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A ‘Hypernova’ model for SN 1998bw associated with gamma-ray burst of 25 April 1998 ¹

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¹Partially based on observations collected at ESO-La Silla

The discovery of the peculiar supernova (SN) 1998bw and its possible association with the gamma-ray burst (GRB) 980425^{1,2,3} provide new clues to the understanding of the explosion mechanism of very massive stars and to the origin of some classes of gamma-ray bursts. Its spectra indicate that SN 1998bw is a type Ic supernova^{3,4}, but its peak luminosity is unusually high compared with typical type Ic supernovae³. Here we report our findings that the optical spectra and the light curve of SN 1998bw can be well reproduced by an extremely energetic explosion of a massive carbon+oxygen (C+O) star. The kinetic energy is as large as $\sim 2 - 5 \times 10^{52}$ ergs, more than ten times the previously known energy of supernovae. For this reason, the explosion may be called a ‘hypernova’. Such a C+O star is the stripped core of a very massive star that has lost its H and He envelopes. The extremely large energy, suggesting the existence of a new mechanism of massive star explosion, can cause a relativistic shock that may be linked to the gamma-ray burst.

SN 1998bw is classified spectroscopically as a type Ic supernova, because its optical spectra lack any hydrogen and helium features and the Si II absorption feature is very different from those of type Ia supernovae⁵. Two recent type Ic supernovae, SNe 1994I^{6,7} and 1997ef⁸, have somewhat similar spectra to that of SN 1998bw and their light curves were well reproduced by models of the collapse-induced explosion of C+O stars (Fig.1). This has led us to construct hydrodynamical models of exploding C+O stars also for SN 1998bw. The model parameters are the stellar mass M_{CO} , the explosion energy E_{exp} , and the mass of the synthesized ⁵⁶Ni M_{56} , assuming that the light is generated by the ⁵⁶Ni decay as in type Ia supernovae.

Despite their spectral similarity, these three type Ic supernovae have distinctly different brightnesses and light curve shapes as seen in Figure 1. This is because the brightness and light curve shape depend mainly on M_{56} and on the pair of values $(E_{\text{exp}}, M_{\text{CO}})$, respectively, while the spectral features are sensitive to the chemical composition, which is basically similar in the C+O stars. The peak bolometric luminosity $\sim 1.6 \times 10^{43}$ ergs s⁻¹ implies that SN 1998bw produced $\sim 0.7M_{\odot}$ of ⁵⁶Ni, which is much more than in SNe 1994I^{6,7} and 1997ef⁸.

The above parameters are tightly constrained by comparing the light curves (Fig. 1), synthetic spectra (Fig. 2), and photospheric velocities (Fig. 3) with the observations of SN 1998bw³. We find that the optical properties of SN 1998bw are best reproduced by a model with $M_{\text{CO}} = 13.8M_{\odot}$, $E_{\text{exp}} = 3 \times 10^{52}$ ergs, and $M_{56} = 0.7M_{\odot}$ (hereafter designated as CO138). A C+O star of this mass originates from a $\sim 40 M_{\odot}$ main sequence star. A compact remnant of mass $M_{\text{rem}} = 2.9M_{\odot}$ must have

been left behind for $0.7M_{\odot}$ ^{56}Ni to be ejected, as required to reproduce the brightness of SN 1998bw. M_{rem} exceeds the upper mass limit for a stable neutron star, suggesting the formation of a black hole.

In order to reproduce the light curve of SN 1998bw, the time of core collapse should be set to coincide with the detection of GRB 980425 to within $+0.7/-2$ days. The rapid rise of the light curve requires the presence of radioactive ^{56}Ni near the surface, implying that large-scale mixing of material took place because of hydrodynamical instabilities. The light curve shape can be reproduced with different explosion models, because the peak width τ_{LC} , which reflects the time scale of photon diffusion, scales approximately as $\tau_{\text{LC}} \propto \kappa^{1/2} M_{\text{ej}}^{3/4} E_{\text{exp}}^{-1/4}$ (ref.13), where $M_{\text{ej}} = M_{\text{CO}} - M_{\text{rem}}$ is the mass of the ejected matter, and κ denotes the optical opacity. However, the photospheric velocity scales in a different manner, as $v \propto M_{\text{ej}}^{-1/2} E_{\text{exp}}^{1/2}$, so that both M_{ej} and E_{exp} can be constrained from the spectroscopic data as follows.

Synthetic spectra¹⁴ of various explosion models were compared with the observed spectra of SN 1998bw at 3 epochs: May 3, 11 and 23. The observed featureless spectra are the result of the blending of many metal lines reaching large velocity and with a large velocity spread. Extensive blending can only be achieved with models that have a large mass in high velocity regions. Therefore, the models that are more massive and have a larger kinetic energy give better fits. For models with $M_{\text{ej}} < 10M_{\odot}$, the photosphere forms at velocities much smaller than those of the observed lines and the lines do not blend as much as in the observed spectra. Figure 2 shows that model CO138 gives consistent fits to the spectra at all three epochs.

Figure 3 shows that the evolution of the photospheric velocity computed from model CO138 (appeared in *lines*) agrees with that obtained from spectral fits (*filled circles*), and with the observed velocities of the Si II (*open circles*) and Ca II (*square*) lines, within the uncertainty arising from the light curve fitting (*dotted lines*). These velocities are among the highest ever measured in supernovae of any types and thus the smaller mass C+O star progenitors can be ruled out. By taking into account the uncertainties, we conclude that massive C+O star models with $E_{\text{exp}} \sim 2 - 5 \times 10^{52}$ ergs and $M_{\text{CO}} \sim 12 - 15M_{\odot}$ reproduce the observed light curve and spectra of SN 1998bw well.

Here we call the supernova with such an extremely large explosion energy ($> 10^{52}$ ergs) a ‘hypernova’¹⁵. The evolutionary process leading to the hypernova could be as follows: The massive progenitor of initially $\sim 40M_{\odot}$ had a particularly large angular momentum and a strong magnetic field owing possibly to the spiraling-in of a companion star in a binary system. The collapse of the massive Fe core at the end of the evolution led to the formation of a rapidly rotating black hole. Then the large rotational energy of the black hole was extracted with a strong magnetic field to induce a successful explosion^{15,16}.

The hypernova could induce a gamma-ray burst in the following way: At the shock breakout in the energetic explosion, the surface layer is easily accelerated to produce a relativistic shock. When it collides with circumstellar or interstellar matter, non-thermal electrons that are produced at the shock front emit high-energy photons via synchrotron emission. The energy of these photons is given by $\sim 160 \text{ keV } (\Gamma/100)n_1^{1/2}$ (ref.17), where Γ denotes the Lorentz factor of the expanding shell and n_1 is the density of the interstellar matter in cm^{-3} . Thus the event could be observed as a gamma-ray burst if Γ becomes as large as ~ 100 . Our preliminary calculations show that spherically symmetric models may not produce large enough energies in gamma-rays. However, an axi-symmetric explosion could produce particularly high speed material by a focused shock wave in the polar direction. The strong radio emission at early phases, which suggests the existence of such a relativistic flow¹⁸, is consistent with the above scenario. Preliminary spectral polarization measurements show that polarization is small ($\sim 1\%$ but possibly decreasing between 4 May and 20 May). Some degree of asymmetry in the envelope morphology is therefore possible, but the precise form depends on the undetermined orientation relative to the line-of-sight. In the near future, late time spectra will provide the heavy element abundances and their velocities in SN 1998bw to test our prediction (given in the legend of Figure 1). The late time decline rate of the light curve is also expected to give further constraints on the model parameters¹⁹.

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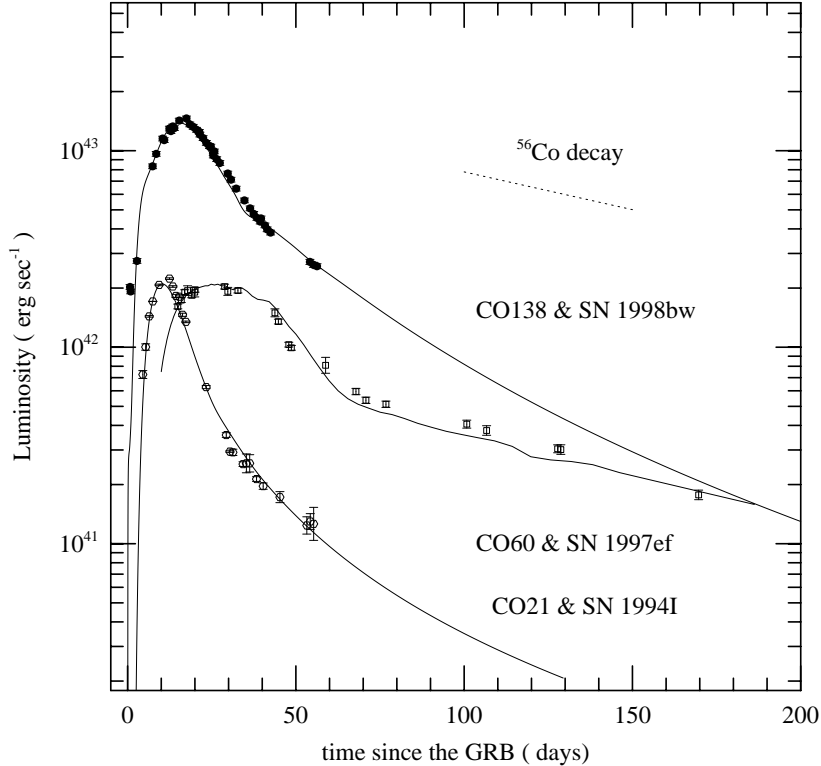


Figure 1: The bolometric light curve of model CO138 ($M_{\text{CO}} = 13.8M_{\odot}$, $E_{\text{exp}} = 3 \times 10^{52}$ ergs, $M_{56} = 0.7M_{\odot}$) compared with the observations of SN1998bw. The time of the core collapse is set at the detection of the GRB980425. The distance to the host galaxy ESO 184-G82 is taken to be $\sim 39 \pm 1$ Mpc, as estimated from the redshift $z \sim 0.0085 \pm 0.0002$ and a Hubble constant $65 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The light curves of other type Ic supernovae SNe 1997ef^{8,9} and 1994I¹⁰ are also shown, for comparison, together with the corresponding theoretical models, CO60 (ref.8, $M_{\text{CO}} = 6.0M_{\odot}$, $E_{\text{exp}} = 10^{51}$ ergs, $M_{56} = 0.15M_{\odot}$) and CO21 (ref.6, $M_{\text{CO}} = 2.1M_{\odot}$, $E_{\text{exp}} = 10^{51}$ ergs, $M_{56} = 0.07M_{\odot}$), respectively. Note that E_{exp} and M_{56} of CO138(SN 1998bw) are very much larger than in the models for the other two type Ic supernovae. The observed V light curves are transformed into the bolometric light curves assuming that the bolometric correction is negligible. The light curves are computed with a radiative transfer code⁸, assuming a detailed balance between photo-ionizations and recombinations and adopting a simplified treatment of line opacity. The explosive nucleosynthesis was calculated using a detailed nuclear reaction network^{11,12} including a total of 211 isotopes up to ^{71}Ge . Our calculation predicts the amount of other radioactive nuclei, $1.4 \times 10^{-3} M_{\odot}$ ^{44}Ti and $1.4 \times 10^{-2} M_{\odot}$ ^{57}Ni , and other stable elements, ^{16}O : 7.6, ^{20}Ne : 0.44, ^{23}Na : 1.2×10^{-6} , ^{24}Mg : 0.46, ^{27}Al : 0.18, ^{20}Si : 0.82, ^{40}Ca : 5.0×10^{-2} , ^{20}Ne : 0.44 (in M_{\odot}).

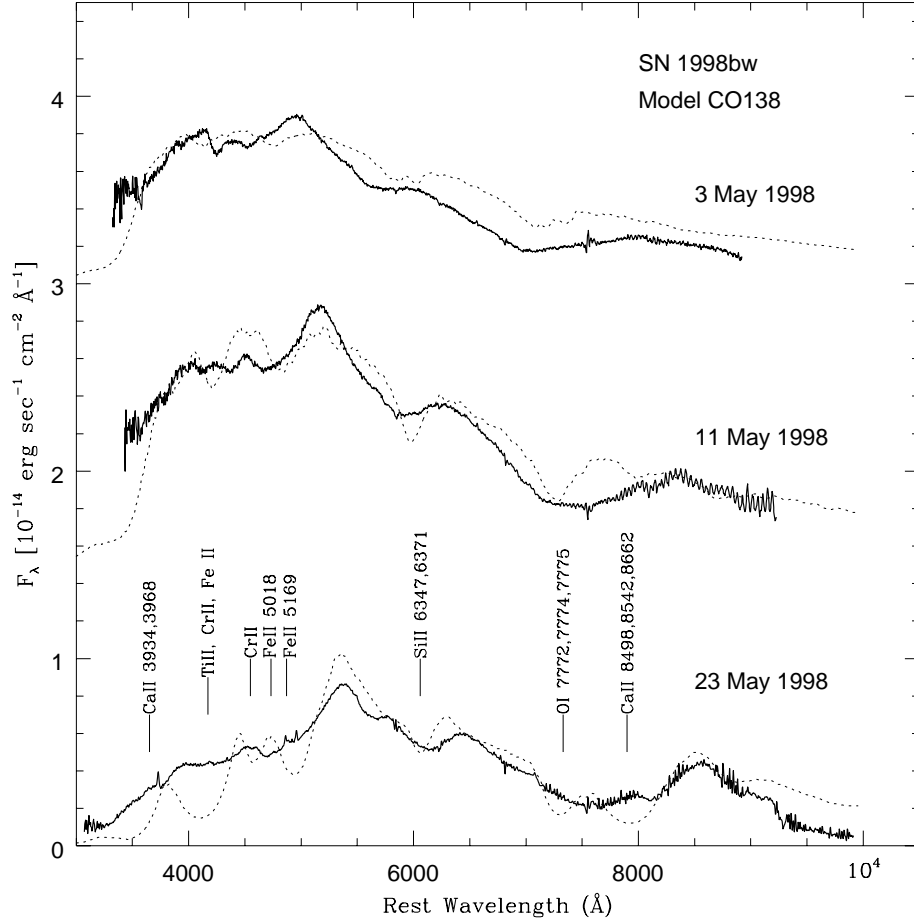


Figure 2: Three observed spectra (full lines, Patat *et al.*, in preparation), where the galaxy background has been subtracted, are compared with the synthetic spectra (dashed lines) computed with the Monte Carlo code¹⁴, improved with the inclusion of photon branching (Mazzali & Lucy, in preparation), using model CO138. The synthetic spectra were computed using the luminosity derived from the light curve and a distance of 39 Mpc, and assuming no reddening. The observed featureless spectra are the result of the blending of many metal lines reaching large velocity and with a large velocity spread. The apparent emission peaks are actually low opacity regions of the spectrum where photons can escape. The 3 May and the 11 May spectra have been shifted upwards by 3.0 and $1.5 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$, respectively. The most important lines are marked on the 23 May spectrum, but they also contribute to the 3 May and 11 May spectra, although with somewhat different ratios. Line blending in the case of SN 1998bw is even more severe than it was in the massive type Ic supernova 1997ef⁸, indicating an even larger mass. The massive progenitor model is the only one that gives the correct extent of line blending. Differences in the blue band between the observed spectrum and the synthetic one are probably due to uncertainties in the determination of the abundance and distribution of Fe-group elements in high velocity parts of the ejecta. The possible presence of O I line absorption in the early spectra complicates any derivation of velocities in the high velocity wings of the feature conceivably ascribed to Ca II absorption.

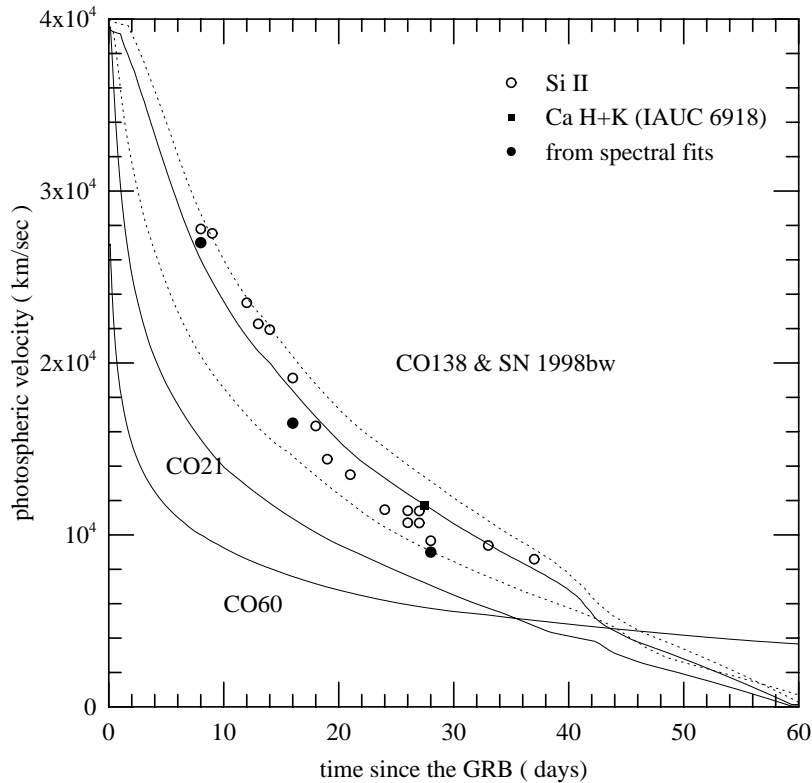


Figure 3: The evolution of the calculated photospheric velocities of CO138, CO60, and CO21 (solid lines), the photospheric velocities obtained from spectral models (filled circles), the observed velocity of the Si II 634.7, 637.1 nm line measured in the spectra at the absorption core (open circles, Patat *et al.* in preparation), and that of the Ca II H+K doublet measured in the spectrum of May 23 (square, ref.4). The observed velocities are in good agreement with the photospheric velocities of CO138, which are much larger velocity than in CO21 and CO60 because of the much larger explosion energy. The upper and lower dotted lines are the velocities of models with $(M_{\text{CO}}, E_{\text{exp}}) = (15 M_{\odot}, 5 \times 10^{52} \text{ ergs})$ and $(12 M_{\odot}, 2 \times 10^{52} \text{ ergs})$, respectively. The light curves of these two models also fit SN 1998bw well. This indicates the acceptable ranges of $M_{\text{CO}} \sim 12 - 15 M_{\odot}$ and $E_{\text{exp}} \sim 2 - 5 \times 10^{52} \text{ ergs}$.