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Peculiar, low-luminosity Type II supernovae: low-energy explosions in massive progenitors?

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ABSTRACT

A number of supernovae, classified as Type II, show remarkably peculiar properties such as an extremely low expansion velocity and an extraordinarily small amount of ^{56}Ni in the ejecta. We present a joint analysis of the available observations for two of these peculiar Type II supernovae, SN 1997D and SN 1999br, using a comprehensive semi-analytic method that can reproduce the light curve and the evolution of the line velocity and continuum temperature. We find that these events are underenergetic with respect to a typical Type II supernova and that the inferred mass of the ejecta is relatively large. We discuss the possibility that these supernovae originate from the explosion of a massive progenitor in which the rate of early infall of stellar material on the collapsed core is large. Events of this type could form a black hole remnant, giving rise to significant fallback and late-time accretion.

Key words: methods: analytical – supernovae: general – supernovae: individual: SN 1997D – supernovae: individual: SN 1999br.

1 INTRODUCTION

Recently, a number of supernovae have been discovered that, according to their spectral properties, are classified as Type II, but that at the same time show remarkably peculiar properties. The first clearly identified example was the exceptionally faint SN 1997D in NGC 1536 (Turatto et al. 1998; Benetti et al. 2001). SN 1997D showed both a very faint radioactive tail in the light curve, indicating an ejected ^{56}Ni mass of only a few $\times 10^{-3}$ M$_{\odot}$, and a low expansion velocity of $\sim$1000 km s^{-1}. Modelling the spectra and light curve Turatto et al. (1998) concluded that a low-energy explosion in a 26-M$_{\odot}$ progenitor star could successfully fit the early observations. The scenario of the low-energy explosion of a high-mass progenitor is also consistent with the late-time ($\sim$400 d) spectral and photometric data (Benetti et al. 2001). Chugai & Utrobin (2000) have presented an alternative analysis in which the progenitor was a star at the low end of the mass range of core-collapse supernovae (8–12 M$_{\odot}$).

The very low luminosity at discovery (10 times less than the peak luminosity reached by SN 1987A) and very small expansion velocity of the ejecta (three to four times less than that of a normal Type II supernova) of SN 1997D suggest that this explosion event was underenergetic. The mechanism that causes the energy of the explosion to be so low is a challenging and important problem in the physics of core-collapse supernovae. In fact, the exact evolution of the star after neutrino reheating depends on the rate of early infall of stellar material on the collapsed core and on the binding energy of the envelope. If both are large, as in high-mass stars ($M >$ 20 M$_{\odot}$), the energy available to accelerate and heat up the ejecta can be greatly reduced and, eventually, may become insufficient to cause a successful explosion. Therefore, after the passage of the shock wave (and possibly the reverse shock formed at the H–He interface) a variable amount of matter may remain gravitationally bound to the collapsed remnant and fall back on to it (Woosley & Weaver 1995). For this reason it was suggested that SN 1997D could host a black hole remnant formed during the explosion (Turatto et al. 1998) and that the luminosity powered by fallback of envelope material on to the central black hole could emerge at approximately 1000–1200 d after the explosion (Zampieri, Shapiro & Colpi 1998). Unfortunately, to date it has not been possible to confirm or disprove this prediction observationally.

After SN 1997D, a number of supernovae with similar observational properties have been identified. These objects appear to define a fairly homogeneous group of explosion events (Pastorello et al., in

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preparation). As for SN 1997D, these supernovae provide a unique opportunity to probe the physics of the explosion and reach a better understanding of both the explosion mechanism and the conditions for the formation of black hole remnants. In this paper we present the results of a joint analysis of the observations of two peculiar Type II supernovae with very low luminosity and expansion velocity, SN 1997D and SN 1999br, which are representative of the properties of the whole group. In particular, SN 1999br represents the most extreme case of a low-luminosity event to date and appears to follow a recently reported correlation between expansion velocities of the ejecta and bolometric luminosities during the plateau phase (Hamuy & Pinto 2002).

In Section 2 we describe the basic spectral and photometric data of these supernovae. Section 3 summarizes the semi-analytic method employed to model the light curve and the evolution of the line velocity and continuum temperature of Type II supernovae. Finally, in Section 4 the main results are presented and their consequences regarding the nature of the progenitors and the energy of the explosion are briefly discussed.

2 PECULIAR TYPE II SUPERNOVAE

Supernova 1997D, serendipitously discovered on 1997 January 14 during an observation of the parent galaxy NGC 1536 (De Mello & Benetti 1997), is the first clearly identified example of a peculiar Type II supernova with a very low luminosity and expansion velocity (Turatto et al. 1998). It was detected when it was already decaying from the plateau and was at least 2 mag fainter than a typical Type II supernova (Patat et al. 1994). The decline rate of the last segment of the bolometric light curve is consistent with complete thermalization of the gamma-rays from the radioactive decay of ^{56}Co into ^{56}Fe. Assuming for SN 1997D the same deposition as in SN 1987A, the ejected ^{56}Ni mass is $\sim10^{-3}$–10^{-2} M$_{\odot}$ (Benetti et al. 2001). The spectra are dominated by a red continuum and P-Cygni profiles of H I, Ba II, Ca II, Na I and Sc II (see Fig. 1). The most striking property of these spectra is the very low expansion velocity inferred from the spectral lines. The minima of the absorption lines give an expansion velocity of approximately 1100–1200 km s^{-1} for H (see Benetti et al. 2001 for details).

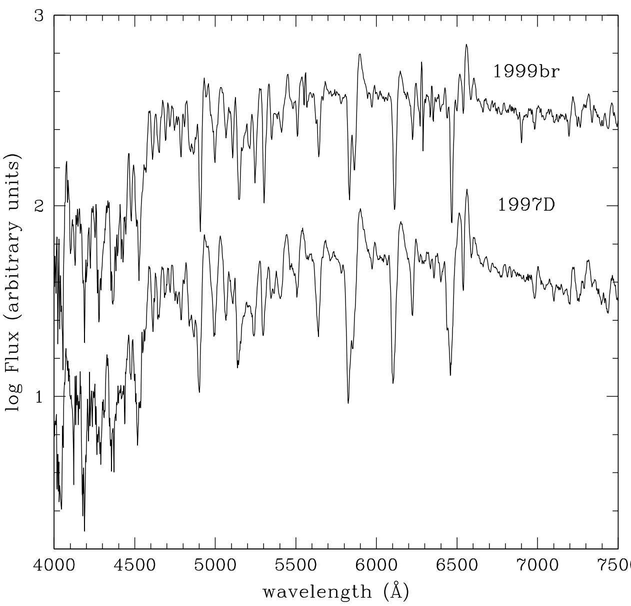

Figure 1. Spectra of SN 1997D and SN 1999br at a phase $\sim$100 d. The spectrum of SN 1999br was obtained on 1999 July 20 at the ESO–Danish 1.54-m telescope equipped with DFOSC (+grism 4). The spectrum of SN 1997D was taken on 1997 January 15 with the ESO 1.52-m telescope (B&C +grating 27).

Recently, other supernovae with properties similar to those of SN 1997D have been identified. A comprehensive analysis of the observations of these peculiar supernovae, including the recently discovered SN 2001dc, will be presented elsewhere (Pastorello et al., in preparation). Here we focus on one particularly representative object, SN 1999br in NGC 4900, discovered on 1999 April 12 (King 1999). Filippenko et al. (1999) pointed out the exceptionally low luminosity of this event. Later, Patat et al. (1999) recognized that SN 1999br shows other properties similar to those of SN 1997D, such as spectra with narrow P-Cygni lines, prominent Ba II features and a low continuum temperature. This supernova had a long plateau lasting at least 110 d with a mean luminosity of only $\lesssim 10^{41}$ erg s^{-1}. It was extensively monitored during the first $\sim$110 d with the CTIO and ESO telescopes, yielding extremely good photometric and spectroscopic coverages (Hamuy et al., in preparation). The spectrum of SN 1999br taken at a phase of $\sim$100 d shows narrow metal lines (Fig. 1). As in the case of SN 1997D, the red continuum and the strength of Ba II lines are caused by the low temperature of the ejecta. The *U–B* bands are strongly affected by line blanketing as the temperature decreases.

As shown in Fig. 1, the spectrum of SN 1997D obtained soon after discovery and that of SN 1999br at $\sim$100 d are strikingly similar in both the continuum and the line components. Taking the ratio of the two spectra results in a rather flat curve where the main deviations are caused by the slightly different linewidth (i.e. different expansion velocities of the ejecta) and spectral resolution. The expansion velocity of SN 1997D is only $\sim$5 per cent larger than that of SN 1999br. The close resemblance of these two spectra, the low inferred expansion velocity ($\sim$1000 km s^{-1}) and the fact that the two supernovae have comparable luminosities strongly suggest that SN 1997D and SN 1999br may be similar events. In the following we will investigate in detail the consequences of this assumption.

SN 1997D was discovered at the end of the plateau stage when the light curve was plummeting. The duration and luminosity of the plateau were inferred by comparison between models and observations and the consequent estimate of the explosion epoch ($\sim$60 d before discovery) was uncertain (Turatto et al. 1998). On the other hand, the date of the explosion of SN 1999br has an uncertainty of only a few days (thanks to a stringent pre-discovery limit). Then, from the similarity of the observational properties (luminosities and spectra) of SN 1997D and SN 1999br, we tentatively assume that the phase of SN 1997D at discovery is $\sim$90–100 d. This assumption will be checked by means of a detailed comparison of spectral-synthesis models with observations, presently under way.

3 THE MODEL

In order to determine the physical properties of a supernova, the observed light curve and spectra are compared with numerical simulations. Usually, it is important to carry out a preliminary investigation in order to obtain an approximate but reliable estimate of the physical conditions of the ejected gas and to establish a framework within which more detailed follow-up calculations can be performed. For these reasons, we have implemented a semi-analytic model in spherical symmetry that can provide a robust estimate of the parameters of the ejecta of Type II supernovae. The novelty of the present approach lies mainly in the fact that the physical properties of the envelope are derived by performing a simultaneous comparison of the observed and simulated light curve, evolution of the line velocity and continuum temperature. The model follows the approach originally introduced by Arnett (1980) and later developed by Arnett & Fu (1989) and Arnett (1996). The treatment of the motion of the recombination front follows in part the work of Popov (1992). The present analysis includes all the relevant energy sources powering the supernova and evolves the envelope in three distinct phases that cover the whole evolution from the photospheric up to the late nebular stages. We also include the energy input from recombination that may be particularly important for low-energy events such as SN 1997D. The model has been tested against numerical radiation–hydrodynamic computations in spherical symmetry under the same assumptions, giving good agreement. The details of the method and its validation will be presented in a companion paper (Zampieri et al., in preparation). Here we briefly summarize the basic ideas.

Full hydrodynamical calculations using realistic pre-supernova models show that the dynamical evolution of the envelope during shock passage is quite complex. The propagation of the shock determines how the explosion energy is distributed in the envelope of the progenitor star. The innermost layers, composed of helium and heavier elements, transfer almost all of their kinetic energy and momentum to the hydrogen envelope. The star mixes but does not homogenize. The actual velocity, density and heavy-element distributions of the post-shock material affect the light curve and estimation of the envelope mass in a major way. In the present analysis we do not consider the evolution of the star during this complex phase but rather assume idealized initial conditions that provide an approximate description of the ejected material after shock (and possible reverse shock) passage, as derived from hydrodynamical calculations. The evolution starts at time $t_{\rm in}$ (since core collapse) when the envelope is essentially free-coasting and in homologous expansion. In realistic explosion calculations, it takes several hours in order for the envelope to relax to this state. We adopt $t_{\rm in} \simeq 5$ h. At this stage, the velocity V of each gas shell is approximately constant and proportional to its position r, $V(r) = V_0(r/R_0)$, where R_0 and V_0 are the initial radius and velocity of the outermost shell of the envelope. Therefore, the radius of each gas shell increases linearly with time: for the outermost shell, $R = R_0 + V_0(t - t_{\rm in})$. The post-shock, ejected envelope is assumed to have spatially constant density ρ (Fig. 2) and total mass $M_{\rm env} = 4\pi\rho R^3/3$. Mass conservation gives $\rho = \rho_0(R_0/R)^3$, where ρ_0 is the initial density. In reality, the outer part of the star develops a steep power-law density structure that affects the light curve during the first few days after shock breakout (which is not included). However, this is only $\sim$1 per cent by mass of the star, while most of the stellar material resides in the inner part with roughly constant density. The latter region dominates the light curve after 10–20 d. The expansion velocity of the envelope as a function of interior (Lagrangian) mass $m(r) = 4\pi\rho r^3/3$ is then $V(m) = V_0(m/M_{\rm env})^{1/3}$ (see Fig. 2). The initial thermal + kinetic energy of the envelope is $E = (3/10)M_{\rm env}V_0^2/f_0$, where f_0 is the initial fraction of kinetic energy. Elements are assumed to be completely mixed throughout the envelope. In our simple spherically symmetric model, their distribution depends only on r (or m). In particular, hydrogen, helium and oxygen are assumed to be uniformly distributed, whereas ^{56}Ni is more centrally peaked (see Fig. 2). Our assumptions concerning the velocity and elemental distributions provide only an approximate description of the actual post-shock structure of the envelope and should be regarded as a potential source of systematic uncertainty in the present model.

The evolution of the supernova envelope starts at time $t_{\rm in}$ and is schematically divided into three phases. During the first stage (a few tens of days) the envelope is hot and completely ionized because of the energy deposited by the shock wave. In the following phase (from 30 to 40 d up to $\sim$100 d), because of the decrease in temperature caused by expansion and radiative diffusion, the envelope recombines and can be schematically divided into two regions, below and above the position of the recombination wavefront. In the third stage (after $\sim$100 d), the ejecta are completely recombined and transparent to optical photons. The evolution is computed by solving the energy balance equation for the envelope gas. The thermal balance is governed by the competition among the energy input from trapped gamma-rays, the $P\,dV$ work and the energy losses through radiative diffusion. Assuming that radiation is in local thermodynamic equilibrium (LTE) with the gas throughout the envelope, the energy balance equation becomes a second-order partial differential equation for the temperature T. Arnett (1996) has shown that, under specific assumptions on the spatial distribution of ^{56}Ni, the energy equation (with appropriate boundary conditions) can be solved by the separation of variables. The function that describes the radial dependence $\psi(r)$ is solution of an eigenvalue equation (see, for example, equation D.48 of Arnett 1996). The final solution has the form

$$T^4(t, r) = T_0^4 \left(\frac{R_0}{R}\right)^4 \psi(x)\phi(t), \qquad (1)$$

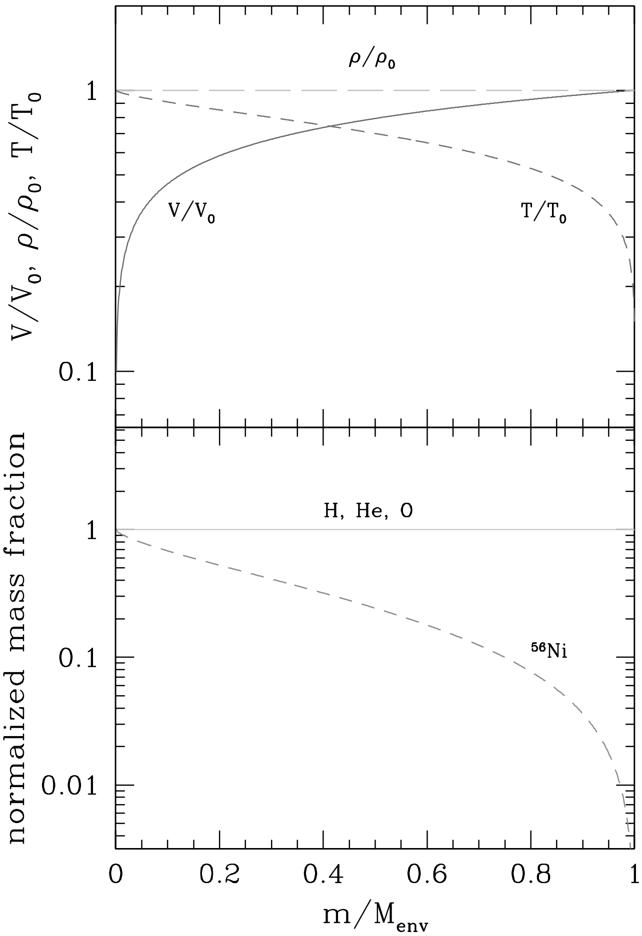

Figure 2. Initial ($t = t_{\rm in}$) conditions of the post-shock envelope in our model. Upper panel: velocity V, density ρ and temperature T distributions as a function of interior (Lagrangian) mass m. Bottom panel: dependence of hydrogen, helium, oxygen and nickel abundances on m.

where $x = r/R$, T_0 is a constant reference temperature, $\phi(t)$ is the function that describes the time-dependence [$\phi(0) = 1$] and, in the limit of zero mean free path, $\psi(x) = \sin(\pi x)/(\pi x)$ (Arnett's 'radiative zero' solution). The term $(R_0/R)^4$ accounts for adiabatic expansion. At $t = t_{\rm in}$, the radial temperature profile is $T/T_0 = \psi(x)^{1/4}$ (see Fig. 2). Once a solution for $\phi(t)$ is calculated, the emitted luminosity is approximately given by the expression for the diffusion luminosity $L = -(4\pi r^2 c)/(3\kappa\rho)[\partial aT^4/\partial r]_{r=R}$, where κ is the gas opacity.

When the gas starts to recombine at $t = t_{\rm rec,0}$, the part of the envelope below the position r_i of the wavefront is assumed to be in LTE with radiation. We adopt the approximation that in this region radiative diffusion can effectively readjust the radial temperature distribution to the changing position of the outer boundary at $r_i = r_i(t)$ ('slow approximation', Arnett & Fu 1989). In this assumption, the spatial dependence of T is essentially given by Arnett's 'radiative zero' solution. Therefore, we search for approximate solutions of the energy equation of the form given in equation (1), with x replaced by x/x_i, $x_i = r_i/R$ and $\psi(x/x_i) = \sin(\pi x/x_i)/(\pi x/x_i)$ (Arnett 1996). The function that gives the time-dependence of the temperature profile, $\phi(t)$, can be computed approximately by setting the diffusion luminosity at recombination equal to the luminosity emitted by a blackbody at the effective temperature, $4\pi r_i^2 \sigma T_{\rm eff}^4$ (Popov 1992). This gives

$$\phi(t) = \frac{3}{4}\kappa\rho_0 R_0 \left(\frac{T_{\rm eff}}{T_0}\right)^4 \left[\left(-y^2\frac{{\rm d}\psi}{{\rm d}y}\right)_{y=1}\right]^{-1} \left(\frac{R}{R_0}\right)^2 x_i, \qquad (2)$$

where $y = x/x_i$ and $T_{\rm eff}$ is the effective temperature, which is approximately constant and nearly equal to the gas ionization temperature. Using equations (1) (with x replaced by x/x_i) and (2), and integrating the energy equation over the ionized region, we obtain an equation for the motion of the recombination wavefront $x_i(t)$. Once a solution for x_i is computed, the bolometric luminosity from the inner envelope is approximately given by (see Zampieri et al., in preparation, for details)

$$L_{r_i} = L + 4\pi r_i^2 v_i \left(aT_{\rm eff}^4/2 + \rho Q_{\rm ion}\right), \qquad (3)$$

where $L = -[(4\pi caT_0^4)/(3\kappa\rho_0)](y^2\,{\rm d}\psi/{\rm d}y)_{y=1} R_0 x_i \phi(t)$ is the diffusion luminosity, the second term on the right-hand side is the total advection luminosity released because of the wavefront motion, $v_i = \dot{x}_i R$ is the wavefront velocity relative to the envelope gas and $Q_{\rm ion}$ is the recombination energy per unit mass.

In the recombined region ($r_i \leqslant r \leqslant R$), the deposition of gamma-ray photon energy through Comptonization and photoelectric absorption of heavy elements is the dominant thermal and radiative process. The optical luminosity emitted in this region originates by the reprocessing of the gamma-rays and becomes important only at the end of the recombination stage (which coincides with the end of the plateau), when the radioactive decay time of ^{56}Co becomes comparable to the expansion time-scale. An approximate expression for this luminosity can be obtained neglecting the internal energy and the $P{\rm d}V$ work in the energy equation and integrating it over the interval $r_i \leqslant r \leqslant R$. The total bolometric luminosity of the envelope during this phase is then

$$L_{\rm tot} = L_{r_i} + 4\pi\rho_0 R_0^3 X_{\rm Ni,0} f(t) \int_{x_i}^1 x^2 \xi_{\rm Ni}(x)\,{\rm d}x, \qquad (4)$$

where $X_{\rm Ni,0}$ and $\xi_{\rm Ni}(x)$ are the central mass fraction and radial distribution of ^{56}Ni, respectively, $f(t) = [3.9 \times 10^{10} {\rm e}^{-t/\tau_{\rm Ni}} + 7.2 \times 10^9({\rm e}^{-t/\tau_{\rm Co}} - {\rm e}^{-t/\tau_{\rm Ni}})]$ erg g^{-1} s^{-1}, and $\tau_{\rm Ni} = 8.8$ d and $\tau_{\rm Co} = 111$ d are the nickel and cobalt decay times, respectively. Following Arnett (1996), we take $\xi_{\rm Ni}(x) = \psi(x) = \sin(\pi x)/(\pi x)$ (see Fig. 2, where the ^{56}Ni abundance is shown as a function of m).

In the third stage, when the envelope has completely recombined, the ^{56}Co radioactive decay time is shorter than the expansion time-scale and the luminosity is given by the second term in equation (4) with $x_i = 0$.

4 RESULTS AND DISCUSSION

Following the discussion in Section 2, we assume that the phase of SN 1997D at discovery is ~90–100 d and that the early light curve and the evolution of the line velocity resemble closely those of SN 1999br. Fig. 3 shows the evolution of the *UBVRI* luminosity, the velocity of metal (Sc II) lines and the continuum temperature of SN 1997D and SN 1999br along with the results of our semi-analytic model calculations. In the top panel, the observed and calculated light curves of SN 1987A are also shown for comparison. The continuum temperatures have been estimated by fitting the spectra with a Planckian function and are affected by a significant uncertainty (±500 K) because of the severe line blanketing at short wavelengths (<4500 Å, see Fig. 1). The line velocity and continuum temperature inferred from the model refer to the photospheric epoch. Hence the final two plots in Fig. 3 are truncated at the end of the recombination phase (~110 d).

Considering the approximations adopted in the model, the general agreement with observations is satisfactory. We emphasize that obtaining a simultaneous 'fit' of the light curve and the evolution of the line velocity and continuum temperature is an essential requirement to obtain a meaningful estimate of the parameters of the ejected envelope. In particular, the long plateau, the apparent break in the line velocity profile at ~30 d and its fast decline impose rather severe constraints on the model. The break appears to be related to the onset of recombination, which terminates when the light curves plummets at ~110 d.

The parameters of the post-shock, ejected envelope required to reproduce the observations of SN 1997D and SN 1999br are listed in Table 1. Only the values of the radius R_0, mass $M_{\rm env}$, ^{56}Ni mass $M_{\rm Ni}$ and outer velocity V_0 (and hence initial energy) of the envelope have been significantly varied. The other model parameters were maintained essentially equal to the values required to reproduce the observations of SN 1987A. In particular, a colour correction factor $f_{\rm c} = T_{\rm c}/T_{\rm eff} = 1.1$–$1.3$ has been adopted to reproduce the observed continuum temperature for all the supernovae. Small colour corrections are rather common in stellar and supernova atmospheres and are induced by distortions of the continuum caused by radiative transfer processes (e.g. scattering, wavelength-dependent opacities; see, e.g., Eastman, Schmidt & Kirshner 1996).

Interpolating simultaneously the light curve and the evolution of the line velocity and continuum temperature results in a rather robust 'fit'. As shown in Table 1, the estimated value of the initial thermal + kinetic energy of the ejecta E indicates that both events were rather underenergetic compared with a typical Type II supernova. The inferred ^{56}Ni mass of SN 1999br is extremely small, testifying to the fact that the energy available to produce and eject nucleosynthetic elements was very low. Furthermore, because of the low luminosity in the plateau stage, the post-explosion envelope is rather compact. The ejected envelope masses, $M_{\rm env}$, are quite large, comparable to those required to reproduce the plateau of typical Type II supernovae. In particular, the ejected envelope mass of SN 1997D is almost three times larger than that estimated by Chugai & Utrobin (2000) and only 30 per cent smaller than that inferred by Turatto et al. (1998). It is worth noting that the gross properties of

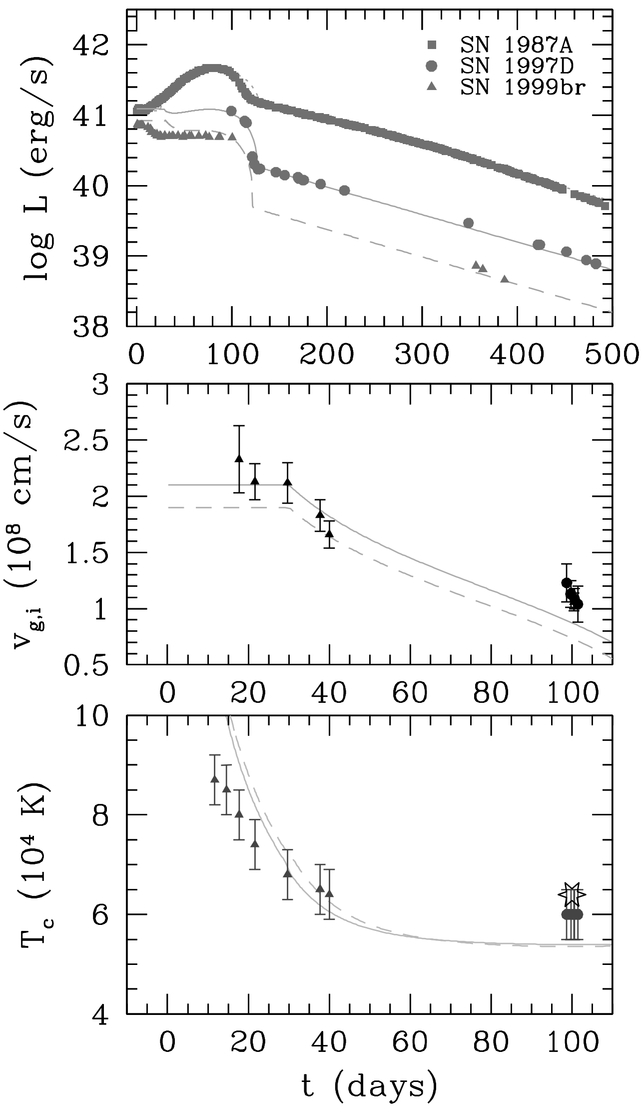

Figure 3. *UBVRI* luminosity, L, velocity of metal (Sc II) lines, $v_{g,i}$, and continuum temperature, T_c, as a function of time for SN 1997D (circles) and SN 1999br (triangles). The light curve of SN 1987A is also shown for comparison. The adopted distance modulus and the estimated total reddening are $\mu = 18.49$, $E(B-V) = 0.18$ for SN 1987A, $\mu = 31.29$, $E(B-V) = 0.02$ for SN 1997D and $\mu = 31.19$, $E(B-V) = 0.02$ for SN 1999br (see Pastorello et al., in preparation, for details). The solid, long-dashed and short-dashed lines represent the model curves. The velocities in the middle panel are those of the gas at the position of the recombination wavefront $v_{g,i} = x_i V_0$. The asterisk is the continuum temperature inferred from the spectral synthesis model of SN 1997D at discovery (Turatto et al. 1998) moved to a phase of ∼100 d.

the light curve and line velocity of SN 1997D and SN 1999br can be roughly accounted for by SN 1987A-like parameters, but simply decreasing the expansion velocity V_0 (and hence the energy E) and ^{56}Ni mass.

Although it is not straightforward to determine the error in the parameters, we estimate that the intrinsic uncertainty of the 'fit' is not larger than ∼30 per cent (see also Zampieri et al., in preparation). Additional sources of systematic errors are related to the approximations introduced in the present analysis, in particular to the choice of the initial conditions. Although it is known that significant mixing occurred in SN 1987A (see, e.g., Woosley 1988), this effect may be less pronounced in other supernovae. The light curve is very sensitive to the prescription for mixing and to the actual velocity distribution as a function of mass $V(m)$. In particular, the luminosity and duration of the plateau depend on the energy and mass of the high-velocity, hydrogen-rich part of the envelope. If the innermost helium and heavier elements layers did not mix appreciably with the hydrogen envelope, they would not produce any observable effect (having very low energy). In this case, the estimated value of $M_{\rm env}$ would simply refer to the hydrogen envelope mass. Then, in general, $M_{\rm env}$ represents a lower limit to the total mass of the ejecta. Furthermore, the estimate of the envelope mass is sensitive to uncertainties in the actual value of the gas opacity and the details of the recombination physics. Here we adopted $\kappa = 0.2$ cm^2 g^{-1}, $t_{\rm rec,0} \simeq 30$ d and $T_{\rm eff} = 4000$–4400 K, values similar to those used for the 'fit' of SN 1987A. Only a larger opacity and/or a delayed onset of recombination could, in principle, allow for smaller envelope masses, but this is not in agreement with what was found for SN 1987A and other Type II supernovae (Zampieri et al., in preparation). The fact that the line velocities at ∼100 d are slightly larger than what was predicted by the model (see Fig. 3) seems to indicate that the assumption of spatially constant density is only approximately correct and that more mass is concentrated in the innermost, low-velocity part of the envelope. This effect may reduce the estimated energy E because the bulk of the kinetic energy is carried by the outer, high-velocity layers.

We emphasize that the present analysis for SN 1997D is based on the assumption that it is an event similar to SN 1999br. However, although the inferred parameters of the ejecta of SN 1997D rely on this hypothesis, the estimates for SN 1999br are certainly valid because they are not affected by uncertainties on the early light curve, the duration of the plateau and the evolution of the line velocity.

Determining the mass of the progenitor is quite a difficult task and, unless a pre-discovery identification is available (see, e.g., Smartt et al. 2002), the inferred value is usually rather uncertain. Adding to the mass of the envelope reported in Table 1 the mass of the collapsed core ($\approx 2\,{\rm M}_\odot$), the progenitors of SN 1997D and SN 1999br have at least 19 and $16\,{\rm M}_\odot$, respectively. We stress that these are most probably lower bounds and the actual values of the progenitor masses are likely to be larger. Therefore, the present estimates situate SN 1997D and SN 1999br in the intermediate-mass progenitor range and rule out that they originate from the low end of the mass range of core-collapse supernovae.

It should be noted that the results of the present analysis are essentially insensitive to the inclusion of Rayleigh scattering from neutral hydrogen. In fact, towards the end of the plateau, $\tau_{\rm ra} \sim \kappa_{\rm ra}\rho r \sim 0.1$, where $r \sim 10^{15}$ cm, $\rho \sim 10^{-12}$ g cm^{-3} and the Rayleigh scattering opacity $\kappa_{\rm ra} \sim 10^{-4}$ cm^2 g^{-1}. Therefore, the outer recombined region is essentially transparent to Rayleigh scattering.

Understanding why the energy of these peculiar Type II supernovae is low is of paramount importance in connection with the hydrodynamics of the explosion and the formation of the central compact object. Because the mass of the iron core before the explosion does not vary significantly with progenitor mass M_* (Woosley & Weaver 1995), the gravitational potential energy liberated during the collapse of the core is roughly independent of M_*. Therefore, the energy of the ejecta depends mostly on neutrino reheating and the hydrodynamic interaction of the supernova shock with the surrounding material. To unbind a spherically symmetric envelope, the shock must overcome the ram pressure of the gas that started to accrete after the collapse of the core (see, e.g., Fryer 1999). With increasing progenitor mass both the ram pressure and the binding energy of the envelope become larger. Therefore, comparatively

Table 1. Parameters of the semi-analytic model.

	R_0 (10^{12} cm)	$M_{\rm env}$ ($\mathrm{M}_\odot$)	$M_{\rm Ni}$ ($\mathrm{M}_\odot$)	V_0 (10^8 cm s^{-1})	E (10^{51} erg)	f_0	κ (cm^2 g^{-1})	$t_{\rm rec,0}$ (d)	$T_{\rm eff}$ (K)	$f_{\rm c}$
SN 1987A	5	18	7.5×10^{-2}	2.7	1.6	0.5	0.2	25	4800	1.1
SN 1997D	9	17	8×10^{-3}	2.1	0.9	0.5	0.2	30	4400	1.2
SN 1999br	7.5	14	2×10^{-3}	1.9	0.6	0.5	0.2	30	4000	1.3

Notes. R_0 is the initial radius of the envelope. $M_{\rm env}$ is the ejected envelope mass. $M_{\rm Ni}$ is the mass of ^{56}Ni. V_0 is the velocity of the envelope material at the outer shell. E is the initial thermal + kinetic energy of the ejecta. f_0 is the fraction of the initial energy that goes into kinetic energy. κ is the gas opacity. $t_{\rm rec,0}$ is the time when the envelope starts to recombine. $T_{\rm eff}$ is the effective temperature during recombination. $f_{\rm c} = T_{\rm c}/T_{\rm eff}$ is the colour correction factor.

less energy remains available to heat up and accelerate the ejecta. The final luminosity and expansion velocity are then small and the resulting supernova is underenergetic (Zampieri 2002). In this respect, it is tempting to note that the difference between the inferred total (kinetic + thermal + binding) energy of SN 1987A ($\sim 2.5 \times 10^{51}$ erg) and the ejected kinetic + thermal energy of SN 1997D is $\sim 1.5 \times 10^{51}$ erg, comparable to the binding energy of the envelope in a 25–30 $\mathrm{M}_\odot$ progenitor star (Woosley & Weaver 1995). Therefore, in SN 1997D, a large fraction of the gravitational potential energy liberated by the collapse of the core may have been spent in trying to unbind the massive envelope.

An important consequence of this scenario is that, because of the low kinetic energy acquired by the envelope, a large fraction of the stellar material (in particular, the innermost layers that have smaller velocities) is likely to remain gravitationally bound to the core after shock passage, falling back on to it. This is also confirmed by the small amount of ^{56}Co present in the ejecta. The fallback of stellar material may also turn the newly formed neutron star into a black hole. If this happens, the late-time fallback on to the central black hole may give rise to detectable emission of radiation with a characteristic power-law decay (Zampieri et al. 1998; Balberg, Zampieri & Shapiro 2000). The detection of this emission in the late-time light curve would provide the first direct evidence for the presence of a black hole in the site of its formation.

We note that the overall picture may be different for a supernova from a massive progenitor where the post-shock envelope retains a significant fraction of its initial angular momentum. In this case, the hydrodynamics of the explosion becomes more complex and may give rise to a high energy, asymmetric explosion (MacFadyen & Woosley 1999).

The present analysis indicates that the parameters of the ejecta of SN 1997D and SN 1999br are consistent with them being intermediate-mass core-collapse supernovae. If the mass of their progenitors is sufficiently large, they could form a black hole remnant, giving rise to significant fallback and late-time accretion on to the central compact object. In order to confirm these findings, more detailed investigations using radiation–hydrodynamic simulations and spectral synthesis calculations are being planned. Clearly, monitoring this type of supernovae from discovery to late phases is of the utmost importance.

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