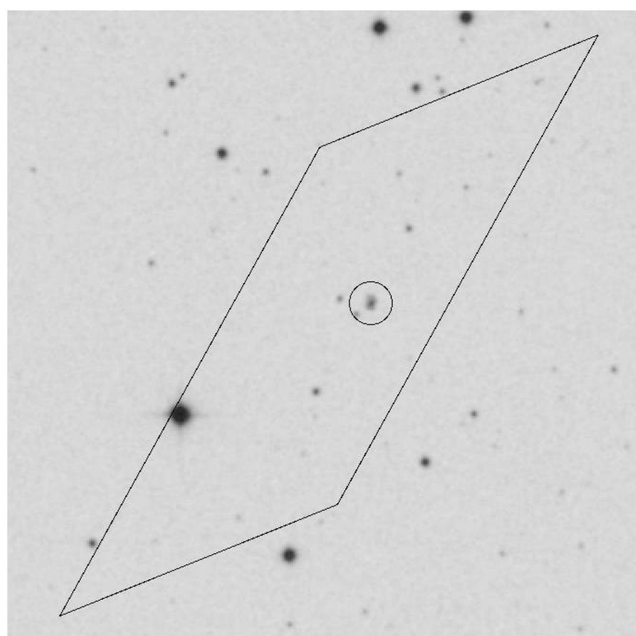

Fig. 6.—Reproduction of a section of the POSS 2 *B* plate ($\sim 5'$ on the side; north is up, east is left) extracted from the ESO Digitized Sky Survey archive (http://www.eso.org/dss) showing the location around the error box of SHB 021201 (*black polygon*). An apparently resolved object (*circled*), previously assumed to be a galaxy, is actually an M star.

TABLE 3
Host Galaxies and Redshifts of SHBs

SHB	Redshift z	Host Galaxy Type	Association Significance	References
000607	0.14	Sb	93%	This work
050509b	0.22	E/S0	3–4 σ	Bloom et al. 2006; Castro-Tirado et al. 2005a; Gehrels et al. 2005
050709	0.16	Sb/c	>3 σ[a]	Fox et al. 2005
050724	0.26	E/S0	>3 σ[a]	Berger et al. 2005; Prochaska et al. 2006
050813	0.72/1.8	E/S0	. . .	Gladders et al. 2005; Berger 2006
001204	>0.25[0.06]	. . .	1[2] σ	This work
000607	>0.25[0.06]	. . .	1[2] σ	This work
790613[b]	. . .	. . .	. . .	

[a] These bursts were localized at subarcsecond resolution using the optical/NIR afterglows, and both fall well within their respective host galaxies (Berger et al. 2005; Fox et al. 2005). Analysis of galaxy densities in extragalactic fields (e.g., Gal-Yam et al. 2006) indicates that chance coincidences are highly unlikely, with an estimated probability $P < 0.5\%$.
[b] We are unable to estimate a redshift or assign a host type for this burst; see § 2.2.

(final position given by Hurley et al. 2002b). Sensitive X-ray observations with the *Chandra* observatory were undertaken by Butler et al. (2002a) and revealed numerous X-ray sources within the initial IPN error box, one of which (source 48; Butler et al. 2002b) showed significant fading and was considered to be a viable candidate for the X-ray afterglow of this event (Fox et al. 2002). However, the final refinement of the IPN localization no longer included source 48. We noted that the strongest *Chandra* source (source 0; Butler et al. 2002a), hitherto outside of previous IPN localizations, was included in the revised error box. This source shows significant decay and is coincident with an optical source detected on Digitized Sky Survey plates (Butler et al. 2002b). Sensitive radio observations taken as part of the afterglow search (Frail & Berger 2002) place a 5 σ upper limit of 250 μJy on radio emission at 5 or 8 GHz from this location, indicating that this source is not a radio-loud AGN.

In view of the tendency of well-localized SHBs to reside in apparently bright hosts (Berger et al. 2005; Bloom et al. 2006) and the detection of strong and long-lasting X-ray afterglows from SHBs (Fox et al. 2005; Berger et al. 2005; Romano et al. 2005), we initially thought that *Chandra* source 0 might be the X-ray afterglow of SHB 020531, and that the underlying optical source might be its host. We therefore did not pursue a "blind" luminosity overdensity test for this field as described above. However, it turned out that the optical spectra of this source showed that it is an AGN (N. Butler et al. 2005, private communication), naturally explaining its X-ray variability and discrediting its association with SHB 020531. Since this burst was not initially part of our plan for statistical study of IPN SHBs, and it has a large set of unique observations (e.g., multiple-epoch *Chandra* observations, deep optical spectroscopy and imaging), much of it unpublished, its late inclusion in our sample hinders our attempt to minimize the effects of a posteriori statistics. We therefore exclude it from the statistical sample discussed below.

3. DISCUSSION

The observations and analysis reported in the previous section allow us to increase the number of SHBs for which redshift and host galaxy information is now available (Table 3). We now turn to investigating what can be learned from this extended sample of events.

3.1. *Host Galaxies*

We have compiled the properties of probable SHB host galaxies in Table 3 and Figure 7 (*gray histogram*). We assign an E/S0 host for the likely cluster event 050813. Inspection of the distribution of observed Hubble types indicates a large fraction of early-type hosts, with some events located within later hosts. The apparent ubiquity of SHBs in galaxies of many types calls to mind another type of explosive phenomenon, namely, SNe of Type Ia, as already mentioned by Fox et al. (2005), Berger et al. (2005), and Prochaska et al. (2006).

SNe Ia are believed to result from a thermonuclear runaway explosion of a white dwarf star, at or near the Chandrasekhar mass, triggered by accretion from or merging with a binary companion. These SNe occur in galaxies of all types, including early-type galaxies with little or no recent star formation, and in this respect they appear to resemble SHBs. We compare the observed Hubble type distribution of host galaxies of SHBs (Table 3) and SNe Ia (from Mannucci et al. 2005) in Figure 7. While SNe Ia indeed occur in E/S0 galaxies, the majority of events explode in spirals, more than half of them in galaxies later than Sa. Most SHBs, on the contrary, appear to occur in early-type hosts. However, due to the small number of events, the apparent difference is not statistically significant. Mannucci et al. (2005) also calculate the rate of SNe Ia per unit of K-band luminosity (an indicator of the old stellar mass). They find that this normalized rate increases by

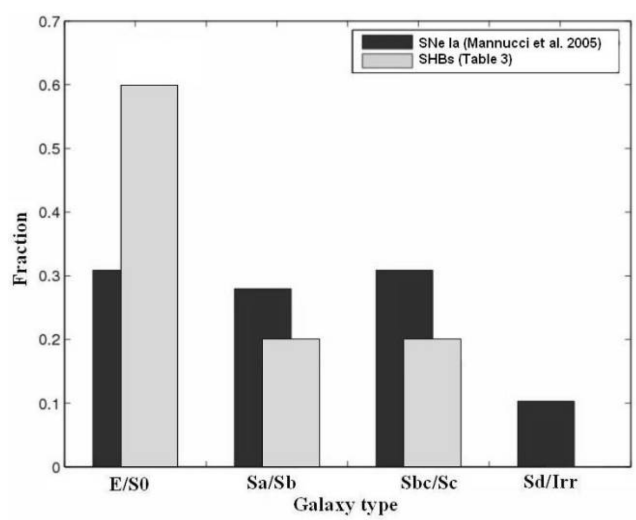

Fig. 7.—Comparison between the host galaxy types of SHBs (from Table 3) and SNe Ia (Mannucci et al. 2005). The fraction of SHBs in early-type galaxies is apparently larger than the fraction of SNe Ia observed in such galaxies in the nearby universe, suggesting that the progenitor systems of SHBs might be longer-lived than those of SNe Ia. [*See the electronic edition of the Journal for a color version of this figure.*]

more than an order of magnitude from E/S0 to Irr galaxies, implying that a significant fraction of the progenitors of SNe Ia are associated with young stars. This is not the case for SHBs. In fact, the sample of SHBs is consistent with all the progenitors coming from an older stellar population, abundant in E galaxies and bulge/spheroid components of early and intermediate spirals, and accounting for $\sim$75% of the total current stellar mass (Fukugita et al. 1998). Thus, the comparison between the observed distributions of SHBs and SN Ia host galaxies (Fig. 7) suggests that SHBs originate from systems that have typical lifetimes similar to or longer than those of SNe Ia.

The lifetimes of SN Ia progenitor systems (often parameterized by the typical delay time $\tau_{\rm Ia}$ between star formation and SN explosion) is currently an open observational question. If all SNe Ia originate from a single class of progenitors, one can assume a unimodal delay-time function parameterized by a typical delay time and a distribution around this mean. Several authors used the observed redshift evolution of SN rates and their redshift distributions, along with a prescription for the star formation history of the universe (Tonry et al. 2003; Barris & Tonry 2006; Strolger et al. 2004) and the host properties of SNe Ia (Mannucci et al. 2005), to constrain the typical delay time. Tonry et al. (2003), Barris & Tonry (2006), and Mannucci et al. (2005) indicate relatively short delay times ($\tau_{\rm Ia} \sim 1$ Gyr for the average population), while the analysis of Strolger et al. (2004) prefers a much longer delay time ($\tau_{\rm Ia} > 2$ Gyr). The combined analysis of SNe Ia in both field and cluster environments (Gal-Yam & Maoz 2004; Maoz & Gal-Yam 2004) indicates that short delay times ($\tau_{\rm Ia} \lesssim$ 1 Gyr) are in conflict with popular star formation history models, while long delay times ($\tau_{\rm Ia} > 3$ Gyr) are inconsistent with SNe Ia being the source of metals in the intracluster medium of rich galaxy clusters. The current consensus may lean toward a shorter delay time. The long delay time advocated by Strolger et al. (2004) appears to be less convincing (critically depending on estimates of the faint SN discovery efficiency in deep *HST* data; see Barris & Tonry 2006) and cannot be reconciled with the straightforward observations of Mannucci et al. (2005) in nearby galaxies.

In any case, since a larger fraction of SHBs apparently occurs in early-type galaxies compared with SNe Ia, they probably have a longer delay time, on average, than the typical delay time of SNe Ia, i.e., of order several Gyr, even if we adopt a shorter delay time for SNe Ia ($\tau_{\rm Ia} \approx 1$ Gyr).

Mannucci et al. (2005) and Scannapieco & Bildsten (2005) consider a two-component model for SNe Ia: a long-lived component, which comprises the entire SN Ia population in early-type galaxies, and a "prompt," short-lived component, proportional to the star formation rate and dominant in late-type galaxies (della Valle & Livio 1994). This model naturally explains the results of Mannucci et al. (2005) and skews the combined rate toward shorter delay times. Interestingly, the distribution of SHB host types is consistent with the expected distribution of the long-lived SN Ia component, which accounts for the majority of events in E galaxies, about 50% in S0/a/b galaxies, about 20% in Sbc/d galaxies, and hardly any in the latest Irr galaxies (Mannucci et al. 2005). Such a component would originate solely from the oldest stellar population and would have a typical age of order 10 Gyr.

It must be noted that our analysis assumes that our search and analysis procedures are not strongly biased toward discovering early-type hosts. This is a fair assumption for single luminous galaxies, as demonstrated by the fact that the luminous galaxy we uncovered (000607-G1) is an intermediate spiral and not a red early-type galaxy. A bias may exist for fainter galaxies, since red galaxies are more clustered than blue ones, and a faint red galaxy that would have escaped notice as a single galaxy may be detected by us due to its association with a galaxy overdensity. Attempts to quantify and correct for this bias will have to await the assembly of larger samples of SHB hosts.

4. CONCLUSIONS

We have analyzed new and archival observations of the fields of well-localized IPN SHBs. Using these data, we determine that SHB 000607 likely occurred in a $z = 0.1405$ luminous Sb galaxy. We use our null results for the fields of two additional SHBs to set a lower limit on the most likely redshift of these events.

We combine our new findings with published data for four SHBs detected by *Swift* and *HETE-2* and examine the properties of this extended sample of events, focusing on the distribution of host galaxy types. We arrive at the following conclusions:

1. SHBs apparently occur in host galaxies of all types, as do SNe Ia. However, compared to SNe Ia, SHBs appear to favor earlier type hosts, suggesting that they originate from a population of progenitors with a longer lifetime, on average. Even if we adopt the shorter values derived for the typical SN Ia delay time ($\sim$1 Gyr), the progenitors of SHBs appear to require a longer delay time, of order several Gyr. Our sample of SHB host galaxies is consistent with SHBs originating solely from the older spheroid/bulge stellar population.
2. Our expanded sample of SHBs with known or probable redshifts implies that a large fraction of SHBs occur at low redshifts ($z < 0.3$; within a distance of $\sim$1 Gpc). This is true even when we consider only the *Swift* sample, for which the threshold is similar to BATSE. This typical redshift is smaller than previous estimates (e.g., Ando 2004; Guetta & Piran 2005), resulting in a higher *observed* local rate of >10 Gpc^{-3} yr^{-1}, based on the observed BATSE rate of $\sim$170 SHBs per year over the entire sky. This is a strict lower limit, since it does not include dim bursts that were missed by BATSE. It also does not account for possible beaming corrections that might be significant (Fox et al. 2005). If SHBs are NS-NS or NS-BH mergers, then this rate predicts a detection of the gravitational waves produced during such mergers by advanced LIGO.

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