Conference Summary
Supernovae and Gamma-Ray Bursts

By J. CRAIG WHEELER

Department of Astronomy, University of Texas, Austin, TX, 78712, USA

There are hints that nearby Type Ia supernovae may be a little different than those at large redshift. Confidence in the conclusion that there is a cosmological constant and an accelerating Universe thus still requires the hard work of sorting out potential systematic effects. Polarization data show that core-collapse supernovae (Type II and Ib/c) probably depart strongly from spherical symmetry. Evidence for exceedingly energetic supernovae must be considered self-consistently with evidence that they are asymmetric, a condition that affects energy estimates. Jets arising near the compact object can produce such asymmetries. There is growing conviction that gamma-ray bursts intrinsically involve collimated or jet-like flow and hence that they are also strongly asymmetric. SN 1998bw is a potential rosetta stone that will help to sort out the physics of explosive events. Are events like SN 1998bw more closely related to “ordinary” supernovae or “hypernovae”? Do they leave behind neutron stars as “ordinary” pulsars or “magnetars” or is the remnant a black hole? Are any of these events associated with classic cosmic gamma-ray bursts as suggested by the supernova-like modulation of the afterglows of GRB 970228, GRB 980326 and GRB 990712?

New data is driving both supernova and γ-ray burst research and suggesting that these subjects may be related. A central issue in both areas is the breaking of spherical symmetry. This conference celebrated as much as any single thing the emergence of evidence and argument for strong breakdown of spherical symmetry for both supernovae and γ-ray bursts and especially the resulting potential for links between them, whether those links are supernovae or “hypernovae.” Supernova studies have also revolutionized the study of cosmology. There spherical symmetry is not at issue, but the prospect of an accelerating Universe presents many challenges.

I cannot synthesize all the energetic work presented in oral talks and poster presentations, never mind over coffee and dinner, at this symposium that mixed two “exploding” fields. I will attempt to give a summary of certain highlights and connective themes that I think will set the course for future research. In §2, I give a brief summary of the exciting work on SN Ia, their associated physics, and their application to cosmology. Some perspectives on γ-ray bursts and their possible link to supernovae or “hypernovae” are presented in §3. New results on the propagation of a jet through a stellar core are given in §4. Some perspectives and conclusions are presented in §5.

1. Type Ia Supernovae and Cosmology

There is a general consensus that the strong majority, if not all, Type Ia supernovae arise in carbon/oxygen white dwarfs of very near the Chandrasekhar mass. The evidence in favor of this was given by Livio (2000) who also summarized the problems of understanding the binary evolution that allows a sufficient number of white dwarfs to grow to carbon ignition at the mass limit. Most of the observed Type Ia are “Branch normal,” (Branch, Fisher & Nugent, 1993) and allowance for deviations from “standard candles” can be made rather successfully with one-parameter brightness/decline rate relations (Phillips 1993; Riess, Press & Kirshner 1996; Perlmutter et al. 1999; Sandage 2000).
A dichotomy of thinking arises at this point. The theorists say that a one-parameter brightness/decline rate relation cannot be the whole story. Theory suggests appreciable variation with input parameters (Khokhlov 2000; Höflich & Dominguez 2000) and the observations themselves suggest departures from one-parameter relations. Observers, on the other hand, point out that utilizing these one-parameter relations works remarkably well in practice in correcting for deviations (Schmidt 2000; Perlmutter 2000; Sandage 2000). The conclusion, as emphasized by Höflich & Dominguez (2000) seems to be that some of the input parameters that are varied independently in the evolutionary and dynamic models – the carbon ignition density, the density of transition from subsonic deflagration to supersonic detonation (Khokhlov, Oran & Wheeler 1997a,b; Niemeyer & Woosley 1997; Khokhlov 2000), rotation, progenitor mass, progenitor metallicity – must be correlated in ways we have yet to elucidate.

To make progress, we must understand the combustion physics (Niemeyer 1999; Khokhlov 2000), and we need to better understand the progenitor evolution (Livio 2000; Höflich & Dominguez 2000). I would be delighted to witness even a shred of direct observational evidence that Type Ia are in binary systems, a conclusion to which I hold firmly despite vivid understanding that there is no proof.

Despite the uncertainties that still plague work on SN Ia, they have been used with great effect to explore cosmological issues. Theory has been used to compare models with individual supernovae in a way that does not require secondary distance calibration. The result is that the value of the Hubble constant is estimated to be $67 \pm 9$ km s$^{-1}$ Mpc$^{-1}$ (Höflich & Khokhlov 1996). Supernova observations calibrated with Cepheid variables give values in the range $60 \pm 9$ km s$^{-1}$ Mpc$^{-1}$ (Sandage 2000) to $65.2 \pm 1.3$ km s$^{-1}$ Mpc$^{-1}$ (Riess et al. 1998).

The application to cosmology has been even more startling (Riess et al. 1998; Perlmutter et al. 1999; Perlmutter 2000; Schmidt 2000). The value of the normalized cosmological matter density derived from Type Ia supernovae is $\Omega_m \sim 1/3$ and that of the cosmological constant, $\Omega_{\Lambda} \sim 2/3$. This raises two sets of issues. One is a possible new view of the Universe. With a cosmological constant that might not be “constant,” there is the potential for closed Universes that expand forever or open Universes that collapse. There must be a consideration of new physics to understand the microscopic origin of the vacuum energy that poses as a cosmological constant and why it is so small, but not zero, at just this epoch.

The other issue is, to use Brian Schmidt’s (2000) phrase, the “mundane.” There may be subtle systematic effects that bias the estimates of brightness of supernovae as a function of redshift and which masquerade as the effect of a cosmological constant. Howell, Wang & Wheeler (1999) have noted that the nearby Type Ia that are used to calibrate the light curve decline relation are primarily discovered photographically so that they are susceptible to the “Shaw effect” of being lost near the centers of galaxies due to saturation, whereas the deep searches are done with CCDs that are less susceptible to this effect. The properties of the Type Ia’s vary with galactic radius (Wang, Höflich & Wheeler 1997; Riess et al. 1999a) and the radial distributions of the calibration sample and the distant sample are distinctly different. This difference may be removed by light curve decline corrections, but such systematic effects need more study. Riess et al. (1999b,c) report that nearby Type Ia might have systematically slower rise times than the cosmological events for similar decay times. Suntzeff (1999) notes that the sample of events that show distinct departures from a one-parameter brightness/decline relation is real and growing and that while 6 of 40 Type Ia in a nearby sample are of the very bright kind, no events like SN 1991T have been observed in the much larger deep sample.

All these developments are hints of systematic effects that must be better understood,
both physically and observationally. Resolving this issue of the cosmological versus the mundane one way or the other will take several year’s hard, slogging work by both theorists and observers in the supernova community. The necessary program of careful comparison of the spectra and light curves of near, intermediate, and far supernovae is underway.

2. Gamma-Ray Bursts, Hypernovae, and Supernovae

2.1. Gamma-Ray Bursts, Collimation, and Jets

The past year has seen discussions of extreme energies, ranging up to $3 \times 10^{54}$ ergs (Kulkarni et al. 1999), and extreme degrees of collimation (Wang & Wheeler 1998). The community seems to have gotten those excesses out of its system and is now buckling down to the hard work of figuring out the true nature of the $\gamma$-ray bursts and their afterglows. Table 1 gives a list of the $\gamma$-ray bursts with observed X-ray afterglows. Table 2 gives a compilation of some of the relevant properties of $\gamma$-ray bursts in the afterglow era (see also http://astro.uchicago.edu/home/web/reichart/grb/grb.html; http://www.aip.de/People/JGreiner/grbgen.html). Excellent reviews of $\gamma$-ray bursts and afterglows were given by Paczyński (2000), Fishman (2000), Piro (2000), Fruchter (2000), Kulkarni (2000), Rees (2000), and Piran (2000).

Prior to BeppoSAX and the discovery of the afterglows, there was some discussion in the literature of the possibility of collimation (Woosley 1993; Rhoads 1997), but by and large the general community paid only lip service to collimation, if any mention was made of it at all. In the last year, the phrase “isotropic equivalent” has become a common and even mandatory part of the vocabulary of papers on $\gamma$-ray bursts and afterglows. Even more recently, judging by postings to “astro-ph,” the specific phrase “jets” has become common parlance. Over this year there has been a maturity from musing about collimation to wide-spread general acceptance that collimation is a critical aspect of some, if not all, $\gamma$-ray bursts.

Judging from presentations at this meeting, I have already lost this battle, but I would like to plead with the community to use the words “collimation” or “jets” or their equivalent when non-spherical flow is implied rather than the phrase “beaming.” The latter is often clear in context, but is prone to confusion with the Lorentz beaming that is purely a kinematic effect of relativistic motion. Authors who want to discuss both collimation and Lorentz beaming in the same paper are inviting confusion if they do not clearly discriminate. The total energy can be determined straightforwardly in principle by multiplying the isotropic equivalent energy with the collimation factor, $\Delta \Omega/4\pi$, but the discussion of luminosity that involves Doppler factors in a more complex way can
Table 2: Information on Gamma-ray Bursts with Afterglows

| GRB  | radio afterglow | redshift | spectral slope | temporal slope |  \(\gamma\)-ray energy | \(\Delta t/\Delta \gamma\) | host galaxy | comment |
|------|----------------|----------|---------------|---------------|------------------------|-----------------------|-------------|---------|
| 970258 | no             | 0.306 \(\pm\) 0.15 | 1.42 \(\pm\) 0.32 | 5 \(\times\) 10\(^{-10}\) | little | 25.5 | red, SN-like excess at 29 d; no jet; peak flux not single power law; no break for 9 months; X-ray reassociation at 10\(^{-3}\) yr; Fe line 12 |
| 970508 | yes            | 0.835 \(\pm\) 0.10 | 1.22 \(\pm\) 0.13 | 3 \(\times\) 10\(^{30}\) | little | 26.2 | no X-ray reassociation; Fe line 13 |
| 970828 | yes            | 3.418 \(\pm\) 0.15 | 1.22 \(\pm\) 0.13 | 3 \(\times\) 10\(^{30}\) | little | 27.1 | host confusion; like SN1998bw at 23 days at z=1.26 |
| 971214 | no             | 0.508 \(\pm\) 0.07 | 1.22 \(\pm\) 0.13 | 3 \(\times\) 10\(^{30}\) | little | 25.4 | no X-ray afterglow |
| 971227 | no             | 1.096 \(\pm\) 0.25 | 1.22 \(\pm\) 0.13 | 3 \(\times\) 10\(^{30}\) | little | 24.6 | changed slope ~ hours, after GRB, before afterglow |
| 980326 | yes            | 0.508 \(\pm\) 0.07 | 1.22 \(\pm\) 0.13 | 3 \(\times\) 10\(^{30}\) | little | 24.6 | BeppoSAX fluence rank 2 |
| 980327 | yes            | 0.508 \(\pm\) 0.07 | 1.22 \(\pm\) 0.13 | 3 \(\times\) 10\(^{30}\) | little | 24.6 | brightest host; no jet |
| 990123 | yes            | 1.608 \(\pm\) 0.25 | 1.22 \(\pm\) 0.13 | 3 \(\times\) 10\(^{30}\) | little | 24.6 | abrupt onset of smooth \(\gamma\)-ray "afterglow" |
| 990308 | yes            | 0.508 \(\pm\) 0.07 | 1.22 \(\pm\) 0.13 | 3 \(\times\) 10\(^{30}\) | little | 24.6 | decay after 40s of strong variability |
| 990510 | yes            | 1.619 \(\pm\) 0.25 | 1.22 \(\pm\) 0.13 | 3 \(\times\) 10\(^{30}\) | little | 24.6 | optical \(\gamma\)-ray; polarization <2.3% |
| 990705 | yes            | 0.508 \(\pm\) 0.07 | 1.22 \(\pm\) 0.13 | 3 \(\times\) 10\(^{30}\) | little | 24.6 | BeppoSAX fluence rank 1 |
| 990712 | yes            | 0.508 \(\pm\) 0.07 | 1.22 \(\pm\) 0.13 | 3 \(\times\) 10\(^{30}\) | little | 24.6 | no host galaxy observed |

\(a_{\text{opt}} \propto \nu_{\text{opt}}^{-\alpha} t^{-\beta}\) isotropic equivalent \(b\) host galaxy \(c\) afterglow \(d\) corrected for reddening

REFERENCES - (1) Djorgovski et al. 1999b. (2) Reichart 1999. (3) Harrison et al. 1999. (4) Hogg \& Fruchter 1999. (5) Galama et al. 1999a. (6) Rhode 1999. (7) Sari, Piran \& Halpern 1999. (8) Fruchter et al. 1999. (9) Metzger et al. 1997. (10) Bloom et al. 1998b. (11) Zharikov et al. 1998. (12) Piro et al. 1998. (13) Yoshida et al. 1999. (14) Kulkarni et al. 1998a. (15) Odewahn et al. 1998. (16) Reichart et al. 1998. (17) Kulkarni et al. 1998b. (18) Piro et al. 1998. (19) Djorgovski et al. 1998a. (20) Bloom et al. 1999b. (21) Fruchter 1999. (22) Reichart et al. 1999. (23) Galama et al. 1999b. (24) Halpern et al. 1999 (980519). (25) Djorgovski et al. 1999a. (26) Djorgovski et al. 1998b. (27) Bloom et al. 1998b. (28) Giblin et al. 1999. (29) Bloom et al. 1999a. (30) Anderson et al. 1999. (31) Akerlof \& McKay 1999. (32) Hjorth, J. et al. 1999a. (33) Schaefer et al. 1999. (34) Vreeswijk et al. 1999. (35) Stanek et al. 1999. (36) Israel et al. 1999. (37) Covino et al. 1999. (38) Wijers et al. 1999. (39) Palazzi et al. 1999. (40) Galama et al. 1999b. (41) Bakos et al. 1999. (42) Hjorth, J. et al. 1999b. (43) Hjorth, J. et al. 1999c.
be hopelessly muddled if the effects of collimation and Lorentz beaming are not clearly
delineated.

At this conference, we heard about energies associated with $\gamma$-ray bursts ranging from $4 \times 10^{50}$ to $3 \times 10^{54}$ ergs (Frail 2000; Kulkarni 2000). In fact, energies of $4 \times 10^{50}$ to $10^{52}$ ergs were associated with the same object! Frail (2000) made a clear case for the need to be careful in how energies are assigned to afterglows. The energies are sensitive to model parameters (e.g. break frequencies), the estimates of which are in turn subject to observational uncertainties. The lower energies represent circumstantial evidence that the highest energies are, indeed, only isotropic equivalents and must be scaled down by a substantial collimation factor.

One expects the decay slopes to become steeper as a collimated flow slows and spreads laterally (Rhoads 1997, 1999), and evidence for steeper slopes and even breaks in the slope have now been observed (Kulkarni et al. 1999; Sari, Piran & Halpern 1999; Harrison et al. 1999; Table 2). This evidence for collimation is only circumstantial, and the rate of change of the slope may be a gradual rather than sudden process (Panaitescu & Mészáros 1998; Moderski, Sikora & Bulik 1999). The slope can also be affected by density gradients in the surrounding medium (Chevalier & Li 1999) and by variations in power output in the underlying “machine” (Li & Chevalier 1999; Dai & Lu 1999a,b). With these caveats, the strongest evidence for collimation is in the brightest sources, with GRB 990123 with an isotropic equivalent $\gamma$-ray energy of $3 \times 10^{54}$ ergs having an estimated collimation factor of $\sim 0.01$ for an actual $\gamma$-ray energy of $\sim 3 \times 10^{52}$ ergs (Kulkarni et al. 1999) and GRB 980519 and GRB 990510 (which went off just after this conference) having a beaming factor of less than $\sim 0.003$ (Sari, Piran & Halpern 1999; Harrison et al. 1999).

This suggests that three of the $\gamma$-ray bursts with the highest isotropic equivalent energy are also the ones with strongest evidence for collimation.

Another recent argument in favor of some form of collimation comes from observations of polarization of $\gamma$-ray bursts. The synchrotron radiation from $\gamma$-ray bursts and their afterglows should be strongly polarized with the degree of polarization from a single patch ranging as high as 70 % (Sari 1999), but if the source is spherically symmetric and the field tangled, then the degree of polarization will be reduced. In this context, the upper limit to the polarization of 2.3% for GRB 990123 (Hjorth et al. 1999a) and the measured polarization of 1.7 % in GRB 990510 (Covino et al. 1999; Wijers et al. 1999) are very significant for being so small. This may suggest that in addition to a tangled magnetic field, we are observing collimated flow and emission (Gruzinov 1999; Ghisellini & Lazzati 1999; Sari 1999). Note that, as Gruzinov stresses, the origin of the magnetic field, assumed to be in near equipartition, remains a major stumbling block for the relativistic blast wave synchrotron emission model.

With the evidence for collimation, there is a suggestion that the true $\gamma$-ray energies of all the $\gamma$-ray bursts are in the range $10^{50}$ - $10^{52}$ ergs, from 0.1 to 10 times the canonical energy of a supernova, but still substantially less than the binding energy of a single neutron star. It is also true that as the evidence for collimation has grown, so have the highest recorded isotropic equivalent energies, leaving most people with the feeling that, at best, the target energy is near the upper end of this range, $\sim 10^{52}$ ergs. The issue becomes the nature of supernovae, hypernovae, and their link to $\gamma$-ray bursts.

2.2. Polarization of Supernovae

Like many people in the supernova community, we at the University of Texas got actively involved in the supernova/soft-gamma-ray repeater/magnetar/$\gamma$-ray burst topic with the advent of SN 1998bw and its possible connection to GRB 980425. We brought
a different perspective to this issue because of work we have done over the last four years on supernova spectropolarimetry.

We have been making spectropolarimetric observations of all accessible supernovae at McDonald Observatory (Wang et al. 1996; Wheeler, Wang & Höflich 1999; Wheeler, Höflich & Wang 1999). The result has been that most Type Ia have low polarization and hence are substantially spherically symmetric. Many have only upper limits of order 0.1 - 0.2%. A few have detected, but low polarization, of order 0.2%. The polarization observed is consistent with theoretical models of delayed detonation models (Wang, Wheeler & Höflich 1997) and may be a useful probe of the combustion physics. We have detected one exception, SN 1997bp, which was observed a week before maximum light to have a polarization of about 1%. The polarization was low in post-maximum spectra, but this event remains a challenge to understand. It is important to establish whether such events are common, the physical reason for the large polarization, and whether or not there could be an asymmetric luminosity distribution that could affect estimates of cosmological parameters.

More importantly in the current context are our observations of presumed core-collapse events, Type II and Type Ib/c. We have found that all such events are polarized at about the 1% level. So far there have been no exceptions in about a dozen events. There could be a myriad reasons for polarization, but our data suggest a very important trend: the smaller the hydrogen envelope, the larger the observed polarization. As an example, SN 1987A with a 10M⊙ envelope had a polarization of about 0.5% (Méndez et al. 1988), SN 1993J and a very similar object, SN 1996cb, with small hydrogen envelopes, ~ 0.1M⊙, were polarized at the 1-2% level (Trammell, Hines & Wheeler 1993; Tran et al. 1997), and Type Ic SN 1997X which showed no substantial hydrogen nor helium was polarized at perhaps greater than 3% (Wheeler, Höflich & Wang 1999). These are difficult observations requiring special care in the reduction to remove the effects of the ISM (the latter greatly aided by wavelength and temporal coverage), and there is a pressing need to expand the statistical sample. Nevertheless, this trend suggests that the core-collapse process itself is strongly asymmetric and that evidence for that asymmetry is damped by the addition of outer envelope material.

The level of polarization we have observed for core collapse events, ~ 1%, requires a substantial asymmetry with axis ratios of order 2 to 1 (Höflich 1995). Asymmetric explosions tend to turn spherical as they expand, so to leave an imprint of an asymmetry of this level in the homologously expanding matter requires a substantially larger asymmetric input of energy or momentum in the explosion process itself. These factors led us to the hypothesis that the core collapse process is intrinsically strongly asymmetric, much more so than current collapse calculations involving convectively unstable neutron stars. It was in this context that we greeted the news of SN 1998bw a year ago.

2.3. SN 1998bw and GRB 980425

SN 1998bw was a shock to both the supernova and γ-ray burst communities. For the supernova community, it was clearly an odd and exciting event, even without the possible association with GRB 980425. Although it resembled a Type Ic in the sense that there was no obvious evidence for H and He, it was different than the canonical Type Ic. It was very bright, it showed very large velocities, and it had a very bright radio source. While not the brightest supernova radio event on record (Weiler 2000), the radio source associated with SN 1998bw was undoubtedly very luminous and arguments based on the brightness temperature alone suggested relativistic motion (Kulkarni et al. 1998b) depending on whether or not one assumed magnetic field equipartition (Waxman & Loeb 1999). On the other hand, the γ-ray community had just gone through the catharsis of
proof that γ-ray bursts were, indeed, at cosmological distances as strongly suggested by the isotropy of the BATSE sources (Fishman 1995, 2000) and confirmed by redshifts measured for a number of the events with detected afterglows. The identification of SN 1998bw with GRB 980425 immediately confused the issue by raising the prospect of substantially different sources of γ-ray bursts that could not be easily differentiated by their γ-ray flux, fluence, time history, or spectra.

I took the opportunity of this meeting to test a rift I had suspected since the Texas Symposium in Paris in December, 1999. I inquired as to the people in the audience who primarily identified themselves with the supernova community and those who identified themselves primarily with the γ-ray burst community. I then asked for a show of hands of those who had reservations about the identification of SN 1998bw with GRB 980425 and of those who were convinced that the two objects were one and the same. While there were some cross-over votes, this exercise basically confirmed my suspicion. The supernova community has bought this identification hook, line, and sinker, based on the odd properties of the supernova. The γ-ray burst community remains substantially suspicious despite the low a priori probability, ~10^{-4} (Galama et al. 1998), of an accidental alignment. One does not do science by democratic vote, and this is more an exercise of sociology than science, so I leave the reader to contemplate the meaning, if any, of the result (and to criticize the unscientific sampling method).

The issues raised by SN 1998bw are these. If one believes that SN 1998bw produced GRB 980425, then there are more than one type of γ-ray burst that cannot be easily distinguished by γ-ray properties. If one does not believe that these two events are identical, there is still a weird supernova to explain and the standard mystery of the nature of the cosmic γ-ray bursts remains. All these possibilities bring with them the strong suggestion that, for both the supernova and for γ-ray bursts, asymmetries and collimation are the rule, not the exception.

Even if one believes the identification of SN 1998bw with the γ-ray burst there are substantially different interpretations of the event. Was it a version of an “ordinary” supernova or was it something better labeled a “hypernova?” The phrase “hypernova” was coined in this context by Paczyński (1998, 2000), who meant by it any event that produced an isotropic equivalent luminosity substantially larger than a supernova, whatever the source of that luminosity, core collapse or merging compact stars. The phrase “hypernova” has taken on a somewhat more specific meaning in the supernova community in the context of attempts to understand the nature of SN 1998bw and possibly related events.

The reason for this evolution of the definition of “hypernova” is that attempts to construct models for SN 1998bw have led to the suggestion that the energy must be substantially in excess of 10^{52} ergs (Iwamoto et al. 1998; Woosley, Eastman & Schmidt 1999; Branch 2000; Nomoto 2000; Woosley 2000) and perhaps also that it had very large ejecta mass and radioactive nickel mass, the latter in excess of 0.5 M_☉ (Iwamoto et al. 1998; Woosley, Eastman & Schmidt 1999). These models were all, by assumption, spherically symmetric, and, if nothing else, ignore the observations that SN 1998bw was polarized. On the other hand, Höflich, Wheeler & Wang (1999) have argued that a sufficiently asymmetric model to account for the polarization (an ellipsoid of axis ratio 2 to 1) could account for the bolometric and multi-color light curves near maximum light. With the proper viewing angle, within about 35° of the symmetry axis for a model with oblate isodensity contours, the luminosity could be substantially higher than the mean spherical equivalent and the peak of the light curve reproduced in a model with an ejecta kinetic energy of 2 × 10^{51} ergs, 2M_☉ of ejecta, and 0.2M_☉ of {^{56}Ni}. The kinetic energy of this model is a little higher than average, but well in the range of energies
deduced for standard core-collapse events, and the other parameters are quite nominal. SN 1998bw may have been a “hypernova” requiring expansion energy more than 10 times that normally associated with supernovae, but that is certainly not necessarily so.

Given its important role, SN 1998bw received a great deal of attention at the conference. It is poignant to note at a conference hosted by STScI that the request by the author and Lifan Wang for Director’s Discretionary Time was turned down in the press of other observational priorities. The result is that there were no UV observations of SN 1998bw. This lack becomes more important as one ponders similar events at large redshift where the UV spectrum is shifted to the visible. We can guess what SN 1998bw would have revealed in such observations, but we will never know.

One of the principle controversies over the identification of SN 1998bw with GRB 980425 is the nature of the afterglow or the lack thereof. This issue was addressed anew by Pian (2000). The first narrow-field instrument BeppoSAX observations revealed two X-ray sources in the original wide-field detection image. Neither corresponded to the location of the supernova. One source (Source 1) was at first thought to be constant and the other (Source 2) to decay in a few days in a manner consistent with other observed X-ray afterglows. This observation has been the origin of understandable suspicion by many that the association of the supernova and the $\gamma$-ray burst were accidental despite the low probability.

Recalibration of positions (Pian et al. 1998) revealed that Source 1 was coincident within the errors with SN 1998bw, but that Source 2 was definitely not associated with the supernova. Further observations showed that Source 1 did vary, but slowly, perhaps a factor of 2 in 10 days. At this conference, Pian presented evidence that Source 2 also declined slowly or was even substantially constant over an interval of more than 100 days. Taken at face value, the data presented by Pian suggest that both Source 1 and Source 2 declined rather slowly after the first NFI observations beginning about 1 day after detection. The flux for both is about $10^5$ less than that first detected in the WFC. It is possible that neither Source 1 nor Source 2 represent an afterglow. It is possible that the afterglow decayed so rapidly from the WFC detection that only background sources were detected at Source 1 and Source 2. The interpretation of the data depend substantially on the confidence placed in the detection of Source 2 at the $3\sigma$ level after day 100. If this detection is true, then it seems unlikely that either Source 1 or Source 2 are an afterglow. If this detection is only an upper limit, then it is still conceivable that Source 2 is an afterglow and the identification of GRB 980425 with SN 1998bw is still open to question. Observations of these sources by ASCA in April may have yielded only upper limits (Harrison 1999), but these may help to resolve this issue.

Danziger et al. (2000) presented photometric, spectroscopic and spectropolarimetric observations of SN 1998bw from ESO. Danziger concluded that the object was asymmetric, in substantial agreement with Höflich, Wheeler & Wang (1999). Nomoto (2000) presented model light curve calculations. He noted that the spherically symmetric models required “hypernova” energies to fit the peak, but that the same models declined too rapidly to fit the tail. He pointed out that one way to account for the tail was to invoke a smaller expansion energy to get greater trapping of $\gamma$-rays at later times. He concluded that this implicit contradiction was evidence for asymmetry. This underlines the basic point of Höflich, Wheeler & Wang (1999) that the energy cannot be determined independently of considerations of asymmetry for the dynamics and radiative transfer.

Danziger et al. (2000) also presented nebular spectra of SN 1998bw. These spectra revealed futher peculiarities. The line of [O I] $\lambda\lambda$ 6300,6364 was broader than the lines of [Fe II]. The Fe lines were comparable in width to those of normal Type Ic in contrast to the expectation from the basic hypernova models that, with their very high energies,
have very high velocities, $\gtrsim 4000 \, \text{km} \, \text{s}^{-1}$, in the inner, iron-rich, regions. Discussion with Nomoto and Mazzali suggested that the spectra could be fit with models, but only by adding ad hoc inner regions of slower moving matter. Such slow matter may be produced in a more realistic, multi-dimensional model, but it is not predicted in the spherically symmetric “hypernova” models.

Branch (2000) presented simple atmosphere models that illustrated the systematic differences between SN 1994I, SN 1997ef, and SN 1998bw. SN 1994I was a canonical, well-studied Type Ic supernova. SN 1997ef was also labeled a Type Ic, but while showing a normal peak luminosity, it had higher velocity at the photosphere than SN 1994I. Branch illustrated how the increased broadening of the lines carved out the red continuum and led to a rather steep decline from the blue. With the even higher photospheric velocities of SN 1998bw, Branch provided convincing evidence that the unprecedentedly steep decline from about 4000 to 5000 Angstroms in the continuum of SN 1998bw near maximum light could be explained. Coupling his atmosphere models with the assumption of spherical symmetry, Branch made estimates of the kinetic energy of each event, concluding that SN 1994I was consistent with $\sim 10^{51}$ ergs, but that both SN 1997ef and SN 1998bw could require “hypernovae” energies of $\gtrsim 10^{52}$ ergs. Branch pointed out that the ball was in the court of advocates of asymmetric models to show that these observations could be explained self-consistently with asymmetries and modest energy. That is completely correct.

An excellent light curve of SN 1998bw is presented by McKenzie & Schaeffer (1999). They have an well time-sampled data set that shows that after an early steep decline from maximum for about 25 days, B, V, and I have declined in a precisely exponential manner. The slopes in the three bands are slightly different and all three are steeper than that expected for $^{56}$Co decay and full trapping of $\gamma$-rays. McKenzie & Schaeffer note that because there must be some leakage of $\gamma$-rays they can only set a lower limit to the amount of $^{56}$Ni produced in SN 1998bw which they determine to be $0.22 \pm 0.09 \, M_\odot$. This lower limit is close to that estimated for the asymmetric models of Höflich, Wheeler & Wang (1999) and substantially less than the hypernova models of Iwamoto et al. (1998) and Woosley, Eastman & Schmidt (1999). Since the light curves are so precisely exponential, the $\gamma$-ray trapping fraction cannot be changing substantially. This suggests that while less than unity, the trapping fraction is substantially greater than 50% or the light curves would be steeply declining to the limit set by positron trapping. This argument suggests that the lower limit set by McKenzie & Schaeffer may be near the actual nickel mass produced by SN 1998bw and in contradiction to the hypernova models.

2.4. Other Possible Supernova/Gamma-Ray Burst Connections

SN 1998bw/GRB 980425 is the most famous and best established supernova/$\gamma$-ray burst connection (despite or because of its debated reality), but other arguments have accumulated for such a connection. Some candidates as of this writing are given in Table 3.

Germany et al. have discussed the case of SN 1997cy. This supernova was odd in its own way and unlike SN 1998bw in many substantial ways. The supernova occurred in a low surface brightness galaxy at a redshift of $z = 0.063$. The date of the explosion is uncertain by a few months. The spectrum is characterized by a very strong line of Hα, unlike SN 1998bw which showed no evidence for hydrogen. The Hα line showed both broad and narrow components reminiscent of Type IIn supernovae (Schlegel 1990). SN 1997cy also showed lines of Fe II and [Fe III] that are more characteristic of the nebular phase of Type Ia events. The light curve of SN 1997cy followed the decay slope
Table 3. SN/GRB Candidates

| SN  | GRB  | SN properties spectra | light curve | flux$^a$ | GRB properties fluence$^b$ | duration(s) | REFERENCES |
|-----|------|------------------------|-------------|---------|---------------------------|-------------|------------|
|     | 970228$^c$ | ~98bw?                 | ~98bw?      | —       | —                         | 80          | 1, 2       |
| 1997cy | 970514? | Mv < -19.4             |             | 4 × 10$^{-7}$ | 1.3                      | 4           |            |
| 1997ef | 970125? | Mv < -19.4             |             | 4 × 10$^{-7}$ | 0.2                      | 5, 6        |            |
|      | 971115? | Mv < -19.4             |             | 4 × 10$^{-6}$ | 35                       | 7           |            |
| 9998bw | 980326 | ~98bw?                 | ~98bw?      | 8 × 10$^{-7}$ | 7 × 10$^{-7}$             | 2 × 10$^{-7}$ | 8, 9, 10, 11 |
| 1999E | 980910? | Mv < -19.4             |             | —       | —                         | 12          |            |
|      | 990712 | ~98bw?                 | ~98bw?      | —       | —                         | —           |            |

$^a$erg cm$^{-2}$ s$^{-1}$ $^b$erg cm$^{-2}$ $^c$BATSE behind Earth

REFERENCES - (1) Reichart (1999). (2) Galama et al. (1999). (3) Germany et al. (1999). (4) Wang & Wheeler (1998). (5) Bloom et al. (1999). (6) Briggs et al. (1998). (7) Galama et al. (1998). (8) Filippenko, Leonard & Riess (1999). (9) Iha et al. (1999). (10) Capellaro, Turatto & Mazzal (1999). (11) Thorsett & Hogg (1999). (12) Hjorth et al. (1999c).

of $^{56}$Co for about 60 days after discovery. The light curve then flattened for 200 days and then proceeded to a more steep decline. Assuming the early part of the light curve to be due to the trapping of $\gamma$-rays from $^{56}$Co decay, Germany et al. deduce that SN 1997cy ejected 2 $M_\odot$ of $^{56}$Ni. They tentatively ascribe the subsequent flattening and decline of the light curve to circumstellar interaction. Germany et al. note that SN 1997cy was about a factor of 50% brighter at discovery than SN 1998bw was at maximum. Late-time radio observations, 16 months after the explosion, revealed no detectable source. Germany et al. argue for a possible connection of SN 1997cy with GRB 970514. This burst lasted $\lesssim 1$ s and was classified as a high-energy event. They estimate the chance association of the two events to be about 1%. If the events were associated, then the $\gamma$-ray energy in the burst was about $4 \times 10^{48}$ ergs, comparable to, but somewhat larger than, that ascribed to SN 1998bw/GRB 980425. Germany et al. also note that the decay of GRB 970508 was similar in slope to SN 1997cy and $^{56}$Co. They also note that SN 1999E had a spectrum similar to SN 1997cy, that SN 1999E was especially bright, and that it might be temporally linked to GRB 980910. One must be somewhat cautious in interpreting the data from SN 1997cy, especially the key observation that the light curve traced cobalt decay. There is no question that the supernova was bright at its redshift. On the other hand, the light curve was observed to fall at the rate of $^{56}$Co for only about 60 days, barely half a $^{56}$Co e-fold time. If the association with GRB 970514 is questioned, then the time of explosion is uncertain and this also impacts the amount of $^{56}$Co one would attribute to the event, even accepting that $^{56}$Co decay is observed.

Another class of association of $\gamma$-ray bursts and supernovae comes from the discovery of transient brightening or modulation of afterglows. Bloom et al. (1999b) argue that a brightening of the light curve of GRB 980326 can be interpreted as the addition of the light of an event like SN 1998bw about 20 days after the explosion if the supernova were at about a redshift of 1. The optical transient became about 60 times brighter than expected from an extrapolation of the decline of flux at earlier times. In addition, Keck spectra showed that the continuum spectrum changed from being blue to being red. The latter is roughly consistent with the radiation from a supernova photosphere, but incon-
sistent with synchrotron radiation as might have occurred if there were delayed energy input or the blast wave ran into a dense cloud, possible alternative models (Panaitescu, Mészáros & Rees 1998; Dai & Lu 1998a,b; Piro et al. 1999a). Bloom et al. note that special circumstances might be necessary to reveal such a late-time rebrightening: a rapid afterglow decay, and a low surface-brightness host galaxy.

Reichart (1999) has advanced similar arguments in a study of an earlier event, GRB 970228. While there is no spectroscopy, Reichart notes that there is much more thorough photometry for GRB 970228 as compared to GRB 980326 and that there is a measured redshift of $z = 0.695$ (Djorgovsky et al. 1999). GRB 970228 showed strong reddening with time, a characteristic not explained by standard relativistic blast wave models. Reichart argues that the afterglow data is not consistent with a single power law spectrum nor a single power law temporal decay, but that it is consistent with the U-band light curve of SN 1998bw appropriately redshifted to the frame of GRB 970228. The spectral energy distribution is also consistent with the convolution of a SN 1998bw-like event and the power-law decline of a relativistic blastwave. Similar conclusions have been reached by Galama et al. (1999). Interestingly, this manifestation of a supernova-like resurgence is seen despite a relatively slow decline in the early afterglow $\propto t^{-1.58}$. The host galaxy was relatively dim compared to the early afterglow and the “supernova” contribution.

The most recent suggestion of such a supernova-like modulation has been given by Hjorth et al. (1999c) for GRB 990712. They argue that the R-band light curve is consistent with a temporal decay of the afterglow like $^{-1}$, a host galaxy of R = 21.76, and a “supernova” like SN 1998bw at the known redshift of $z = 0.430$ (Galama et al. 1999b).

Although it is not at all clear that it should be presented in this context, for completeness I will add the possibility that SN 1987A produced a jet of some sort, if not a $\gamma$-ray burst. Wang & Wheeler (1998), Cen (1998), and Nakamura (1998) all noted that if supernovae make jets that have some connection to $\gamma$-ray bursts there might be some relevance to the “mystery spot” of SN 1987A. Motivated by Cen’s comments in this connection, Nisenson & Papalios (1999) re-examined their speckle data on SN 1987A and argued in favor of both a jet and counter jet from SN 1987A. From the kinematics they concluded that the counter jet must have moved at relativistic speeds. Some sort of jets might be produced in many core collapse events (see §3), but there is still debate and doubt on the reality of these jets. There is, of course, no direct link to a $\gamma$-ray burst.

On the other hand, Nagataki (1999) makes a convincing case that a jet-like explosion in SN 1987A can resolve many of the issues of outward mixing of radioactive elements and line profiles.

### 3. Jet-Induced Supernovae

The goal of producing robustly asymmetric supernovae, weak $\gamma$-ray bursts of the sort observed in SN 1998bw/GRB 980425, and perhaps collimated high-energy bursts of $\gamma$-rays that could contribute to the cosmological $\gamma$-ray bursts suggests the following general picture. The best chance of imprinting the asymmetry and producing some sort of $\gamma$-ray burst is in the absence of an extended hydrogen envelope which could slow, delay, or disperse the propagation of an asymmetric flow of energy from a newly-formed neutron star. This makes a Type Ib/c, and especially a Type Ic configuration, a likely site for study, independent of the similarities of SN 1998bw to Type Ic.

The progenitor of a Type Ic is envisaged to be the core of a massive star, perhaps in excess of $15M_\odot$ on the main sequence, which has shed its hydrogen and helium by a winds or binary mass transfer. The iron core in such a progenitor collapses to form a neutron
star, and the outer layers of Si, O, and C with longer free-fall times hover momentarily. The neutron star bounces and produces a standing shock that stalls without inducing an explosion. If the neutron star is a pulsar, then it is possible to create an MHD jet up the rotational axis at the time of the formation of the neutron star as in the old calculation of Leblanc & Wilson (1970). Such a jet could induce the requisite asymmetry in the ejecta and accelerate in the density gradient to produce a weak γ-ray burst. If the pulsar were very highly magnetized, a magnetar (Duncan & Thompson 1992; Kouveliotou et al. 1998; Harding 2000), then the pulsar could also potentially produce an intense flux of Poynting radiation (Uskov 1992,1994; Thompson 1994; Mézáros & Rees 1997; Blackman & Yi 1998; see also Ostriker & Gunn 1971; Bisnovatyi-Kogan 1971). This Poynting flux would tend to flow out through the weakest part of the hovering mantle, namely the wound punched by the MHD jet. For very large magnetic fields, the collimation and energetics could be sufficient to produce a cosmic γ-ray burst.

This outline of a possible scenario illustrates a host of places where more rigorous physics is needed to determine whether the hypothesized outcome is reasonable. One issue is the propagation of the initial MHD jet out through the mantle and its effect on the star. This issue has been recently addressed by Khokhlov et al. (1999).

Khokhlov et al. adopt a progenitor Type Ib/c model consisting of a a spherical helium star of radius $R_{\text{star}} = 1.88 \times 10^{10}$ cm and mass $M_{\text{star}} \simeq 4.1 M_\odot$. The inner Fe/Si core with mass $M_{\text{core}} \simeq 1.6 M_\odot$ and radius $R_{\text{core}} = 3.82 \times 10^8$ cm is assumed to have collapsed on a timescale much faster than the outer, lower-density material. This core is replaced by a point gravitational source with mass $M_{\text{core}}$ representing the newly formed neutron star. The remaining mass, $\simeq 2.5 M_\odot$, consists of an O-Ne-Mg inner layer surrounded by the C-O and He mantles.

The jets are assumed to enter the mantle at two polar locations at $R_{\text{core}}$. An inflow with velocity $v_j$, density $\rho_j$ and pressure $P_j$ is imposed. The jet parameters are chosen to represent the results of LeBlanc & Wilson (1970). At $R_{\text{core}}$, the jet density and pressure are the same as those of the background material, $\rho_j = 6.5 \times 10^5$ gm cm$^{-3}$ and $P_j = 1.0 \times 10^{33}$ ergs cm$^{-3}$, respectively. The radii of the cylindrical jets entering the computational domain are approximately $r_j = 1.2 \times 10^8$ cm. The jet velocity at $R_{\text{core}}$ was held constant at $v_j = 3.22 \times 10^9$ cm s$^{-1}$ for 0.5 s. This results in a mass flux rate of $\sim 9.5 \times 10^{31}$ gm s$^{-1}$ with an energy deposition rate $dE/dt = 5 \times 10^{50}$ erg s$^{-1}$ for each jet. After 0.5 s, the velocity of the jets at $R_{\text{core}}$ was gradually decreased to zero at approximately 1 s. The total energy deposited by the jets was $E_j \simeq 9 \times 10^{50}$ ergs and the total mass ejected is $M_j \simeq 2 \times 10^{32}$ grams or $\simeq 0.1 M_\odot$. These parameters are consistent with, but somewhat less than, those of the LeBlanc-Wilson model.

As the jets move outward, they remain collimated and do not develop much internal structure. A bow shock forms at the head of the jet and spreads in all directions, roughly cylindrically around each jet. The jet characteristic time, $\tau_j \simeq 1$ s, is much shorter than the sound crossing time of the star, $\tau(R_{\text{star}}) \simeq 10^3$ s. The jets stay collimated enough to reach the surface as strong jets. The stellar matter is shocked by the bow shock, and acts as a high-pressure confining medium by forming a cocoon around the jet. The sound crossing time of the dense O-Ne-Mg envelope, $\tau(\sim 10^9$ cm) $\simeq 10$ s, is only ten times longer than $\tau_j$, and the jets are capable of penetrating this dense inner part of the star in $\sim 2$ s. By the time the jets penetrate into the less dense C-O and He layers, the inflow of material into the jets has been turned off. By this time, however, the jets have become long bullets of high-density material moving through the background low-density material almost ballistically. The higher pressures in these jets cause them to spread laterally. This spreading is limited by a secondary shock that forms around each jet between the jet and the material already shocked by the bow shock. The radius of
Figure 1. Jet evolution after breakout for the case of a progenitor which has lost its hydrogen rich-envelope (from Khokhlov et al. 1999). The frames show the density in the x-z plane passing through the center of the computational domain. The time since the beginning of the simulation is given in the upper left. The sizes of the frames are $\Delta x = 6.1 \times 10^{10}$ cm and $\Delta z = 1.125 \times 10^{11}$ cm.

The jets, $\sim 3 \times 10^9$ cm as they emerge from the star, is larger than the initial radius, $\sim 10^8$ cm, but it is still significantly less than the radius of the star. After about 5.9 s, the bow shock reaches the edge of the star and breaks through. Figure 1 shows the subsequent evolution of the star after the breakthrough. By $\approx 20$ s, most of the material in the jets has left the star and will propagate into the interstellar medium ballistically.

The laterally expanding bow shocks generated by the jets move toward the equator where they collide with each other. The result is that the material in the equatorial plane is compressed and accelerated more than material in other directions (excluding the jet material). At $t \approx 29$ s, the equatorial flow reaches the outer edge of the star, and the star begins to settle into the free expansion regime. The computation was terminated at $\approx 35$ s, before free expansion was attained. The stellar ejecta at this time is highly asymmetric. The density contour of $50$ gm cm$^{-3}$, which is the average density of the ejecta at this time, forms an oblate configuration with the equator-to-polar velocity and density ratios $\approx 2/1$ and $4/1$, respectively. Complex shock and rarefaction interactions inside the expanding envelope will continue to change the distribution of the parameters inside the ejecta. Nonetheless, we expect that the resulting configuration will resemble an oblate ellipsoid with a very high degree of asymmetry $\geq 2$.

The asymmetric explosion generated in this calculation provides ejection velocities that are comparable to those observed in supernovae, but with especially high velocities near
the jet axis. For this particular calculation, an energy of $9 \times 10^{50}$ ergs is input at the base of the jets. This energy is divided roughly equally between the emerging jets and the bulk of the asymmetric ejecta. The total mass in the two jets is $M_j \simeq 0.1 M_\odot$ and the total kinetic energy is $E_j \simeq 5 \times 10^{50}$ ergs. The average velocity of the jets is about $25,000 \text{ km s}^{-1}$. The outer 2.5 $M_\odot$ of mantle material is ejected with kinetic energy of $5 \times 10^{50}$ ergs and average velocity $3,000 - 4,000 \text{ km s}^{-1}$.

The jet-induced explosion is entirely due to the action of the jet on the surrounding star. The mechanism that determines the energy of such an explosion is related to the shut-off of the accretion onto the neutron star by the lateral shocks that accelerate the material outwards. The explosion thus does not depend on neutrino transport or re-acceleration of the stalled shock.

The result of this calculation is a highly nonspherical supernova explosion with two high-velocity jets of material moving in polar directions and oblate, highly distorted ejecta containing most of the supernova material. This jet-induced explosion thus provides a satisfactory account of the degree of polarization and asymmetry observed for typical core-collapse supernovae. The luminosity and photospheric velocities will be a function of the aspect angle. This model gives at least the possibility of reproducing a standard Type Ic like SN 1994I by observations along the equator where the velocity and luminosity (and perhaps the $\gamma$-ray flux) will be minimum, but the polarization will be maximum, of reproducing SN 1997ef by an observation at intermediate angles, and reproducing SN 1998bw by observation near the poles (within 35 degrees; Höflich, Wheeler & Wang 1999) where the velocity and luminosity will be maximum and the polarization a minimum, albeit with perhaps somewhat higher explosion energy. This scheme might thus account for many of the properties of these three events as outlined by Branch (2000) without requiring a “hypernova” for any of them.

The jets provide a large kinetic energy per unit solid angle. When the jets break through the stellar photosphere, a small amount of mass will be accelerated down the density gradient to high velocities. Khokhlov et al. (1999) did not have sufficient resolution to make quantitative predictions; however, a small fraction of the material at the stellar surface had a velocity of up to $\sim 90,000 \text{ km s}^{-1}$. There is thus a good likelihood of producing a weak $\gamma$-ray burst and a radio outburst of the type seen in SN 1998bw/GRB 980425 by the relativistic shock ejection mechanism of Colgate (1975).

Khokhlov et al. (1999) assumed that the jets were generated by a magneto-rotational mechanism during core collapse and neutron star formation (LeBlanc & Wilson 1970). The LeBlanc & Wilson calculation was criticized by Meier et al. (1976) as requiring extreme parameters of the progenitor star. These issues need to be re-examined in the current context, but several things are worth noting about the Meier et al. analysis. They argue that the MHD axial flow found by Leblanc & Wilson will not propagate to the stellar surface as a jet. The calculation of Khokhlov et al. shows this to be incorrect. Meier et al. based their analysis on stellar evolution calculations of the day, but they adopted a stellar core with central density of about $10^{10}$ gm cm$^{-3}$ giving a binding energy of about $10^{52}$ ergs. This exaggerates the binding energy of the initial core by about a factor of 10 compared to modern calculations and gives an incorrectly small value of a key parameter of Meier et al., the ratio of the binding energy of the newly-formed neutron star to that of the initial core. Meier et al also did not consider the possibility of an $\alpha - \Omega$ dynamo that could lead to exponential growth of the magnetic field (Duncan & Thompson 1992). The whole question of the initiation of MHD jets in association with neutron star formation needs to be considered anew.

A different mechanism of jet generation involving neutrino radiation or perhaps MHD jets during collapse of a very massive star into a black hole has been recently discussed by
MacFadyen & Woosley (1999) and Woosley (2000) in the context of “collapsar” models of γ-ray bursts. The energy input rate and total energy of the jets in the calculation of MacFadyen & Woosley are similar to those of Khokhlov et al. (1999), but by choice of initial conditions, MacFadyen & Woosley inject energy into the jets as thermal energy whereas Khokhlov et al. assume the input as kinetic energy. Apparently this gives less mass in the jets for MacFadyen & Woosley and they find that their jets rapidly accelerate to relativistic speeds, whereas the jets of Khokhlov et al. remain sub-relativistic. This affects the dynamics of the jets. It is as if MacFadyen & Woosley were blowing a jet of air through water and Khokhlov et al. were blowing a jet of water through water. If there is to be a strong γ-ray burst due to Poynting flux from the neutron star as sketched earlier, there must be a subsequent phase where, to extend the analogy, a second jet of air blows out through the water jet. Clearly, an extensive amount of work is required to understand the origin of jets in this general context, their sensitivity to mode of initiation, and their propagation through various progenitor stars from compact cores through extended supergiants.

4. Perspectives and Conclusions

A principle issue that confronts the subject of γ-ray bursts is that of diversity. Occams razor is a powerful tool, but sometimes it is not adequate for all of nature’s handiwork. One measure of progress in this century was the development of our understanding of “novae.” We now know that this apparently rather similar category of optical outbursts included a wide range of astrophysical phenomena: dwarf novae, classical novae, X-ray transients, and supernovae. A great amount of painstaking observational work and theoretical understanding was required to separate these categories, including the understanding that some of the “nebulae” hosting “novae” were galaxies giving rise to supernovae. It is sobering to recognize that the differences between X-ray transients involving black hole accretion and classical novae involving thermonuclear explosions on the surfaces of white dwarfs were only fully recognized in the last decade or so.

One must keep an open mind that something like this diversity of phenomena may occur in the γ-ray bursts despite obvious similarities and in the absence of other information. That information gap is now being filled in a rush in the age of the afterglow. The separation of γ-ray bursts into two morphological groups by the length of the outburst is well established and into different hardness categories is suspected (Lamb 1999; Fishman 2000). The γ-ray bursts with afterglows show a variety of light curve behaviors, some with monotonic power law declines, some with breaks or gradual changes of slope (Table 2). Some of the afterglows are seen in the X-ray, but not in the optical despite simple arguments that say Lorentz beaming should be more pronounced in higher energy bands. Time will tell whether this diversity in phenomenology is telling us about the complexity of a single category or a diversity of physical phenomena that share some properties.

SN 1998bw/GRB980425 plays a key role here. This event (and other apparently extreme supernovae) lies on the conceptual border between extreme classes of models. On one hand, one has asymmetric supernovae that appear to be commonly associated with the core collapse phenomenon, Type II and Type Ib/c. SN 1998bw could be an extreme version of that physics, requiring energies in the upper range for other observed supernovae, perhaps $2 \times 10^{51}$ ergs versus $10^{51}$ ergs for most core collapse events and $1.3 \times 10^{51}$ ergs for the well-measured SN 1987A. In this case, SN 1998bw is predicted to leave behind a neutron star, a pulsar, perhaps even a magnetar. In the other extreme of some order parameter, we have the classic cosmological γ-ray bursts as revealed by
BeppoSAX and the sterling follow-up work that has been done in all wavelengths. These cosmic \(\gamma\)-ray bursts could be "hypernovae" involving jets originating in "collapsars" as discussed by Woosley (2000) or neutron star-neutron star or neutron star-black hole collisions (or the many variations on that theme) or maybe both. In this picture, SN 1998bw might represent a mild, not so collimated or powerful version of the cosmological bursts. In this case, SN 1998bw is predicted to leave behind a black hole. Clearly, SN 1998bw remains a potential rosetta stone, one of fading, but still detectable brilliance at the time of the conference.

Too many issues arise in the total sweep of supernova and \(\gamma\)-ray burst research to touch on here. There are some topics that fall in the interstices that may illuminate both, and these are worth comment.

One interesting issue is the amplitude of the Lorentz factor. The Lorentz factor is typically limited to \(\lesssim 10\) in both AGN's and the stellar mass black hole sources with superluminal jets, the microquasars (Mirabel & Rodriguez 1994; Fender 1999), whereas it is understood that that the Lorentz factors in \(\gamma\)-ray bursts must be \(\gtrsim 100\) (Baring & Harding 1997). What is the difference in the physics of these situations? One factor that is thought to limit the speed of black hole jets is radiation drag by photons emitted from the surrounding disk (Sikora et al. 1996; Luo & Protheroe 1999). Does this phenomenon, as well as baryon loading, affect the models based on black hole accretion? Has nature, through the AGN and microquasars, already told us what black hole accretion does, or is the massive accretion rate postulated for "collapsar" models sufficient to account for the difference? Do \(\gamma\)-ray bursts with their exceedingly large Lorentz factors require some physical basis that is very different than accreting black holes?

In principle, either newly-born neutron stars or black holes could generate jets. How are those cases to be differentiated as we explore SN 1998bw and the other candidate "hypernova" events. One interesting possibility is to look at the iron abundances in X-ray spectra, as discussed by Piro (2000; see also Mészáros & Rees 1998; Piro et al. 1999a; Lazzati, Campana & Ghisellini 1999; Vietri et al. 1999; Table 2. Note that a work widely referred to by Yoshida et al. 1999, based on ASCA observations of GRB 879828, does not seem to have been submitted). Another important issue to explore is the nature of the birth of a "magnetar" with a magnetic field ranging up to perhaps \(10^{16}\) G compared to the birth of a "normal" pulsar with a dipole field of \(10^{12}\) G.

The recognition that \(\gamma\)-ray bursts may involve collimated flows has become widespread. There is already a debate about when and at what speed, lateral expansion of jets will occur and with what effect on the spectrum and temporal behavior of the afterglow. The question of different collimation and Lorentz beaming of the \(\gamma\)-ray burst and afterglow must be addressed. Chevalier (2000; Li & Chevalier 1999; Chevalier & Li 1999) has emphasized the difference of afterglows propagating into density gradients as opposed to uniform density environments. In general, a spherical relativistic blast wave propagating into a density gradient will give a light curve that declines more steeply than the case of a constant density. The result is that the effects of density gradients, for instance winds with density profile \(\rho \propto r^{-2}\), can mimic the effects of a collimated jet that slows and spreads in a constant density environment. In addition, prolonged energy input into the blast wave can result in a shallower light curve decline in the case with a density gradient in a manner that can mimic the effect of a spherical blast wave in a constant density medium. The luminosity of a jet could fluctuate in space and time for dynamical and kinematic reasons. If one asks about collimated flow into an environment with density gradients, even clumpiness, then the range of phenomenology could be quite great (Mészáros, Rees & Wijers 1998). These issues could be related. While relativistic blast waves propagating in a steady state wind will decelerate, those propagating through
steeper profiles ($\rho \propto r^{-n}$ with $n > 3$; Shapiro 1980) will accelerate (Colgate 1975; Shapiro 1980) and the gradient itself can lead to collimation (Shapiro 1979). My guess is that the full potential complexity of the behavior of collimated flow has not yet been appreciated nor evaluated.

Once again, while it is fading, SN 1998bw could be an important resource for raising these issues. All models for this event presuppose a stripped core of a massive star. A strong wind is the most likely candidate for the mass loss and the radio emission has already given evidence for a relativistic blast wave interacting with a $\rho \propto r^{-2}$ density gradient (Li & Chevalier 1999). Follow-up of SN 1998bw in all possible wavelengths until it is completely unobservable is strongly encouraged!

Finally, one of the most exciting events in a string of recent revolutions was the recording of the contemporary optical outburst associated with GRB 990123 (Akerlof et al. 1999). This burst was seen at 9th magnitude and Kehoe (2000) emphasized that they cannot guarantee having detected the peak due to their sampling! Kehoe also emphasized that they have observed other events at lower limits so some $\gamma$-ray bursts, at least, are not this bright. Still, some obviously are and the lesson for the ROTSE group and the LOTIS and other groups who are trying to do automated contemporary detections is to just be patient. There must be more such events.

What an incredible event this single observation of GRB 990123 represented. At 9th magnitude, this optical flare was almost naked eye! One of the first things that occurred to me, somewhat facetiously, was encouraging hoards of private citizens to go out every night in their back yards with a decent pair of binoculars and look for these events. BATSE detects about one $\gamma$-ray burst per day. If every one were like GRB990123, there should be a bright optical flash for a minute or so once a day somewhere on the sky that would be easily visible with a decent pair of binoculars. A pair of binoculars allows you to see about one part in a thousand of the total sky. If you looked every night for three years running, you just might get lucky.

As it so happens, Gerry Fishman and Janet Mattei of the AAVSO were way ahead of me. They are already talking about working with amateurs with decent sized telescopes and commercial CCD’s to undertake a project akin to Joe Patterson’s Backyard Astronomy, the program he coordinates from Columbia. With this kind of organization we may indeed see the era of Backyard Cosmology.

4.1. Acknowledgments

My thanks personally and on behalf of all the attendees at the meeting for a job well done to Mario Livio and the Scientific Organizing Committee, to Patrick Godon and Rosie Diaz-Miller for handling the expert and neophyte Power Point operators as well as all the other A-V tasks, and especially to Lorraine Garcia and Theresa Bailey for their excellent work on the symposium arrangements and the myriad issues and questions that always arise during such a conference. I am grateful for scientific discussions of supernovae and gamma-ray bursts with Lifan Wang, Peter H"oflich, Rob Duncan, Alexei Khokhlov, Elaine Oran, Insu Yi, Brian Schmidt, Saul Perlmutter, Alan Sandage, David Branch, Eddie Baron, Don Lamb, Shri Kulkarni, Josh Bloom, Dave Meier, Peter Mészáros, Martin Rees, Stan Woosley and Andrew MacFadyen. Special thanks go to Howie Marion for helping with the data collection and to Martin Lang for LaTeX wrangling. This research was supported in part by NSF Grant 95-28110, NASA Grant NAG 5-2888, and a grant from the Texas Advanced Research Program.
REFERENCES

Akerlof, C. W. et al. 1999, Nature, 398, 400
Anderson, M. I. 1999, Science, 283, 2075
Bakos, G. et al. 1999, IAUC 7225
Baring, M. G. & Harding, A. K. 1997, ApJ, 491, 663
Bisnovatyi-Kogan 1971, Soviet Astronomy AJ, 14, 652
Blackman, E. G. & Yi, I. 1998, ApJ, 498, L31
Bloom, J. S. et al. 1998, ApJ, 508, L21
Bloom, J. S. et al. 1999a, ApJ, 518, L1
Bloom, J. S. et al. 1999b, Nature, submitted, astro-ph/9905301
Branch, D. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press, astro-ph/9906168
Bond, H. E. 1997, IAUC, 6654
Branch, D., Fisher, A. & Nugent, P. 1993, AJ, 106, 2383
Capellaro, E., Turatto, M. & Mazalli, P. 1999, IAUC 7091
Cen, R. 1998, ApJ, 507, L131
Chevalier, R. A. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press
Chevalier, R. A. & Li, Z.-Y. 1999, ApJ, 520, L29.
Colgate, S. A. 1975, ApJ, 198, 439
Covino et al. 1999, A&A, in press, astro-ph/9906319
Dai, Z. G. & Lu, T. 1998a, A&A, 333, L87
Dai, Z. G. & Lu, T. 1998b, Phys Rev Lett, 81, 4301
Dai, Z. G. & Lu, T. 1999a, ApJ, 519, L155
Dai, Z. G. & Lu, T. 1999b, ApJ, submitted, astro-ph/9906109
Djorgovski, S. G. 1998a, GCN 025
Djorgovski, S. G. et al. 1998b, ApJ, 508, L17
Djorgovski, S. G. et al. 1999a, GCN 189
Djorgovski, S. G. et al. 1999b, GCN 289
Danziger, J. et al. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press
Duncan, R. C. & Thompson, C. 1992, ApJ, 392, L9
Fender, R. P. 1999, in Astrophysics and Cosmology, Springer-Verlag, in press, astro-ph/9907050
Filippenko, A. V., Leonard, D. C. & Riess, A. G. 1999, IAUC 7091
Fishman, G. J. 1995, PASP, 107, 1145
Fishman, G. J. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press
Frail, D. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press
Fruchter, A. S. 1999, ApJ, 512, L1
Fruchter, A. S. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press
Fruchter, A. S. et al. 1999, ApJ, 516, 689
Galama, T. J. et al. 1998, Nature, 395, 670
Galama, T. J. et al. 1999a, ApJ, submitted, astro-ph/9907264
Galama, T. J. et al. 1999b, GCN 388
Ghisellini, G. & Lazzati, D. 1999, MNRAS, in press, astro-ph/9906471
J. C. Wheeler: Conference Summary

Giblin, T. W. et al. 1999, ApJ, submitted, astro-ph/9908139

Gruzinov, A. 1999, ApJ, submitted, astro-ph/9905276

Halpern, J. P., Kemp, J., Piran, T. & Bershadsky, M. A. 1999, ApJ, 517, L105

Harding, A. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press

Harrison, F. A. 1999, private communication

Harrison, F. A. et al. 1999, ApJ, in press, astro-ph/9905306

Hjorth, J. et al. 1999a, Science, 283, 2073

Hjorth, J. et al. 1999b, GCN 389

Hjorth, J. et al. 1999c, GCN 403

Höflich, P. 1995, ApJ, 440, 821

Höflich, P. & Domínguez, I. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press

Höflich, P. & Khokhlov, A. 1996, ApJ, 457, 500

Höflich, P., Wheeler, J. C. & Wang, L. 1999, ApJ, 521, 179

Hogg, D. W. & Fruchter, A. S. 1999, ApJ, 520, 54

Howell, D. A., Wang, L. & Wheeler, J. C. 1999, ApJ, in press, astro-ph/9908127

Israel, G. L. et al. 1999, A&A, in press, astro-ph/9906401

Iwamoto, K. et al. 1998 Nature, 395, 672

Jha, S., Garnavich, P., Challis, P. & Kirshner, R. P. 1999, IAUC 7090

Kehoe, R. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press

Khokhlov, A. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press

Khokhlov, A.M., Oran, E.S. & Wheeler, J.C., 1997a, Combustion & Flame, 108, 503

Khokhlov, A.M. Oran, E.S., Wheeler, J.C., 1997b, ApJ, 478,678.

Khokhlov, A.M., Höflich, P. A., Oran, E. S., Wheeler, J. C., Wang, L. & Chcthelkanova, A. Yu. 1999, ApJ, in press, astro-ph/9904419

Kouveliotou, C., Strohmayer, T., Hurley, K., Van Paradijs, J., Finger, M. H., Dieters, S., Woods, P., Thompson, C. & Duncan, R. C. 1998, ApJ, 510, 115

Kulkarni, S. et al. 1998a, Nature, 393,35

Kulkarni, S. et al. 1998b, Nature, 395, 663

Kulkarni, S. et al. 1999, Nature, 398, 389

Kulkarni, S. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press

Lamb, D. Q. 1999, A& A, in press, astro-ph/9909026

Lazzati, D., Campana, S. & Ghisellini, G. 1999, MNRAS, in press, astro-ph/9902058

LeBlanc, J. M. & Wilson, J. R. 1970, ApJ, 161, 541

Li, Z.-Y. & Chevalier, R. A. 1999, ApJ, in press, astro-ph/9903489

Livio, M. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press

Luo, Q. & Protheroe, R. J. 1999, MNRAS, 304, 800

MacFadyen, A. & Woosley, S. E. 1999, ApJ, in press, astro-ph/9810274

McKenzie, E. H. & Schaefer, B. E. 1999, ApJ, submitted

Meier, D., Epstein, R. I., Arnett, W. D. & Schramm, D. N. 1976, ApJ, 204, 869

Méndez, M., Clocchiatti, A., Benvenuto, G., Feinstein, C. & Marraco, U.G. 1988, ApJ, 334, 295

Metzger, M. R. et al. 1997, IAUC 6676

Mészáros, P. & Rees, M. J. 1997, ApJ, 482, L29
Mészáros, P. & Rees, M. J. 1998, MNRAS, 299, L10
Mészáros, P., Rees, M. J. & Wijers 1998, ApJ, 499, 301
Mirabel, I. F. & Rodríguez, L. F. 1994, Nature, 371, 46
Moderski, R., Sikora, M. & Bukil, T. 1999, ApJ, submitted, astro-ph/9904310
Nagataki, S. 1999, ApJ, in press, astro-ph/9907109
Nakamura, T. 1998, Prog. Theor. Phys. 100, 921
Niemeyer, J. & Woosley, S. E. 1997, ApJ, 475, 740
Niemeyer, J. 1999, ApJ, in press, astro-ph/9906142
Nisenson, P. & Papalilios, C. 1999, ApJ, 518, L29
Nomoto, K. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press
Odewahn, S. C. et al. 1998, ApJ, 509, L5
Ostriker, J. P. & Gunn, J. E. 1971, ApJ, 164, L95
Paczynski, B. E. 1998, ApJ, 494, L45
Paczynski, B. E. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press, astro-ph/9909048
Palazzi, E. et al. 1999, GCN 377
Panaiteșcu, A. & Mészáros, P. 1998, ApJ, 492, 683
Panaiteșcu, A. & Mészáros, P. & Rees, M. J. 1998, ApJ, 503, 314
Perlmutter, S. et al. 1999, ApJ, 517, 565
Perlmutter, S. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press
Phillips, M. M. 1993, ApJ, 413, L108
Pian, E. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press
Pian, E. et al. 1998, GCN 158
Piran, T. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press
Piro, L. et al. 1999a, ApJ, 514, L73
Piro, L. et al. 1999b, A&A, in press, astro-ph/9906363
Piro, L. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press
Rees, M. J. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press
Reichart, D. E. 1998, ApJ, submitted, astro-ph/9901139
Reichart, D. E. 1999, ApJ, 521, 111
Reichart, D. E. et al. 1999, ApJ, 517, 692
Rhoads, J. E. 1997, ApJ, 487, L1
Rhoads, J. E. 1999, ApJ, submitted, astro-ph/9903399
Riess, A. G., Press, W. H. & Kirshner, R. P. 1996, ApJ, 473, 588
Riess, A. G. et al. 1998, AJ, 116, 1009
Riess, A. G. et al. 1999a, AJ, in press
Riess, A. G. et al. 1999b, ApJ, submitted, astro-ph/9907037
Riess, A. G. et al. 1999c, ApJ, submitted, astro-ph/9907038
Sandage, A. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press
Sari, R. 1999, ApJ, submitted, astro-ph/9906503
Sari, R., Piran, T. & Halpern, J. P. 1999, ApJ, 519, L17
Schlegel, E. M. 1990, MNRAS, 244, 269
Schaefer, B. E. et al. 1999, ApJ, in press, astro-ph/9907235
Schmidt, B. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press
Shapiro, P. R. 1979, 223, 831
Shapiro, P. R. 1980, 236, 958
Sikora, M., Sol, H., Begelman, M. C. & Madejski, G. M. 1996, MNRAS, 280, 781
Stanek, K. Z. et al. 1999, ApJ, 522, L39
Suntzeff, N. 1999, Aspen Summer Workshop.
Thompson, C. 1994, MNRAS, 270, 480
Thorsett, S. E. & Hogg, D. W. 1999, GCN 197
Trammell, S.R., Hines, D.C. & Wheeler, J.C. 1993, ApJ, 414, L21
Tran, H.D., Filippenko, A. V., Schmidt, G. D., Bjorkman, K. S., Januzzi, B. J. & Smith, P. S. 1997, PASP, 109, 489
Uslov, V. V. 1992, Nature, 357, 452
Uslov, V. V. 1994, MNRAS, 267, 1035
Vietri, M., Perola, C., Piro, L. & Stella, L. 1999, MNRAS, in press, astro-ph/9906288
Vreeswijk, P. M. et al. 1999, GCN 310, 324
Wang, L., Höflich, P. & Wheeler, J. C. 1997, ApJ, 483, L29
Wang, L., Wheeler, J. C. & Höflich, P. 1997, ApJ, 476, L27
Wang, L. & Wheeler, J.C. 1998, ApJ, 584, L87
Wang, L., Wheeler, J. C., Li, Z. W. & Clocchiatti, A. 1996, ApJ, 467, 435
Wang, L., Wheeler, J. C. & Höflich, P. 1999, in: SN 1987A, eds. Phillips et al., PASP, in press
Waxman, E. & Loeb, A. 1999, ApJ, 515, 721
Weiler, K. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press
Wheeler, J. C., Höflich, P. & Wang, L. 1999, Workshop on Future Directions of Supernova Research: Progenitors to Remnants, eds. J. Danziger and S. Cassisi, in press
Wijers, R. A. M. J. et al. 1999, ApJ, in press, astro-ph/9906346
Woosley, S. 1993, ApJ, 405, 273
Woosley, S., Eastman, R. & Schmidt, M. 1999, ApJ, 516, 788
Woosley, S. E., MacFadyen, A. I. & Heger, A. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press, astro-ph/9909034
Yoshida, A. et al. 1999, preprint
Zharikov, S. V., Sokolov, V. V. & Baryshev, Yu. V. 1998, A&A, 337, 356
1988, ApJ, 334, 295