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**Gamma-Ray Bursts and Type Ic Supernova: SN 1998bw**

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**ABSTRACT**

Recently a Type Ic supernova, SN 1998bw, was discovered coincident with a gamma-ray burst, GRB 980425. The supernova had unusual radio, optical, and spectroscopic properties. Among other things, it was especially bright for a Type Ic and rose quickly to maximum. When modeled in the usual way as a spherically symmetric explosion, this requires a large mass of $^{56}$Ni, 0.45 - 0.60 M$_\odot$, a quite massive star, and a very large explosion energy. We explore here models based upon helium stars in the range 9 - 14 M$_\odot$ and carbon-oxygen stars 6 - 11 M$_\odot$ which experience unusually energetic explosions (kinetic energy $0.5 - 2.8 \times 10^{52}$ erg). Bolometric light curves and multi-band photometry are calculated and compared favorably with observations. No spectroscopic data are available at this time, but both LTE and non-LTE spectra are calculated for the model that agrees best with the light curve, a carbon-oxygen core of 6 M$_\odot$ exploded with a kinetic energy of $2.2 \times 10^{52}$ erg. We also examine potential mechanisms for producing the observed gamma-ray burst (GRB) - shock break-out and relativistic shock deceleration in circumstellar material. For spherically symmetric models, both fail to produce a GRB of even the low luminosity inferred for GRB 980425. The high explosion energies required to understand the supernova are in contrast to what is expected for such massive stars and may indicate that a new sort of explosion has been identified, possibly the consequence of a collapsar (Woosley 1993, 1996) whose main sequence mass was $\sim 35$ M$_\odot$ (helium core mass 14 M$_\odot$). Indeed a more likely explanation for what was seen is a highly asymmetric explosion in which the GRB was produced by a relativistic jet, perhaps viewed obliquely, and only a fraction of the total stellar mass was ejected, the remainder accreting into a black hole. The ejected mass (but not the $^{56}$Ni mass), explosion energy, and velocities may then be
smaller. Other associations between luminous Type Ic supernovae and GRB’s may exist and should be sought, but most Type Ib and Type Ic supernovae do not make GRB’s.

Subject headings: gamma rays: bursts — stars: supernovae

1. Introduction

Gamma-ray bursts (GRB’s) have been a challenge to theorists and a source of fascination for all for over 30 years and many models have been suggested to explain them (Nemiroff 1993). Lately major progress has occurred in understanding GRB’s because of accurate localizations provided by the Beppo-Sax mission. These locations allow rapid follow-up observations with optical, x-ray, and radio telescopes that have yielded exciting information about GRB counterparts. Two bursts have been found to lie in galaxies having red-shifts of 0.83 and 3.42 and are inferred to have had enormous energies, $\sim 10^{52}$ erg and $\sim 3 \times 10^{53}$ erg for GRB 970508 and GRB 971214 respectively. It is currently believed that most gamma-ray bursts occur at such great distances that their mean energy is at least $10^{51}$ erg in gamma-rays alone, times an uncertain beaming factor that might reduce the energy by up to 100 at the expense of requiring many more events.

This developing paradigm was challenged last month by the discovery (Galama et al. 1998ab) of a supernova, SN 1998bw, Type Ib (Sadler et al. 1998; Lidman et al. 1998) and later Ic (Patat & Piemonte 1998), within the 8 arc minute error box of GRB 980425 (Soffita et al. 1998). Extrapolation of the supernova light curve implied an explosion time consistent with the GRB, an extremely unlikely occurrence unless the two were associated. Further, the supernova was unusual, presenting a radio luminosity 100 times brighter than typical Type Ib’s, brighter in fact than any supernova ever observed before (Wieringa et al. 1998). Moreover, relativistic expansion was inferred (Kulkarni et al 1998), the spectrum was unusual (Lidman et al. 1998; Patat & Piemonte 1998) and the light was curve brighter (Galama et al. 1998b) than typical for a Ib or Ic. In toto the case for a GRB-supernova association is compelling.

However, the redshift to the barred spiral galaxy where the supernova occurred is only 0.0085 (Tinney et al. 1998) and the burst was not an extraordinarily bright one. The duration and count rate for Beppo Sax were in fact comparable to GRB 971214 at a red shift of 3.42. From this we infer that the gamma-ray burst, which lasted 30 seconds, had an energy that was about $10^{48}$ erg, or $10^3 - 10^4$ times fainter than a typical cosmological GRB. The BATSE detector on Compton Gamma-Ray Observatory also saw the burst (Galama et
al. 1998b) for about 35 s and inferred a total energy of $8.5 \pm 1.0 \times 10^{47}$ erg in gamma-rays. BATSE saw no emission above 300 keV for this burst, making it another example of the so-called “no high energy” GRB’s, about 25% of the BATSE sample. At this luminosity, other GRB’s like GRB 980425 would have been invisible had they occurred 20 times farther away, so unless this was an extremely serendipitous observation, there must be a very high spatial density of these events, perhaps thousands of times that of the “classical” BATSE bursts (modulo the beaming factors). This requires a source that is very common in nature. Indeed, since BATSE observations can be explained with an event rate of $10^{-7}$/yr/L* galaxy (Wijers et al. 1998), this suggests an event at least 1% as frequent as supernovae.

In order to explain the brilliance of SN 1998bw, if it is powered by the decay of radioactivity like other Type I’s, it is necessary to synthesize and eject $\approx 0.45$ M$_\odot$ of $^{56}$Ni in the explosion. Since this was not a Type Ia supernova - and we know of no way to make GRB’s or strong radio sources based on Type Ia supernovae - we invoke massive stars. But then the large $^{56}$Ni mass requires, in traditional models, both a very massive star and a high explosion energy. The energy must also be large in order to accelerate the mass - several times that in a typical Type Ib supernova - to the observed high velocities and to make the light curve peak in only 17 days (Galama et al. 1998b). Finally, we are prejudiced by the belief that GRB’s require stars so massive that the neutrino powered “hot bubble” mechanism for supernova explosion fails (Woosley 1993). This also leads us to consider stars whose main sequence mass was over 30 M$_\odot$.

As we were writing our paper, the preprint by Galama et al. (1998b) appeared which references similar conclusions, at least a massive stellar explosion with large energy, reached in a paper by Iwamoto et al. (1998). We have not seen that paper and our work has proceeded independently.

In the following sections we describe the modeling of the supernova explosion, calculate the fraction and energy of relativistic mass ejected, and examine the model light curve and spectrum. We also attempt to understand how the supernova might have made a GRB. The interaction of the supernova shock with circumstellar material has an appealing physical basis and might be expected to occur frequently, but the gamma-ray energy requirements even for this faint burst are large and are not obtained (in spherical symmetry) even for very violent explosions. We do find models that agree well with the multi-band photometry of the supernova and from these are able to make predictions about the spectrum - unknown to us as of this writing.

The large explosion energy and lack of a straightforward way of making the GRB in spherical symmetry suggest that something unusual happened in SN 1998bw. In the Conclusions we discuss what it may have been.
2. Simulations

2.1. The Explosion

The models we use, which might eventually be tuned to give better agreement, are based upon massive stars - 25 - 35 $M_\odot$ on the main sequence, that have lost their hydrogen envelope and perhaps even their helium shell. For 25 $M_\odot$, this may require membership in a close binary; for 35 $M_\odot$, radiative mass loss will suffice. Once the helium core is uncovered rapid mass-dependent mass loss may commence (Langer 1989) that removes a portion of the helium shell. We thus experiment with both the helium cores and the carbon-oxygen cores of these massive stars. All calculations of the explosion and expansion were carried out using the KEPLER code (Weaver, Zimmerman, & Woosley 1978). The light curve and approximate spectra are calculated using a different approach (§3.4, 3.5).

Our first model uses the 9.12 $M_\odot$ helium core of a 25 $M_\odot$ main sequence star similar to the one evolved to presupernova by Woosley & Weaver (1995). Because we are interested in the correct density distribution in the atmosphere of the star (for shock acceleration), it was important that the surface of the helium star be fine zoned and in thermal and hydrostatic equilibrium. It takes time for the star to relax into this equilibrium and this cannot be accomplished by a star that is already exploding. So rather than try to make a "stripped down" helium core, we used the 25 $M_\odot$ model at carbon ignition to construct our model. The hydrogen envelope was removed (down to a hydrogen mass fraction of 0.01) and the rezoner allowed to prepare a very finely zoned surface as the outer helium layer expanded. A surface boundary pressure of $10^8$ dyne cm$^{-2}$ was necessary to keep the star numerically stable. This did not appreciably affect the structure. $10^{-5}$ $M_\odot$ (8 zones) into the atmosphere, the pressure exceeded this boundary value by 10 and the radius had decreased by only 9%. This boundary pressure was of course removed when the star exploded. The outer zone was $2 \times 10^{-6} M_\odot$. This atmosphere was allowed to relax into thermal and hydrostatic equilibrium and the star was then evolved, without farther mass loss, through neon, oxygen, and silicon burning to the presupernova state. As a presupernova, the star had a luminosity of $1.8 \times 10^{39}$ erg s$^{-1}$ and radius $2.5 \times 10^{11}$ cm. As before, the iron core mass was 1.78 $M_\odot$. This star was then exploded using a piston as described in Woosley & Weaver (1995). The final kinetic energy at infinity was varied (Table 1). This series of models is called HE9 with a suffix to indicate explosion energy.

Three other presupernova models were similarly constructed. The next used the 6.55 $M_\odot$ carbon-oxygen core of the 25 $M_\odot$ star at carbon depletion. Fine surface zoning was again engineered with outer zones typically $\sim 10^{27}$ g. The radius of the star at explosion was $1.22 \times 10^{10}$ cm and the luminosity $6.6 \times 10^{38}$ erg s$^{-1}$. Models from this series are
denoted CO6. Two additional models were extracted from a 35 M\(_\odot\) star at carbon ignition. This gave a helium core of 14.13 M\(_\odot\) (Models HE14) and a carbon-oxygen core of 11.03 M\(_\odot\) (Models CO11).

These models were all exploded using pistons parameterized so as to give a specified kinetic energy at infinity for the ejecta (Woosley & Weaver 1995). Typical values for the “\(\alpha\)” parameter were 10 - 20. The piston was located at the edge of the iron core in each case (1.78 M\(_\odot\) in the 25 M\(_\odot\) derived models; 2.03 M\(_\odot\), for the 35 M\(_\odot\) derived models). Nucleosynthesis was followed as in Weaver, Zimmerman, & Woosley (1978) using the nuclear reaction set described in Woosley & Weaver (1995). The final kinetic energies and abundances of \(^4\)He, \(^{16}\)O, \(^{28}\)Si, and \(^{56}\)Ni are given in Table 1.

3. Observational Properties

3.1. Shock Break Out

The first model ever proposed for gamma-ray bursts was supernova shock break-out (Colgate 1969, 1974). The outer layers of the star are heated by the eruption of the strong shock wave, then release their energy as the layers expand. We followed here the emergence of the shock using the KEPLER hydrodynamics code (Weaver, Zimmerman, & Woosley 1978) and a simple prescription for the opacity - electron scattering based upon a full solution of the Saha equation (Ensman & Woosley 1988). As previously noted, the zoning of the outer layers was very fine, logarithmically smooth down to 10\(^{-6}\) M\(_\odot\). The radiation transport for this early stage was calculated using a simple single temperature model of flux-limited radiative diffusion. It is known that this approach underestimates the temperature of the burst by up to about two (Ensman & Burrows 1992), but the luminosity should not be far off and both should suffice for present purposes.

The results for a representative sample of our models are given in Table 2. Typical burst luminosities are 10\(^{43}\) - 10\(^{44}\) erg s\(^{-1}\) for up to several seconds. Typical photon energies (3 kT) are about a keV. While bright and potentially detectable, this burst of radiation is over two orders of magnitude softer and four orders of magnitude fainter than what was seen in GRB 980425.
3.2. Relativistic Mass Ejection?

As the shock progresses through the outer layers of the star, it accelerates. If the density gradient is steep enough and the shock strong enough, a portion may even become relativistic. Analytic solutions of ultra-relativistic shocks and semi-analytic solutions of mildly relativistic shocks exist (Johnson & McKee 1971; McKee & Colgate 1973; Gnatyk 1985). For an exponentially declining density profile, the product of the Lorentz factor ($\Gamma$) and the velocity of the shock ($\beta = v/c$ where $c$ is the speed of light) is given by (Gnatyk 1985):

$$\Gamma \beta \propto (\rho r^{N+1})^{-\alpha},$$

where $N$ is a geometric factor set to 2 for spherical symmetry, and $\alpha$ is determined, via simulations, to be $\sim 0.20$.

We can use this scaling relation to estimate the energy ejected as a function of $\Gamma$ for lower mass zones than we are able to carry in our present (Newtonian) hydrodynamical calculation. In Figs. 1 and 2 the quantities $\rho r^3$ and $Q = \Gamma \beta (\rho r^3)^{0.2}$ are plotted as functions of the mass outside of radius $r$. The density and radius are evaluated in the presupernova star; $\Gamma$ and $\beta$ are evaluated after the matter has reached the coasting phase. The scaling relation for $\Gamma$ is not precise because it neglects the internal energy deposited by the shock and the subsequent acceleration that energy causes (Fryer & Woosley 1998a). However the near constancy of $Q$ suggests that we can extrapolate the well determined sub-relativistic solution calculated here to higher $\Gamma$’s.

Taking a representative range of $Q \approx 3 - 4 \times 10^5$ and a scaling relation between $\rho r^3$ and external mass $M = 10^{32}(\rho r^3/10^{32})^{4/3}$ (Fig. 1), we estimate the kinetic energy, $\Gamma M c^2$, contained in material having $\Gamma \geq 10$ to be $10^{41} - 10^{42}$ erg. For $\Gamma$ of 3 the range is $10^{44} - 10^{45}$ erg. This is several orders of magnitude less than required to produce the GRB.

Sub-relativistic matter is also unlikely to produce the burst. To carry $10^{48}$ erg requires a minimum of $\sim 10^{27}$ g. This matter will interact with its own mass before giving up its energy. For a mass loss rate of $10^{-5} M_\odot$ y$^{-1}$ and speed $10^8$ cm s$^{-1}$, the radius where this will happen is at least $\sim 10^{14}$ cm. The light crossing time for this region is $\sim 10^4$ s, so the burst would be too long and faint. Raising the mass loss can give a smaller interaction radius and shorter burst, but at the expense of becoming optically thick to the gamma-rays that are produced. It seems likely that an enduring hard x-ray flash will be created - an analogue to what was seen in SN 1993 J (Leising et al. 1994; Fransson, Lundquist, & Chevalier 1996). This lasted about a hundred days at 50 - 100 keV.

An additional concern is that the radio emission implies relativistic expansion even days after the GRB occurred (Kulkarni & Frail 1998). There is roughly $5 \times 10^{49}$ erg in the
outer $10^{-3}$ M$_\odot$ of ejecta of our models here, all moving at about 1/3 c. This could certainly provide a bright radio source, but the expansion would not be relativistic.

### 3.3. The Supernova Light Curve

UBVRI photometric observations of SN 1998bw have been reported by Galama et al. (1998b) and show the supernova falling in brightness when first observed (0.6 days after the GRB 980425), then rising to a maximum of $M_V = -19.4$ (a distance of 36 Mpc based on the object’s redshift, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, and $A_V = 0.2$ mag, is used throughout this discussion). We have used these observations to estimate the “bolometric luminosity” ($L_{UVOIR}$) by integrating over the $UBVRI$ photometry. To do so, we extend the spectrum beyond the I-band using a blackbody tail and beyond the U-band with a spline. The results are not sensitive to the treatment of the infrared, but there is some ambiguity in the treatment of the ultraviolet. Our procedure here is influenced by previous analyses of supernovae that had broad wavelength coverage (e.g., Type Ic SN 1994I). Type I supernovae of all subclasses are affected by line blanketing and it is important to cut off the ultraviolet spectrum quickly relative to the best fitting blackbody. The photometric evolution of this object is consistent with other objects which have a rapidly falling ultraviolet spectrum. The derived bolometric flux would only be in significantly error if there were a large amount of flux below 3000 Å. This appears unlikely except at the earliest times (less than three days after the GRB). The derived bolometric light curve is given in Table 3 and in Figs. 3 and 4.

These observational data were used to discriminate among possible models. Each model was evolved with the KEPLER hydro-code to $10^5$ seconds after explosion at which point a link was made to a multi-group radiation transport code, EDDINGTON (Eastman & Pinto 1993). This code solves the time-dependent transport equation, in the co-moving frame, simultaneously determining the gas temperature by balancing heating and cooling. The heating rate includes energy deposition by gamma-rays from radioactive decay. Gamma-ray transport was computed using a single energy group approximation to compute the transport each of gamma-ray line (Woosley et al. 1994).

For the EDDINGTON light curve calculations, the KEPLER grid, which consisted of 370 to 700 zones, was remapped onto a grid of 80 zones. The composition was artificially “moderately mixed”, which is to say a running boxcar average using a grid 1 M$_\odot$ wide was calculated sliding the grid out through the star. For those models that had a helium shell, this was not sufficient mixing to bring $^{56}$Ni up into the helium. Bringing $^{56}$Ni into the helium layer would probably produce a Type Ib, not Ic supernova (Woosley & Eastman...
The opacity included contributions from He I-II, C I-VI, O I-VIII, Si I-X, S I-X, Ca I-XII, Fe I-XIV, Co I-XIV and Ni I-XIV. Processes included inner shell and valence shell photoionization, bremsstrahlung, electron scattering, and line opacity from 90,000 lines, which was represented using the expansion opacity described by Eastman & Pinto (1993).

The light curve calculations assumed local thermodynamic equilibrium (LTE). Gas excitation and ionization was computed by solving the Saha-Boltzmann equation at the local temperature and density. Because the density is so low here, the assumption of LTE is questionable. This assumption remains approximately valid because the gas is radiatively driven into thermal equilibrium. But as the ejecta becomes more transparent, the assumption of LTE gets progressively worse. In general, we find that LTE tends to overestimate the population of excited states, underestimate the ionization, and underestimate the gas temperature.

For the present light curve calculations (Figs 3 - 5), the frequency grid consisted of 500 groups covering the range $30 < \lambda < 5 \times 10^4$ angstroms. Because of this low resolution, spectral features computed by the light curve code are smeared, but the spectrum is still adequate for photometry.

The best fit to the light curve and photometry is for our lowest mass, highest energy explosions (Table 1), those based on the 6 $M_\odot$ carbon-oxygen core. Even these models do not rise fast enough to agree with observations during the first few days. More mixing of $^{56}$Ni to nearly the surface of the explosion would give a more rapid rise, but in one dimension this mixing would keep a larger volume hot and ionized at late time and increase the photospheric radius. This would make the supernova too red. Another possibility is that the pre-explosive star had a helium layer and a larger radius. The release of shock deposited energy by helium recombination would then give a brief “plateau” in the light curve as is often calculated for Type Ib models. There are some indications in the data of the first few days that the supernova initially faded slightly. This would be consistent with helium recombination. Alternatively the explosion was not spherically symmetric (§5).

### 3.4. The Supernova Spectrum

In order to evaluate the effects of the LTE approximation and low frequency resolution, we carried out a higher resolution, non-LTE calculation of the spectrum of Model CO6C near maximum light (Fig. 6; 14.4 days). This calculation assumed steady state between energy deposition and emission. Gamma-ray transport was computed with the Monte Carlo
code FASTGAM (Pinto & Woosley, 1988) using a frequency grid of 30,000 groups and a spatial grid of 41 radial zones. Ions included were He I-II, C I-IV, O I-IV, Si I-IV, S I-IV, Ca I-IV, Fe I-IV and Co I-IV. The broadband photometry predicted by this Model was shown in Fig. 5 as solid points.

The agreement with the observations is much improved over the predictions of the LTE calculation. In particular, the predicted U band flux is a magnitude brighter in the non-LTE calculation. Fig. 6 shows the spectrum predicted by the non-LTE calculation of Model CO6C just prior to peak light, (the calculation is at 14.4 days). Although we have not yet had access to any optical spectroscopy of SN 1998bw, the maximum light spectrum of CO6C has many of the properties displayed in the maximum light spectrum described by Patat & Piemonte (1998): it peaks near 5400 angstroms and shows strong absorptions by C II, O I, O II, Si II, S II and Ca II. The model does have a He I $\lambda5876$ absorption feature, which Patat says was not present in SN 1998bw. However, it is weak, highly blue shifted, and could easily be mistaken for something else. Also, the He I $\lambda6678$ is very weak in Model CO6C, and blended with C II and O II, consistent with Patat’s report on SN 1998bw.

The velocities here are very high. In the unmixed model, most of the helium (which came from photodisintegration in Model CO6C) was moving between 0 and 12,000 km s$^{-1}$; carbon was appreciably abundant (over 1% by mass) only at speeds greater than 25,000 km s$^{-1}$; oxygen was abundant over 14,000 km s$^{-1}$; magnesium, 15,000 km s$^{-1}$ and up; silicon 12,000 to 26,000 km s$^{-1}$; calcium, 12,000 - 15,000 km s$^{-1}$; and cobalt ($^{56}$Ni) was found between 0 and 14,000 km s$^{-1}$. This inverted speed distribution for helium and heavier elements might be a distinctive feature in the spectrum of a CO-explosion as opposed to that of a helium star. In a helium star there might be a bimodal distribution of helium in velocity. In a CO star high velocity helium is weak (arbitrarily we defined the outer boundary of the CO model as where helium went to 1% by mass in the 25 M$_{\odot}$ star igniting carbon burning). The velocities here are higher than reported by Patat & Piemonte (1998).

In a later paper, when spectroscopic data is available, we hope to treat the spectral evolution of SN 1998bw in greater detail. However, from the information at hand it seems that, photometrically at least, SN 1998bw is well modeled as the explosion of a carbon-oxygen core of 6 M$_{\odot}$ with a kinetic energy of $\sim 2 \times 10^{52}$ erg which naturally yields a $^{56}$Ni mass near 0.5 M$_{\odot}$. The fact that we used a CO core without an appreciable layer of helium still in place is in part an expedient. It may well be that a helium core of the same mass and explosion energy would have worked just as well. If detailed spectroscopic analysis shows that the high velocities, e.g., of Model CO6C, are not present, this may indicate an asymmetric explosion (§5).
4. Other Supernovae

So why have we not observed events like this before? Or have we? Wang and Wheeler (1998) have compared the correlation of supernovae with GRB’s and find a positive correlation with Type Ic’s, but no correlation between GRB’s and other supernovae. There have only been 16 supernovae classified as Type Ic during the six year period 1992-1997 as listed in the Asiago Catalog (Barbon et al. 1993). Presumably many others have been missed, but they do not affect the argument. the BATSE sky coverage is about one third, so one might expect about 5 SN Ic-GRB correlations if all SN Ic are GRBs. But there may also be considerable variation in the GRB’s from supernova to supernova. Perhaps only the stars with the highest mass and biggest explosion energies make a visible GRB, or maybe they must be observed from a certain angle. Nevertheless, it would be interesting to search the known GRB error boxes for subsequent supernovae - but when would the supernova be discovered? Two weeks later, a month?

We checked only three cases because we knew them to be unusually luminous Type Ic’s. These were SN 1992ar (discovered as part of the Calan/Tololo survey, Hamuy & Maza 1992); SN 1997cy, (discovered as part of the Mount Stromlo Abell Cluster supernova search, Germany et al. 1997); and SN 1997ef (Nakano & Sano 1997). SN 1992ar was discovered in late July, 1992 and GRB 920616 occurred about two sigma from the SN’s position. SN 1997ef, discovered on November 25, 1998, has also been pointed out by Wang and Wheeler along with its coincidences (within 3-sigma error boxes) with GRB 971115 and GRB 971120. While it is interesting that both of these supernovae have a reasonable GRB candidate, neither is a particularly compelling case because of the large separation between GRB and the centroid of the error box. However, the situation is different for SN 1997cy. This supernova (not in Wang and Wheeler’s list) had a bizarre spectrum, with broad Ic-like lines like observed in SN 1997ef and 1992ar, but also a Hα line with broad and narrow components. SN 1997cy was also the most luminous supernova ever discovered, having $M_R \approx -21$ at maximum. GRB 970514, a burst with a smaller than typical error box (3-degrees), occurred less than a degree away at a time compatible with the discovery and pre-discovery images. This object is the subject of a paper by Germany et al. (1998). So perhaps SN 1998bw is not an isolated case.

However, we want to state clearly that we do not believe that all or even a majority of Type Ib (or Ic) supernovae make GRB’s. Most of these supernovae are very well modelled by a lower mass explosion (3 - 4 M$_\odot$ helium core) that makes about one-third as much $^{56}$Ni as SN 1998bw and expands with moderate energy $\sim 10^{51}$ erg (e.g., Woosley & Eastman 1997). Even the more massive stars and unusual explosions studied here might only make a GRB when viewed at certain angles. As we discuss in the next section, the GRB is probably
beamed while the supernova is certainly visible at all angles. We expect a GRB supernova association only in the unusual case and two-thirds of these will be missed by BATSE.

5. Conclusions

SN 1998bw was and continues to be an unusual supernova. When modeled as a spherically symmetric explosion, it requires an energy over $20 \times 10^{51}$ erg, a $^{56}$Ni mass over 0.45 $M_\odot$, rapid expansion, high stellar mass, and high mass loss rate (to explain the radio). Of course the most unusual property of SN 1998bw was its proximity to GRB 980425. We have assumed here that the two are related and have looked for ways the supernova might make the burst. For our one-dimensional models we found none.

However, we do find good agreement with the multiband photometry of Galama et al. (1998b), and the bolometric light curve integrated from that data, and the explosion of a 6 $M_\odot$ core of carbon, oxygen, and heavy elements with final kinetic energy $2 - 2.5 \times 10^{52}$ erg. The explosion leaves behind a 1.78 $M_\odot$ (baryonic mass) object, presumably a neutron star and makes about 0.5 $M_\odot$ of $^{56}$Ni. However the mass of the remnant and the explosion energy were not calculated in a consistent way, but were free parameters. We do not think it is critical that our best fit was a carbon-oxygen core and not a helium core; the key quantity is the energy to mass ratio. Type Ic supernovae have weak helium lines chiefly as a consequence of weaker mixing between the helium and $^{56}$Ni shells than in Type Ib (Woosley & Eastman 1997). Even this very energetic explosion is too faint the first few days of the supernova. There are two explanations for this - either there was a helium layer with a larger photospheric radius than the carbon-oxygen core used here that gave a brighter “plateau” before the radioactive decay energy diffused out, or the explosion was asymmetric, ejecting some $^{56}$Ni almost to the surface at some angles - a very mixed model. However, spherically symmetric mixing would have given a larger photosphere and perhaps a redder supernova than was observed (Woosley & Eastman 1997). Helium may be present in the spectrum even in our carbon-oxygen core models, but it is chiefly from photodisintegration and would be the slowest not the fastest moving ejecta. High velocity helium would be a signature of a helium star.

All in all, though the parameters may be extreme, especially the explosion energy, one could model SN 1998bw in a qualitatively similar way to other Type Ib and Ic supernovae, that is if it were not the origin of GRB 980425.

But we believe that it was. So what happened? Can nature really provide $2 \times 10^{52}$ erg to a supernova whose main sequence mass was over 25 $M_\odot$? Current belief (e.g., Burrows
1998; Fryer 1998) is to the contrary. If anything, the explosion actually becomes weaker as one goes to larger mass. The iron core is larger and can potentially provide more neutrinos, but it is also close to criticality and the mass flux from the imploding mantle of the star is formidable. It is very difficult to stop the implosion before the neutron star gives way and collapses to a black hole.

And so it may be that something else happened here, that the explosion was not spherical and powered by neutron star formation, but very asymmetric and powered by jets from black hole formation. Bodenheimer and Woosley (1983) first considered such an outcome to black hole formation and found that a supernova still resulted. Woosley (1993) and Hartmann & Woosley (1995) emphasized jet production and proposed an association of this model with gamma-ray bursts. Initially this model was referred to as the “failed supernova” (because the prompt supernova mechanism failed), and later as the “collapsar model” (Woosley 1996), because it was the outcome of a collapsed star. A model having very similar characteristics, called the “hypernova”, has been discussed by Paczynski (1997). Fryer & Woosley (1998b) have also discussed setting up very similar conditions in the merger, by common envelope, of a stellar mass black hole and the helium core of a massive supergiant star. Current two dimensional studies of the collapsar model by MacFadyen and Woosley (1998ab) are encouraging. Specifically they find, in the collapse of a 14 $M_\odot$ rotating helium star to a black hole, an accretion rate of over 0.1 $M_\odot$ s maintained for about 10 s as the black hole grows from 2 $M_\odot$ to 7 $M_\odot$. The Kerr parameter, $a$, grows to $\sim 0.9$ early on. For these conditions, Popham, Woosley, & Fryer (1998) find that the annihilation of neutrinos radiated from the viscous disk deposits up to $10^{51}$ erg s$^{-1}$ along the rotational axis of the black hole. Thus energies as much as $10^{52}$ erg are potentially available. Some of this energy goes into accelerating relativistic jets along the rotational axes, but more may go into ejecting a lot of mass at lower speeds. MacFadyen & Woosley have not calculated the evolution beyond 15 s. Large amounts of energy can also potentially be extracted from the rotation of the black hole (e.g., Meszaros & Rees 1997).

Viewed this way, GRB 980425 was a low energy analogue of the enormously more luminous “classic” GRB’s. Both are produced by black hole accretion, but in GRB 980425 the jet energy was weaker and $\Gamma$, along our line of sight, lower. Perhaps if we had viewed GRB 980425 straight down the axis a more powerful, harder GRB would have been seen. Or maybe the helium core mass, rotation rate, and therefore black hole accretion rate were not so extreme in GRB 980425 as in other GRB’s. Viewed from the side though, in any case, the emission from the high $\Gamma$ jet would have been suppressed and spread over a much longer time, probably invisible. But even at our angle there may have been, say, $10^{-7} - 10^{-6}$ $M_\odot$ moving with $\Gamma \approx 10$. Colliding with the pre-explosive mass loss at about $10^{13} - 10^{14}$ cm, this would have made the observed burst (Meszaros & Rees 1993). If we had seen SN
1998bw at still lower latitudes, the GRB would have been missed.

Once spherical symmetry is abandoned an entirely different solution becomes possible for the supernova. If matter can fall in to close to the black hole and come out again (MacFadyen & Woosley 1998b), the production of $^{56}$Ni is not directly tied to the shock energy and pre-explosive density structure of the star. It is as if $^{56}$Ni could be made “convectively”. The one number we view with some confidence here is that SN 1998bw made about 0.5 $M_{\odot}$ of $^{56}$Ni. But suppose it could do so while only ejecting a few solar masses of heavy elements and helium. Then the correlation between $^{56}$Ni mass and explosion energy is lost. SN 1998bw could have been a slower moving, lower energy explosion (shared by a smaller ejected mass) than we have calculated here and still have peaked as early as it did.

It is unfortunate that so many questions remain unresolved. First, is it certain that SN 1998bw and GRB 980425 are the same thing? Future missions with smaller error boxes (e.g., HETE-2) should show if this is the case. Finding other historic Type Ic supernovae in coincident with GRB locations from BATSE would also lend credence to this identification. We have given two possible examples. There may be more.

Can a combination of theory and observation still tell us what happened in this supernova/GRB? Continued spectroscopic monitoring of the supernova will obviously be an important diagnostic as the supernova enters (has in fact already entered) its nebular phase. What widths and asymmetries are apparent in the lines of oxygen, iron, silicon, calcium, and carbon? Are the high velocities of Model CO6C really there? What is the mass of the ejecta? Multi-dimensional modeling of the explosion and radiation transport in the collapsar model should also show whether it can explain the observations. If it does not, perhaps something even more interesting has occurred.

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REFERENCES

Barbon, R., Benetti, S., Cappellaro, E., Patat, F., & Turatto, M. 1993, Mem.Soc.Astron.Ital 64, 1083 (update [http://athena.pd.astro.it/~supern/snean.txt](http://athena.pd.astro.it/~supern/snean.txt))

Benetti, S. & Pizzella, A. 1997 IAU Circ 6708
Bodenheimer, P., & Woosley, S. E. 1983, ApJ, 269, 281

Burrows, A. 1998, 9th Ringberg Castle Workshop on Nuclear Astrophysics, eds. E. Müller & W. Hillebrandt, MPA Green Report

Colgate, S. A. 1969, CanJPhys, 46, s476

Colgate, S. A. 1974, ApJ, 187, 333

Eastman, R. G. & Pinto, P. A. 1993, ApJ 412, 731

Ensman, L. M., & Woosley, S. E. 1988, ApJ, 333, 754

Ensman, L. M., & Burrows, A. 1992, ApJ, 393, 742

Fransson, C., Lundquist, P., & Chevalier, R. A. 1996, ApJ, 461, 993

Fryer, C. 1998, *Proc. Second Oak Ridge Symp. on Atomic and Nuclear Astrophysics*, ed. T. Mezzacappa et al., in press, and ApJ, in preparation

Fryer, C., & Woosley, S. E. 1998a, ApJ, in press

Fryer, C., & Woosley, S. E. 1998b, ApJ, in press

Galama, T. J., Vreeswijk, P. M., Pian, E., Frontera, F. Doublier, V., & Gonzalez, J.-F. 1998a, IAU Circ. 6895

Galama, T. J., et. al. 1998b, preprint, [astro-ph/9806175](http://arxiv.org/abs/astro-ph/9806175), Nature, in press.

Garnavich, P., Jha, S., Kirshner, R., & Challis, P. 1997, IAU Circ 6786

Germany, L., Reiss, D., Schmidt, B., Stubbs, C. 1997, IAU Circ 6706

Germany, L., Reiss, D., Schmidt, B., Stubbs, C., 1998, to be submitted to ApJL

Gnatyk, B.I., 1985, Soviet Astronomy Letters, 11, 331

Hamuy, M. & Maza, J. 1992, IAU Circ 5574

Hartmann, D. H., & Woosley, S. E. 1995, Proc. COSPAR meeting, Adv. in Spac. Res., 15, No. 5, 143.

Iwamoto, K. et al., as cited in Galama et al. (1998b)

Johnson, M.H., & McKee, C.F., 1971, Phys. Rev. D, 3, 4
Langer, N. 1989, A&A, 220, 135
Leising, M. D. et al. 1994, ApJL, 431, L95
Lidman, C., Doublier, V., Gonzalez, J.-F., Augusteijn, T., et al. 1998, IAUC 6896
Kulkarni, R., Bloom, J. S., Frail, D. A., Ekers, R., Wieringa, M., Wark, R., & Higdon, J. L. 1998, IAUC Circ. 6903
MacFadyen, A., & Woosley, S. E. 1998a, BAAS, 20, No. 2, 874
MacFadyen, A., & Woosley, S. E. 1998b, ApJ, in preparation
McKee, C.R., & Colgate, S.A., 1973, ApJ, 181, 903
Meszaros, P., & Rees, M.J., 1993, ApJ, 405, 278
Meszaros, P., & Rees, M.J., 1997, ApJL, 482, L29
Nakano, S. & Sano, Y. 1997, IAU Circ 6778
Nemiroff, R. J.. 1993, in AIP Conf Proc. 307, *Gamma-Ray Bursts: Second Huntsville Workshop*, Eds. G. Fishman, J. Brainerd, & K. Hurley, p. 730
Paczynski, B. 1997, ApJL, 484, L45
Patat, F., & Piemonte, A. 1998, IAUC 6918
Pinto, P. A., & Woosley, S. E. 1988, ApJ, 329, 820
Popham, B., Woosley, S. E., & Fryer, C. 1998, ApJ, in preparation
Sadler, E. M., Stathakis, R. J., Boyle, B. J., & Ekers, R. D. 1998, IAU Circ. 6901
Soffita, P. et al. 1998, IAU Circ 6884
Tinney, C., Stathakis, R., & Cannon, R. 1998, IAU Circ. 6896
Wang, L., & Wheeler, J. C. 1998, preprint astro-ph/9806212
Weaver, T.A., Zimmerman, G.B., & Woosley, S.E., 1978, ApJ, 225, 1021
Wieringa, M., Frail, D., Kulkarni, S., Higon, J. L., Wark, R., Bloom, J. S. et al. 1998, IAUC 6896
Wijers, R. A. M. J., Bloom, J. S., Bagla, J. S., & Natarajan, P., 1998, MNRAS, 294, L13
Woosley, S. E. 1993, ApJ, 405, 273

Woosley, S. E. 1996, in Gamma-Ray Bursts: 3rd Huntsville Symposium, AIP Conf. Proc 384, eds. C. Kouveliotous, M. Briggs, & G. Fishman, AIP:New York, 709

Woosley, S. E., Eastman, R. G., Weaver, T. A., & Pinto, P. A. 1994, ApJ, 429, 300

Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181

Woosley, S. E., & Eastman, R. G. 1997, in Thermonuclear Supernovae, eds. P. Ruiz-Lapuente, R. Canal, & J. Isern, NATA ASI series, 821
Table 1. Explosions Simulated

| Model | Mass ($M_\odot$) | Kinetic Energy ($10^{51}$ erg) | Mass $^4$He ($M_\odot$) | Mass $^{16}$O ($M_\odot$) | Mass $^{28}$Si ($M_\odot$) | Mass $^{56}$Ni ($M_\odot$) |
|-------|------------------|-------------------------------|------------------------|--------------------------|-------------------------|------------------------|
| CO6A  | 6.55             | 5.5                           | 0.06                   | 3.3                      | 0.28                    | 0.32                   |
| CO6B  | 6.55             | 15                            | 0.14                   | 3.1                      | 0.36                    | 0.42                   |
| CO6C  | 6.55             | 22                            | 0.20                   | 2.9                      | 0.40                    | 0.47                   |
| CO6D  | 6.55             | 28                            | 0.26                   | 2.8                      | 0.42                    | 0.49                   |
| CO11A | 11.0             | 9.1                           | 0.09                   | 6.3                      | 0.54                    | 0.68                   |
| CO11B | 11.0             | 25                            | 0.21                   | 5.9                      | 0.70                    | 0.84                   |
| HE9A  | 9.12             | 3.7                           | 2.4                    | 3.0                      | 0.35                    | 0.51                   |
| HE9B  | 9.12             | 7.7                           | 2.4                    | 2.9                      | 0.39                    | 0.58                   |
| HE9C  | 9.12             | 21                            | 2.5                    | 2.5                      | 0.54                    | 0.77                   |
| HE14A | 14.1             | 4.2                           | 2.8                    | 6.2                      | 0.46                    | 0.73                   |
| HE14B | 14.1             | 10                            | 2.8                    | 6.0                      | 0.51                    | 0.86                   |

*a*“CO” models are carbon-oxygen cores devoid of any helium surface layer. “HE” models retain their helium shells.

Table 2. Shock Break Out

|         | (10$^{42}$ erg s$^{-1}$) | (10$^6$ K) | (FWHM sec) |
|---------|----------------------------|------------|------------|
| CO6A    | 3.0                        | 2.2        | 0.24       |
| CO6B    | 9.1                        | 3.0        | 0.11       |
| CO6D    | 19                         | 3.6        | 0.08       |
| CO11A   | 5.6                        | 1.3        | 5.8        |
| HE9B    | 130                        | 1.2        | 4.0        |
| HE9C    | 270                        | 1.4        | 2.5        |
Table 3. The Bolometric Light Curve of SN 1998bw

| Days After GRB Event | $\log(L_{UV\text{OIR}})$ ergs s$^{-1}$ |
|----------------------|----------------------------------------|
| 2                    | 42.38                                  |
| 5                    | 42.63                                  |
| 10                   | 42.94                                  |
| 15                   | 43.05                                  |
| 20                   | 43.00                                  |
| 25                   | 42.88                                  |
| 30                   | 42.75                                  |
| 35                   | 42.63                                  |
| 40                   | 42.53                                  |
Fig. 1.— The quantity $\rho r^3$ is plotted as a function of external mass for the three pre-explosive models employed in this study. An empirical relation $M_{\text{ext}} \propto (\rho r^3)^{4/3}$ is apparent.
Fig. 2.— The quantity $\Gamma \beta (\rho r^3)^{0.2}$ is plotted as a function of external mass for several runs after they have reached homologous expansion. Note the near constancy of this product over a large range in external mass, pre-explosive stellar radius, and explosion energy. The upturn of some of the models for low external mass is artificial and a consequence of the velocity approaching the speed of light in the non-relativistic hydro-code. Scaling this quantity to lower values of $\rho r^3$ allows us to estimate the energy and mass ejected as a function of $\Gamma$. 
Fig. 3.— The bolometric light curve for the 9 M$_\odot$ helium core explosions (Table 1) as calculated using EDDINGTON compared to the bolometric light curve obtained by digitizing and integrating the data of Galama et al. (1998b). The distance is assumed to be 36 Mpc ($H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$) and the reddening $A_V = 0.20$. The bolometric data points are obtained by extrapolating a Planck tail into the infrared and a spline into the ultraviolet. Even the most energetic HE9 explosions rise too slowly and peak too late to agree with observations.
Fig. 4.— The bolometric light curve for the 6 M$_{\odot}$ carbon-oxygen core explosions (Table 1) as calculated using EDDINGTON compared to the bolometric light curve (see Fig. 3). For Models CO6C and CO6D the agreement is acceptable, although the models still rise too slowly to explain the brightness of the supernova during the first few days.
Fig. 5.— The multi-band photometry for Model CO6C as calculated using the EDDINGTON code compared to the observations of Galama et al. (1998b). Also given as solid points at maximum light are the results of a non-LTE spectral calculation of the same model. At least at peak light, the agreement between the non-LTE calculation and observations is excellent.
Fig. 6.— The non-LTE spectrum of Model CO6C at maximum optical light (solid curve) compared to the LTE spectrum (dashed curve) used to evaluate the photometric evolution. Both spectra are theoretical. An observed spectrum was not available at this writing.