1. INTRODUCTION

The first few months of 1997 brought a major breakthrough in one of the outstanding mysteries of modern astrophysics: the cosmic γ-ray bursts (GRBs) (Klebesadel, Strong, & Olson 1973; Fishman 1995). The quest for an explanation of GRBs had been handicapped by a lack of direct knowledge of the distance to the bursts. This changed on 1997 February 28 when BeppoSAX localized a burst, GRB 970228, sufficiently well that an optical follow-up was feasible (Frontera et al. 1998). The result was the discovery of the first optical counterpart (van Paradijs et al. 1997). Two months later, in early May, BeppoSAX found another GRB, enabling another optical identification (GRB 970508; Bond 1997). In this case, foreground absorption lines show that the source is at a redshift in excess of $z = 0.863$, proving that the source is at a cosmological distance (Metzger et al. 1997).

Early estimates of the energy of GRBs assuming cosmological distances gave energies comparable to the kinetic energy of supernovae (SNe), $\sim 10^{51}$ ergs, entirely in γ-rays. From the lower limit to the redshift of the optical counterpart of GRB 970508 and the observed maximum brightness, $R \approx 19.6$ mag (Castro-Tirado et al. 1997), one can deduce a distance and hence the absolute brightness. For isotropic emission, this event was about a factor of 100 brighter than a Type Ia SN at a redshift of 1. A third optical counterpart was associated with GRB 971214. The apparent host galaxy for this event has a redshift of $z = 3.42$ (Kulkarni et al. 1998a). For isotropic emission, this event requires $3 \times 10^{53}$ ergs in γ-rays.

2. SN 1998bw AND GRB 980425

Soffitta et al. (1998) reported the detection by the BeppoSAX Gamma-Ray Burst Monitor of a GRB on April 25.90915 UT (GRB 980425). The BATSE experiment on the Compton Gamma Ray Observatory (CGRO) confirmed the detection (Kippen et al. 1998). The event was average in terms of the BATSE burst flux/fluence distribution. Galama et al. (1998) reported SN 1998bw offset from the nucleus of the face-on barred spiral galaxy ESO 184-G82. This position is within the error box of GRB 980425, but does not coincide with either of the two X-ray sources of the BeppoSAX Narrow-Field Instrument (NFI) image (Pian et al. 1998). Lidman et al. (1998) reported peculiar spectral properties for the SNe. Wieringa et al. (1998) reported that no radio sources were detected within the 1σ error radius of the two NFI sources, but that there is a bright radio source that coincides with the optical astrometric position given by Galama et al. (1998). At the distance to ESO 184-G82, the radio source was more than 3 times as luminous as SN 1988Z, one of the most luminous radio SNe. Given the seemingly small likelihood of finding the radio source and the SN in this field, it is very probable that these events are associated with GRB 980425 despite the apparent discrepancy of the positions with the NFI locations. This is supported by analysis of the radio source that strongly suggests that it is expanding relativistically (R. A. Chevalier 1998, private communication; Kulkarni et al. 1998b). Independent of the association with the GRB, this is direct evidence that SNe can produce relativistic outflows.

The association of an SN with GRB 980425 may substantially alter the interpretation of the GRB afterglow. The current fireball model involves the shock interaction between relativistic ejecta and the circumstellar/interstellar matter. The association with an SN means that this interaction is not the only mechanism that produces optical emission, although the interaction is certainly important for producing the radio emission and perhaps the γ- and X-rays (Mészáros & Rees 1997a). The UV/optical emission of SN 1998bw is likely to consist of two parts, one from the stellar ejecta and the other from synchrotron emission produced in accord with the popular fireball model.

The optical spectra of SN 1998bw resemble those of SN 1997ef. At early times, both SN 1997ef and SN 1998bw showed broad emission/absorption features with a FWHM of $\approx 50,000$ km s$^{-1}$. All of the features in SN 1997ef evolved rapidly to the red at a rate of $\approx 15000$ km s$^{-1}$ day$^{-1}$ during the first week of discovery (Garnavich et al. 1997). At later times, the spectrum of SN 1997ef resembled a Type Ic SN, which is char-
characterized by little evidence for hydrogen, helium, or the strong Si II line of Type Ia SNe. Sadler et al. (1998) suggest an association of SN 1998bw with a Type Ib SN, but it is clear that early spectra did not resemble canonical Type Ib or Ic SNe. Optical spectro-polarimetry of SN 1997ef did not reveal polarization to an upper limit of 1.5% (Wang, Howell, & Wheeler 1998).

3. OTHER SUPERNova–GAMMA-RAY BURST ASSOCIATIONS

To investigate other possible SN-GRB correlations, knowledge of the SN explosion dates is required. The light curves of Type Ia SNe are normally very homogeneous with rise time from the date of explosion to optical maximum being ~2–3 weeks. The light curves of Type Ib/c SNe are less uniform, but the rise to maximum is fast, ranging from 3 weeks for Type Ib SNe to within 2 weeks for Type Ic SNe. The light curves of Type II SNe are much more diverse. The rise time is much longer, and it is difficult to estimate their explosion dates based on the rather sparse data available. We concentrate in this study on SNe of Types Ia and Ib/c only.

One hundred one Type Ia SNe and 17 Type Ib/c SNe discovered after 1991 June were selected from the Asiago SN catalog based on the availability of light-curve information. Only SNe of redshift less than 0.1 were chosen, and the sample contains only SNe discovered not later than 1 month past optical maxima. The Ia sample contains ~70% of all the SNe at redshift less than 0.1 discovered from 1991 June to 1998 April. A total of 21 Type Ib/c SNe were listed in the Asiago catalog, but four of them are not suitable for this analysis because of poorly known dates of explosions. Information on the phase at discovery of each SN was collected from various IAU Circulars and published literature. To search for the GRB counterpart of an SN, the dates of explosion are restricted to 10–25, 10–25, and 7–18 days before optical maximum for SNe of Types Ia, Ib, and Ic, respectively. A systematic error of 2° is added to the BASTE error boxes when identifying SN-GRB pairs.

Table 1 shows all of the SNe in our sample whose coordinates are within the 2° error boxes of the BASTE sources and occurred at the expected SN explosion epoch. Column (1) gives the identification of the SN; column (2) gives the spectral type; column (3) gives the estimated dates of optical maxima of the SNe using the same notation as for GRBs—year, month, and day (the greater than sign indicates that the maxima are definitely after the dates shown); column (4) gives the right ascension; column (5) gives the declination; column (6) gives the GRB counterpart; columns (7) and (8) are the right ascension and declination of the corresponding GRB, respectively; column (9) gives the BATSE error box; and column (10) gives the angular separation between the GRB candidates and the SN. The right ascension and declination are all given for equinox J2000.0.

Table 1 shows that of the 118 well-observed SNe since CGRO/BATSE was launched, seven Type Ia and five Type Ib/c SNe were found to be within the 2° error box of the associated GRB. The pairs shown in Table 1 are not necessarily true physical pairs. Interplanetary network (IPN) coordinates are available for two pairs: SN 1996N–GRB 960310 and SN 1997Y–GRB 970120. Both deviate from the nearest points on the IPN are by more than ~13° and thus can be excluded as real associations. Better coordinates and a larger Type Ib/c SN sample are required to establish or exclude each SN as a GRB producer. In addition, the peculiar SN 1997ef was slightly outside the 2° error box of GRB 971115. It is thus not clear if SN 1997ef has a GRB counterpart similar to SN 1998bw. The BATSE sky coverage ranges from one-third to one-half (Hakkila et al. 1998); therefore, the expected number of Type Ia SN–GRB correlations is ~34–51 if all of the Type Ia SNe are GRB producers. The fact that only seven Type Ia SN–GRB pairs were found implies that Type Ia SNe are not GRB producers. Assuming no intrinsic SN–GRB correlation, the probability of finding an SN being associated with at least one GRB during an acceptable time window is typically less than 10%. This probability is calculated as \[ 1 - \left( 1 - P_i \right)^N \], where \( P_i \) is the BATSE 2° error box divided by 4π sr for all GRBs that occurred in the SN temporal window of column (2), and \( N \) is the total number of these error boxes allowed by the temporal window of the SN. The number of Type Ia SN–GRB pairs is consistent with the hypothesis that SNe of Type Ia are not GRB producers. If the detection of SN-GRB pairs follow a Poisson distribution, the fact that we found no more than six pairs implies that the hypothesis that Type Ia SNe are GRB producers can be excluded at greater than the 4 σ level. The SN Type Ib/c–GRB pairs seem to indicate a higher rate of association. The expected number of SN Type Ib/c–GRB pairs under the

| SN Number (1) | Type (2) | Date (yymdd) (3) | R.A. (deg) (4) | Decl. (deg) (5) | GRB Number (6) | R.A. (deg) (7) | Decl. (deg) (8) | Error (deg) (9) | Δ (deg) (10) |
|---------------|----------|------------------|----------------|----------------|----------------|----------------|----------------|----------------|-----------|
| 1992ae ....... | Ia        | >920627 321.1    | ~61.6          | 920613         | 312.9          | ~55.6          | 5.0            | 6.8            |
| 1992al ....... | Ia        | ~920727 311.5    | ~51.4          | 920708         | 308.3          | ~49.9          | 3.9            | 2.0            |
| 1992at ....... | Ia        | ~920717 321.8    | ~37.0          | 920628         | 317.8          | ~27.3          | 8.0            | 8.3            |
| 1992bg ....... | Ia        | ~921016 115.5    | ~62.5          | 920925         | 129.7          | ~58.7          | 5.4            | 7.7            |
| 1995ae ....... | Ia        | >950926 341.4    | ~8.8           | 950917         | 339.9          | ~14.7          | 6.6            | 5.9            |
| 1997Y ....... | Ia        | >970202 191.4    | ~54.7          | 970120         | 196.1          | 60.8           | 3.8            | 6.6            |
| 1997dg ....... | Ia        | ~970928 355.1    | 26.2           | 970907         | 346.9          | 11.26          | 8.6            | 16.8           |
| 1996at ....... | Ib/c      | ~961009 17.1     | ~1.0           | 960925         | 29.3           | ~13.9          | 8.7            | 17.6           |
| 1996N ....... | Ib        | ~960310 54.7     | ~26.3          | 960221         | 47.8           | ~31.2          | 4.4            | 7.5            |
| 1997B ....... | Ic        | ~971014 88.3     | ~17.9          | 971218         | 97.75          | ~21.73         | 12.8           | 11.2           |
| 1997dq ....... | Ib        | ~971110 175.2    | 11.5           | 971013         | 167.0          | 2.7            | 9.0            | 11.8           |
| 1997ef ....... | 2         | ~971205 119.3    | 49.6           | 971115         | 84.6           | 41.7           | 12.0           | 25.2           |
| 1997ei ....... | Ic        | ~971205 178.5    | 58.5           | 971120         | 155.7          | 76.4           | 10.1           | 19.6           |

Note.—Right ascension and declination are given for equinox J2000.0.

The Asiago catalog may be found at http://athena.pd.astro.it/supern/sneantxt.
assumption that all SNe of Type Ib/c produce GRBs is ~5–8, which is consistent with the four potential pairs given in Table 1.

4. THE CASE FOR STRONG COLLIMATION

The previous section shows that Type Ia SNe, which are expected to undergo thermonuclear explosion, are not GRB producers. At least some GRBs are produced in SNe like SN 1998bw. The data are consistent with the hypothesis that Type Ib/c SNe are effective GRB producers. Events like SN 1998bw may call for a reinterpretation of the physical nature of GRBs. From the γ-ray fluence of GRB 980425 and the recession velocity (assuming $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$), the total γ-ray energy is $7 \times 10^{47}$ ergs. The γ-ray energy of the other relatively nearby events associated with Type Ib/c SNe in Table 1 is $\sim 10^{46}$–$10^{48}$ ergs, assuming spherical geometry. This is completely consistent with an origin in SNe. The question arises as to the nature of the very distant, apparently very energetic GRBs. These could also be related to SNe if a portion of the γ-ray energy is strongly collimated. In particular, the SN-GRB connection suggests that we are dealing with energies that are a fraction of an SN energy, perhaps 10%, not 100 or more times an SN energy. Strong collimation, in turn, demands a much higher incidence rate. If, for example, $\sim 10^{46}$ ergs were collimated into 0.1% of 4π sr in the form of a highly relativistic jet, the equivalent energy would be $10^{48}$ ergs if sphericity were assumed. The required rate of events would be correspondingly higher by a factor of $10^3$, so GRBs would have to occur about once in 100 yr per bright galaxy, not once per 10$^4$ yr, the canonical number for GRBs and one associated with neutron star coalescence rates (Narayan, Piran, & Shemi 1991). This rate could be lower by more than 2 orders of magnitude if the redshift for GRBs is as high as $z \sim 6$, giving a larger volume and lower rate per bright galaxy. A frequency of once per 100 yr is a conventional rate for SNe.

5. DISCUSSION

Woosely (1993; see also Fryer & Woosely 1998) anticipated the utility of bare stellar cores as a site for GRBs. Woosely’s “failed Type Ib” scenario involved accretion from a torus onto a central black hole and associated neutrino production with mild collimation affecting the energetics and event rates. Paczynski’s (1998) “hypernova” scenario is generically related by invoking a failed Type Ib that makes a black hole, but invokes a large magnetic field to yield a “dirty fireball” with relatively large energy and again mild collimation. With strong collimation, the energy could correspond to that of an SN with a proportional effect on the event rates (P. Shapiro 1998, private communication). We suggest that it is successful SNe of Type Ib/c that make GRBs.

If GRBs, both at high and low redshift, are indeed produced by Type Ib/c SNe, highly collimated, relativistic jets are required to solve the energy problem for the distant bursts. We would expect that such beams are stopped by the massive envelopes of Type II SNe, but that strong asymmetries are generated. For Type Ib/c SNe progenitors that have lost most or all of their envelopes, the relativistic beams may survive to impact on the surroundings and create the phenomena associated with GRBs.

This interpretation requires that there are both isotropic and nonisotropic components to the GRBs and associated phenomena. The isotropic component may be neither collimated nor Lorentz boosted and beamed. The anisotropic component must be subject to both. The γ-ray energy associated with the Type Ib/c SNe ($\sim 10^{46}$–$10^{48}$ ergs) is extremely faint compared with the other BeppoSAX GRBs for which we know something about their distances. It is also a minor fraction of the energy released during an SN event. If $10^{50}$ ergs of γ-ray energy were collimated into a cone of $10^{-3}$ of 4π sr and pointed toward the Earth, we would see an apparent isotropic GRB energy of $10^{50}$ ergs or a fluence of $\sim 10$ ergs cm$^{-2}$ at the distance of SN 1998bw. This implies that we are seeing in GRB 980425 the isotropic component of the γ-ray flux. In some other direction it would have presumably been a factor of $\sim 10^4$ brighter. Such an event would be visible at redshift greater than 3.

The ratio of the luminosities of the collimated, boosted component and the isotropic component may be related to the apparent energy ratios, assuming both components to be isotropic. Comparing GRB 971214 (Kulkarni et al. 1998a) to GRB 980425 gives a ratio of $3 \times 10^{52}$/$7 \times 10^{47}$ or $4 \times 10^4$. If this is a representative ratio, then for the same detection limits, the volume sampled by the distant collimated, boosted component is $3 \times 10^4$ times that of the nearby component. If the distant component is collimated into only $10^{-3}$ of 4π sr, there should be $3 \times 10^1$ distant, strongly collimated GRBs for every “local” isotropic event. This means that in the current BATSE catalog there should be very few local events. The BATSE catalog should thus be dominated by the distant, collimated events, in complete accord with the isotropy of that sample. On the other hand, we apparently do see a few local events, the Type Ib/c SNe of Table 1. To make our hypothesis plausible, the luminosity ratio of the collimated, beamed component to the isotropic component must be closer to $\sim 10^4$. There may be a distribution of collimation and Lorentz factors and boosted luminosities and corresponding Malmquist bias so that GRB 971214 is not typical.

From the brightness temperature, R. A. Chevalier (1998, private communication) and Kulkarni et al. (1998b) have deduced that the radio source associated with SN 1999bw is expanding relativistically. It is surprising that an SN produced relativistic ejecta. If the radio flux is reduced by a factor of $\sim 10^4$, one gets the characteristic radio flux for Type Ib/c SNe. The radio emission from SN 1999bw could be from the jet but with a viewing angle greater than zero, or perhaps after the jet has slowed and the radio emission is more nearly isotropic so there is less boost. A component of the radio could arise from more normal radio emission associated with collision of SN ejecta with the circumstellar medium. We note that when it initially forms, the jet from the SN core might be unstable, yielding beaming in time-dependent directions, whereas the radio arises in a later blast-wave phase when the propagation and beaming directions are well established.

Spectropolarimetry of SNe has already given evidence for strong anisotropy of the core collapse process. All SNe of Types II and Ib/c are polarized, but nearly all Type Ia SNe are not (Wang et al. 1996). There could be a number of reasons why the ejecta of SNe are asymmetric, but the hypothesis that the core collapse process itself is a major contributor yields the prediction that for smaller buffering envelopes, the polarization should be greater. Indeed, Type Ic SN 1997X produced the largest polarization of any SN yet measured, $\sim 6%$–$7\%$, although a fraction of this could be from interstellar dust (Wang, Wheeler, & Höflich 1998).

If all core collapse events produce jets containing $\sim 10^{50}$ ergs of energy, $\sim 10^{-7}$ of the neutron star binding energy, then current calculations of core collapse may need to be revised. Core collapse must probably include rotation and magnetic fields as
intrinsic components. The question of how to make a tightly collimated jet from core collapse will clearly require a separate effort. We note two relevant issues. Pulsars show typical runaway velocities of $500 \text{ km s}^{-1}$, requiring a kinetic energy of $\sim 10^{49} \text{ ergs}$. Pulsar runaway might well be linked to the momentum imbalance involved in generating two not quite equal jets with total energy of $\sim 10^{50} \text{ ergs}$. The formation of jets might also be enhanced if the magnetic field were larger than often assumed. Models for soft $\gamma$-ray repeaters require fields of $\sim 10^{15} \text{ G}$ (Duncan & Thompson 1992). Recent detection of a spin-down in a soft $\gamma$-ray repeater is consistent with such a large field (Kouveliotou et al. 1998). The calculation of LeBlanc & Wilson (1970) of a rotating, magnetic core yielded a magnetic field of $\sim 10^{15} \text{ G}$ and an axial jet with an energy of $\sim 10^{50} \text{ ergs}$. Blackman & Yi (1998; see also Thompson 1994; Mészáros & Rees 1997b) have noted that the energy in a jet associated with a pulsar might be in the form of large-amplitude electromagnetic waves, rather than relativistic particles, per se.

By the hypothesis presented here, SN 1987A must have created an embryonic jet in its core. Even if this hypothesis is correct, it is not clear how such a jet could penetrate the hydrogen envelope, which is known to have been massive. Nevertheless, it might be appropriate to reexamine the “mystery” spot in SN 1987A.

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