The Progenitors of Short-Hard Gamma-Ray Bursts from an Extended Sample of Events

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ABSTRACT

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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 those of 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) using new and archival optical and X-ray observations. We show that we can likely identify the host galaxies/clusters for additional two bursts, significantly expanding the sample of SHBs with known hosts and/or distances. In particular, we determine at a very high probability > 3σ that the bright SHB 790613 occurred within the rich galaxy cluster Abell 1892, making it probably the nearest SHB currently known. We show that the brightest galaxy within the error box of SHB 000607, at \( z = 0.1405 \), is most likely the host galaxy of this event. Additionally, we rule out the existence of galaxy overdensities (down to \( \approx 21 \text{ mag} \)) near the locations of two other SHBs, and set a lower limit on their probable redshift. We combine our SHB sample with events discovered recently by the Swift and HETE-2 missions, and investigate the properties of the extended sample. This sample enables us to determine that the progenitors of SHBs are typically older than these of type Ia SNe, implying a typical life time of several Gyr. We also show that it is unlikely that there is a significant population of progenitors with life time \( \lesssim 1 \text{Gyr} \). This result is difficult to reconcile with the popular model of neutron-star mergers as the progenitors of SHBs. We note that long SHB life times, if confirmed, imply that very few such events occur above \( z = 1 \), and that those above \( z = 0.5 \) should preferably occur in galaxy clusters. 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 with forthcoming facilities, should they result from compact binary mergers.

*Subject headings:* Gamma-Ray: Bursts
1. Introduction

The short-hard class of the Gamma-Ray Burst (GRB) population (Kouveliotou et al. 1993; SHB hereafter) makes up a quarter of the entire GRB population observed by BATSE\(^1\) with an all-sky detection rate of \(\approx 170 \text{ y}^{-1}\) (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, Meszaros & Horvath 1998; Magliocchetti, Ghirlanda & Celotti 2003) and small value of \(< V/V_{\text{max}} >\) (Katz & Canel 1996; Schmidt 2001; Guetta & Piran 2005) suggested a cosmological origin.

In the last few months the long-expected breakthrough in this field has finally occurred, facilitated by accurate localizations of SHBs by the \textit{Swift}\(^2\) and \textit{HETE-2}\(^3\) spacecrafts. The discovery of the X-ray afterglow of GRB 050509b by the \textit{Swift} X-ray Telescope (XRT; Gehrels 2005) led to its localization to within a few arc-seconds, in close proximity to a bright elliptical galaxy, a member of a galaxy cluster at \(z = 0.22\) (Bloom et al. 2005; Kulkarni et al. 2005; Castro-Tirado \textit{et al.} 2005; Gehrels 2005; Prochaska et al. 2005). Sensitive follow-up imaging of the XRT localization revealed many background galaxies within the error circle but no optical afterglow (Kulkarni et al. 2005; Gehrels 2005; Bloom \textit{et al.} 2005; Hjorth \textit{et al.} 2005; Castro-Tirado \textit{et al.} 2005) and the lack of sub-arcsecond 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 2005; Bloom \textit{et al.} 2005; Eisenstein, Hogg & Padmanabhan 2005).

The accurate localization of SHB 050709 by \textit{HETE-2} (Butler \textit{et al.} 2005) and the subsequent discovery of X-ray (Fox \textit{et al.} 2005) and optical (Price \textit{et al.} 2005; Hjorth \textit{et al.} 2005) afterglow emission pinpointed the location of this SHB to sub-arcsecond accuracy, and led to the identification and detailed characterization of its host galaxy (Fox \textit{et al.} 2005; Covino \textit{et al.} 2005; Prochaska \textit{et al.} 2005). 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 similar star formation rate to Sb/c galaxies.

Shortly after, SHB 050724 was localized by \textit{Swift}, and turned out to have a rich afterglow spectrum including X-ray (Romano \textit{et al.} 2005; Fox \textit{et al.} 2005), radio (Cameron & Frail

\(^1\)http://www.batse.msfc.nasa.gov/batse/
\(^2\)http://swift.gsfc.nasa.gov/docs/swift/swiftsc.html
\(^3\)http://space.mit.edu/HETE/Welcome.html
2005; Berger et al. 2005) and optical/IR (Gal-Yam et al. 2005; Berger et al. 2005; Castro-Tirado et al. 2005; Cobb & Bailyn 2005; Wiersema et al. 2005). The afterglow detection led to an unambiguous association of this burst with a red early-type galaxy (Berger et al. 2005; Prochaska et al. 2005) at $z = 0.257$. A few weeks later, SHB 050813 was localized by Swift and associated with a galaxy cluster at $z = 0.722$ (Gladders et al. 2005; Berger 2005; Prochaska et al. 2005; Berger 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 recent observations suggest, when taken together, that a significant fraction, perhaps even all 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 super-giant flare from a Soft Gamma-ray Repeater (SGR 1806-20). The temporal structure and luminosity of this event indicated it would have appeared as an SHB had it occurred in a nearby galaxy (Duncan 2001; Dar 2005; Nakar et al. 2005; Palmer et al. 2005; Hurley et al. 2005), and this possibility raised a flurry of speculations about the possible association of SHBs with extra-galactic SGRs. In Nakar et al. (2005) 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 has 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 extra-galactic SGRs. The latter result was independently confirmed, using other approaches, by Palmer et al. (2005); Popov & Stern (2005) and Lazzati, Ghirlanda & Ghisellini (2005). Recent analysis by Tanvir et al. (2005) reveals an apparently significant correlation between SHBs from the BATSE catalog and nearby galaxies, with the correlation getting stronger when galaxies of earlier type are considered. Since known SGRs are observed in star-forming regions and are generally assumed to be young neutron stars, this result further indicates that SGRs do not contribute significantly to the SHB population, even in the nearby Universe. 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 arcmin$^2$ error boxes of SHBs, 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 May-August 2005, is therefore promising and timely. Here we report the results of such an investigation.
2. Observations

We have compiled all the SHBs localized to within error boxes smaller than 10 arcmin$^2$ with $|\text{Galactic latitude}| > 20$, ending up with 5 SHBs: 790613, 000607, 001204, 021201 and 020531. We have defined the following observational test to be carry 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. We obtained spectra of brighter galaxies, determined their redshifts, and include this additional information in our statistical analysis. 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 790613

SHB 790613 was a short ($\sim 48\text{ms}$) 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). Examination of optical ($BVI$) images, taken with the robotic 60$''$ telescope (P60) at Palomar Observatory, revealed a field dense with red galaxies both within and outside of the error box. Four reddish galaxies all with $i < 20.5$ were within, or on the edge of, this small error box. This is an apparently high density of galaxies even when compared to the surrounding dense area. The imaging data show that these galaxies have similar colors (Fig. 1) and suggest that they are probably physically associated. In order to test whether this galaxy density is unique we extract from the SDSS (Abazajian et al. 2005) a catalog of galaxies that cover $\approx 24 \text{ deg}^2$ from regions with Galactic extinction comparable to that in the direction of SHB 790613. We find that the probability to find four or more galaxies with $m < 20.5$, in a 0.7 arcmin$^2$ area, is $\approx 1\%$.

A query of the NED database$^4$ has shown that this burst occurred within 6.5$'$ from the cataloged center of a rich Abell galaxy cluster (Abell 1892; richness class $\mathcal{R} = 1$ [(Abell 1958)]; cataloged redshift $z = 0.09$ based on a single galaxy redshift [(Struble & Rood 1999)], and therefore somewhat uncertain). The Abell galaxy cluster catalog (Abell 1958) contains 2712 galaxy clusters, of which 1894 ($\approx 70\%$) are considered to be rich ($\mathcal{R} \geq 1$). The completeness of the catalog and the resulting sky density of clusters is a strong function

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$^4$http://nedwww.ipac.caltech.edu/
of Galactic latitude. Abell (1958) reports \( \approx 0.08 \) clusters per degree\(^2\) at Galactic latitude 40° (the galactic latitude of SHB 790613 is 37.6°), of which \( \approx 0.06 \) are expected to be rich. The chance probability to find a rich cluster within 6.5′ (\( \approx 0.1° \)) 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 unlikely to be spurious, even considering that we have checked for a similar association (with negative results) in 4 other cases. Therefore we hereafter assume that GRB 790613 occurred at \( z = 0.09 \) and resided in one of the cluster early type galaxies. At this redshift, the total isotropc-equivalent energy emitted by this SHB is \( 6 \times 10^{49} \) erg (between 0.15 – 5 MeV). The burst luminosity is \( \approx 1 \times 10^{51} \) erg sec\(^{-1}\) cm\(^{-2}\).

Note that if the progenitor of this SHB was a NS-NS merger (Eichler et al. 1989; Narayan, Paczynski & Piran 1992) then its host galaxy can also be located outside of the error-box (1 arcmin corresponds to \( \approx 100 \) kpc at \( z = 0.09 \), which a NS binary with a modest initial kick velocity can travel before it merges).

### 2.2. SHB 000607

SHB 000607 was well-localized by the IPN (error box area 5.6 arcmin\(^2\); Hurley et al. 2002). In our previous study of this event (Nakar et al. 2005) we have 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. 2). In order to examine the probability to find such a galaxy within the error box we first calibrated its \( R \) magnitude using P60 observations of Landolt (1992) standard stars, obtained during a photometric night. We then converted it to Sloan Digital Sky Survey (SDSS) \( r \) and \( i \) magnitudes using synthetic photometry applied to the P200 spectrum, as described in Poznanski et al. (2002). We obtain \( r = 17.9 \pm 0.1 \) and \( i = 17.3 \pm 0.1 \).

We estimate 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):

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

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

At \( z = 0.14 \) (proper distance of 580 Mpc) \( L_{000607-G1} \approx 1.3 \pm 0.1 \) L\(_*\) (using the P200 spectrum for k-corrections) both in \( r \) and \( i \). Thus \( \phi(L > L_{000607-G1}) \approx 6 \times 10^{-4} \) Mpc\(^{-3}\) and within a distance of 580 Mpc there are about \( 5 \times 10^5 \) galaxies that are as bright or brighter than 000607-G1, implying an angular density of \( 3 \times 10^{-3} \) arcmin\(^{-2}\). Therefore the probability
Fig. 1.— A color image of the IPN error box of SHB 790613 (green polygon) made from P60 $BV_I$ imaging. Four galaxies with apparently similar colors are visible (green circles).
| SHB   | Telescope | Instrument | Exposure          | UT Date     |
|-------|-----------|------------|-------------------|-------------|
| 790613| P60       | CCD        | $B$ (450s), $V$ (450s), $I$ (450s) | Aug. 12, 2005 |
| 000607| P60       | CCD        | $R$ (720s)        | Sep. 28, 2005 |
| 001204| P60       | CCD        | $B$ (450s), $V$ (450s), $I$ (450s) | Aug. 11, 2005 |
|       | P60       |            | $V$ (1500s), $R$ (1500s), $I$ (900s) | Sep. 28, 2005 |
|       | LCO100    | Tek5       | $V$ (180s), $I$ (90s) | Sep. 2, 2005 |
| 021201| P60       | CCD        | $B$ (600s), $V$ (600s), $I$ (600s) | Sep. 17, 2005 |

| Spectroscopy: |
|---------------|
| 000607-G1     | P200       | DBSP       | Red+Blue (900s)  | Feb. 6, 2005 |
| 001204-G1     | P200       | DBSP       | Red+Blue (2700s) | Aug. 13, 2005 |
| 001204-G2     | P200       | DBSP       | Red+Blue (10800s)| Sep. 9, 2005 |

Note. — P60 = Palomar 60′′ robotic telescope. P200 = Palomar 200′′ Hale telescope. LCO100 = Las Campanas Observatory 100′′ Du Pont telescope. Spectroscopic observations 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 $\approx 1$ Å and $\approx 5$ Å, respectively.
to find such a bright galaxy within the 5.6 arcmin$^2$ error box of GRB 000607 is $\approx 2\%$ while the probability to find it anywhere within the four error boxes searched (a total angular area of 21 arcmin$^2$) is $\approx 7\%$. We conclude that the association between this galaxy and GRB 000607 is significant ($\approx 2\sigma$) though not definitive. 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 for peculiar or noteworthy properties (colors, morphology, etc.). At a redshift of $z = 0.14$, the total isotropic-equivalent energy emitted by this SHB would be $2 \times 10^{49}$ erg (between $50 - 300$ keV) and $2 \times 10^{50}$ erg between $0.15 - 5$ MeV. The corresponding burst luminosity is $\approx 5 \times 10^{51}$ erg sec$^{-1}$ cm$^{-2}$.

The spectrum 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 $\approx 0.3 \, M_\odot \, y^{-1}$ from the observed H$\alpha$ luminosity, similar to that of the host galaxy of SHB 050709 (Fox et al. 2005).

### 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. 2002). In our previous study of this event (Nakar et al. 2005) we have identified the brightest blue galaxy in this field, 001204 – G1. We have since acquired P200 spectroscopy indicating that this galaxy is at $z = 0.31$ (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'' Du Pont telescope at Las Campanas Observatory, reveals 5 more red galaxies within the error box (Fig. 4), brighter than $r \approx 21$. P200 spectroscopy of the brightest of these (001204 – G2) indicates 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 cover $\approx 15$ 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 $\approx 6$. We therefore conclude that the error box of SHB 001204 does not contain any uncommonly bright galaxy or a galaxy overdensity down to this limit.

Valuable information can be extracted also from a null detection. Bases on the association of SHBs with an older stellar population (at least a few time $10^8$ years 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,
Fig. 2.— The spectrum of the bright galaxy 000607-G1, identified as the likely host of SHB 000607. We determine the redshift from Hα (6563 Å) and NII (6585 Å) in emission (see lower panel for a detailed view) and Na D (5896 Å) in absorption. OIII (5007 Å) is weak or absent. Telluric absorption is present near 6000 Å (circled cross). The spectrum 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 $\approx 0.3 M_\odot \, \text{y}^{-1}$ from the observed Hα luminosity. This is actually an upper limit as the Hα line is contaminated by nearby NII (6550 Å) emission (bottom panel). The strength of the resolved NII 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.
Fig. 3.— P200 spectrum of 001204−G1. Areas affected by strong sky line residual have been excised. Prominent emission lines (OIII 5007+4949 Å, Hβ, OII 3727 Å) indicate $z = 0.31$. The emission line strength and overall shape are consistent with those of a late spiral (Sbc or similar).
traced by the UV light, a larger fraction of which is associated with intrinsically less luminous galaxies. As discussed in Nakar et al. (2005) this assumption implies that likely host galaxies should be more luminous than $\approx 0.33[0.02]L_\star$ at $1[2]\sigma$ in these colors. The brightest galaxy for which we did not obtain a redshift in the error box of GRB 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 $\gamma$ rays of $E_{iso} = 5[0.25] \times 10^{50}$ 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. 2002). In our previous study of this event (Nakar et al. 2005) we have identified what appeared to be a bright blue galaxy in a Palomar Observatory Sky Survey 2 (POSS2) $B$ plate of this field obtained on 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 point like in $R$ and $I$ POSS2 plates obtained during 1997-1998, as it does on older plates from the USNO plate archive. The extended appearance of this source is therefore either related to a plate defect, or suggests that this star has undergone an unusual ejection/illumination event around 1995.

There are no other bright galaxies in this error box, which is included in the Sloan Digital Sky Survey Data Release 4 (SDSS DR4; released in July 2005, 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 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. 2005) the lower limit on the energy release in $\gamma$ rays for SHB 021201 is $E_{iso} = 5[0.25] \times 10^{50}$ 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 other spacecrafts from the IPN (final position given by Hurley et al. 2002). Sensitive X-ray observations with the Chandra observatory were undertaken by Butler et al. (2002) and revealed numerous

\[5\text{http://www.nofs.navy.mil/data/fchpix/}\]
X-ray sources within the initial IPN error box, one of which (source #48, Butler et al. 2002) showed significant fading, and was considered to be a viable candidate for the X-ray afterglow of this event (Fox, Kulkarni & Weissman 2002). However, the final refinement of the IPN localization no longer included source #48. We noted that the strongest Chandra source (#0, Butler et al. 2002), hitherto outside of previous IPN localizations, was included in the latest revised box. This source shows significant decay and is coincident with an optical source detected on DSS plates (Butler et al. 2002). Sensitive radio observations taken as part of the afterglow search (Frail & Berger 2002) place a 5σ upper limit of 250μJy on radio emission at 5 or 8 Ghz from this location, indicating this source is not a radio-loud AGN.

In view of the tendency of well-localized SHBs to reside in apparently bright hosts (Kulkarni et al. 2005; Berger et al. 2005; Bloom et al. 2005) 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 may be the X-ray afterglow of SHB 020531, and that the underlying optical source may be its host. We therefore did not pursue a “blind” luminosity overdensity test for this field as described above. However, it turns out that optical spectra of this source show it is an AGN (Butler et al. 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, its late inclusion in our sample will hinder our attempt to minimize effects of a posteriori statistics. We therefore exclude it from the statistical sample discussed here.

3. Discussion

The observations and analysis reported in the previous section allow us to significantly increase the number of SHBs for which redshift and host galaxy information is now available (Table 2). We now turn to investigate what can be learned from this extended sample of events.

3.1. Host galaxies

We have compiled the properties of known SHB host galaxies in Table 2 and Fig. 7 (dark blue histogram). We assign E/S0 hosts for cluster events (790613 and 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, supernovae (SNe).
of type Ia, as already mentioned by Fox et al. (2005), Berger et al. (2005), and Prochaska et al. (2005).

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. However, comparing the observed Hubble type distribution of host galaxies of SHBs (Table 2) and SNe Ia (from Mannucci et al. 2005; light grey histogram in Fig. 7), clearly suggests a difference between these two phenomena. While SNe Ia indeed occur in E/S0 galaxies, the majority of events explode in spirals, and more than half in galaxies later than Sa. Most SHBs, on the contrary, appear to occur in early type hosts. The probability that the observed SHB host galaxies are drawn from the SN Ia host distribution of Mannucci et al. (2005) is small ($P \sim 7\%$). Mannucci et al. (2005) calculate also the rate of SNe Ia per unit $K$-band luminosity (an indicator of the old stellar mass). They find that this normalized rate increases by 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 current census 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, Hogan & Peebles 1998). Thus, the comparison between the observed distributions of SHBs and SNe Ia host galaxies (Fig. 7) indicates that SHBs originate from systems that have longer typical lifetimes than those of SNe Ia.

The lifetime of SN Ia progenitor systems (often parameterized by the typical delay time $\tau_{Ia}$ between star formation and SN explosion) is currently an open observational question. If all SNe Ia originate from the same 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 2005; 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 (2005) and Mannucci et al. (2005) indicate relatively short delay times ($\tau_{Ia} \sim 1$ Gyr) while the analysis of Strolger et al. (2004) prefers a much longer delay time ($\tau_{Ia} > 2$ 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 ($\tau_{Ia} \lesssim 1$ Gyr) are in conflict with popular star formation history models, while long delay times ($\tau_{Ia} > 3$ Gyr) are inconsistent with SNe Ia being the source of metals in the intra-cluster medium (ICM) of rich galaxy clusters. The current consensus may lean toward a shorter delay time. The long delay time
Fig. 4.— A color image of the IPN error box of SHB 001204 (green) made from LCO $VI$ and P60 $R$-band photometry. The blue galaxy discussed by Nakar et al. (2005; 001204 $- G1$; cyan circle) is at $z = 0.31$, while the brightest red galaxy in the field (001204 $- G2$; large red circle) is at $z = 0.388$ (Fig. 6). Additional red galaxies are indicated by smaller red circles.

| SHB  | Redshift | Host Galaxy | Association significance | Reference |
|------|----------|-------------|--------------------------|-----------|
| 790613 | 0.09     | E/S0        | $\sim 3\sigma$          | This work |
| 000607 | 0.14     | Sb          | $\sim 2\sigma$          | This work |
| 050509b | 0.22     | E/S0        | $3 - 4\sigma$           | Bloom et al. 2005; Kulkarni et al. 2005 |
|        |          |             |                          | Castro-Tirado et al. 2005; Gehrels 2005 |
| 050709 | 0.16     | Sb/c        | Secure                  | Fox et al. 2005 |
| 050724 | 0.26     | E/S0        | Secure                  | Berger et al. 2005; Prochaska et al. 2005 |
| 050813 | 0.72     | E/S0        | -                       | Gladders et al. 2005; Berger 2005 |
| 001204 > 0.25[0.06] | - | $1[2]\sigma$ | This work |
| 000607 > 0.25[0.06] | - | $1[2]\sigma$ | This work |
Fig. 5.— P200 spectrum of 001204 − G2 (black). 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 (green) suggests this is an early spiral galaxy.
Fig. 6.— Reproduction of a section of the POSS2 B plate extracted from the ESO digital sky survey archive (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.
Fig. 7. — A comparison between the host galaxy types of SHBs (from Table 2) and SNe Ia (Mannucci et al. 2005). The fraction of SHBs in early type galaxies is significantly larger than the fraction of SNe Ia observed in such galaxies in the nearby Universe, indicating that the progenitor systems of SHBs are probably longer-lived than those of SNe Ia.
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 2005]) 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 occur in early type galaxies compared with SNe Ia, they must have a significantly 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 ($\tau_{\text{Ia}} \approx 1 \text{ Gyr}$). This finding disfavors the binary NS merger model for SHBs if NS mergers are indeed dominated by systems with very short ($\approx \text{My}$) typical delay times (e.g., Tutukov & Iungel'Son 1993; Belczyński & Kalogera 2001; Perna & Belczynski 2002).

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, dominant in late-type galaxies. 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 contributes to the rate in the latest Ir 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 future samples of SHB hosts.

### 3.2. Redshift distribution

An alternative approach to constrain the lifetime distribution of SHB progenitors, $P(\tau_{\text{SHB}})$, is to use the observed SHB redshift distribution in conjunction with the observed flux distribution (Ando 2004; Guetta & Piran 2005). These observed quantities are determined by three components: the intrinsic redshift distribution, the intrinsic luminosity
function and observational selection effects (detection threshold and efficiency, ability to determine the redshift and so on). So, using two observed distributions we attempt to solve for two unknown intrinsic functions (assuming that the observational selection effects can be accounted for) of which only one is expected to be related directly to the progenitor lifetime (the intrinsic redshift distribution). It therefore might be expected that this approach will prove less constraining than the more direct investigation based on host galaxy type. On the other hand, it takes advantage of the large amount of data collected by the BATSE experiment, and is thus worth exploring.

Guetta & Piran (2005) predict the observed redshift distribution of SHBs assuming that the luminosity function is a broken power-law and that the intrinsic redshift distribution is a convolution of the lifetime distribution with the star formation rate history (a similar approach was used to probe SN Ia delay times, e.g., by Madau, della Valle & Panagia 1998 and Gal-Yam & Maoz 2004). The observed flux distribution and the detection threshold are taken from the BATSE catalog. Ando (2004) conducted a similar study but considered a wider range of luminosity functions, lifetime distributions, and star formation histories. In Fig 8 (right panel) we depict the redshift distribution calculated by Guetta & Piran (2005) under the assumption $P(\tau_{SHB}) \propto 1/\tau_{SHB}$ deduced from the observed sample of Galactic NS-NS binaries (Champion et al. 2004). Fig 8 also shows the observed distribution of the four bursts detected by Swift (which is expected to have a detection threshold comparable to BATSE) and HETE-2. We do not include in this analysis the IPN bursts (Fig. 8, left panel) for which the detection threshold is expected to be much higher. Although the sample is very small, the null hypothesis that the observed redshift distribution is drawn from the predicted one is clearly ($> 3\sigma$) rejected. Three out of the four bursts are at $z < 0.3$, a region that includes only 7% of the model distribution. Including only the three Swift bursts reduces the rejection significance to $\approx 2\sigma$. Comparison with the range of models presented by Ando (2004) yields similar results. This suggests that the lifetime distribution of SHBs favors longer lifetimes than those inferred from the observed distribution of Galactic NS-NS binaries. Taken at face value, the observed properties of well-localized SHBs are difficult to reconcile with the latest predictions based on the popular NS-NS merger progenitor model.

Strong observational selection effects against the detection of NS-NS binaries with short merger timescales are expected to skew the observed merger timescale distribution toward longer values. Correcting for this bias would make the NS-NS binary model predictions even more discrepant with the observed SHB redshift distribution. A selection effect that might prevent the detection of old binary systems may be introduced by the (relatively) short lifetimes of pulsars, which are used to detect such systems. It might be that there is a large number of old ($\sim 10$ Gy) NS binaries in our Galaxy composed of two “dead” pulsars. Nevertheless, the currently known NS binary sample contains too many systems with a
relatively short lifetime ($\lesssim 1$ Gyr) that are disfavored by the observe redshift distribution of SHBs, as well as by the galaxy type analysis of the previous section.

What possible explanations may allow to reconcile the observed distributions with the predictions from NS-NS merger models? It may be that the Swift threshold for SHB detection is higher than that of BATSE (perhaps due to the hard SHB spectrum, while Swift is more sensitive in softer bands). The recent Swift SHB detection statistics seems to indicate, though, that the SHB detections efficacies of both instruments are actually comparable. Yet another resolution may be that the true SHB luminosity function is very different from the range considered by Ando (2004) and Guetta & Piran (2005), which fits the BATSE data well, or a combination of these two effects. Another possibility is that this is a result of the small sample available, making our results vulnerable to selection effects (the significance levels reported throughtout properly account for the statistical impact of the small sample size). Finally, it is possible that the true typical lifetime of NS binaries is much longer than currently indicated by the very few known NS binary systems. These issues certainly merit further investigation.

4. conclusions

We have analyzed new and archival observations of the fields of well-localized IPN SHBs. Using these data, we determine that SHB 790613 is associated with a rich galaxy cluster, probably at $z = 0.09$, and that SHB 000607 has likely occurred in a $z = 0.14$ 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 recent SHBs detected by Swift and HETE-2, and examine the properties of this extended sample of events. Focussing on the distribution of host galaxy types, as well as on the SHB redshift distribution. We arrive at the following conclusions:

- SHBs apparently occur in host galaxies of all types, as do SNe Ia. However, SHBs appear to favor early-type hosts compared to SNe Ia, a strong indication that they originate from a population of progenitors which has 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. This finding disfavors the binary NS merger model for SHBs if NS mergers are indeed dominated by systems with very short ($\approx My$) typical delay times (e.g., Tutukov & Iungel’Son 1993; Belczyński & Kalogera 2001; Perna & Belczynski 2002). The current sample of SHB host galaxies is consistent
Fig. 8.— The redshift distribution of SHBs. **Left:** the observed redshift distribution of SHBs from *Swift + HETE-2* (blue) and the IPN (green). We also mark the 1σ lower limits on the redshift of two additional IPN SHBs (grey). **Right:** Comparison between the *Swift + HETE-2* SHB sample, and the model predictions (solid line) from Guetta & Piran (2005), calculated assuming the observed distribution of merger delay times for NS-NS binaries.
with SHBs originating solely from the older spheroid/bulge stellar population, suggesting a typical life time of $\sim 10 \text{ Gyr}$ in this case.

- The observed redshift distribution of SHBs appears inconsistent with recent NS-NS merger model predictions based on BATSE luminosity functions, universal star formation rate histories, and, specifically, the distribution of delay times indicated by the known sample of NS binaries in our galaxy (Ando 2004; Guetta & Piran 2005). The binary NS-NS merger model is disfavored by the data, as it predicts too many short-lived/high redshift progenitor systems. Observational selection biases against binary NS-NS systems with long merger time scales and/or against the detection of late-type host galaxies, and/or modified SHB luminosity function, perhaps coupled with Swift being less sensitive than BATSE, are required for the NS-NS model to remain viable. Increased statistics combined with additional modeling work would probably shed more light on this issue.

- Long SHB progenitor lifetimes, if born out by further investigations, imply that SHBs should hardly occur above $z \sim 1$. Additionally, if the typical SHB delay time is several Gyr, then we predict that the sample of SHBs discovered at $0.5 < z < 1$ will show a strong preference to reside in the centers of galaxy clusters. At these redshifts, the age of the Universe becomes comparable to the SHB lifetime, so such events would occur where the oldest stellar population is concentrated. According to hierarchical galaxy formation models, the first stars, in the first galaxies, tend to form at the most extreme initial density peaks, which later evolve to be the locations of rich galaxy clusters.

- Our expanded sample of SHBs with known or probable redshifts implies that a large fraction of SHBs occur at a low redshifts ($z < 0.3$; within a distance of $\sim 1 \text{ Gpc}$). 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 $> 10 \text{ Gpc}^{-3} \text{ yr}^{-1}$, based on the observed BATSE rate of $\sim 170 \text{ SHBs}$ 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 which 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.

Acknowledgments

We thank S. Ando, N. Butler, A. Coil, B. Gerke, S. Phinney and C. Steidel for help and advice. A.G. acknowledges support by NASA through Hubble Fellowship grant #HST-
HF-01158.01-A awarded by STScI, which is operated by AURA, Inc., for NASA, under contract NAS 5-26555. E.N. was supported by a senior research fellowship from the Sherman Fairchild Foundation. E.B. acknowledges support by NASA through Hubble Fellowship grant #HST-HF-01171.01-A awarded by STScI, which is operated by AURA, Inc., for NASA, under contract NAS 5-26555. AMS is supported by the NASA Graduate Student Research Program. SRK’s research is supported by NSF and NASA. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This research has made use of the USNOFS Image and Catalogue Archive operated by the United States Naval Observatory, Flagstaff Station (http://www.nofs.navy.mil/data/fchpix/).

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This preprint was prepared with the AAS LaTeX macros v5.2.