On the origin of short GRBs with Extended Emission and long GRBs without associated SN

Maurice H.P.M. van Putten\(^1\) *, Gyeong Min Lee\(^1\), Massimo Della Valle\(^2,4\), Lorenzo Amati\(^3,4\) and Amir Levinson\(^5\)

\(^1\)Astronomy and Space Science, Sejong University, 98 Gunja-Dong Gwangin-gu, Seoul 143-747, Korea
\(^2\)Istituto Nazionale di Astrofisica, Osservatorio Astronomico di Capodimonte, Salita Moiariello 16, I-80131 Napoli, Italy
\(^3\)Istituto Nazionale di Astrofisica - IASF Bologna, via P. Gobetti 101, I-40129 Bologna, Italy
\(^4\)International Center for Relativistic Astrophysics, Piazzale della Repubblica 2, I-65122, Pescara, Italy
\(^5\)School of Physics and Astronomy, Tel Aviv University, 69978 Tel Aviv, Israel

ABSTRACT
The Burst and Transient Source Experiment (BATSE) classifies cosmological gamma-ray bursts (GRBs) into short (less than 2 s) and long (over 2 s) events, commonly attributed to mergers of compact objects and, respectively, peculiar core-collapse supernovae. This standard classification has recently been challenged by the Swift discovery of short GRBs showing Extended Emission (SGRBEE) and nearby long GRBs without an accompanying supernova (LGRBN). Both show an initial hard pulse, characteristic of SGRBs, followed by a long duration soft tail. We here consider the spectral peak energy \(E_{p,i}\)-radiated energy \(E_{iso}\) correlation and the redshift distributions to probe the astronomical and physical origin of these different classes of GRBs. We consider Swift events of 15 SGRBs, 7 SGRBEEs, 3 LGRBNs and 230 LGRBs. The spectral-energy properties of the initial pulse of both SGRBEE and LGRBNs are found to coincide with those of SGRBs. A Monte Carlo simulation shows that the redshift distributions of SGRBs, SGRBEE and LGRBNs fall outside the distribution of LGRBs at 4.75 \(\sigma\), 4.67 \(\sigma\) and 4.31 \(\sigma\), respectively. A distinct origin of SGRBEEs with respect to LGRBs is also supported by the elliptical host galaxies of the SGRBEE events 050509B and 050724. This combined evidence supports the hypothesis that SGRBEE and LGRBNs originate in mergers as SGRBs. Moreover, long/soft tail of SGRB and LGRBNs satisfy the same \(E_{p,i}\)–\(E_{iso}\) Amati-correlation holding for normal LGRBs. This fact points to rapidly rotating black holes as a common long-lived inner engine produced by different astronomical progenitors (mergers and supernovae).

Key words: stars: black holes – gamma-ray bursts: general – stars: neutron stars

1 1. INTRODUCTION
The bimodal distribution in the Burst and Transient Source Experiment (BATSE) catalogue of cosmological gamma-ray bursts (GRB) reveals long GRBs (LGRB) commonly associated with core-collapse in massive stars \cite{Woosley1993} and short GRBs (SGRBs) commonly associated with mergers of compact objects, i.e., neutron stars with another neutron star (NS-NS, \cite{Eichler1989}) or a stellar mass black hole companion (NS-BH, \cite{Paczynski1991}). The first is supported by three pieces of evidence: i) supernovae (SNe) accompanying a few nearby events \cite{Hiorth2011}; ii) detection of SN features in the spectra of “rebrightenings” during GRB afterglow decay, at intermediate redshifts, most recently GRB 130427A at \(z = 0.34\) \cite{Melandri2013, Maselli2013}, up to \(z \approx 1\) \cite{DellaValle2003}; iii) the host galaxies are spiral and irregular with active star formation \cite{Fruchter2004} typical for environments hosting core-collapse SNe (CC-SNe; \cite{Kelly2008, Raskin2008, Modjaz2011}). If detected, afterglow emissions of SGRBs tend to be very weak compared to those of LGRBs, consistent with less energy output and pointing to hosts lacking star formation. Weak X-ray afterglow discoveries made by High Energy Transient Explorer-2 (HETE II) in GRB 050509B and Swift in GRB 050507 \cite{Berger2006} were anticipated for GRBs from rotating black holes \cite{vanPutten2001}.

\* E-mail: mvp@sejong.ac.kr

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where $\mu_{S}^{EE} = 0.5286$, $\mu_{S} = 0.8587$, $\mu_{L}^{N} = 0.1870$, and $\mu_{L} = 2.1069$.

We now consider the probability that, by mean redshift, our sample of SGRBEE ($n_{1} = 7$), SGRB ($n_{2} = 15$) and LGRBNs ($n_{3} = 3$) are drawn from the observed distribution of LGRBs ($n = 230$). Because of the small $n$ samples and the broad distribution of redshifts of LGRBs (with an observational bias towards low $z$), we proceed with an MC test by drawing samples of size $n_{i}$ ($i = 1, 2, 3$) from the distribution of the $n = 230$ redshifts of the latter. Doing so $N$ times for large $N$, we obtain distributions of averages $m_{i}$ of the redshifts in these small $n$ samples under the Bayesian null-hypothesis of coming from the distribution of redshifts of LGRBs. Fig. 2 shows the results for MC with $10^{6}$ realizations. A comparison with such MC test on a Gaussian distribution with mean $\bar{z}$ and standard deviation $\sigma_{z} = 1.3459$ of LGRBs is included for reference. The results clearly demonstrate the need for a Monte Carlo simulation on the observed distribution of redshifts of LGRBs for an accurate estimate of confidence levels, especially when departures from $\bar{z}$ are substantial. Based on (1), the MC analysis shows

$$\begin{align*}
\text{SGRBEE} & \not\subset \text{LGRB} : \sigma \approx 4.6700 \\
\text{SGRB} & \not\subset \text{LGRB} : \sigma \approx 4.7530 \\
\text{LGRBN} & \not\subset \text{LGRB} : \sigma \approx 4.3140
\end{align*}$$

Relative to normal LGRBs, the distinct morphology of SGRBEE and LGRBNs in Fig. 2 and redshifts (2) provides evidence that SGRBEE and LGRBN belong to the same class of events and likely originate in mergers as do classical SGRBs. A technically long duration EE to a merger explains LGRBNs, i.e., LGRBs without association with an SN. This interpretation is further supported by the elliptical host galaxies of SGRB 050509B and GRBEE 050724, which sets these events rigorously apart from massive star progenitors to normal LGRBs.

Our MC results (2) also show that our sample of SGRB(EE)s has negligible contamination by short duration events derived from LGRBs with durations $T_{90} \leq 20$ s, that may be present at redshifts $z > 1$ (Bromberg et al. 2013). The time scale of 20 s derives from a 10 s time-scale of shock break-out in CC-SNe identified in a detailed matched filtering analysis of the 1491 LGRBs in the BATSE catalogue (van Putten 2012). Furthermore, the soft tails of both SGRBEE and LGRBN show a location in the $E_{p,i} - E_{iso}$ plane consistent with that of LGRBs associated with an SN and, more generally, with the Amati-correlation for normal LGRBs, that are all expected to be associated with a SN by the correlation of their redshift distribution to the cosmic star formation rate, $E_{iso}$ of the two SGRBEEs highlighted in Fig. 2 (GRB 071227 and GRB 050724) fall within the range of the $E_{iso}$'s of normal LGRBs with SNe and, in fact, are at the lower end of the $E_{iso}$ of the SGRBEEs listed in Table 1. SGRBEE and LGRBNs should hereby have essentially the same observational selection effects. On this basis, (2) shows SGRBEEs and LGRBs to be distinct populations at a level of confidence exceeding $4 \sigma$.

## 3 MERGERS AND EXTENDED EMISSION

A merger origin of SGRBs and SGRBEEs naturally accounts for a delay in redshift relative to the cosmic star formation
rate and a dissociation to host galaxy type. Mergers of interest are NS-NS and NS-BH coalescence, producing stellar black holes with an accretion disc or torus (BHS) in common with core-collapse of high mass stars (more massive than those producing neutron stars).

A BHS may produce a long-lived inner engine in angular momentum loss from rapidly rotating black holes, as opposed to short-lived activity from hyper-accretion onto a slowly spinning black hole following tidal break-up of a PNS (van Putten & Ostriker 2001). In particular, high reso-

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**Table 1.** Swift detections of SGRB, SGRBEE and LGRBNs sorted by redshift.

| SGRB  | \(T_{90}\) | \(z\)  | Host | \(E_{iso}^c\) (10^{52} erg) | \(E_{p}^c\) (keV) |
|-------|------------|-------|------|-----------------------------|------------------|
| 061201| 0.760      | 0.111 | galaxy cluster [1]         | 0.013            | 969               |
| 050509B | 0.073       | 0.225 | elliptical galaxy [2]   | 0.00027±0.0001 [3] | -                |
| 060520B | 0.131       | 0.287 | massive red galaxy [4] | 0.022           | 193               |
| 130603B | 0.18        | 0.356 | SFR [5]                  | 0.21±0.2 [6]    | 90 [6]            |
| 070724A | 0.4         | 0.457 | moderate SF galaxy [7]  | -               |                  |
| 051221A | 1.400       | 0.547 | SF, late type galaxy [8] | 0.25 [9]       | 35 [9]            |
| 131004A | 1.54        | 0.717 | low mass galaxy [10]    | -               |                  |
| 101219A | 0.6         | 0.718 | faint object [11]       | 0.48            | 842               |
| 061217 | 0.210       | 0.827 | faint galaxy [12]       | 0.008           | 12 [11]          |
| 090510 | 0.3         | 0.903 | field galaxy [13]       | 3.8 [13]       | -                 |
| 070429B | 0.47        | 0.904 | star forming ≃1.1M\(_{⊙}\) yr\(^{-1}\) [14] | -               | -                 |
| 060501 | 0.49        | 1.131 | -                        | 0.027           | [15]              |
| 100724A | 1.4         | 1.288 | probably LGRB [16]       | -               | -                 |
| 050813 | 0.45        | 1.8   | galaxy cluster [17,18]  | 0.017           | [18]              |
| 090426 | 1.2         | 2.609 | irregular SF galaxy [19] | -               | -                 |

| SGRBEE | 060614 d e f g | 108.7 | 0.125 | faint SFR [20,21] | 0.21±0.09 [20] | 55 [20] |
|--------|----------------|-------|-------|-------------------|---------------|---------|
| 050724 e f g | 0.09        | 0.258 | elliptical, weak spiral [22] | 0.0009 [23] | -       |
| 071277A e f | 1.8         | 0.384 | edge-on spiral [24]   | 0.008 [25]    | -       |
| 061210 d e f g | 85.3        | 0.41  | bulge dominated [26]  | 0.046 [26]    | -       |
| 061006 d e f g | 129.9       | 0.438 | exponential disc profile [27] | 0.18          | 955     |
| 070714B d e f g | 64          | 0.92  | moderately SF galaxy [28] | 0.16 [28,29] | -       |
| 050911 d e c | 16.2        | 1.165 | M82 cluster [30]        | 0.0019            | [30]    |

| LGRBN   | 060505 | d e f g | 0.089 | spiral, ionized H, no SN [31] | 0.0012 [21] - 0.0039 | 120     |
|---------|--------|---------|-------|--------------------------------|------------------|---------|
| 060614 | 0.125 | d e f g | 108.7 | faint SFR, no SN [20] | 0.21±0.09 [21] | -       |
| 060121 | 46     | 0.342 | no SN [32] | -               | 0.68            | 630     |

\[ a\] From HEASARC [2014]; \[ b\] galaxy type, SN association; \[ c\] isotropic-equivalent energy and peak energy for events with reliable estimates of the bolometric \(E_{iso}\), across a large enough energy band, under the assumption \(\Omega_m = 0.3\) and a Hubble constant \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\).

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**Figure 1.** (Left:) the redshifts of 230 LGRBs in the Swift catalogue shows a mean redshift \(\mu = 2.11\) with standard deviation \(\sigma = 1.35\). This distribution is significantly biased to towards low redshifts. (Right:) same for SGRB, SGRBEE, LGRBN and SGRBEE+LGRBNs.
mal spin energy hyper-energetic GRB-SNe, whose output exceeds the max-
on extended emission.) This safely accounts for the most produced in mergers, PNS are short-lived with no bearing inner engine, i.e., rapidly rotating black holes, not PNS. (If LGRBNs with mergers involving the latter.

spin energy of a Kerr black hole of mass $M = 1.45 M_\odot$ and radius $R = 12$ km to be compared with the maximal spin energy $E_{\text{rot}} = 6 \times 10^{54}$ erg of a Kerr black hole of mass $M = 10 M_\odot$ (van Putten et al. 2011).

4 DISCUSSION

The Swift discovery of SGRBEEs, e.g., GRB 060724, and LGRBNs, e.g., GRB 060614, highlights a new diversity in LGRBs with no apparent association with massive stars. Based on an MC analysis, the observed redshift distributions of SGRB and SGRBEEs are distinct from that of LGRBs at 4.75$\sigma$ and 4.67$\sigma$, respectively. Further supported by their distinct morphology in the $E_{p, i} - E_{\text{iso}}$ plane and hosts that include elliptical galaxies, this points to a common origin in mergers of both, i.e., of the NS-NS and NS-BH variety with long-lived and short-lived inner engines, respectively.

In a common origin of SGRBEEs and LGRBNs, we identify the initial pulse with the “switch on” of SGRBEEs in binary coalescence similar as in classical SGRBs (see also Ghirlanda et al. (2011)) and the extended emission with a rotating black hole, rather than a PNS, slowly losing angular momentum.

The fact that the soft tail of SGRBEE and LGRBNs follows the Amati-correlation holding for normal LGRBs points to a common long-lived inner engine which is a rotating black hole to all three groups. This is consistent with (a) the absence of any signature of PNS formation in a high-frequency analysis of BeppoSAX light curves (van Putten et al. 2014) and (b) evidence for black hole spin-down observed in normalized light curves in the BATSE catalogue (van Putten 2012). Apart from the low number counts, the only reservation would be extremely sublumino- nous CC-SNe (cf. Pastorello et al. 2007), that would be undetectable in our sample LGRBNs.

Following Guetta & Della Valle (2007), local rates of GRB-SNe and LGRBNs can be estimated from the observed events taking into account finite angular and temporal sky coverage and sensitivity distance. With no correction for
beaming, we find, respectively, the event rates $1.13^{+1.94}_{-0.87}$ (cf. Guetta et al. [2011]) and $0.053^{+0.10}_{-0.036}$ Gpc$^{-3}$ yr$^{-1}$. It shows a ratio of LGRB/N to GRB-SN of about 5%, and likely no larger than about 30%.

Acknowledgments. The authors gratefully acknowledge C. Tout for comments which have considerably improved the readability of this letter.

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