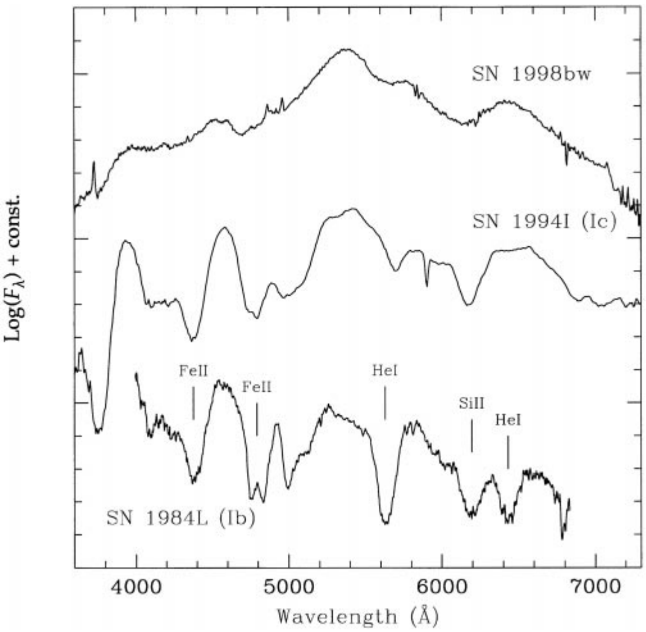

Figure 2 Representative spectra near maximum light of SN1998bw, SN1994I (type Ic; ESO supernova archive, courtesy of M. Turatto), and SN1984L (type Ib)[28]. Hydrogen lines, characteristic of type II supernovae, and Si II, characteristic of type Ia supernovae, are absent in the spectrum of SN1998bw. The strong He I 5876 line which characterizes type Ib supernovae is very weak in SN1994I and absent in SN 1998bw. The overall shape of the spectrum of SN1998bw is similar to that of a type Ic supernova, although the spectral features are less pronounced. The difference is strongest in the 3,500–5,000 Å region, where the Ca II and Fe II lines are much weaker than in SN1994I. In this respect, SN1998bw appears to represent an extreme case in the odd class of type Ic supernovae.

amounts of ^{56}Ni (~0.7 solar masses) have to be synthesized in the explosion[16]; the large energy and ^{56}Ni mass would be unprecedented for a core-collapse supernova.

If one accepts the possibility that GRB980425 and SN1998bw are associated, one must conclude that GRB980425 is a rare type of GRB, and SN1998bw is a rare type of supernova. The radio properties[8,9] of SN1998bw show the peculiar nature of this event independent of whether or not it is associated with GRB980425.

The consequence of an association is that the γ-ray peak luminosity of GRB980425 is $L_\gamma = (5.5 \pm 0.7) \times 10^{46}\,\mathrm{erg\,s^{-1}}$ (in the 24–1,820 keV band) and its total γ-ray energy budget is $(8.1 \times 1.0) \times 10^{47}$ erg. These values are much smaller than those of 'normal' GRBs which have peak luminosities of up to $10^{52}\,\mathrm{erg\,s^{-1}}$ and total energies[5] up to several times 10^{53} erg. This implies that very different mechanisms can produce GRBs which cannot be distinguished on the basis of their γ-ray properties, and that models explaining GRB980425/SN1998bw are unlikely to apply to 'normal' GRBs and vice versa. □

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A hypernova model for the supernova associated with the γ-ray burst of 25 April 1998

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The discovery of the unusual supernova SN1998bw, and its possible association with the γ-ray burst GRB 980425[1–3], provide new insights into the explosion mechanism of very massive stars and the origin of some classes of γ-ray bursts. Optical spectra indicate that SN1998bw is a type Ic supernova[3,4], but its peak luminosity is unusually high compared with typical type Ic supernovae[3]. Here we report our findings that the optical spectra

and the light curve of SN1998bw can be well reproduced by an extremely energetic explosion of a massive star composed mainly of carbon and oxygen (having lost its hydrogen and helium envelopes). The kinetic energy of the ejecta is as large as (2–5) × 10^{52} erg, more than ten times that of previously observed supernovae. This type of supernova could therefore be termed 'hypernova'. The extremely large energy suggests the existence of a new mechanism of massive star explosion that can also produce the relativistic shocks necessary to generate the observed γ-rays.

SN1998bw is spectroscopically classified 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 supernovae[5]. Two recent type Ic supernovae, SN1994I[6,7] and 1997ef[8], have somewhat similar spectra to that of SN1998bw 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 for SN1998bw, assuming that the light is generated by the ^{56}Ni decay as in type Ia supernovae. The model parameters are the stellar mass M_{CO}, the explosion energy E_{exp} and the mass of the synthesized ^{56}Ni M_{56}.

Despite their spectral similarity, these three type Ic supernovae have distinctly different brightnesses and light-curve shapes (Fig. 1). This is because the brightness and light-curve shape depend mainly on M_{56} and a pair of (E_{exp}, M_{CO}), respectively, while the spectral features are sensitive to the chemical composition, which is basically similar among the C + O stars. The peak absolute luminosity $\sim 1.6 \times 10^{43}$ erg s^{-1} implies that SN1998bw produced $\sim 0.7 M_\odot$ of ^{56}Ni, which is much larger than in SN1994I[6,7] and SN1997ef[8] (here $M_\odot$ is the solar mass).

The above parameters are constrained tightly by comparing the light curves (Fig. 1), synthetic spectra (Fig. 2) and photospheric velocities (Fig. 3) with the observations of SN1998bw[3]. We find that the optical properties of SN1998bw are best reproduced by a model with $M_{CO} = 13.8 M_\odot$, $E_{exp} = 3 \times 10^{52}$ erg, and $M_{56} = 0.7 M_\odot$ (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 $M_{rem} = 2.9 M_\odot$ must have been left behind for $0.7 M_\odot$ ^{56}Ni to be ejected, as required to reproduce the brightness of SN1998bw. This

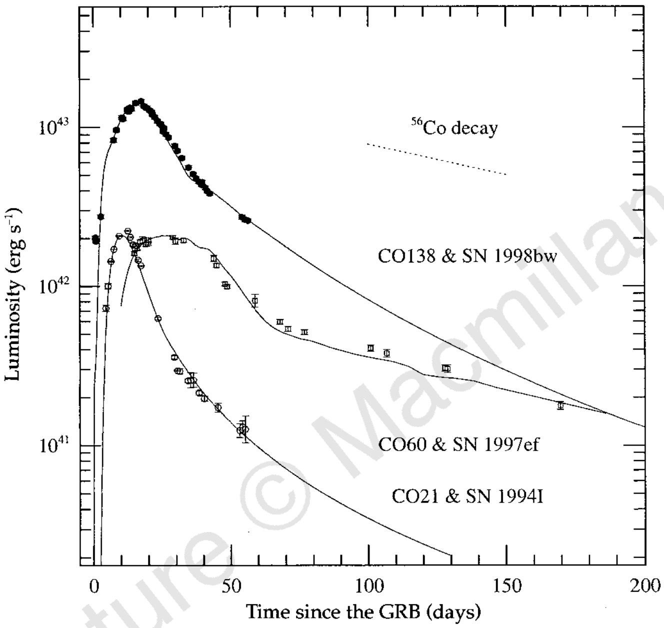

Figure 1 Light curves of three type Ic supernovae, SN1998bw, 1997ef, 1994I and their models. The bolometric light curve of model CO138 ($M_{CO} = 13.8 M_\odot$, $E_{exp} = 3 \times 10^{52}$ erg, $M_{56} = 0.7 M_\odot$) compared with the observations of SN1998bw. The time of the core collapse is set at the detection of GRB980425. The distance to the host galaxy ESO184-G82 is taken to be $\sim 39 \pm 1$ Mpc, as estimated from the redshift $z \approx 0.0085 \pm 0.0002$ and a Hubble constant 65 km s^{-1} Mpc^{-1}. The light curves of other type Ic supernovae SN1997ef[8,16] and SN1994I[17] are also shown, for comparison, together with the corresponding theoretical models, CO60 (ref. 8, $M_{CO} = 6.0 M_\odot$, $E_{exp} = 10^{51}$ erg, $M_{56} = 0.15 M_\odot$) and CO21 (ref. 6, $M_{CO} = 2.1 M_\odot$, $E_{exp} = 10^{51}$ erg, $M_{56} = 0.07 M_\odot$), respectively. We note that E_{exp} and M_{56} of CO138 (SN1998bw) are much larger than in the models for the other two type Ic supernovae. The observed V-band 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 code[8], 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[18,19] 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 (in $M_\odot$) ^{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.

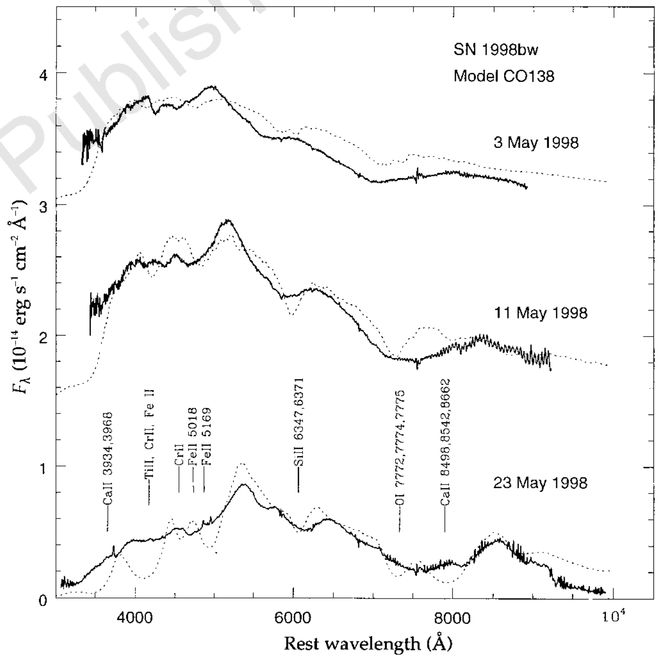

Figure 2 Observed spectra of SN1998bw and synthetic spectra. Three observed spectra (full lines; F.P. *et al.*, manuscript in preparation), where the galaxy background has been subtracted, are compared with the synthetic spectra (dashed lines) computed with a Monte Carlo model[10], improved with the inclusion of photon branching (P.A.M. and L. B. Lucy, manuscript 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 3.0×10^{-14} and 1.5×10^{-14} erg s^{-1} cm^{-2} Å^{-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 SN1998bw is even more severe than it was in the massive type Ic supernova 1997ef[8], 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.

mass M_{rem} exceeds the upper mass limit for a stable neutron star, suggesting the formation of a black hole.

To reproduce the light curve of SN1998bw, the time of core collapse should be set to coincide with the detection of GRB980425 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, possibly owing to hydrodynamical instabilities. The light-curve shape can be reproduced with different explosion models, because the peak width τ_{LC}, which reflects the timescale of photon diffusion, scales approximately as $\tau_{LC} \propto \kappa^{1/2} M_{ej}^{3/4} E_{exp}^{-1/4}$ (ref. 9), where $M_{ej} = M_{CO} - M_{rem}$ is the mass of the ejected matter, and κ denotes the optical opacity. However, the photospheric velocity scales in a different manner, as $v \propto M_{ej}^{-1/2} E_{exp}^{1/2}$, so that both M_{ej} and E_{exp} can be constrained from the spectroscopic data as follows.

Synthetic spectra[10] of various explosion models were compared with the observed spectra of SN1998bw at three 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 $M_{ej} < 10 M_\odot$, 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 (upper solid line) agrees with that obtained from spectral fits (filled circles), and with the observed velocities of the Si II (open circles) and Ca II (squares) lines, within

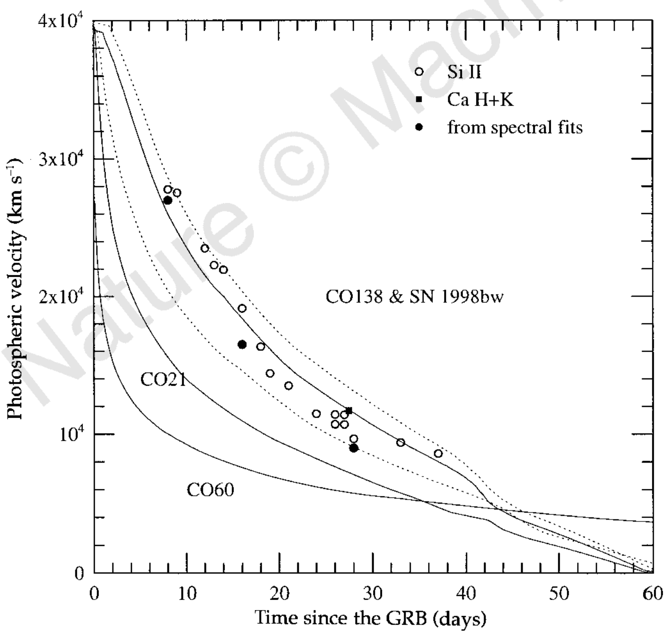

Figure 3 Photospheric velocities of SN1998bw. The evolution of the calculated photospheric velocities of CO138, CO60, and CO21 (solid lines), the photospheric velocity obtained from spectral models (filled circles), the observed velocity of the Si II 634.7, 637.1 nm line measured in the spectra at the absorption core (open circles, F. Patat *et al.*, manuscript 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 than in CO21 and CO60 because of the much larger explosion energies. The upper and lower dotted lines are the velocities of models with $(M_{CO}, E_{exp}) = (15 M_\odot,\ 5 \times 10^{52}\,\mathrm{erg})$ and $(12 M_\odot, 2 \times 10^{52}\,\mathrm{erg})$, respectively. The light curves of these two models also fit SN1998bw well. This indicates the acceptable ranges of $M_{CO} \approx (12\text{–}15) M_\odot$ and $E_{exp} \approx (2\text{–}5) \times 10^{52}$ erg.

the uncertainty arising from the light-curve fitting (dotted lines). These velocities are among the highest ever measured in supernovae of any type 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 $E_{exp} \approx (2\text{–}5) \times 10^{52}$ erg and $M_{CO} \approx (12\text{–}15) M_\odot$ reproduce well the observed light curve and spectra of SN1998bw.

Here we call the supernova with such an extremely large explosion energy ($>10^{52}$ erg) a 'hypernova'[11]. The evolutionary process leading to the hypernova would be as follows. The massive progenitor of initially $\sim 40 M_\odot$ had a particularly large angular momentum and a strong magnetic field, owing possibly to the spiralling-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[11,12].

The hypernova could induce a γ-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 approximately by 160 keV $(\Gamma/100)^4 n_1^{1/2}$ (ref. 13), 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 γ-ray burst if Γ becomes as large as $\sim$100. Our preliminary calculations show that spherically symmetric models may not produce large enough energies in γ-rays. However, an axi-symmetric explosion could produce particularly high-speed material by a focused shock wave in a polar direction. The strong radio emission at early phases, which suggests the existence of such a relativistic flow[14], is consistent with the above model. Preliminary spectral polarization measurements show that polarization is small ($\sim$1%, but possibly decreasing between 4 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 SN1998bw to test our prediction (given in Fig. 1 legend). The late-time decline rate of the light curve is also expected to give further constraints on the model parameters[15]. □

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