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EXPECTED CHARACTERISTICS OF THE SUBCLASS OF SUPERNOVA GAMMA-RAY BURSTS

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ABSTRACT

The spatial and temporal coincidence of gamma-ray burst (GRB) 980425 and supernova (SN) 1998bw has prompted speculation that there exists a subclass of GRBs produced by SNe ("S-GRBs"). A physical model motivated by radio observations lead us to propose the following characteristics of S-GRBs: (1) prompt radio emission and an implied high brightness temperature close to the inverse Compton limit, (2) high expansion velocity ($\gtrsim$50,000 km s^{-1}) of the optical photosphere as derived from lines widths and energy release larger than usual, (3) no long-lived X-ray afterglow, and (4) a single-pulse GRB profile. Radio studies of previous SNe show that only (but not all) Type Ib and Ic SNe potentially satisfy the first condition. We investigate the proposed associations of GRBs and SNe within the context of these proposed criteria and suggest that ~1% of GRBs detected by BATSE may be members of this subclass.

Subject headings: gamma rays: bursts — supernovae: general — supernovae: individual (SN 1998bw)

1. INTRODUCTION

With the spectroscopic observations of the optical afterglow of gamma-ray burst (GRB) 970508 by Metzger et al. (1997) came proof that at least one GRB is at a cosmological distance. Kulkarni et al. (1998a) later added another cosmological GRB, which, based on an association with a high-redshift galaxy, had an implied energy release of $E_\gamma \gtrsim 10^{53}$ ergs. However, not all GRBs have been shown to be associated with distant host galaxies. Only about half of all GRBs are followed by long-lived optical afterglow, and one in four produce a longer-lived radio afterglow at or above the 100 μJy level. In contrast, X-ray afterglow has been seen for almost all *BeppoSAX*-localized bursts. Until recently, the emerging picture had been that all GRBs are located at cosmological distances and these GRBs (hereafter cosmological GRBs, or C-GRBs) are associated with star-forming regions and that C-GRBs are the death throes of massive stars.

The discovery of a supernova (SN 1998bw) both spatially (chance probability of 10^{-4}) and temporally coincident with GRB 980425 (Galama et al. 1998a, 1998b) suggests the existence of another class of GRBs. Remarkably, SN 1998bw showed very strong radio emission with rapid turn-on; it is, in fact, the brightest radio SN to date (Wieringa et al. 1998). This rarity further diminishes the probability of chance coincidence (Sadler, Stathakis, & Boyle 1998). From the radio observations, Kulkarni et al. (1998b) concluded that there exists a relativistic shock [bulk Lorentz factor, $\Gamma \equiv (1-\beta^2)^{-1/2} \gtrsim 2$] even 4 days after the SN explosion. Kulkarni et al. argue that the young shock had all the necessary ingredients (high Γ, sufficient energy) to generate the observed burst of gamma rays.

We feel that the physical connection between GRB 980425 and SN 1998bw is strong. Accepting this connection then implies that there is at least one GRB that is not of distant cosmological origin but is instead related to an SN event in the local universe ($\lesssim$100 Mpc). We refer to this category of GRBs as supernova-GRBs or S-GRBs. Many questions arise: How common are S-GRBs? How can they be distinguished from C-GRBs? What are their typical energetics?

In this paper, accepting the physical model advocated by Kulkarni et al. (1998b), we enumerate the defining characteristics of the class of S-GRBs. We then apply these criteria to members of this proposed class and conclude with a discussion of the potential number of S-GRBs.

2. HOW TO RECOGNIZE S-GRBs

The expected characteristics of S-GRBs is motivated by the model developed to explain the radio observations of SN 1998bw. Briefly, from the radio data, Kulkarni et al. (1998b) conclude that the radio emitting region is expanding at least at $2c$ (4 days after the explosion) and slowing down to c, 1 month after the burst. Indeed, one expects the shock to slow down as it accretes ambient matter. Thus, it is reasonable to expect the shock to have had a higher Γ when it was younger. The expectation is that this high-Γ shock is also responsible for the observed burst of gamma rays (synchrotron or inverse Compton scattering). Of note, whereas in C-GRBs the primary afterglow is optical, in S-GRBs the primary afterglow is in the radio band. We now enumerate the four criteria of S-GRBs:

1. *Prompt radio emission and high brightness temperature*.—An unambiguous indication of a relativistic shock in an SN is when the inferred brightness temperature, T_B, exceeds $T_{\rm icc} \sim 4 \times 10^{11}$ K, the so-called inverse Compton catastrophe temperature (see Kulkarni & Phinney 1998). The energy in the particles and the magnetic field is the smallest when $T_B \simeq T_{\rm eq}$, the so-called "equipartition" temperature ($T_{\rm eq} \sim 5 \times 10^{10}$ K; Readhead 1994). The inferred energy increases sharply with increasing T_B. For SN 1998bw, even with $T_B = T_{\rm eq}$, the inferred energy in the relativistic shock is 10^{48} ergs, which is already significant. If $T_B > T_{\rm icc}$, the inferred energy goes up by a factor of 500 and thus approaches the total energy release of a typical SN (~10^{51} ergs). Thus, the condition $T_B < T_{\rm icc}$ is a reasonable inequality to use. This then leads to a lower limit on Γ. We consider the shock to be relativistic when $\Gamma\beta > 1$. For SN 1998bw, Kulkarni et al. (1998b) find $\Gamma\beta \gtrsim 2$.

It is well known that prompt radio emission (by this we

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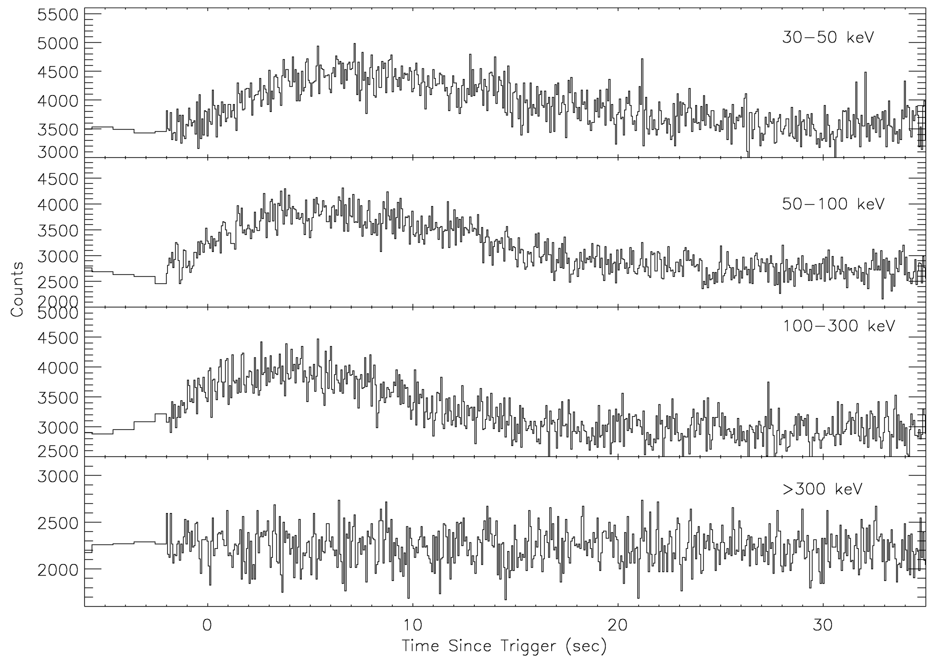

FIG. 1.—Four-channel light curve of GRB 980425 (BATSE trigger 6707) associated with SN 1998bw. The single pulse (SP) appears cuspless, unlike most SP BATSE bursts. The hard-to-soft evolution is clear from the progression of the peak from channels 3 to 1 over time.

mean a timescale of a few days) is seen from Type Ib/Ic SNe (Weiler & Sramek 1988; Chevalier 1998). Radio emission in Type II SNe peaks on very long timescales (months to years). No Type Ia SN has yet been detected in the radio. Thus, the criterion of prompt radio emission (equivalent to high T_B) will naturally lead to selecting only Type Ib/Ic SNe. High brightness temperature is achieved when the radio flux is high. Indeed, the radio luminosity of SN 1998bw was 2 orders of magnitude larger than the five previously studied Type Ic/Ic SNe (van Dyk et al. 1993).

2. *No long-lived X-ray afterglow*.—In our physical picture above, we do not expect any long-lived X-ray emission since the synchrotron lifetime of X-ray–emitting electrons is so short. The lack of X-ray afterglow from GRB 980425 in the direction of SN 1998bw is consistent with this picture.

3. *A simple GRB profile*.—In the model we have adopted, the gamma-ray and the radio emission is powered by an energetic relativistic shock. Is it likely that there is more than one relativistic shock? Our answer is no. There is no basis to believe or expect that the collapse of the progenitor core will result in multiple shocks. It is possible that the nascent pulsar or a black hole could be energetically important, but the envelope matter surely will dampen down rapid temporal variability of the underlying source. From this discussion we conclude that there is only one relativistic shock. Thus, the gamma-ray burst profile should be very simple: a single pulse (SP).

The light curve of GRB 980425 (Fig. 1) is a simple single pulse (SP) with a ∼5 s rise (HWHM) and a ∼8 s decay. Like most GRBs (e.g., Crider et al. 1997; Band 1997), the harder emission precedes the softer emission with channel 3 (100–300 keV) peaking ∼1 s before channel 1 (25–50 keV). Unlike most GRB light curves, the profile of GRB 980425 has a rounded maximum instead of a cusp.

4. *Broad line emission and bright optical luminosity*.—Kulkarni et al. (1998b) noted that the minimum energy in the relativistic shock, $E_{\min}$, is 10^{48} ergs and that the true energy content could be as high as 10^{52} ergs. Even the lower value is a significant fraction of energy of the total supernova release of ordinary SNe ($E_{\rm tot} \sim 10^{51}$ ergs). Clearly, a larger energy release in the supernova would favor a more energetic shock and, hence, increase the chance such a shock could produce a burst of gamma rays. Indeed, there are indications from the modeling of the light curve and the spectra that the energy release in SN 1998bw was 3×10^{52} ergs (Woosley, Eastman, & Schmidt 1998; Iwamoto et al. 1998), a factor of ∼30 larger than the canonical SN. This then leads us to propose the final criterion: indications of a more-than-normal release of energy. Observationally, this release is manifested by large expansion speed, which leads to the criterion of broad emission lines and bright optical luminosity.

Nakamura (1998) suggests that S-GRBs derive their energy from the formation of a strongly magnetized pulsar rotating at millisecond period. Futhermore, he advocates that S-GRBs must possess "non-high-energy" (NHE; see Pendleton et al. 1997) profiles (i.e., little flux above 300 keV). However, Nakamura's model does not address the most outstanding feature of SN 1998bw—its extremely unusual radio emission. Our model is silent on whether the bursts should be NHE or HE since that would depend on the details of the emission mechanism and the importance of subsequent scattering.

There is an implicit assumption on the part of several authors (e.g., Nakamura 1998; Woosley et al. 1998; Wang & Wheeler 1998) that S-GRBs are intimately connected with Type Ic SNe. Within the framework of our model, the key issue is whether there exists a relativistic shock that can power the gamma rays. Clearly this relativistic shock is distinctly different from the low-velocity shock that powers the optical emission. Thus, the connection between GRB emission and the optical properties of the SN is bound to be indirect (e.g., our fourth criterion).

3. APPLICATION OF CRITERIA TO PROPOSED ASSOCIATIONS

We now apply the above four criteria motivated by a specific physical model to proposed S-GRBs (Wang & Wheeler 1998;

TABLE 1
SUPERNOVAE/GRB ASSOCIATIONS

SN/BATSE Trigger	SN Type	Prompt Radio?	$\delta\theta$[a] ($N\ \sigma$)	v_{max} (km s^{-1})	GRB Type	D[b] (Mpc)	S[c] ($\times 10^{-7}$) (ergs cm^{-2})	E[d] (ergs)
1998bw/6707	Ic	Y	0.0	60000[e]	SP/NHE	39.1[f]	44[g]	8.1×10^{47}
1997ei/6488	Ic	NA	2.4	13000[h]	SP/NHE	48.9[i]	7.69	2.2×10^{47}
1997X/5740	Ic	NA	3.1	16000[j]	SP/HE	17.0[i]	5.88	2.0×10^{46}
1994I/2900	Ib/c	Y	4.4	14000[k]	SP/NHE	7.10[i]	32.6	2.0×10^{46}
1997ef/6488	Ib/c?	NA	NA	15000[l]	SP/NHE	53.8[i]	7.69	2.7×10^{47}
1997ef/6479	Ib/c?	NA	NA	15000[l]	MP/HE	53.8[i]	99.5	3.4×10^{48}
1992ad/1641	Ib	NC[m]	2.0	NA	NA	19.50[i]	NA	NA
1997cy/6230	IIPec	NA	NA	5000[n]	SP/HE	295[n]	2.22	2×10^{48}
1993J/2265	IIt	N	NA	13000[o]	SP/NHE	3.63[p]	1.53[p]	2.4×10^{44}

NOTE.—GRB and SN properties of the suggested pairs by Wang & Wheeler (1998) and Woosley, Eastman, & Schmidt (1998) are compared against the expected criteria of S-GRBs (see § 2). The associations are listed in order of decreasing likelihood that the SN/GRB falls into the S-GRB subclass. Those with the least amount of information are placed at the bottom of the list. The last two entries are of Type II SNe (and would not therefore have met criterion one) and are thus listed separately. NA = not available.

[a] Distance of SN from BATSE position in units of number of BATSE σ ($N\ \sigma$). From Kippen et al. (1998). In the case of GRB 980425, the SN 1998bw lies near the center of the small (~8′) *BeppoSAX* error circle.

[b] Assuming $H_0 = 65$ km s^{-1} Mpc^{-1} with $D \simeq cz/H_0$ with z, the heliocentric redshift, from noted reference.

[c] Fluence in BATSE channels 1–4 (24–1820 keV). From BATSE Gamma-Ray Catalog unless noted.

[d] Required isotropic energy (>25 keV).

[e] R. A. Stathakis communication in Kulkarni et al. 1998b.

[f] Tinney et al. 1998.

[g] Galama et al. 1998a, 1998b.

[h] Based on a spectrum provided in Wang, Howell, & Wheeler 1998.

[i] de Vaucouleurs et al. 1991.

[j] Benetti et al. (1997).

[k] Wheeler et al. 1994.

[l] Based on Filippenko (1998).

[m] The prompt radio criterion is not constrained (NC) by the late radio detections.

[n] Benetti, Pizzella, & Wheatley 1997.

[o] Filippenko & Matheson (1993).

[p] Freedman et al. 1994.

Woosley et al. 1998). We searched for more potential GRB-SN associations by cross-correlating the earlier WATCH and Interplanetary Network (IPN) localizations (Atteia et al. 1987; Lund 1995; Hurley et al. 1997) with an archive catalog of supernovae.[2] We found no convincing associations in archival GRB/SN data before the launch of the Burst and Source Transient Experiment (BATSE). Thus, our total list remains at nine, seven from Wang & Wheeler (1988) and two from Woosley et al. (1998).

We reject the following proposed associations: (1) SN 1996N/GRB 960221 (Wang & Wheeler 1998). The IPN data rule out this association on spatial grounds alone. This lack of association was independently recognized by Kippen et al. (1998). (2) SN 1992ar/GRB 920616 (Woosley et al. 1998). The associated GRB appears not to exist in the BATSE 4B Catalog,[3] and furthermore, there are no other GRBs within a month that are spatially coincident with the SN. (3) SN 1998T/GRB 980218 (Wang & Wheeler 1998). This is ruled out on spatial grounds from the IPN data (Kippen et al. 1998).

In Table 1 we summarize the proposed associations. They are ranked according to the viability of the association based on the four criteria discussed in the previous section. The pulse profile for each GRB is characterized as either simple/single pulse (SP) or multipulse (MP). The SN type was drawn from the literature, as was the distance to the host galaxy. The isotropic gamma-ray energy release is computed from the publicly available fluence (BATSE 4B Catalog) and the assumed distance.

It is unfortunate that crucial information—the early radio emission observations—are missing for all but one SN (1994I). SN 1994I does have early radio emission (IAU Circ. 5963; Rupen et al. 1994). However, according to Kippen et al. (1998), the associated candidate GRB 940331 is more than 4 σ away from the location of SN 1994I. Thus, either the GRB associated with this event is not observed by BATSE, or this event is not an S-GRB.

4. DISCUSSION

From the observations (primarily radio) and analysis of SN 1998bw we have enumerated four criteria to identify S-GRBs. We have attempted to see how well the proposed associations of S-GRBs fare against these criteria. Unfortunately, we find the existing data are so sparse that we are unable to really judge if the proposed criteria are supported by the observations.

Independent of our four criteria, the expected rate of S-GRBs is constrained by the fact that this subclass is expected, with the assumption of a standard candle energy release, to have a homogeneous Euclidean ($\langle V/V_{max}\rangle = 0.5$) brightness distribution. Since there is a significant deviation from Euclidean in the BATSE catalog (e.g., Fenimore et al. 1993), S-GRBs cannot comprise a majority fraction of the BATSE catalog. Indeed, as studies show (e.g., Pendleton et al. 1997), ≈25% of the BATSE GRB population can derive from homogeneous population.

From the *BeppoSAX* observations we know that at least 90% of *BeppoSAX*-identified GRBs have an X-ray afterglow. Thus, at least in the *BeppoSAX* sample, the population of S-GRBs is further constrained to be no more than 10% using the criterion

[2] The updated Asiago Supernova Catalogue of Barbon, Capellaro, & Turatto 1989 (maintained by E. Capellaro) is available at http://athena.pd.astro.it/~supern/.

[3] The BATSE Gamma-Ray Burst Catalog (maintained by C. A. Meegan et al.), including the BATSE 4B Catalog, is available at http://www.batse.msfc.nasa.gov/data/grb/catalog/.

of no X-ray afterglow. However, it is well known that *BeppoSAX* does not trigger on short bursts—duration $\lesssim$ a few seconds—and thus this statement applies only to the longer bursts.

The small number of candidate associations prohibits us from drawing any firm conclusions based on common characteristics. Nonetheless it is of some interest to note that four of our top five candidate S-GRBs (the exception is 6479) are single-pulsed (SP) bursts. We clarify that the ordering in Table 1 did not use the morphology of the pulse profile in arriving at the rank. We remind the reader that roughly half of all BATSE bursts are SP, and these mostly are sharp spikes (<1 s) or exhibit a fast rise followed by an exponential decay—the so-called FREDs. Thus, only a subclass of SP bursts could be S-GRBs.

What could be the special characteristics of this sub-class of SPs? In search of this special subclass, we note that the profile of GRB 980425 (Fig. 1) exhibits a rounded maximum and is quite distinctive. A visual inspection of the BATSE 4B catalog shows that there are only 15 bursts with similar profiles; we note that such bursts constitute 1% of the BATSE bursts. Interestingly, most of these bursts appear to have the same duration as GRB 980425, although this may be due to bias in our selection. It is heartening to note that an independent detailed analysis of GRB light curves by Norris, Bonnell, & Watanabe (1998) confirmed the small fraction (1%–2%) of GRB light curves that meet our proposed criteria.

We end with some thoughts and speculation on the population of S-GRBs. Assuming the fluence of the GRB 980425 is indicative of the subclass, we find a canonical gamma-ray energy of $E \simeq 8 \times 10^{47}\ h_{65}^{-2}$ ergs. Although BATSE triggers on flux (rather than fluence), 80% of the bursts with fluence $S \gtrsim 8 \times 10^{-7}$ ergs cm^{-2} will be detected (Bloom, Fenimore, & in't Zand 1997). Thus, BATSE can potentially probe the class of S-GRBs out to $\sim$100 h_{65}^{-1} Mpc. van den Bergh & Tammann (1991) concluded that the rate of Ib/Ic SNe is roughly half that of Type II SNe. Thus, the expected rate of Type Ib/Ic SNe is 0.3 per day out to a distance of 100 h_{65}^{-1} Mpc. This can be compared with the daily rate of $\sim$3 GRBs per day at the BATSE flux limit. Thus, if all Type Ib/Ic SNe produced an S-GRB, then the fraction of S-GRBs is 10%, consistent with the upper limit on the fraction due to the X-ray afterglow criterion found above. But, since most known SNe do not fit our criteria 1 and 4, the fraction constrained by the Type Ib/Ic rates is likely much smaller.

The sky distributions of SNe and GRBs that fit our four criteria but are not necessarily correlated (as in SN 1998bw/GRB 980425) can be used as an indirect test of the S-GRB hypothesis. Norris et al. (1998) have shown that the anisotropy of the 21 Type Ib/Ic SNe are marginally inconsistent with the isotropy of the 32 SP GRBs. We note, however, that most current search strategies are optimized to discover SNe in regions of large galaxy overdensity (presumably biased toward the supergalactic plane), which may cause the observed SNe anisotropy to be larger than it truly is. Further, most SNe Ib/Ic do not fit our criteria 1 and 4, and thus it is unwarranted to simply correlate all Type Ib/Ic SNe to SP GRBs.

We conclude with two suggestions for observations that directly test the S-GRB hypothesis. Even with the poor localization of BATSE, a Schmidt telescope equipped with large plates can be employed to search for SNe out to a few hundred megaparsecs. This is the best way to constrain the S-GRB population frequency. Second, S-GRBs will dominate the GRB number counts at the faint end of the flux distribution. From this perspective, future missions should be designed to have the highest sensitivity with adequate localization.

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