CONSTRAINTS ON ASSOCIATION OF SINGLE-PULSE GAMMA-RAY BURSTS AND SUPERNOVAE

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We explore the hypothesis, similar to one recently suggested by Bloom and colleagues, that some nearby supernovae are associated with smooth, single-pulse gamma-ray bursts, possibly having no emission above $\sim 300$ keV. We examine BATSE bursts with durations longer than 2 s, fitting those which can be visually characterized as single-pulse events with a lognormal pulse model. The fraction of events that can be reliably ascertained to be temporally and spectrally similar to the exemplar, GRB 980425 – possibly associated with SN 1998bw – is 4/1573 or 0.25%. This fraction could be as high as 8/1573 (0.5%) if the dimmest bursts are included. Approximately 2% of bursts are morphologically similar to GRB 980425 but have emission above $\sim 300$ keV. A search of supernova catalogs containing 630 detections during BATSE’s lifetime reveals only one burst (GRB 980425) within a 3-month time window and within the total 3-$\sigma$ BATSE error radius that could be associated with a type Ib/c supernova. There is no tendency for any subset of single-pulse GRBs to fall near the Supergalactic Plane, whereas SNe of type Ib/c do show this tendency. Economy of hypotheses leads us to conclude that nearby supernovae generally are not related to smooth, single-pulse gamma-ray bursts.

Subject headings: gamma rays: bursts – temporal analysis – supernova
1. INTRODUCTION

GRB 980425 was located inside the BeppoSAX Wide Field Camera (WFC) error circle, along with two weak X-ray sources, one of which faded away within ~ 2–3 days after the gamma-ray burst, as observed by the BeppoSAX Narrow Field Instruments (Pian et al. 1998). An unusual supernova (SN), apparently of type Ic, was also detected within the WFC error circle (Galama et al. 1998), not positionally coincident with either X-ray source. A radio source, detected by Wieringa et al. (1998) ~ 3 days after the burst, brightened to become approximately two orders of magnitude more luminous than any previously studied radio source associated with a type Ic SN and was inferred to be expanding relativistically (Kulkarni et al. 1998b). Modeling of the optical light curve implies an explosion energy of ~ $2-5 \times 10^{52}$ ergs, and core collapse within ~ 1 day of GRB 980425 (Iwamoto et al. 1998). These observations and deductions have led many investigators to consider strongly the proposition that GRB 980425 and onset of SN 1998bw are one and the same event: The combined positional and temporal chance probability has been estimated as ~ $10^{-4}$ (Galama et al. 1998), and the explosion dynamics and energetics could possibly power an observable gamma-ray at the distance to SN 1998bw (~ 38 Mpc).

In this paper we further examine the hypothesis discussed by Bloom et al. (1998) that GRBs with time profiles resembling that of GRB 980425 (BATSE trigger #6707) may be associated in general with SNe type Ib or Ic. Bloom et al. detail the criteria for inclusion in a supernova-GRB (S-GRB) class, including: prompt radio emission with high brightness temperature; no long-lived X-ray afterglow; broad line emission and high optical luminosity; and a gamma-ray profile consisting of a single, relatively smooth, broad pulse. The single shock expected in a SN core collapse would be expected to give rise to a single gamma-ray pulse.

The pulse in GRB 980425 exhibited the dominant GRB spectral evolutionary mode: At lower energies pulses tend to peak later and exhibit longer decay timescales (Norris 1995; Norris et al. 1996). Since this behavior is observed in most GRBs, it is not a constraining diagnostic. Also, as noted by Wang & Wheeler (1998), GRB 980425 had no significant high-energy (NHE) emission above 300 keV (see Pendleton et al. 1997). Most bursts exhibit significant HE emission, but approximately one-third – mostly dim bursts – do not. It can easily be demonstrated that bright bursts (practically all of which have HE emission), when (1) signal-to-noise (s/n) equalized to dim burst intensity levels and (2) redshifted to approximate the spectral distribution of dim bursts, then virtually reproduce the brightness distribution of the putative NHE class (Bonnell & Norris 1998). Thus it is likely that the apparent NHE class results from the combination of a brightness bias effect and an extrinsic (cosmological redshift) selection effect. Nevertheless, for the putative
S-GRB class, the NHE characteristic may be a distinguishing signature. Thus if gamma-ray diagnostics are of any value in recognizing S-GRB events, the salient feature is a solitary smooth, broad pulse, and possibly NHE.

Kippen et al. (1998) undertook an examination of the whole set of GRBs, comparing their positions and times of occurrence with those of SNe and found that at most ~ 0.2–2.5% of GRBs could be associated with known SNe. Our goal is to define more quantitatively the possible members of the putative class of broad, single-pulse GRBs within the BATSE sample, and to determine the possible degree of association with nearby SNe. We also consider the possible role of the NHE spectral discriminator for the putative S-GRB class. In section 2 we describe our program for determining a sample of bursts which are similar to GRB 980425, and in section 3 we describe the search for SNe which could be associated with bursts in our single-pulse sample. In section 4 we discuss implications of our results and other evidence on the possible association of nearby SNe and single-pulse GRBs.

2. SINGLE-PULSE BURST SAMPLE

We performed a several-step program, starting with the largest available sample of bursts and decimating the sample according to criteria designed to preserve recognizable wide, single-pulse GRBs. Through May 1998 there were 2092 BATSE bursts available in the GRO Science Support Center archive. Following the procedures described in Bonnell et al. (1997), we constructed concated time profiles for all bursts where possible, requiring timing overlap for the 1.024-s continuous DISCLA data and the 0.64-ms PREB and DISCSC data types. We then fitted backgrounds for each of the four energy channels (25–50, 50–100, 100–300, > 300 keV), and estimated $T_{90}$ durations using a standard noise equalization and thresholding procedure, also described in Bonnell et al., for all bursts with sufficient data preceding and following the burst. Even though some short bursts ($T_{90} < 2$ s) consist of a single pulse, we elected to study only long bursts ($T_{90} > 2$ s) since the main criterion for resemblance to GRB 980425 is a relatively wide pulse with a smooth peak (Bloom et al. 1998). This concatenation, background fitting, and duration measurement process yielded a usable sample of 1153 long bursts and 420 short bursts, or a total of 1573 bursts.

Given very high s/n data, ideally one might reliably determine the number of pulses within a completely automated program. Such an approach may be realizable even with low s/n data (see for instance, Scargle 1998). However, at very low s/n levels, even automated algorithms cannot
yield confident estimates of the number of pulses present. We therefore visually examined the entire long burst sample at 256-ms and 1024-ms resolution, making a very liberal selection of bursts which could possibly be single-pulse events. We then examined this decimated set of 116 bursts, viewing each event alternately at two resolutions, 128-ms and 512-ms, with the four channels color-coded. We made three such passes and on the final pass recorded a lower limit to the number of pulses visually apparent for each burst. We declared 68 bursts to have at least one pulse, 26 at least two pulses, and 22 more than two pulses. This subjective decision included the necessary deliberation on correlation of emission across energy channels, which is difficult to render into an automatic procedure since the amount of energy-dependent lag is, a priori, unpredictable, especially given the multi-pulse nature of most GRBs. We then proceeded to use a least squares fitting algorithm (see Press et al. 1992) to quantify our subjective estimates of the number of pulses per burst, and to measure the pulse widths.

In the subsequent analysis, we used background-subtracted data, propagating the variance of background count rates in all fitting procedures. We normalized burst time profiles to the s/n level of GRB 980425, since it is the exemplar against whose intensity the judgment should be made if a burst appears to be a single pulse. We have found that a lognormal pulse model (Brock et al. 1994) is an adequate, but not perfect, representation of long, single-pulse bursts:
I(t) = A_{\text{max}} \exp\left\{-\frac{1}{2} \left[ \frac{(\log(t - t_0) - \mu)}{\sigma} \right]^2 \right\}, \quad t > t_0
I(t) = 0, \quad t \leq t_0
\hspace{1cm} (1)

where $A_{\text{max}}$ is the pulse peak amplitude; $t_0$ is the time of pulse onset; $\mu$ and $\sigma$ are the mean and standard deviation in log[time], respectively. We summed channels 2 and 3 (50–300 keV) and fitted the resulting time profiles at 256-ms resolution with a lognormal pulse and took the peak of the fitted pulse to be the measure of peak intensity. In subsequent fits and evaluations described below, if the burst’s fitted $A_{\text{max}}$ was higher than that of GRB 980425, its background-subtracted time profiles in each of the four channels were reduced by the factor $A_{\text{max}} / A_{\text{980425}}$, and synthetic noise was added to realize variances approximately equal to those in the exemplar (see Norris et al. 1994). Dimmer bursts were analyzed without this signal-to-noise equalization. The fitted peak intensity for GRB 980425 is 1145 counts s$^{-1}$. Approximately half the bursts have lower peak intensities. We could have chosen to equalize all bursts to the peak intensity of the dimmest burst included (242 counts s$^{-1}$), but reliable pulse enumeration would then become quite problematic. In fact, we experienced much difficulty visually evaluating bursts with peak intensities $\lesssim 0.6$ times that of the exemplar. Rather than contaminate the study with unreliable measurements we elected to delete bursts with peak intensities below 720 counts s$^{-1}$ in some final considerations, although we continued to analyze all 116 bursts in the original sample.

Using the lognormal pulse model, we fitted the 256-ms time profiles in channels 1, 2, 3, and 2+3 separately. The fits were examined many times to evaluate correspondence between the visual appearance of the fit and the reduced chisquare ($\chi^2_{\text{red}}$) statistic in three intervals: the interval containing the fitted pulse for amplitudes $> 0.1 \cdot A_{\text{max}}$, and the background intervals preceding and following the fitted pulse. The occurrence of high $\chi^2_{\text{red}}$ values was fairly well correlated with intervals in each channel where we had visually determined an extra pulse to be present. But often, narrow temporal features which obviously constituted such a pulse did not raise $\chi^2_{\text{red}}$ above a critical threshold ($\sim 1.5$–$1.7$) above which most bursts with more than one pulse ranked. We therefore constructed a correlated residuals statistic for the fitted pulse interval, which is sensitive to adjacent residuals of the same sign:

$$R = \frac{\sum_{i=0}^{N-1} \{ S(X_i) S(X_{i+1}) (X_i^2 + X_{i+1}^2)^{1/2} \}}{(N-1)}, \hspace{1cm} (2)$$

where $S(X)$ is the sign of the $X$. When large ($\gtrsim 0.4$) and positive, the $R$ statistic was sensitive to obvious correlated residuals that the $\chi^2_{\text{red}}$ often did not reflect. Combined, the $\chi^2_{\text{red}}$ and $R$
statistics were almost as good as the visual passes in determining if more than one significant pulse was present. However, these statistics cannot by themselves account for the effect of spectral evolution which shifts temporal emission features to later times at lower energies. A few obviously double-pulse bursts were missed by the $\chi^2_{\text{red}}$ and R statistics, and so we elected to rely on the original visual judgment for number of pulses in the final analysis. In each case, the bursts we discuss in the next section have acceptable $\chi^2_{\text{red}}$ and R statistics for channels 1, 2 and 3, and for the intervals preceding, during and following the fitted pulse.

Next, using the s/n equalized profiles, we recorded if significant HE emission (channel 4, > 300 keV) was present within the interval containing the fitted pulse for channel 3 (such that $I(t) > 0.1 \cdot A_{\text{max}}$), and the preceding 2 s. The criterion for HE was 3.5 $\sigma$ above background for the total variance in either the entire interval or the longest subinterval with contiguous positive residuals. In Figure 1 we plot the burst full width at half maximum (FWHM) vs. $\chi^2_{\text{red}}$ for the fitted pulse interval, channels 2+3. Circles indicate bursts with fitted $A_{\text{max}}$ above the 720 counts s$^{-1}$ threshold; filled (open) circles are NHE (HE). Similarly, triangle symbols indicate bursts below the threshold – deemed too dim to determine reliably the number of pulses present. The exemplar, GRB 980425, is plotted with an $\times$ symbol. Finally, we recorded which bursts had a fitted pulse with a FWHM within a factor of three of the FWHM (12 s) for GRB 980425 in channels 2+3, thereby marking bursts with FWHM in the range 4 – 36 s. These bursts lie between the vertical dashed lines in Figure 1. Notice that some narrow bursts are not well fitted by the lognormal pulse model, as evidenced in Figure 1 by their higher $\chi^2_{\text{red}}$ values. Narrower bursts often tended to have a sharp peak superposed near the top of the otherwise well-fitted lognormal model. This sharp peak characteristic does not satisfy the criterion of Bloom et al. (1998) that calls for a broad, smooth pulse without a cusp.

There may be a selection effect in favor of identifying relatively long bursts with HE: Only 40% (14/35) of bursts with FWHM narrower than 4 s have HE, whereas 76% (25/33) of wider bursts have HE. It is probable that this apparent trend arises from our HE identification procedure, which necessarily tests more channel-4 bins for longer bursts. In this respect, GRB 980425 is distinguished from most broad-pulse bursts – it is the longest, single-pulse NHE burst that we find above the amplitude threshold.

The trend for wider pulses to exhibit a larger time lag from high to low energy – concomitant with hard-to-soft spectral evolution (Norris et al. 1996) – is apparent in Figure 2 (symbols have same meaning as in Figure 1), where we have plotted the lag between times of fitted peaks in channels 1 and 3 vs. pulse FWHM for channels 2+3. For our purpose the salient feature of this
plot is that, within the FWHM range 4 – 36 s, there is a strong trend for the dimmest bursts (triangle symbols) to have small lags relative to their FWHM. It is probable that these dim events do not consist of a single pulse. Rather, their relatively small energy-dependent lags, compared to the overall width of the emission, suggest a compound pulse structure with constituent pulses evolving independently. When these bursts are ignored, the trend of larger time lag with wider FWHM has considerably less scatter.

Table 1 lists the 68 bursts in our single-pulse sample with their dates, BATSE trigger numbers; HE/NHE designation; pulse FWHM, $\chi^2_{\text{red}}$, and peak amplitude for the fits in channels 2+3; BATSE position in right ascension and declination, and associated statistical error, to which a systematic error should be added in quadrature (Briggs et al. 1998). Thirty bursts have NHE (indicated by 0 in the HE/NHE column). Eight of these NHE bursts fall within a factor of three of the FWHM of GRB 980425; their trigger numbers are 1301, 2510, 2665, 3168, 6234, 6444, 6673, and 6707. Their time profiles (original s/n) and lognormal pulse fits for channels 2+3 are plotted in Figure 3. Four NHE bursts (2510, 2665, 6673, and 6707) have peak amplitudes above the threshold cut. Bursts in this last set can fairly reliably be said to resemble GRB 980425 in all respects. Also, 24 bursts with HE fall in the FWHM inclusion range, with 19 bursts above the threshold cut.

Thus the proportion of events in our usable sample that fit the two distinguishing criteria of the putative S-GRB class as defined by their exemplar GRB 980425 – smooth, single-pulse and NHE – is 4/1573 (0.25%). This fraction is possibly as high as 8/1573 (0.5%) if the dimmest bursts, which tend not to exhibit energy-dependent lags commensurate with their FWHM and thus are probably not single pulses, are all included. If the NHE criterion were not invoked, then the respective proportions would be (4+19)/1573 (1.5%) and (8+24)/1573 (2%).

One very interesting single-pulse burst, GRB 971208 (BATSE trigger 6526), continued for >1000 s with an intervening Earth occultation (Connaughton et al. 1998; V. Connaughton; private comm.), and thus we could not expeditiously fit an accurate background and did not include it in our sample. Its FWHM (50–300 keV) is ~ 250 s, a factor of ~ 5 wider than the widest burst in Table 1. GRB 971208 was unusually monolithic for such a long burst, easily fitting the criterion for inclusion in the single-pulse sample. It attained a peak intensity roughly half that of GRB 980425, and did exhibit HE emission.
3. SEARCH FOR GRB CORRELATION WITH SNe

We now compare the positions and first observation times of SNe detected during the BATSE era with our sets of single-pulse GRBs, searching for significant correspondences in position and time, and considering the reported SN type. This comparison yields an estimate for the fraction of single-pulse GRBs that could be associated with *known* SNe. We then discuss a correction to this estimate, assuming the degree of SN detection completeness as a function of time in recent years.

The Central Bureau for Astronomical Telegrams maintains the IAUC supernovae catalog for public use at the web site http://cfa-www.harvard.edu/cfa/ps/lists/Supernovae.html. This catalog contains all reported SNe to date. We extracted the 630 SNe detected from 1991 to July 20, 1998. Table 2 summarizes the SN type and number detected per year, 1991–1998. Types Ib and Ic are small minorities compared to types Ia, II, and unknowns. Type Ib accounts for 7; type Ic accounts for 13; and one is designated as type Ib/c. Designation of a SN type is not always definitive, as analysis of spectral information which becomes available often demand a more appropriate classification. Inspection of the last row in Table 2 shows that SN detections have been increasing since 1996. The total at end of 1998 will be ~ 200. Thus, the detection completeness during 1991–1995 relative to 1998 is ~ 25%. The actual detection completeness is difficult to estimate, given the zone of avoidance, and local obscuration within the host galaxy.

There are two primary selection criteria for SN–GRB correspondence: location and time window. We take the SN positions to be exact, whereas many SN light curves are not well mapped. SNe are often discovered weeks to months after the explosions; hence the time of core collapse is not always well constrained. Therefore we consider time lags up to 3 months, from GRB onset time to first detection of the SN. The inverse situation obtains for GRBs: The onset time is known perfectly well, but most positional information comes from the BATSE localizations. Following Kippen et al. (1998) we adopt the 1.6° systematic error determined from the minimal model of Briggs et al. (1998). We obtained the statistical errors (see Table 1) for our GRB sample from the current BATSE catalog (Meegan et al. 1998). Typically, the combined 1-σ positional error is a few degrees. Since we wished not to miss any potential SN-GRB association, we allowed for angular separations of up to 3 σ.

We then searched for SNe in each 3-month post-GRB time window allowing for up to 3-σ positional separations between each SN and GRB. We examined the two single-pulse GRB sets with FWHM within the range 4 – 36 s: the 8 NHE bursts, and the 24 HE bursts. The search results are summarized in Table 3. For both sets we find three pairs which satisfy our temporal
and positional criteria. For the NHE set, only one pair involves a type Ib or Ic SN: GRB 980425 – SN 1998bw. For the HE set, one pair involves an unknown SN type: GRB 961026 – SN 1996ce. We also searched for a SN association with GRB 971208 and found none.

To determine the chance probability of finding three NHE–SN and three HE–SN pairs, we performed 1000 Monte Carlo realizations, choosing the positions randomly, but using the BATSE 3-σ errors from the NHE and HE sets. For ~ 50% of the trials, we found ≥ 2 positional coincidences with SN positions for both sets; for ~ 30% of the trials, we found ≥ 3 coincidences.

About 50% (80%) of the single-pulse NHE (HE) bursts were detected in the 1991–1996 period. Thus, the low relative SN detection completeness during the first six years of BATSE, combined with the very high uncertainty in our knowledge of absolute completeness admits the possibility that all single-pulse GRBs in our sample could be associated with SNe.

The larger size (32) of the combined NHE+HE single-pulse set is interesting because BATSE should be able to detect the putative S-GRBs out to only ~ 100 Mpc (Bloom et al. 1998). In principle, the distribution of this larger set might turn out to be significantly anisotropic since the dominant feature – the Supergalactic Plane – is a rather linear structure (Hudson 1993; see also Hartmann, Briggs & Mannheim 1996). Nearby SNe might also be expected to show a preference for the Supergalactic Plane. We were able to find redshifts for two-thirds of the 21 SN of type Ib or Ic found in the IAUC supernovae catalog, and they are indeed nearby: the redshifts are z <~ 0.0175, i.e., up to roughly twice the distance of SN 1998bw (z = 0.0085). In Figure 4 we plot these SNe in the supergalactic coordinate system. The continuous line is the Galactic Plane. Note that 16 of these 21 SNe fall within 30° of the Supergalactic Plane, and that they tend to avoid the region near the Galactic Plane. The quadrupole moment, \( <\sin^2 b - 1/3> \) for the SN distribution with respect to the Supergalactic Plane (b = supagalactic latitude) is significantly oblate at the 2-σ level, \( -0.138^{+0.067}_{-0.043} \), where we have estimated errors via the bootstrap approach (Efron & Tibshirani 1993). Figure 5 shows the 32 single-pulse GRBs in the same coordinate system. The symbols have the same meanings as in Figure 1. There appears to be no tendency for any subset of single-pulse GRBs to fall near the Supergalactic Plane. The quadrupole moment for the entire GRB single-pulse set is \( -0.003^{+0.05}_{-0.05} \), not significantly different from zero.
4. DISCUSSION

A very small fraction (0.25%) of BATSE GRBs can be reliably determined to resemble GRB 980425, both in their single-pulse nature and NHE spectra. Approximately three times as many GRBs resemble GRB 980425’s temporal morphology but have HE spectra. No subset of our single-pulse GRBs shows a tendency to cluster near the Supergalactic Plane, which one might expect if the sources of such bursts lie within the nearby supercluster. Economy of hypotheses suggests that relatively long, single-pulse GRBs are probably caused by some mechanism other than core collapse of a nearby SN. Several arguments from the X-ray and gamma-ray observations support this conclusion.

First, GRB 980425 was about a factor of three brighter than GRB 970508 in X-ray peak flux. The X-ray peak flux during the GRB was reported by Soffitta et al. (1998) as $\sim 3$ Crab or $\sim 7.5 \times 10^{-8} \text{ ergs cm}^{-2} \text{ s}^{-1}$ (2–10 keV), compared to $\sim 2.5 \times 10^{-8} \text{ ergs cm}^{-2} \text{ s}^{-1}$ for GRB 970508 (Piro et al. 1998). If we assume that the fading X-ray source found in the BeppoSAX WFC field of view is the true counterpart, then we can estimate a two-point power-law decay index: The first point of the X-ray afterglow can be estimated to be a factor of five below the X-ray peak flux during the GRB itself, as is the case for the power-law of GRB 970508 extrapolated to 10 s after event onset. This first flux value for GRB 980425 is then $\sim 1.5 \times 10^{-8} \text{ ergs cm}^{-2} \text{ s}^{-1}$. The second measurement was obtained during a 27.7 hr integration (April 26.31–27.46) that commenced 9.6 hours after the burst (Pian et al. 1998). The identified source (1SAXJ1935.3-5252) was detected at an average flux level of $\sim 1.6 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$ (2–10 keV), which would represent a decay by a factor of $\sim 10^5$ over a timescale of a fraction of a day, similar to other BeppoSAX X-ray afterglows. Taking the second point in time to be the geometric mean of the NFI observation’s start and end times relative to the GRB, we find for the ratio of fluxes

$$\frac{I_2}{I_1} \sim 10^{-5} = (t_2/t_1)^{-\alpha} \sim (6.8 \times 10^4 \text{ s} / 10 \text{ s})^{-\alpha},$$

implying $\alpha \sim 1.3$. This is intermediate between the power-law decay indices for the optical and X-ray time histories of GRB 970508 ($\alpha = 1.1$; Piro et al. 1998) and GRB 971214 ($\alpha \sim 1.4$; Kulkarni et al. 1998a). We conclude that the X-ray decay signature for GRB 980425 would then be quite similar to that for other GRBs if in fact 1SAXJ1935.3-5252 was the true counterpart. If 1SAXJ1935.3-5252 were to be observed repeatedly and never seen to recur, this would be further evidence consistent with its association with GRB 980425.
Second, amongst long bursts \((T_{90} > 2 \text{ s})\) we find a continuum of widths for “single-pulse” bursts. Also from our visual examinations, \(\chi^2_{\text{red}}\), and correlated residuals statistic, we observe a continuum of auxiliary, smaller emissions superposed on otherwise smooth, single-pulse events. This suggests a gradual transition to more complex time profiles, and possibly a fundamental difficulty in ascribing a definite number of pulses to a given burst. Thus it is difficult to make a clean, dichotomous classification into single-pulse events and multi-pulse events.

Third, if we require NHE as a criterion for membership in the putative S-GRB class, then as can be seen from Figure 2, ~ 75% of the longer single-pulse bursts (in the FWHM range, 4 – 36 s) – otherwise similar to GRB 980425 – have HE and thus do not fit the whole S-GRB paradigm. In fact, the percentage of HE bursts amongst long BATSE bursts in general, is comparable, ~ 66%. This suggests that spectral hardness is not a good discriminator within the single-pulse group. (Rather the presence of HE appears to be merely a brightness bias effect in the general BATSE sample; see Bonnell & Norris 1998.) It then becomes difficult to understand how the putative S-GRB class members, ostensibly observed off the beam axis and therefore expected theoretically to be much softer (Bloom et al. 1998; Wang & Wheeler 1998), are to be spectrally distinguished from other GRBs. S-GRBs might be members of the whole set of GRBs – rather than NHE single-pulse events – but then there would be no diagnostic value in the gamma-ray observations, and the lack of a clear spectral differentiator would remain. We note that Kippen et al. (1998) investigate the correlation between SNe and the whole set of GRBs, and find an upper limits of 0.2% to 2.5% of BATSE GRBs that can be associated with SNe, depending on whether or not the dimmest bursts are considered.

On the other hand, there is one statistical argument in favor of the reality of an S-GRB class: Of the more than twenty bursts detected by BeppoSAX with X-ray or optical afterglows, none besides GRB 980425 has single-pulse morphology. Should BeppoSAX accumulate as many as ~ 100 bursts with definitive X-ray afterglows – which are not expected from S-GRBs due to the short synchrotron lifetime inferred from radio observations (Bloom et al. 1998) – then we would expect ~ 3 single-pulse events with FWHM longer than ~ 4 s. This would constitute additional evidence against the putative S-GRB class.
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http://cossc.gsfc.nasa.gov/cossc/batse/batseburst/sixtyfour_ms/bckgnd_fits.html
http://cossc.gsfc.nasa.gov/cossc/batse/batseburst/sixtyfour_ms/
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| GRB yymddd | BATSE Trigger | HE (s) | FWHM (s) | $\chi^2_{\text{red}}$ | $A_{\text{max}}$ (counts s$^{-1}$) | R.A. (deg) | Dec. (deg) | Error (deg) |
|------------|---------------|--------|---------|---------------------|---------------------------------|----------|---------|-----------|
| 910706     | 493           | 1      | 1.93    | 1.65                | 1350                            | 256.63   | -43.69  | 2.26      |
| † 910721   | 563           | 1      | 7.64    | 0.88                | 2880                            | 315.52   | -14.29  | 1.31      |
| 910826     | 727           | 1      | 2.65    | 0.96                | 1290                            | 69.12    | 48.51   | 3.54      |
| 911022     | 914           | 0      | 2.07    | 1.01                | 2560                            | 123.91   | 70.34   | 1.03      |
| 911204     | 1145          | 0      | 1.29    | 3.48                | 1530                            | 68.69    | -21.60  | 1.98      |
| 911208     | 1153          | 0      | 3.32    | 1.14                | 353                             | 38.15    | -53.11  | 8.93      |
| 920116     | 1301          | 0      | 10.10   | 1.04                | 242                             | 140.24   | 11.78   | 8.05      |
| † 920216   | 1406          | 1      | 8.79    | 0.72                | 2500                            | 156.92   | 1.17    | 1.10      |
| 920301     | 1456          | 1      | 11.50   | 1.09                | 419                             | 344.18   | 16.83   | 3.17      |
| † 920307   | 1467          | 1      | 7.51    | 1.47                | 2560                            | 355.57   | -45.15  | 1.16      |
| 920830     | 1883          | 1      | 3.22    | 1.09                | 6030                            | 258.53   | -73.99  | 0.54      |
| † 920901   | 1885          | 1      | 18.20   | 0.95                | 779                             | 261.65   | 16.06   | 2.33      |
| 930214     | 2191          | 1      | 5.20    | 0.90                | 709                             | 282.83   | -44.51  | 2.10      |
| † 930214   | 2193          | 1      | 31.20   | 0.88                | 2090                            | 194.80   | 26.77   | 1.03      |
| 930316     | 2252          | 1      | 14.00   | 1.04                | 633                             | 12.82    | -62.67  | 3.02      |
| † 930326   | 2267          | 1      | 4.68    | 1.13                | 1120                            | 138.83   | 21.34   | 3.58      |
| 930416     | 2306          | 1      | 2.76    | 1.19                | 1190                            | 144.55   | -24.18  | 3.66      |
| † 930612   | 2387          | 1      | 13.60   | 1.46                | 4390                            | 103.07   | -69.76  | 0.40      |
| † 930706   | 2432          | 1      | 5.09    | 0.79                | 1430                            | 210.09   | -1.36   | 1.31      |
| 930724     | 2460          | 0      | 1.26    | 2.32                | 1220                            | 75.92    | 0.23    | 4.01      |
| † 930807   | 2484          | 1      | 6.10    | 0.99                | 1620                            | 275.10   | -56.84  | 1.33      |
* 930902    | 2510          | 0      | 7.90    | 1.62                | 756                             | 103.12   | 16.15   | 2.56      |
* 931128    | 2665          | 0      | 4.42    | 1.38                | 1890                            | 142.64   | 18.21   | 1.57      |
| 940110     | 2749          | 0      | 1.45    | 0.93                | 1530                            | 337.60   | -10.80  | 3.06      |
| 940115     | 2760          | 0      | 2.47    | 1.11                | 1050                            | 216.00   | 54.01   | 3.07      |
| 940226     | 2848          | 0      | 3.65    | 1.02                | 512                             | 303.12   | -21.95  | 6.86      |
| 940227     | 2851          | 0      | 1.30    | 0.70                | 513                             | 343.96   | 36.11   | 11.81     |
| 940313     | 2880          | 1      | 1.59    | 2.50                | 3520                            | 109.45   | -14.46  | 1.85      |
| 940516     | 2980          | 0      | 1.80    | 1.31                | 687                             | 175.52   | 12.96   | 5.96      |
| 940521     | 2986          | 0      | 2.58    | 2.01                | 632                             | 295.76   | 50.61   | 6.18      |
| Date   | Code  | Type | Value1 | Value2 | Value3 | Value4 | Value5 | Value6 | Value7 | Value8 | Value9 | Value10 |
|--------|-------|------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|
| 940529 | 3003  | 1    | 12.60  | 1.43   | 2810   | 214.84 | 58.93  | 0.46   |
| 940530 | 3005  | 1    | 6.60   | 0.91   | 916    | 111.42 | -1.57  | 2.54   |
| 940827 | 3139  | 0    | 3.39   | 0.78   | 434    | 281.06 | -4.52  | 4.81   |
| 940828 | 3141  | 1    | 2.32   | 1.94   | 470    | 338.68 | 51.74  | 4.40   |
| 940830 | 3143  | 0    | 1.84   | 1.27   | 2990   | 193.66 | 25.66  | 1.58   |
| 940904 | 3155  | 1    | 1.40   | 1.86   | 2250   | 243.38 | 44.09  | 4.58   |
| 940915 | 3168  | 0    | 10.20  | 1.31   | 413    | 219.42 | 47.70  | 4.53   |
| 941026 | 3257  | 1    | 12.10  | 1.00   | 2920   | 205.96 | -6.53  | 0.47   |
| 941031 | 3267  | 1    | 19.70  | 1.06   | 398    | 39.66  | -57.29 | 3.49   |
| 950413 | 3505  | 0    | 0.58   | 1.67   | 607    | 261.26 | 64.37  | 4.77   |
| 950420 | 3515  | 0    | 3.44   | 1.36   | 834    | 281.03 | -46.47 | 3.64   |
| 950911 | 3789  | 1    | 1.90   | 2.01   | 2770   | 226.94 | -10.73 | 1.87   |
| 951014 | 3866  | 1    | 1.03   | 2.94   | 5460   | 167.85 | -20.64 | 1.15   |
| 951015 | 3869  | 0    | 3.62   | 2.25   | 1160   | 2.99   | -12.30 | 1.93   |
| 951016 | 3870  | 0    | 1.54   | 1.07   | 16600  | 35.82  | -24.36 | 0.35   |
| 951019 | 3875  | 0    | 1.11   | 0.80   | 3220   | 161.51 | -87.81 | 1.80   |
| 951102 | 3892  | 0    | 1.74   | 1.42   | 2140   | 189.64 | -35.23 | 2.30   |
| 951209 | 3939  | 0    | 0.93   | 3.02   | 2370   | 138.93 | 2.15   | 2.23   |
| 951213 | 3954  | 1    | 3.95   | 2.66   | 6870   | 283.98 | -6.82  | 0.60   |
| 960331 | 5387  | 1    | 9.92   | 0.93   | 1740   | 274.81 | 15.19  | 1.42   |
| 960409 | 5417  | 1    | 2.47   | 0.49   | 9840   | 42.54  | 41.92  | 1.34   |
| 960418 | 5434  | 1    | 5.17   | 1.09   | 803    | 91.12  | 7.91   | 2.44   |
| 960624 | 5517  | 1    | 3.16   | 0.94   | 2000   | 98.96  | 32.05  | 1.83   |
| 960720 | 5545  | 1    | 1.79   | 0.99   | 2930   | 262.43 | 49.33  | 1.59   |
| 961026 | 5645  | 1    | 8.23   | 1.21   | 911    | 202.89 | 26.01  | 2.69   |
| 961220 | 5719  | 1    | 2.17   | 1.18   | 2310   | 6.90   | 17.33  | 1.47   |
| 970226 | 6102  | 1    | 14.40  | 1.23   | 334    | 335.50 | -36.66 | 3.90   |
| 970302 | 6111  | 1    | 11.00  | 1.58   | 1020   | 275.92 | 21.02  | 2.90   |
| 970508 | 6225  | 1    | 4.47   | 1.34   | 1060   | 132.41 | 80.62  | 2.30   |
| 970510 | 6228  | 0    | 3.59   | 1.33   | 417    | 12.84  | -0.84  | 6.95   |
| 970517 | 6234  | 0    | 7.82   | 1.37   | 440    | 333.58 | 17.32  | 4.62   |
| 970825 | 6346  | 1    | 51.10  | 1.16   | 572    | 89.26  | -10.18 | 2.70   |
| 971013 | 6432  | 0    | 3.75   | 0.72   | 1540   | 221.75 | -63.87 | 2.08   |
| 971022 | 6444  | 0    | 16.60  | 1.20   | 377    | 238.93 | -31.87 | 5.48   |
| 971127 | 6504  | 1    | 8.40   | 0.77   | 2810   | 225.61 | 31.93  | 1.44   |
| 980325 | 6657  | 1    | 18.70  | 1.16   | 933    | 208.79 | -53.64 | 1.43   |
| Date   | Channel | HE | FWHM | $\chi^2_{\text{red}}$ | $A_{\text{max}}$ | Peak | Selection Cuts |
|--------|---------|----|------|------------------------|------------------|------|-----------------|
| 980401 | 6673    | 0  | 8.20 | 0.98                   | 728              | 35.44| NHE, FWHM inclusion range, peak > 720 counts s$^{-1}$ |
| 980425 | 6707    | 0  | 11.90| 1.21                   | 1150             | 291.91| HE, FWHM inclusion range, peak > 720 counts s$^{-1}$ |

*a* HE = 1 (0) indicates (No) emission above 300 keV in single-to-noise equalized profile.

*b* FWHM, $\chi^2_{\text{red}}$, and $A_{\text{max}}$ for fitted pulse interval, channels 2 and 3 summed.

* Burst survives selection cuts:  NHE, within FWHM inclusion range, and peak > 720 counts s$^{-1}$

† Burst survives selection cuts:  HE, within FWHM inclusion range, and peak > 720 counts s$^{-1}$
**TABLE 2**

Supernovae Detections During CGRO/BATSE Era

| Type       | '91 | '92 | '93 | '94 | '95 | '96 | '97 | '98 | All |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| SN I       | 0   | 2   | 0   | 1   | 11  | 0   | 1   | 0   | 15  |
| SN Ia      | 2   | 16  | 20  | 22  | 21  | 50  | 72  | 44  | 247 |
| SN Ia Pec. | 1   | 1   | 0   | 0   | 0   | 0   | 0   | 0   | 2   |
| SN II      | 2   | 11  | 9   | 10  | 17  | 15  | 24  | 17  | 105 |
| SN IIp     | 0   | 2   | 1   | 1   | 1   | 0   | 2   | 1   | 8   |
| SN IIb     | 0   | 0   | 0   | 0   | 0   | 1   | 1   | 0   | 2   |
| SN Ib      | 0   | 0   | 0   | 0   | 0   | 1   | 3   | 3   | 7   |
| SN Ic      | 0   | 0   | 1   | 2   | 2   | 3   | 3   | 2   | 13  |
| SN Ib/c    | 0   | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 1   |
| Unknown    | 58  | 38  | 5   | 2   | 3   | 18  | 53  | 38  | 215 |
| **Total**  | 63  | 71  | 36  | 40  | 57  | 92  | 163 | 108 | 630 |
# TABLE 3
Temporal/Positional Coincidences: Supernova – Gamma-Ray Burst

| SN     | SN Obs. | Type | GRB Date | BATSE Trigger | Distance (deg) | Error (deg) |
|--------|---------|------|----------|---------------|----------------|-------------|
|        | yymmdd  |      | yymmdd   |               |                |             |
| NHE Bursts |        |      |          |               |                |             |
| 1992I  | 920229  | II   | 920116   | 1301          | 17.86          | 8.21        |
| 1992C  | 920128  | II   | 920116   | 1301          | 20.97          | 8.21        |
| 1998bw | 980428  | Ib   | 980425   | 6707          | 1.15           | 2.31        |
| HE Bursts |        |      |          |               |                |             |
| 1994ad | 941110  | II   | 941031   | 3267          | 6.86           | 3.84        |
| 1996ce | 961216  | ?    | 961026   | 5645          | 5.42           | 3.13        |
| 1997cx | 970712  | II   | 970508   | 6225          | 3.16           | 2.80        |

\(^{a}\) First detection date of SN.
Figure Captions

Fig. 1. – Reduced $\chi^2$ for the fitted pulse region vs. pulse FWHM in channels 2+3 (50–300 keV). Circles indicate bursts with $A_{\text{max}}$ above 720 counts s$^{-1}$ threshold; triangles indicate bursts below our threshold – too dim to determine reliably the number of pulses present. Filled (open) symbols are NHE (HE). Vertical dashed lines indicate FWHM region within factor of 3 of FWHM for GRB 980425 ($\times$ symbol).

Fig. 2. – Time lag between fitted peaks, channels 1 and 3, vs. FWHM in channels 2+3. Symbols have same meaning as in Figure 1. Vertical dashed lines indicate FWHM region within factor of 3 of FWHM for GRB 980425 ($\times$ symbol). Bursts with peak amplitude below threshold (triangles) and within FWHM inclusion range tend to have small lags, possibly indicative of compound pulse structure.

Fig. 3. – Time profiles in the energy range 50–300 keV for the eight bursts which pass selection criteria: (1) visual categorization as one-pulse event; (2) no emission > 300 keV in signal-to-noise equalized time profile; (3) acceptable correlated residuals; and (4) FWHM of fitted pulse in channels 2+3 within a factor of three of FWHM for trigger 6707. The abscissa range for all twelve plots is 120 s. Triggers 2510, 2665, 6673, and 6707 (GRB 980425) have peak amplitudes above our threshold of 720 counts s$^{-1}$.

Fig. 4. – The 21 SN of type Ib or Ic found in the IAUC supernovae catalog, plotted in the supergalactic coordinate system. The continuous line is the Galactic Plane. Sixteen SNe fall within $30^\circ$ of the Supergalactic Plane. Square plotted on top of SN 1998bw.

Fig. 5. – The 32 single-pulse GRBs plotted in the supergalactic coordinate system. Symbols have same meanings as in Figure 1, with square plotted for GRB 980425. No subset of single-pulse GRBs shows a tendency to cluster near the Supergalactic Plane.
Fig. 1
Fig. 2
