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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 both optically and in the radio, and it rose quickly to maximum. 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 $0.5–2.8 \times 10^{52}$ ergs). Bolometric light curves and multiband 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 2.2×10^{52} ergs. We also examine potential mechanisms for producing the observed gamma-ray burst (GRB)—shock breakout 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. However, the high explosion energies required to understand the supernova are in contrast to what is expected for such massive stars and indicate that a new sort of explosion may have been identified, possibly the consequence of a collapsar. Indeed a more likely explanation for what was seen is a highly asymmetric explosion in which the GRB was produced by mildly relativistic matter ($\Gamma \approx 5$) running into circumstellar matter along the line of sight to the Earth. The explosion itself was powered by black hole accretion and jets, but unlike "ordinary" gamma-ray bursts, the jets were not of sufficient energy and duration to effectively reach large values of Γ. They may also not have been oriented in our direction. The ejected mass (but not the ^{56}Ni mass) and explosion energy are then smaller. Other associations between luminous Type Ic supernovae and GRBs may exist and should be sought, but most Type Ib and Type Ic supernovae do not make GRBs.

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

1. INTRODUCTION

Gamma-ray bursts (GRBs) have been a challenge to theorists and a source of fascination for all for over 30 yr, and many models have been suggested to explain them (Nemiroff 1993). Lately major progress has occurred in understanding GRBs 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 redshifts of 0.83 and 3.42 and are inferred to have had enormous energies, $\sim 10^{52}$ ergs and $\sim 3 \times 10^{53}$ ergs 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} ergs in *gamma-rays alone* times an uncertain beaming factor that might reduce the energy by a factor of up to 100 at the expense of requiring many more events.

This developing paradigm was challenged last month by the discovery (Galama et al. 1998a, 1998b; Lidman et al. 1998) of a supernova, SN 1998bw, Type Ib (Sadler et al. 1998) and later Ic (Patat & Piemonte 1998), within the 8′ 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 (chance of coincidence is estimated at 1.1×10^{-4} by Galama et al. 1998b). Further, the supernova was unusual, presenting a radio luminosity 100 times brighter than that of a typical Type Ib, brighter in fact than any supernova ever before observed (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 redshift of 3.42. From this we infer that the gamma-ray burst, which lasted 30 seconds, had an energy that was about 10^{48} ergs, or 10^3–10^4 times fainter than a typical cosmological GRB. The BATSE detector on the *Compton Gamma Ray Observatory* also saw the burst (Galama et al. 1998b) for about 35 s and inferred a total energy of $8.5 \pm 1.0 \times 10^{47}$ ergs in gamma-rays. BATSE saw no emission above 300 keV for this burst, making it another example of the so called "no high-energy" GRBs, about 25% of the BATSE sample. At this luminosity, other GRBs 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 hundreds of times that of the "classical" BATSE bursts (*modulo* the beaming factors). This requires a source that is very common in nature. Indeed, BATSE observations can be explained with an event rate of 10^{-7} yr^{-1} L_* galaxy (Wijers et al. 1998), suggesting 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 supernovae, we shall find it necessary to synthesize and eject $\gtrsim 0.45\ M_\odot$ of ^{56}Ni in the explosion. If it was a massive star that exploded, and the strong radio emission suggests that it was, 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 GRBs 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, a preprint by Galama et al. (1998b) appeared that 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 multiband 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 our 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 experimented 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 (§§ 3.3 and 3.4).

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 obtaining 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

TABLE 1
EXPLOSIONS SIMULATED

Model	Mass ($M_\odot$)	Kinetic Energy (10^{51} ergs)	Mass ^{4}He ($M_\odot$)	Mass ^{16}O ($M_\odot$)	Mass ^{28}Si ($M_\odot$)	Mass ^{56}Ni ($M_\odot$)
CO6A[a]	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.

1.8×10^{39} ergs s^{-1} and radius 2.5×10^{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 letter (A, B, C, ...) 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 1.22×10^{10} cm and the luminosity 6.6×10^{38} ergs 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 α 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 et al. (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 Breakout*

The first model ever proposed for gamma-ray bursts was supernova shock breakout (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 et al. 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 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.

The results for a representative sample of our models are given in Table 2. Typical burst luminosities are 10^{43}–10^{44} ergs s^{-1}, with duration less than a second (in practice the duration will be limited by the stellar light crossing time). However, the stellar zoning, though fine by ordinary evolutionary standards (10^{-6} $M_\odot$) and all that could be stabilized against sound waves propagating in the star, still has a large optical depth to electron scattering in the outer zone. The actual temperature and energy for the breakout transient will thus be underestimated and the timescale overestimated.

We can attempt a correction using the (nonrelativistic) formulae (eqs. 36–38) of Matzner & McKee (1999, preprint received after our paper was submitted) for $n = 3$. This calculation gives the second set of entries for each model in Table 2. Apparently our coarse zoned supernova model underestimates the temperature and energy by about an order of magnitude and overestimates the duration even more. These numbers themselves are still underestimates of the energy and temperature though, because the radiation will be blueshifted by the relativistic motion of the emitting

TABLE 2

SHOCK BREAKOUT

Model	$L_{\rm peak}$ (10^{42} ergs s^{-1}	$T_{\rm peak}$ (10^6 K)	Duration (FWHM s)	Energy (10^{42} ergs)
CO6A	3.0	2.2	0.24	0.7
CO6A	...	30	3(−4)	30
CO6B	9.1	3.0	0.11	1.0
CO6B	...	40	1(−4)	60
CO6D	19	3.6	0.08	1.5
CO6D	...	40	8(−5)	80
CO11A	5.6	1.3	5.8	30
CO11A	...	20	1(−3)	200
HE9B	130	1.2	4.0	500
HE9B	...	7.3	0.07	5000
HE9C	270	1.4	2.5	700
HE9C	...	8.8	0.04	9000

layer (Colgate 1969) and because other relativistic effects are left out of the Matzner-McKee formulae (McKee & Colgate 1973). Still, the energies in Table 2 are orders of magnitude short of what is required for SN 1998bw ($\sim 10^{48}$ ergs). As we shall see in the next section, the energy in material that is more than mildly relativistic ($\Gamma \gtrsim 3$) is very small and one does not expect the corrections to the Matzner-McKee formulae to be very large for moderate Γ. The duration of the transient, for our more compact cores that have high temperatures, would also be short compared to the observed GRB ($R/c \sim 0.3$ s vs. ~ 20 s) and would become even shorter for larger Γ (as $R/(2\Gamma^2 c)$ with R the stellar radius; Rees 1966).

Though the problem is worth further investigation, we conclude that direct emission from shock breakout in a massive star as proposed by Colgate (1969, 1974) is unlikely to be the explanation of 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 becomes relativistic. Analytic solutions of ultrarelativistic shocks and semianalytic solutions of mildly relativistic shocks exist (Johnson & McKee 1971; McKee & Colgate 1973). For an exponentially declining density profile, the product of the Lorentz factor (Γ) and the velocity of the shock ($\beta = v/c$ where c is the speed of light) is given by an interpolation between nonrelativistic and ultrarelativistic scaling laws (Gnatyk 1985):

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

where N is a geometric factor set to 2 for spherical symmetry and α is determined, via simulations, to be ~ 0.20.

We can use this scaling relation to estimate the energy ejected as a function of Γ for lower mass zones than we are able to carry in our present (Newtonian) hydrodynamical calculation. In Figures 1 and 2 the quantities ρr^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; Γ and β are evaluated after the matter has reached the coasting phase. The scaling relation for Γ 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

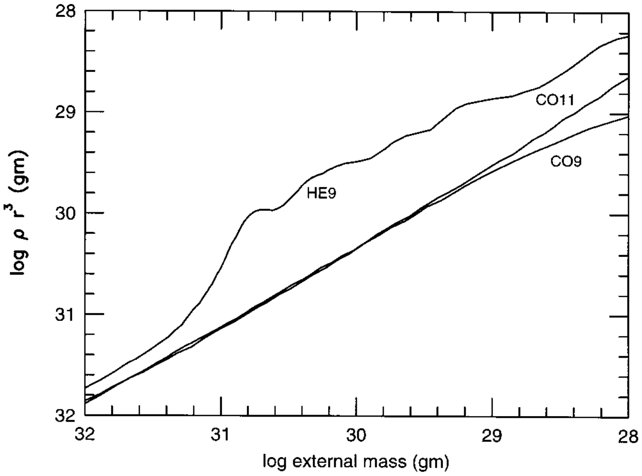

FIG. 1.—Quantity ρr^3 is plotted as a function of external mass for the three preexplosive models employed in this study. An empirical relation $M_{\rm ext} \propto (\rho r^3)^{4/3}$ is apparent.

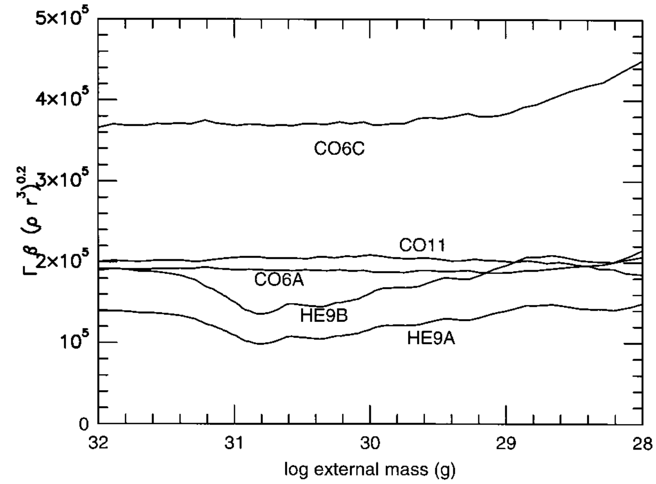

FIG. 2.—Quantity $\Gamma\beta(\rho r^3)^{0.2}$ is plotted as a function of external mass for several runs after they have reached homologous expansion. Note the near constancy of this product over a large range in external mass, preexplosive stellar radius, and explosion energy. The upturn of some of the models for low external mass is artificial and a consequence of the velocity approaching the speed of light in the nonrelativistic hydrocode. Scaling this quantity to lower values of ρr^3 allows us to estimate the energy and mass ejected as a function of Γ

constancy of Q suggests that we can extrapolate the well-determined subrelativistic solution calculated here to higher Γ.

Taking a representative range of $Q \approx 3\text{–}4 \times 10^5$ and a scaling relation between ρr^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 $\Gamma \gtrsim 10$ to be 10^{41}–10^{42} ergs. For Γ of 3 the range is 10^{44}–10^{45} ergs. This is several orders of magnitude less than required to produce the GRB.

Subrelativistic or mildly relativistic ($\Gamma \lesssim 3$) matter is also unlikely to produce the burst. To carry 10^{48} ergs requires a minimum of $\sim 10^{27}$ g. Subrelativistic matter will interact with approximately its own mass before giving up its energy. For a preexplosive stellar mass loss rate of $10^{-5}\ M_\odot$ $\rm y^{-1}$ 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 $\gtrsim 3000$ 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 et al. 1998). There is roughly 5×10^{49} ergs in the outer $10^{-3}\ M_\odot$ of ejecta of our models here, all moving at about $\frac{1}{3}$ c. This could certainly provide a bright radio source, but the expansion would not be relativistic.

What would work in a spherical model is a small amount of material, roughly $10^{-7}\ M_\odot$, accelerated to $\Gamma \gtrsim 5$. This would also correspond to $\sim 10^{48}$ ergs, but the matter would give up its energy after interacting with $1/\Gamma = 0.2$ of its mass and, moreover, the resultant radiation would be beamed so that the effective duration was $R/(2\Gamma^2 c) \approx 10$ s. However, unless the Gnatyk (1985) scaling relation grossly misrepresents the energy distribution at $\Gamma = 5$, our spherical models are incapable of providing these conditions. While the problem warrants further study, we conclude that a spherical explosion, even of 3×10^{52} ergs in the relatively low mass of model CO6D, has difficulty explaining the radio and gamma-ray observations.

It is possible though for an *asymmetric* explosion to have an even larger amount of energy (per unit solid angle) focused into a smaller mass. In the collapsar model the jet intersects about $\frac{1}{60}$ of the sky in each hemisphere (MacFadyen & Woosley 1999). This reduces the above estimates of mass and energy appreciably. The shock velocity is also different for a sustained jet as opposed to that caused by a piston at the origin. The burst itself would be only about 3×10^{46} ergs and the mass at $\Gamma \gtrsim 5$, about 3×10^{-9} $M_\odot$. The necessary explosion energy is correspondingly reduced to a few times 10^{51} ergs. Of course there would also be 30 undetected events of this sort for every one that is seen.

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) and 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" ($L_{\rm UVOIR}$) 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 that have a rapidly falling ultraviolet spectrum. The derived bolometric flux would only be in significant error if there were a large amount of flux below 3000 Å. This appears unlikely except at the earliest times (less than three

TABLE 3

THE BOLOMETRIC LIGHT CURVE OF SN 1998BW

Days After GRB Event	$\log (L_{\rm UVOIR})$ 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

days after the GRB). The derived bolometric light curve is given in Table 3 and in Figures 3 and 4.

These observational data were used to discriminate among possible models. Each model was evolved with the KEPLER hydrocode to 10^5 seconds after explosion, at which point a link was made to a multigroup radiation transport code, EDDINGTON (Eastman & Pinto 1993). This code solves the time-dependent transport equation, in the comoving 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 370–700 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

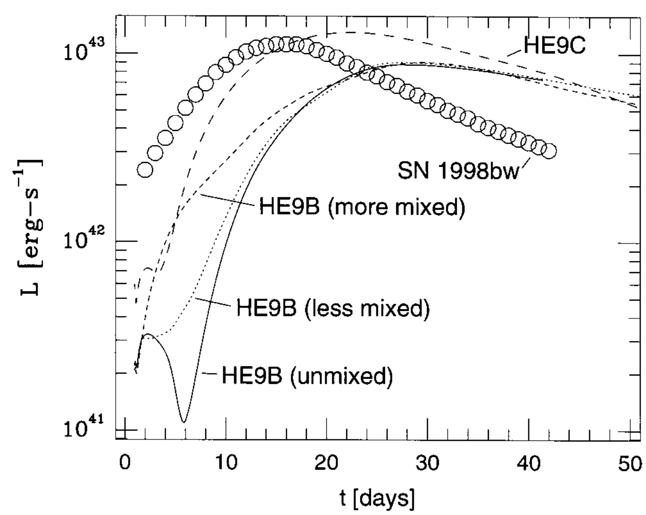

FIG. 3.—Bolometric light curve for the 9 $M_\odot$ helium core explosions (Table 1) as calculated using EDDINGTON compared to the bolometric light curve obtained by digitizing and integrating the data of Galama et al. (1998b). The distance is assumed to be 36 Mpc ($H_0 = 70$ km s^{-1} Mpc^{-1}) and the 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.

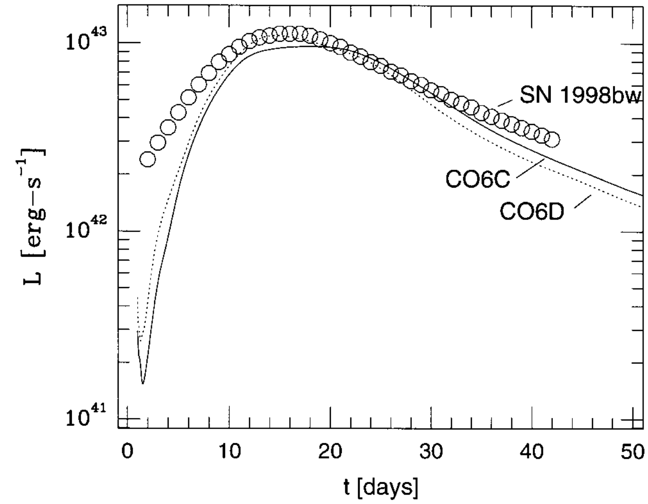

FIG. 4.—Bolometric light curve for the 6 $M_\odot$ carbon-oxygen core explosions (Table 1) as calculated using EDDINGTON compared to the bolometric light curve (see Fig. 3). For models CO6C and CO6D the agreement is acceptable, although the models still rise too slowly to explain the brightness of the supernova during the first few days.

would probably produce a Type Ib, not Ic supernova (Woosley & Eastman 1997).

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 $30 < \lambda < 5 \times 10^4$ Å. 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 almost to 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 preexplosive star had a helium layer and a larger radius. Wolf Rayet stars often have false photospheres because of their large mass loss rate. 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

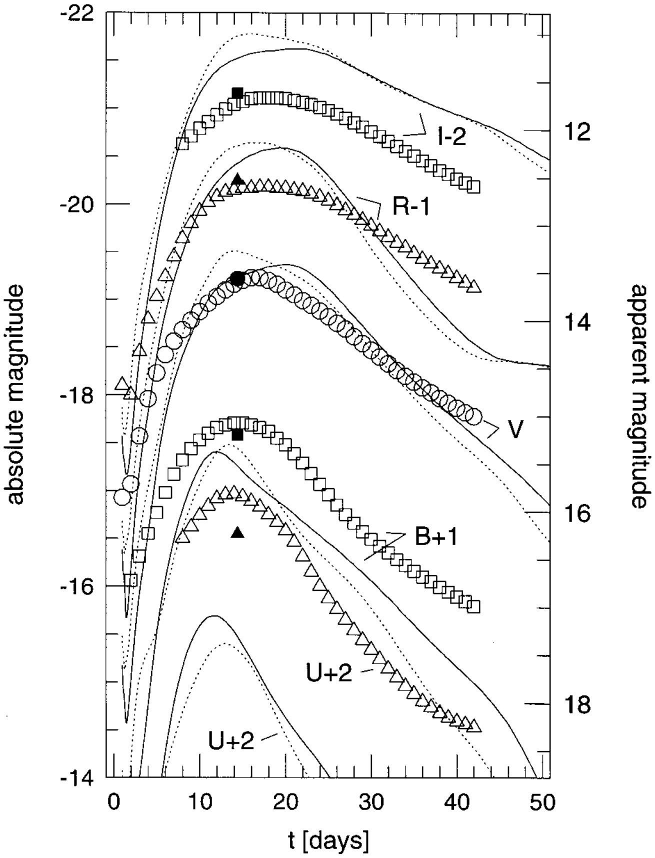

FIG. 5.—Multiband photometry for model CO6C as calculated using the EDDINGTON code compared to the observations of Galama et al. (1998b). Also given as solid points at maximum light are the results of a non-LTE spectral calculation of the same model. At least at peak light, the agreement between the non-LTE calculation and observations is excellent.

in the data of the first few days that the supernova initially faded slightly. This would be consistent with helium recombination.

Another possibility is that the supernova was not spherically symmetric (see also § 5). The very rapid rise to peak would then be ^{56}Ni ejected or almost ejected from the star, but only in our direction, or perhaps circumstellar interaction.

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 Figure 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. Figure 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

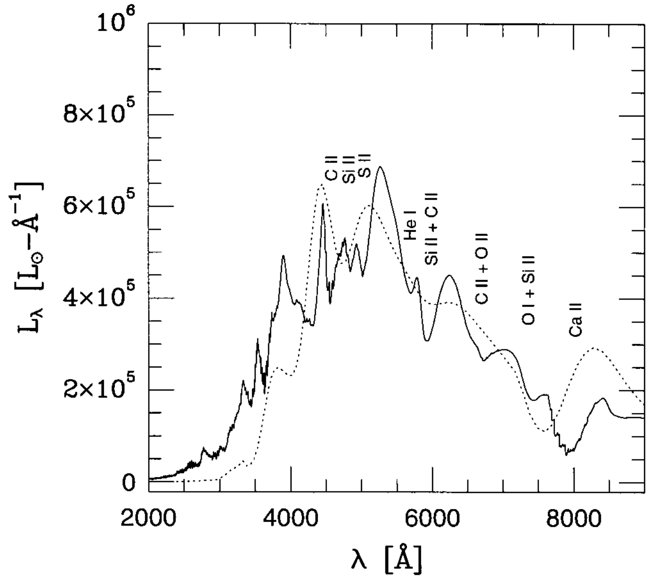

FIG. 6.—Non-LTE spectrum of model CO6C at maximum optical light (*solid curve*) compared to the LTE spectrum (*dashed curve*) used to evaluate the photometric evolution. Both spectra are theoretical. An observed spectrum was not available at this writing.

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 Å 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 λ5876 absorption feature, which Patat & Piemonte say was not present in SN 1998bw. However, it is weak, highly blueshifted, and could easily be mistaken for something else. Also, the He I λ6678 is very weak in model CO6C, and blended with C II and O II, consistent with Patat & Piemonte'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 12,000–26,000 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 are 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 $\sim 2 \times 10^{52}$ ergs, 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 & Wheeler (1998) have compared the correlation of supernovae with GRBs and find a positive correlation with Type Ic supernovae, but no correlation between GRBs and other supernovae. There have only been 16 supernovae classified as Type Ic during the 6 yr period 1992–1997 as listed in the Asiago Catalog (Barbon et al. 1993).[1] 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 five SN Ic-GRB correlations if all SN Ic are GRBs. But there may also be considerable variation in the GRBs 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 supernovae. 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 1992 July and GRB 920616 occurred about two σ from the SN's position. SN 1997ef, discovered on 1998 November 25 has also been pointed out by Wang & Wheeler (1998) along with its coincidences (within 3 σ 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 the GRB and the centroid of the error box. However, the situation is different for SN 1997cy. This supernova (not in Wang & Wheeler's list) had a bizarre spectrum, with broad Ic-like lines like those 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°), occurred less than a degree away at a time compatible with the discovery and prediscovery images. This object is the subject of a paper by Germany et al. (1999). 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 GRBs. Most of these supernovae are very well modeled 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 $\sim 10^{51}$ ergs (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.

[1] Update available at http://athena.pd.astro.it/ supern/snean.txt.

5. CONCLUSIONS

SN 1998bw was and continues to be an unusual supernova. When modeled as a spherically symmetric explosion, it requires an energy over 20×10^{51} ergs, 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), 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 $\times 10^{52}$ ergs. 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 several possible explanations for this. Perhaps 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 maybe the explosion was asymmetric, ejecting some ^{56}Ni almost to the surface at some angles—a very mixed model. Spherically symmetric mixing would not work. It would give 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. The early light curve could also have been due to circumstellar interaction.

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 2×10^{52} ergs 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 & 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 & Woosley (1998, 1999) 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 $\gtrsim 0.9$ early on. For these conditions, Popham, Woosley, & Fryer (1999) find that the annihilation of neutrinos radiated from the viscous disk deposits up to 10^{51} ergs s^{-1} along the rotational axis of the black hole. Large amounts of energy can also potentially be extracted from the rotation of the black hole (e.g., Meszaros & Rees 1997). Thus energies as much as 10^{52} ergs are potentially available. This energy goes into accelerating energetic (though not necessarily relativistic) jets along the rotational axes. If the jets succeed in penetrating the star (and this may take 5–10 s), they then may expand uninhibited, and, if they have enough energy, accelerate to relativistic speeds and make a strong GRB. But if they don't, an energetic, asymmetric supernova will still result. Every GRB would make a supernova of this sort, but not every supernova makes a strong GRB, not even those powered by black hole accretion.

Viewed this way, GRB 980425 was a low-energy analogue of the enormously more luminous "classic" GRBs. Both are produced by black hole accretion, but in GRB 980425 the jet energy was weaker and Γ, at least 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, but not one too violent or the relativistic optical afterglow would have overshadowed the supernova. Perhaps, for a variety of reasons (MacFadyen & Woosley 1999), the accretion rate in GRB 980425 was not as high or as enduring as in other GRBs. But even so, at our angle there may have been, say, 10^{-7} to 10^{-6} $M_\odot$ moving with $\Gamma \approx 10$. Colliding with the preexplosive 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 1999), the production of ^{56}Ni is not directly tied to the shock energy and preexplosive 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, helium, silicon, calcium, and carbon? Is high velocity ($\sim$30,000 km s^{-1}) helium present? This would indicate that the surface was helium rich, an important clue to the supernova progenitor and explosion energy. Are the high velocities of model CO6C really there for other elements? What is the mass of the ejecta? Multidimensional 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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