A SEARCH FOR PULSATIONS IN SHORT GAMMA-RAY BURSTS TO CONSTRAIN THEIR PROGENITORS

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ABSTRACT

We searched for periodic and quasi-periodic signals in the prompt emission of a sample of 44 bright short gamma-ray bursts (GRBs) detected with Fermi/GBM, Swift/BAT, and CGRO/BATSE. The aim was to look for the observational signature of quasi-periodic jet precession, which is expected from black hole (BH)–neutron star (NS) mergers, but not from double NS systems. Thus, this kind of search holds the key to identifying the progenitor systems of short GRBs and, in the interim before gravitational wave detectors become on-lines, represents the only direct way to constrain the progenitors. We tailored our search to the nature of the expected signal by properly stretching the observed light curves by an increasing factor with time, after calibrating the technique with synthetic curves. None of our GRBs showed evidence for periodic or quasi-periodic signals. In particular, for the seven unambiguously short GRBs with the best signal-to-noise ratios, we obtained significant upper limits to the amplitude of the possible oscillations. This result suggests that BH–NS systems do not dominate the population of short GRB progenitors, as described by the kinematic model of Stone et al.

Key words: accretion, accretion disks – gamma-ray burst: general – methods: data analysis – techniques: photometric

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Several lines of evidence suggest that short duration gamma-ray bursts (hereafter, SGRBs; durations $T_{90} \lesssim 2–3\,\text{s}$), or at least a sizable fraction of them, have a cosmological origin and are the electromagnetic counterpart to the coalescence of compact binary systems, such as double neutron stars (NSs) or a NS and a black hole (BH; e.g., see Nakar 2007; Berger 2011 for reviews; see also Fong & Berger 2013; Berger et al. 2013; Tanvir et al. 2013). We define $T_{90}$ as the time during which the cumulative time counts increase from 5 to 95% above background, thus encompassing 90% of the total GRB counts (Kouveliotou et al. 1993). During the merging, an accretion disk is thought to be produced by the tidal disruption of an NS around a more compact NS or before an NS is swallowed by a BH. Either way, eventually the system evolves toward the formation of a BH with a debris torus around it. The resulting neutrino-cooled accretion flow leads the hyperaccreting BH to develop a collimated outflow into a pair of anti-parallel jets (e.g., see Lee & Ramirez-Ruiz 2007).

A potential means to distinguish between NS–NS and NS–BH mergers concerns the signature of the disk and jet precession in the electromagnetic signal, i.e., the SGRB itself. In the case of an NS–BH merger, precession is expected for a tilted disk and jet due to Lense–Thirring torques from the BH spin (Stone et al. 2013, and references therein). These authors (hereafter, SLB13) assumed thick disks precessing as solid body rotators and built upon numerical relativity simulations of this kind of mixed mergers. According to their results, for a reasonable set of values in the parameter space, i.e., BH spin and mass, disk viscosity, and misalignment angle between the accretion disk and the BH equatorial plane, a quasi-periodic modulation in the $\gamma$-ray signal is to be expected for a sizable fraction of NS–BH mergers. The predicted precession period $T_p$ increases with time proportionally to $t^{4/3}$ due to viscous spreading of the disk and, for a given mixed compact system, starts from a few tens of ms at the beginning of the SGRB and ends with about one order of magnitude longer values. The average expected number of cycles is just a few, typically $N_{\text{cycles}} \lesssim 10$. In all scenarios SLB13 considered, these two observables lie in the range $4.5 \lesssim \langle N_{\text{cycles}} \rangle \lesssim 7.5$ and $30\,\text{ms} \lesssim \langle T_p(\tau_{1/2}) \rangle \lesssim 100\,\text{ms}$, where $T_p(\tau_{1/2})$ is the half-way precession period for a given merger.

The aim of this letter is to search for this kind of quasi-periodic signal in the data of the brightest SGRBs detected with the Fermi Gamma-ray Burst Monitor (GBM; Meegan et al. 2009), the Swift Burst Alert Telescope (BAT; Barthelmy et al. 2005a), and the Compton Gamma Ray Observatory (CGRO) Burst And Transient Source Experiment (BATSE; Paciesas et al. 1999), exploiting the exquisite time resolution available with these instruments. This search offers the only direct way to observationally distinguish between the two classes of progenitors based on their electromagnetic emission and naturally complements forthcoming gravitational wave studies. This paper is organized as follows. The data selection is described in Section 2. The technique we set up to carry out a dedicated search is outlined in Section 3. Results and their discussion follow in Sections 4 and 5, respectively.

2. DATA SELECTION

2.1. Sample Selection

We took all the events observed by the Fermi/GBM from 2008 July to 2012 December. For each GRB, we extracted and summed the 1 ms light curves of the two most illuminated NaI detectors in the 8–1000 keV energy band with the HEASOFT package (v6.12) following the Fermi team threads.3 Light curves affected by spikes due to the interactions of high-energy particles with the spacecraft were rejected (Meegan et al. 2009). We derived the $T_{90}$ and $T_{2\sigma}$ time intervals, where the boundaries of

3 http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/gbm_grb_analysis.html
the latter correspond to the first and the last bin whose counts exceed the \(5\sigma\) signal threshold above background.

We selected the SGRBs by requiring \(T_{90} < 3\ s\) and ended up with 160 GRBs, 18 of which have a minimum signal-to-noise ratio \((S/N)\) of 20, as computed over the \(T_{90}\) interval. As far as the \(T_{90}\) distribution is concerned, our selected sample of \(S/N > 20\) SGRBs is representative of the full sample of SGRBs, as suggested by a Kolmogorov–Smirnov test.

The same selection criteria were applied to the Swift/BAT sample using all the events detected up to early 2013 June. We found 30 GRBs with \(T_{90} < 3\ s\), 12 of which passed the final \(S/N > 20\) threshold. The mask-weighted light curves had previously been extracted from the event files following the BAT team threads and are for the 15–150 keV detector passband. In addition to the 1 ms light curves, for the two brightest events of the sample, namely 051221A and 120323A, we used 0.1 ms resolution to explore the very high-frequency behavior.

From an initial sample of 61 BATSE SGRBs with high \(S/N\), we excluded all the cases for which the time-tagged event (TTE) data did not cover the entire profile. Unfortunately, several bright bursts were excluded, because the on board memory could record only up to 32,768 events around the trigger time. Consequently, we were left with 14 SGRBs whose profiles were extracted in the 20–2000 keV energy range.

Summing up, our final sample includes 44 SGRBs (18 Swift, 12 Swift, and 14 CGRO) with high \(S/N > 20\). A finer subdivision of the final sample is provided in the following section, aimed at establishing how genuinely short each selected burst is.

2.2. Short versus Intermediate GRBs

Evidence for the existence of a third group of GRBs with intermediate durations and hardness ratios (HRs) between short and long ones was found by several authors for different datasets (e.g., Horváth 1998; Mukherjee et al. 1998; Horváth et al. 2008; Huja et al. 2009; Řípa et al. 2009; Horváth 2009; but see also Koen & Bere 2012). In this context, we adopted the classification procedures obtained by Horváth et al. (2006) for CGRO/BATSE and by Horváth et al. (2010) for Swift/BAT to assess the nature of our selected sample of bursts, based on the combination of HR and \(T_{90}\). We assigned each GRB a probability \(p\) of belonging to the short group through the “indicator function,” out of the three classes: short, intermediate, and long. As expected, all GRBs had negligible probability of belonging to the long group. We defined as “truly SGRB” (T-SGRB) the GRBs with \(p > 0.9\). The GRBs with \(0.8 < p < 0.9\) are defined as “likely SGRB” (L-SGRB), whereas the remaining cases \((p < 0.8)\) were conservatively classified as “possibly intermediate” (P-IGRB). Actually, several members of the P-IGRB group are more likely to be genuine short than intermediate bursts. However, our choice was aimed at assuring the least possible contamination with ambiguous cases.

Figure 1 shows the HR–\(T_{90}\) diagram for the three different datasets: each panel compares the properties of our selected GRBs with those of the corresponding catalog: Sakamoto et al. (2011) for Swift/BAT, Paciesas et al. (2012) and Goldstein et al. (2012) for Fermi/GBM, and Paciesas et al. (1999) for CGRO/BATSE. The HR values for the Swift/BAT sample were calculated as the fluence ratio in the bands (50–100 keV)/(25–50 keV) as in Sakamoto et al. (2011), while (300–100 keV)/(50–100 keV) was adopted for the Fermi/GBM and the CGRO/BATSE datasets. To compute the membership probability for the GRBs detected with the Fermi/GBM, we used the same parameters used for the CGRO/BATSE owing to the similar energy passbands. Although in principle this may lead to some misclassified Fermi/GBM GRBs, in practice the two Fermi T-SGRBs appear to be robustly so (large filled circles in the middle panel of Figure 1).

3. DATA ANALYSIS PROCEDURE

We studied the power density spectrum (PDS) of each light curve in two different ways. PDSs were calculated adopting the Leahy normalization (Leahy et al. 1983). To fit the PDSs, we used the technique set up by Vaughan (2000) based on a Bayesian treatment with Markov Chain Monte Carlo techniques. Two analytical models were assumed to describe the PDS...
For each GRB, we took the time axis. To this aim, we devised a technique that was tailored for the expected signal. For each GRB, we took the $T_{5\sigma}$ interval boundaries and associated two corresponding precession periods: let $t_0$ and $t_1$ be the start and end times of the $T_{5\sigma}$ interval, respectively, and let $T_{p,0}$ and $T_{p,1}$ be the corresponding precession periods, respectively. We stretched the time axis according to the continuously increasing $T_p$, as described by

$$T_p(t) = T_{p,0} \left(1 + \frac{t - t_0}{t_s}\right)^{4/3},$$

where the constant $t_s$ is defined as

$$t_s = \frac{t_1 - t_0}{(T_{p,1}/T_{p,0})^{3/4} - 1}.$$

The values of $T_{p,0}$ and $T_{p,1}$ were chosen so as to match the typical values obtained by SLB13 (typically, values were $T_{p,0} = 0.01$ and $T_{p,1} = 0.6$ s).

We calculated the new count rates in each of the new temporal bins starting from the original photon arrival times at the detector. Earlier bins at $t < t_0$ were left unaffected. We attributed a fictitious duration of 1 ms to the new bins. We made sure the new bins corresponded to a number of 5 bins per precession period. This automatically implies that a possible quasi-periodic pulsation such as that described by Equation (3) should correspond to a frequency $5/2 = 2.5$ times as small as the Nyquist one (i.e., 200 Hz in our case) in the stretched PDS.

For each SGRB in our dataset, we preliminarily carried out the same analysis on a set of synthetic curves that were derived from a smoothed version of the original light curve of the SGRB. The smoothed version was then modulated with different values of the fractional amplitude with a periodic signal with a period varying according to Equation (3). For each SGRB, we determined the minimum amplitude for which the PDS of the synthetic stretched light curve gave a $2\sigma$ detection. We also searched the synthetic PDS, adopting slightly different trial $T_{p,0}$ and $T_{p,1}$ values from the exact values used to build the corresponding stretched curves. As a result, the detection did not crucially depend on the choice of trial $T_{p,0}$ and $T_{p,1}$ within a given range. This check is important since this is the case for real curves for which the possible true periods are unknown.
priori. Further details on how the synthetic light curves were generated and on the calibration of this technique are given in the Appendix. Hereafter, we refer to this search as the stretched PDS search.

4. RESULTS

The canonical search identified just a couple of SGRBs with power exceeding the 2σ threshold (Gaussian units) in one frequency bin each. The chance probability of a 2σ fluctuation occurring within a given PDS is 4.5%. Out of 44 different PDS, the expected number of >2σ fluctuations is 1.98, i.e., in agreement with the observed number of two cases. Hence, no evidence for the presence of periodic or quasi-periodic signals was found. In the absence of detection, we derived, for each GRB, a 2σ upper limit to the fractional amplitude averaged out over the frequency range of interest, i.e., from 10 to 30 Hz. The amplitude is normalized to the peak count rate of each SGRB. The average minimum detectable amplitude depends on the time interval the PDS is calculated: it clusters around 3% (17%) of the peak for the fixed (5σ) time interval (Figure 3).

Likewise, we did not find any evidence for the quasi-periodic signals in the stretched PDS search. However, as the calibration on synthetic curves has shown, we could obtain useful upper limits on the pulsational amplitude for the four, five, and five SGRBs with the highest S/N detected by Fermi, Swift, and the CGRO, respectively. This reduced sensitivity with respect to the canonical search is a consequence of the low number of expected cycles coupled with the statistical quality of the data. Figure 4 shows the 2σ upper limits on the fractional amplitude for a modulation with an increasing precession period superimposed on the overall profile of each SGRB as in Equation (3) as a function of S/N for these 14 events. With reference to the short/intermediate classification provided in Section 2.2, 7 out of these 14 GRBs are T-SGRBs, while 4 are L-SGRBs and 3 are P-IGRBs. As shown in Figure 4, even if we neglect the P-IGRB group, our results do not change in essence, although the reduced number of events demands caution in generalizing them to larger samples of GRBs. The burst with the highest S/N and most stringent upper limit on its fractional amplitude corresponds to GRB 120323A detected with Fermi/GBM. It is a P-IGRB, so the probability of it being a misclassified intermediate GRB is negligible. Still, it is worth noting that it has a 78% probability of not being a genuine SGRB and a mere 22% chance of being an intermediate GRB.

Although the quasi-periodic oscillation (QPO) search has given negative results, an interesting product of the canonical search is the continuum properties for an ensemble of bright SGRBs, which is studied here for the first time. Figure 5 shows the distribution of the power-law indices for both the PL and the BPL models, upon selection of the most accurately measured values (|α(σ)| < 0.5). A comparison with analogous results obtained for a sample of long Fermi/GBM GRBs (S. Dichiara et al. in preparation) shows no outstanding difference in the power-law index distribution between short and long GRBs. However, the small number of SGRBs lacks the sensitivity required to reveal fine differences.

For the SGRBs whose PDSs are best fit with a broken power law, the break frequency is mostly connected to the overall duration of the main spike, whose timescale is predominant in the total PDSs of SGRBs.
5. DISCUSSION AND CONCLUSIONS

The canonical search for periodic or quasi-periodic signals did not yield any detections, in agreement with previous analogous searches (Kruger et al. 2002), down to a limiting peak-normalized amplitude that is typically around 10%–20% when the PDS is calculated over the 5σ time interval.

In addition, we devised and calibrated a technique to detect the signature of a periodic signal potentially hidden within the time profiles of some SGRBs, characterized by a continuously increasing period, from a few tens of milliseconds up to a fraction of a second or so throughout the duration of SGRB. This kind of signal has theoretically been predicted in the case of a mixed merger (NS–BH), where the tilted jet and accretion disk with respect to the BH spin is expected to cause the jet precession and a periodic gamma-ray signal in the prompt emission such as that described above (SLB13). Likewise, no significant detection at 2σ out of a sample of 44 SGRBs was obtained by our tailored technique either, where we call this technique the stretched PDS search. However, we could extract useful upper limits on the fractional amplitude of such a modulated signal for 14 GRBs, with values distributed from 10% to 90%. When we exclude the three GRBs that appear to have a non-negligible (p > 0.2) probability of belonging to the intermediate duration group, the results do not change in essence. The reduced sensitivity of the stretched PDS search compared with that of the canonical one is due to smaller numbers of expected cycles, which couples with a more critical dependence on S/N, as revealed by the synthetic curves used for calibration.

An interesting outcome of our canonical PDS search concerns the continuum properties of the PDS for an ensemble of bright SGRBs (see Table 1 in electronic format). Unlike the case for long GRBs (e.g., see Dichiara et al. 2013 and references therein), this is the first time we could usefully study these properties for SGRBs, whose study has been hampered so far by lower S/N with respect to long GRBs. This was also made possible by the Bayesian procedure that was recently proposed by Vaughan (2010) to properly model the PDSs of time series affected by a strong red noise component, such as the case of SGRB time histories (e.g., see Huppenkothen et al. 2013). Two alternative models were adopted: a simple or a broken power law in addition to the white noise constant. A preliminary comparison with the analogous properties of a sample of bright long GRBs (S. Dichiara et al. in preparation) reveals no striking difference between the two power-law index distributions (Figure 5). Regardless of the PDS continuum interpretation, this may suggest a common general mechanism that rules the shock formation and the gamma-ray emission production.

The implications of our results do not allow us to rule out the physical scenario envisaged by SLB13 as the possible interpretation of the prompt emission of SGRBs for two main reasons. First of all, the sample of SGRBs for which our non-detection is meaningful is still statistically too small to draw firm conclusions. This is even more so when one neglects the few GRBs that could belong to the intermediate duration group. Second, the possibility that the few cases of interest could correspond to either other kind of mergers, such as NS–NS or mixed mergers with unfavorable space parameters, such as the accretion disk viscosity or the misalignment angle between jet axis and BH spin, is not negligible for just a few cases. Furthermore, according to the recent physical classification proposed by Bromberg et al. (2013), there could be collapsar events disguised as SGRBs, whose presence could partially explain the observed lack of evidence for the pulsations expected for NS–BH mergers. Nonetheless, in addition to being the first attempt of a dedicated search on a valuable dataset, our analysis indicates that such mixed systems might not be a dominant fraction among the population of currently detected SGRBs, at least as envisaged in the model by SLB13. A definitive answer will come from a larger sample with comparable statistical quality in combination with the wealth of information that will be independently gathered through the study of gravitation wave radiation.
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APPENDIX

CALIBRATION OF THE STRETCHED PDS SEARCH

For each SGRB, we carried out a series of simulations aimed at calibrating the sensitivity of our stretched PDS search. We first binned the original curve to a rough resolution so as to reduce the high-frequency variability (both real and statistical fluctuations). The smoothed version of the light curve was then obtained by interpolation of the coarsely binned curve by means of C-splines. To simulate the predicted periodicity, we modulated a smoothed version of the original light curve with a sinusoidal signal assuming the temporal evolution of \( T_p \) of Equation (3). Specifically, to obtain the synthetic light curves, we preliminarily had to calculate the pulsational phase as a function of time, \( \phi(t) \). Since \( T_p \) continuously varies with time, we had to integrate the infinitesimal relation

\[
\frac{d\phi}{dt} = \frac{2\pi}{T_p} \frac{dN}{dt} = \frac{2\pi}{T_p} \frac{dt}{T_p}.
\]

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\]

\[\phi(t) = \frac{2\pi}{T_p} \int_{t_0}^{t} \frac{dt'}{T_p(t')} = \frac{6\pi t_s}{T_p(0)} \left[ 1 - \left( 1 + \frac{t - t_0}{t_s} \right)^{-1/3} \right]. \tag{A1}\]

Equivalently, the number of cycles at time \( t \), \( N(t) \) is given by

\[N(t) = \frac{\phi(t)}{2\pi} = \frac{3t_s}{T_p(0)} \left[ 1 - \left( 1 + \frac{t - t_0}{t_s} \right)^{-1/3} \right]. \tag{A2}\]

The final number of cycles is given by Equation (A2) at \( t = t_1 \) and can be conveniently expressed as

\[N = \frac{(t_1 - t_0)}{T_p(0)} \frac{3x^3}{1 + x + x^2}, \tag{A3}\]

where we defined \( x = \left( \frac{T_p(0)}{T_p(1)} \right)^{1/4} \). The trivial case of constant periodicity \( (T_p) = (T_p(0)) \) is easily recovered: \( N = (t_1 - t_0)/T_p(0) \). Finally, statistical noise was added to the synthetic light curves, which were then processed exactly the same way as real curves according to the stretched PDS search described in Section 3.

REFERENCES

Barthelmy, S. D., Barbier, L. M., Cummings, J. R., et al. 2005a, SSRv, 120, 143
Barthelmy, S. D., Chincarini, G., Burrows, D. N., et al. 2005b, Natur, 438, 994
Berger, E. 2011, NewAR, 55, 1
Berger, E., Fong, W., & Chornock, R. 2013, ApJL, 744, L23
Bromberg, O., Nakar, E., Piran, T., & Sari, R. 2013, ApJ, 764, 179
Dichiara, S., Guidorzi, C., Amati, L., & Frontera, F. 2013, MNRAS, 431, 3608
Fong, W., & Berger, E. 2013, ApJ, 776, 18
Goldstein, A., Burgess, J. M., Preece, R. D., et al. 2012, ApJS, 199, 19
Horváth, I. 1998, ApJ, 508, 727
Horváth, I. 2009, Ap&SS, 323, 83
Horváth, I., Bagoly, Z., Balázs, L. G., et al. 2010, ApJ, 713, 552
Horváth, I., Balázs, L. G., Bagoly, Z., Ryde, F., & Mészáros, A. 2006, A&A, 447, 23
Horváth, I., Balázs, L. G., Bagoly, Z., & Veres, P. 2008, A&A, 489, L1
Huja, D., Mészáros, A., & Répa, J. 2009, A&A, 504, 67
Huppenkothen, D., Watts, A. L., Uttley, P., et al. 2013, ApJ, 768, 87
Koen, C., & Bere, A. 2012, MNRAS, 420, 405
Kouveliotou, C., Meegan, C. A., Fishman, G. J., et al. 1993, ApJL, 413, L101
Kruger, A. T., Loredo, T. J., & Wasserman, I. 2002, ApJ, 576, 932
Leahy, D. A., Darbrot, W., Elsner, R. F., et al. 1983, ApJ, 266, 160 (L83)
Lee, W. H., & Ramirez-Ruiz, E. 2007, NPhS, 9, 17
Meegan, C., Lichten, G., Bhat, P. N., et al. 2009, ApJ, 702, 791
Mukherjee, S., Feigelson, E. D., Jogesh Babu, G., et al. 1998, ApJ, 508, 314
Nakar, E. 2007, PhR, 442, 166
Paciesas, W. S., Meegan, C. A., Pendleton, G. N., et al. 1999, ApJS, 122, 465
Paciesas, W. S., Meegan, C. A., von Kienlin, A., et al. 2012, ApJS, 199, 18
Répa, J., Mészáros, A., Wigger, C., et al. 2009, A&A, 498, 399
Sakamoto, T., Barthelmy, S. D., Baumgartner, W. H., et al. 2011, ApJS, 195, 2
Stone, N., Loeb, A., & Berger, E. 2013, PhRvX, 3D, 04103 (SLB13)
Tanvir, N.R., Levan, A. J., Fruchter, A. S., et al. 2013, Natur, 500, 547
Vaughan, S. 2010, MNRAS, 402, 307