Peculiar, Low Luminosity Type II Supernovae: Low Energy Explosions in Massive Progenitors?

L. Zampieri, A. Pastorello, M. Turatto, E. Cappellaro, S. Benetti, G. Altavilla, P. Mazzali, M. Hamuy

1 INAF - Astronomical Observatory of Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy
2 Department of Astronomy, University of Padova, Vicolo dell'Osservatorio 2, I-35122 Padova, Italy
3 Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA
4 INAF - Astronomical Observatory of Capodimonte, Via Moiariello 16, I-80131 Napoli, Italy
5 INAF - Astronomical Observatory of Trieste, Via Tiepolo 11, I-34131 Trieste, Italy
6 The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101, USA

Accepted ... Received ...; in original form ...

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 $^{56}\text{Ni}$ 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 under-energetic 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: supernovae: general – supernovae: individual: SN 1997D – supernovae: individual: SN 1999br – methods: analytical

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 $^{56}\text{Ni}$ mass of only a few $\times 10^{-3} M_\odot$, and a low expansion velocity of $\sim 1000$ km s$^{-1}$. Modeling the spectra and light curve Turatto et al. (1998) concluded that a very 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 ($\sim 400$ days) spectral and photometric data (Benetti et al. 2001). Chugai & Utrobin (2001) 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 (3-4 times less than that of a normal Type II) of SN 1997D suggest that this explosion event was under-energetic. 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 onto it (Woosley & Weaver 1995). For this reason it was early 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 onto the central black hole could emerge at about 1000–1200 days after the explosion (Zampieri, Shapiro & Colpi 1998)). Unfortunately, to date it has not been possible to confirm or disprove observationally this prediction.

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. 2002). 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 3 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 14 January 1997 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 $\sim 10^{-3} - 10^{-2}$ $M_\odot$ (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 Figure 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 about 1100–1200 km s$^{-1}$ for H (see Benetti et al. 2001 for details).

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 2001d6c, will be presented elsewhere (Pastorello et al. 2002). Here we focus on one particularly representative object, SN 1999br in NGC 4900, discovered on 12 April 1999 (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 days with a mean luminosity of only $\lesssim 10^{41}$ erg s$^{-1}$. It was extensively monitored during the first $\sim 110$ days with the CTIO and ESO telescopes, yielding extremely good photometric and spectroscopic coverages (Hamuy et al. 2002). The spectrum of SN 1999br taken at a phase of $\sim 100$ days shows narrow metal lines (Figure 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 Figure 1, the spectrum of SN 1997D obtained soon after discovery and that of SN 1999br at $\sim 100$ days 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 slightly different line width (i.e. different expansion velocities of the ejecta) and spectral resolution. The expansion velocity of SN 1997D is only $\sim 5\%$ 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 ($\sim 60$ days before discovery) was uncertain (Turatto et al. 1999). On the other hand, the date of the explosion of SN 1999br has an uncertainty of only a few days.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Spectra of SN 1997D and SN 1999br at a phase $\sim 100$ days. The spectrum of SN 1999br was obtained on 1999 July 20 at the ESO-Danish 1.54m telescope equipped with DFOSC (+grism 4). The spectrum of SN 1997D was taken on 1997 January 15 with the ESO 1.52m telescope (B&F+grating 27).}
\end{figure}
(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 $\sim 90 - 100$ days. 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 to 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 in 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 (1982) and later developed by Arnett & Fu (1989) and Arnett (1999). The treatment of the motion of the recombinant 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 3 distinct phases that cover the whole evolution from the photospheric up to the late nebular stages. We include also the energy input from recombination that may be particularly important for low energy events like 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. 2002). 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 comprised 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 $t_{\text{in}}$ (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 $t_{\text{in}} \approx 5$ hrs. 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, $R = R_0 + V_0(t - t_{\text{in}})$. The post-shock, ejected envelope is assumed to have spatially constant density $\rho$ and total mass $M_{\text{env}} = 4\pi\rho R^3/3$. Mass conservation gives $\rho = \rho_0(R_0/R)^3$, where $\rho_0$ 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 $1\%$ 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 days. The expansion velocity of the envelope as a function of interior (Lagrangian) mass $m(r) = 4\pi\rho r^3/3$ is then $V(m) = V_0(m/M_{\text{env}})^{1/3}$ (see Figure 3). The initial thermal+kinetic energy of the envelope is $E = (3/10)M_{\text{env}}V_0^2/f_0$, 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 Figure 3). Our assumptions about 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 $t_{\text{in}}$ and is schematically divided into 3 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 30–40 days up to $\sim 100$ days), 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 recombinant front. In the third stage (after $\sim 100$ days), the ejecta are completely recombined and transparent to optical photons. The evolution is computed 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 PdV work and the energy losses through radiative diffusion. Assuming that radiation is in 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 separation of variables. The function that describes the radial dependence $\psi(r)$ is solution of an eigenvalue equation (see e.g. equation D.48 of Arnett (1996)). The final solution has the form

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

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 $t = t_{\text{in}}$, the radial temperature profile is $T/T_0 = \psi(x)^{1/4}$ (see Figure 3).
where \( L = -(4\pi c T_0^4)/(3\kappa\rho)|\partial aT^4/\partial r|_{r=R} \), \( \kappa \) is the gas opacity.

When the gas starts to recombine at \( t = t_{rec,0} \), 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 \([4]\), 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 approximately computed setting the diffusion luminosity at recombination equal to the luminosity emitted by a blackbody at the effective temperature, \( 4\pi r_i^2 \sigma T_{eff}^4 \) (Popov (1992)). This gives

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

where \( y = x/x_i \), and \( T_{eff} \) is the effective temperature, approximately constant and nearly equal to the gas ionization temperature. Using equations \([3]\) (with \( x \) replaced by \( x/x_i \)) and \([4]\), 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. (2002) for details)

\[
L_{bol} = L + 4\pi r_i^2 \nu_i (aT_{eff}^4/2 + \rho Q_{ion}), \tag{3}
\]

where \( L = -(4\pi c T_0^4)/(3\kappa\rho)|\partial aT^4/\partial r|_{r=R} \) \( \phi(t) \) is the diffusion luminosity, the second term on the right hand side is the total advection luminosity released because of the wavefront motion, \( v_i = x_i/R \) is the wavefront velocity relative to the envelope gas and \( Q_{ion} \) is the recombination energy per unit mass.

In the recombined region \( (r_i < r < R) \), 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 (that coincides with the end of the plateau), when the radioactive decay time of \( ^{56}\text{Co} \) becomes comparable to the expansion timescale. An approximate expression for this luminosity can be obtained neglecting the internal energy and the PdV work in the energy equation and integrating it over the interval \( r_i < r < R \). The total bolometric luminosity of the envelope during this phase is then

\[
L_{bol} = L_{tot} + 4\pi \rho_0 R_0^3 X_{Ni,0} f(t) \int x^2 \xi_{Ni}(x) dx. \tag{4}
\]

where \( X_{Ni,0} \) and \( \xi_{Ni}(x) \) are the central mass fraction and radial distribution of \( ^{56}\text{Ni} \), \( f(t) \approx \left[ 3.9 \times 10^{9} e^{-t/\tau_{Ni}} + 7.2 \times 10^{9} (e^{-t/\tau_{Co}} - e^{-t/\tau_{Ni}}) \right] \) erg \( s^{-1} \), \( \tau_{Ni} \approx 8.8 \text{ days} \) and \( \tau_{Co} \approx 111 \text{ days} \) are the Nickel and Cobalt decay times. Following Arnett (1996), we take \( \xi_{Ni}(x) = \psi(x) = \sin(\pi x)/(\pi x) \) (see Figure 2(a) where the \( ^{56}\text{Ni} \) abundance is shown as a function of \( m \)).

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

### 4 RESULTS AND DISCUSSION

Following the discussion in § 2, we assume that the phase of SN 1997D at discovery is \( \approx 90 - 100 \text{ days} \) and that the early light curve and the evolution of the line velocity resemble closely those of SN 1999br. Figure 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 fitting the spectra with a Planckian and are affected by a significant uncertainty (±500 K) because of the severe line blanketing at short wavelengths (< 4500 Å, see Figure 1). The line velocity and continuum temperature inferred from the model refer to the photospheric epoch. Hence the last two plots
and short-dashed lines represent the model curves. The velo-

ci-

ties in the mid panel are those of the gas at the position of the

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. (2002) for details). The solid, long-dashed and short-dashed lines represent the model curves. The velocities in the mid 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 $\sim 100$ days.

in Figure 3 are truncated at the end of the recombination phase ($\sim 110$ days).

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 $\sim 30$ days and its fast decline impose rather severe constraints on the model. The break appears to be related to the onset of recombination, that terminates when the light curves plummets at $\sim 110$ days.

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 $M_{env}$, $^{56}$Ni mass $M_{Ni}$, 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 $f_c = T_c / T_{eff} = 1.1 - 1.3$ 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”. The estimated value of the initial thermal+kinetic energy of the ejecta $E$ indicates that both events were rather under-energetic compared to a typical Type II supernova. The inferred $^{56}$Ni mass of SN 1999br is extremely small, testifying 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 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 & U trobin (2000) and only 30% smaller than that inferred by Turatto et al. (1998). It is worth noting that the gross properties of 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 $\sim 30\%$ (see also Zampieri et al. (2002)). 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 $M_{env}$ would simply refer to the Hydrogen envelope mass. Then, in general, $M_{env}$ 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 $\kappa = 0.2 \, cm^2 \, g^{-1}$, $t_{rec,0} \simeq 30$ days and $T_{eff} = 4000 - 4400$ K, values similar to those used for the “fit” of SN 1987A. Only a larger opacity and/or a delayed onset of recombina-
Table 1. Parameters of the semi-analytic model

|          | $R_0$ (10$^{12}$ cm) | $M_{env}$ ($M_\odot$) | $M_{Ni}$ ($M_\odot$) | $V_0$ (10$^8$ cm s$^{-1}$) | $E$ (10$^{51}$ erg) | $f_0$ (cm$^2$ g$^{-1}$) | $\kappa$ | $t_{rec,0}$ (days) | $T_{eff}$ (K) | $f_c$ |
|----------|----------------------|------------------------|-----------------------|---------------------------|---------------------|------------------------|--------|------------------|-------------|------|
| SN 1987A | 5                    | 18                     | 7.5 x 10$^{-2}$       | 2.7                       | 1.6                 | 0.5                    | 0.2    | 25               | 4800        | 1.1  |
| SN 1997D | 9                    | 17                     | 8.0 x 10$^{-3}$       | 2.1                       | 0.9                 | 0.5                    | 0.2    | 30               | 4400        | 1.2  |
| SN 1999br| 7.5                  | 14                     | 2.0 x 10$^{-3}$       | 1.9                       | 0.6                 | 0.5                    | 0.2    | 30               | 4000        | 1.3  |

$R_0$ is the initial radius of the envelope  
$M_{env}$ is the ejected envelope mass  
$M_{Ni}$ 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  
$\kappa$ is the gas opacity  
$t_{rec,0}$ is the time when the envelope starts to recombine  
$T_{eff}$ is the effective temperature during recombination  
$f_c = T/T_{eff}$ is the colour correction factor.
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 1997TD 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 onto 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.

ACKNOWLEDGMENTS

We thank the referee Stan Woosley for valuable comments. We acknowledge support from the Italian Ministry for Instruction, University and Research (MIUR) through grant Cofin MM02905817 and the Italian Space Agency (ASI) under grant ASI 1/R/70/00. M. H. acknowledges support for this work by NASA through Hubble Fellowship grant HST-HF-01139.01-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS 5-26555.

REFERENCES

Arnett, W. D., 1980, ApJ, 237, 541
Arnett, W. D., Fu, A., 1989, ApJ, 340, 396
Arnett, W. D., 1996, Supernovae and Nucleosynthesis, Princeton
Balberg, S., Zampieri, L., Shapiro, S. L., 2000, ApJ, 541, 860
Benetti, S. et al., 2001, MNRAS, 322, 361
Chugai, N. N., Utrobin, V. P., 2000, A&A, 354, 557
De Mello, D., Benetti, S., 1997, IAUC 6537
Eastman, R. G., Schmidt, B. P., Kirshner, R., 1996, ApJ, 466, 911
Filippenko, A. V. et al., 1999, IAUC 7143
Fryer, C. L., 1999, ApJ, 522, 413
Hamuy, M., Pinto, P. A., 2002, ApJ, 566, L63
Hamuy, M. et al., 2002, in preparation
King, J. Y., 1999, IAUC 7141
MacFadyen, A. I., Woosley, S. E., 1999, 524, 262
Pastorello, A. et al., 2002, in preparation
Pataf, F., Barbon, R., Cappellaro, E., Turatto, M., 1994, A&A, 282, 731
Pataf, F., et al., 1999, IAUC 7183
Popov, D. V., 1992, ApJ, 414, 712
Smartt, S. J., Gilmore, G. F., Tout, C. A., Hodgskin, S. T., 2002, ApJ, 565, 1089
Turatto, M. et al., 1998, ApJ, 498, L129
Woosley, S. E., 1988, ApJ, 330, 218
Woosley, S. E., Weaver, T. A., 1995, ApJS, 91, 181
Zampieri, L., Colpi, M., Shapiro, S. L., Wasserman, I., 1998, ApJ, 505, 876
Zampieri, L., Shapiro, S. L., Colpi, M., 1998, ApJ, 502, L149
Zampieri, L. et al., 2002, in preparation
Zampieri, L., 2002, in Proceedings of the XIV Congress on General Relativity and Gravitational Physics, “Recent Developments in General Relativity, Genoa 2000”. Cianci, R., Collina, R., Francaviglia, M., Fré, P. Eds., Springer, p. 301