The Exceptionally Bright Type Ib Supernova 1991D. *

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Received ................; accepted ................

ABSTRACT

Photometric and spectroscopic observations of the peculiar Type Ib Supernova 1991D are presented. SN 1991D was exceptionally bright for a Type Ib supernova. The He I lines were rather weak and the velocity at the photosphere as a function of time was unusually low. Comparison of the observed and synthetic spectra indicates that either hydrogen was ejected with a minimum velocity of 12,000 km s⁻¹ or the spectrum contained features caused by lines of Ne I. Light curve modelling suggests that the progenitor probably had a very large radius (∼10¹⁴ cm) and that a considerable amount of ⁵⁶Ni was synthesized during the explosion (∼0.7M☉). We suggest a progenitor model of SN 1991D that involves a binary system.

Key words: Supernovae: general – Supernovae: 1991D

1 INTRODUCTION

Core collapse in massive stars is believed to be responsible for supernovae of Types II, Ib, Ib and Ic. Those of Type II (SNe II) are characterized by the presence of conspicuous hydrogen lines in their optical spectra. SNe Ib show strong hydrogen lines around the time of their maximum brightness, but later these lines become weak or even disappear, while He I lines develop. SNe Ic develop strong He I lines after maximum, while hydrogen lines are weak or absent. SNe Ic lack conspicuous hydrogen and He I lines (as well as the distinctive strong absorption of SNe Ia due to Si II λλ 6347, 6371). For more details on the supernova spectral classification we refer the reader to a recent review by Turatto (2002).

Two recent papers (Matheson et al. 2001, hereafter M01; Branch et al 2002, hereafter B02) have advanced our understanding of SN Ib and Ic spectra. M01 presented a large number of optical spectra of SNe Ib and Ic, and were able to clarify some of the spectroscopic properties of these two types. B02 compared photospheric–phase spectra of 11 SNe Ib (mostly from M01) with synthetic spectra generated with the parameterized supernova synthetic-spectrum code SYNOW. They found a tight relation between the ve-

* Based on observations collected at the European Southern Observatory, Chile, ESO4-004-45K

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Figure 1. SN 1991D in PGC 84044. The image is an R frame taken at ESO-MPI2.2m telescope on Apr. 17, 1991. The seeing was 1.5 arcsec
2 OBSERVATIONS

SN 1991D was discovered by Remillard et al. (1991) on CCD images obtained on Feb. 6 and 7 UT on a faint spiral arm of PGC 84044, a Seyfert 1 galaxy.

Kirshner (1991) and Filippenko & Shields (1991) classified the event as Type Ib/c and Ib, respectively, on the basis of spectra taken on Feb. 10-11 and Feb. 23. Kirshner also noted that given the magnitudes reported by Remillard, SN 1991D could be as luminous as a Type-Ia supernova (see Sect. 2.1).

CCD photometric and spectroscopic observations were obtained at La Silla on 10 different nights using five different telescopes. Data reduction followed the standard procedures making use of a PSF fitting technique for the SN photometric measurements.

2.1 Photometry

The measured magnitudes of SN 1991D and the estimated internal errors (in brackets) are reported in Tab.1. The internal consistency of the SN magnitudes in different nights has been checked mostly using star A of Fig. 1 (V= 16.41 ± 0.04, B−V= 0.79 ± 0.04, V−R= 0.48 ± 0.06).

The B, V and R light curves of SN 1991D are shown in Fig. 2. The light curves are very fast and show that the SN was discovered near maximum. The post-maximum decline rates are steeper than the radioactive decay of 56Co into 56Fe. Since in SN 1991D the decline rates are steeper than the 56Co decay rate (0.98 mag (100d)−1), the γ-rays increasingly escaped from the ejecta without being thermalized, consistent with a low-mass of the ejecta.

SN 1991D suffers only moderate galactic reddening, E(B−V)= 0.062 (Schlegel et al. 1998) and there is no evidence of additional extinction in the parent galaxy. From our best S/N spectra we derive an upper limit of 0.2A for the interstellar Na I D absorptions, which implies E(B−V)inter = 0.026 according to an empirical relation between these two quantities (Benetti et al. 2002a, in preparation).

In this paper a total reddening of E(B−V)=0.06 ± 0.03 is assumed. The parent galaxy heliocentric velocity is 12528 ± 87 km s−1 (from NED), which corresponds to μ= 36.43(±0.03) − 5log(H0/65).

In Fig. 2 the absolute V light curve of SN 1991D is compared with those of the Type Ib 1999dn and 1990I and Type Ic SN 1994I. To match the peak of SN 1991D, the 1994I and 1999dn curves have been shifted brighter by 2.1 and 3.0 magnitudes, respectively (when the total reddening is taken into account), while that of SN 1990I has to be shifted brighter by only 0.2 magnitudes. Figure 3 confirms that the SN 1991D light curves are as fast as those of SNe 1994I and 1990I. Moreover, given the V measurements by Remillard et al. (1991) (we have tentatively assigned an error of 0.3 mag on these measurements) this event reached an absolute MV maximum of about −20.2 ± 0.3, making SN 1991D the most luminous SN Ib yet reported, and among the few reliably measured supernovae to have been brighter than SNe Ia (Richardson et al. 2002). We want to stress that our own first observation corresponds to MV ≃ −19.0 ± 0.1; even this is quite bright for a SN Ib. Fig. 3 also indicates that the V light curve possibly reached maximum at JD=48290 ± 2 (e.g. Feb. 2, 1991).

2.2 Spectroscopy

The journal of the spectroscopic observations is given in Tab. 2. The table lists for each spectrum the date (col.1),
Table 1. Photometric measurements of SN 1991D

| date       | J.D. | B     | V     | R     | instr. |
|------------|------|-------|-------|-------|--------|
| 12/2/91    | 48299.80 | 16.82(05) |       |       | NTT    |
| 13/2/91    | 48300.80 | 17.74(05) | 17.16(05) |       | NTT    |
| 21/2/91    | 48308.79 | 19.34(05) | 18.42(05) | 17.86(05) |       |
| 24/2/91    | 48311.80 | 19.66(05) | 18.55(05) | 18.05(05) | D1.54  |
| 07/4/91    | 48353.75 | 21.32(10) | 20.05(05) | 19.39(05) | D1.54  |
| 17/4/91    | 48363.71 | 21.43(10) | 20.24(05) | 19.56(05) | 2.2    |
| 20/4/91    | 48367.76 | 20.26(05) |       |       |        |
| 07/8/91    | ≤22.50(20) | ≤22.00(20) |       |       | 3.6    |

NTT = ESO NTT + EMMI
3.6 = ESO 3.6m telescope + EFOSC1
D1.54 = Danish 1.54m + CCD Camera
2.2 = MPI 2.2m telescope + EFOSC2

Table 2. Spectroscopic observations of SN 1991D

| Date       | phase* (days) | inst.** | exp (min) | range (Å) | res. (Å) |
|------------|---------------|----------|-----------|-----------|----------|
| 12/02/91   | +10           | NTT      | 20        | 4050-8050 | 15       |
| 21/02/91   | +19           | 3.6      | 60        | 3800-9700 | 20       |
| 20-21/03/91| +47           | 1.5      | 135       | 3950-9300 | 15       |
| 17/04/91   | +74           | 2.2      | 30        | 5500-8100 | 15       |
| 21/04/91   | +78           | 3.6      | 60        | 3600-7050 | 20       |

* - relative to the estimated epoch of V maximum JD=2448290
** - See note to Table 1 for coding

The phase relative to the time of V maximum (col.2), the instrument used (col.3), the exposure time (col.4), the wavelength range (col.5), and the resolution as measured from the FWHM of the night-sky lines (col.6). In order to improve the S/N ratio, in some cases different exposures, even on consecutive nights, have been averaged. In such cases the total exposure time is reported.

The flux calibration of the spectra has been checked against the photometry and in the case of discrepancies the spectra were adjusted. Figure 4 illustrates the spectroscopic evolution of SN 1991D from phase +5d to +78d.

The first two spectra have relatively blue continua with P–Cygni lines mostly due to Fe II, Ca II and He I. The presence of He I λ5876, λ6678, and λ7065 is clear, but because the He I lines are weaker in SN 1991D than in the events of the B02 sample, and λ4471 is in a region of strong Fe II absorption, the presence of λ4471 cannot be confirmed. The expansion velocity as calculated from the deep absorption produced by He I 5876 and assuming negligible contamination from NaID, is about 5800 km s\(^{-1}\), definitely lower than the velocities shown by typical SNe Ib at similar epochs (∼10000 km s\(^{-1}\), and up to ∼13500 km s\(^{-1}\) in SN 1990I). However, in SN 1991D there may also be weak highly blueshifted He I lines with a velocity similar to that seen in SN 1990I (cf. upper panel of Fig. 4).

The spectrum of phase +19d shows a He I λ5876 absorption that has an unusual triangular shape. The He I lines are quite weak compared to those of a typical SN Ib such as SN 1999dn (see upper panel of Fig. 4).

The overall appearance of the +78d spectrum is similar to those of other SNIIb/c (see Fig. 5) but with some notable differences. The He I 5876–NaID absorption, still the dominant feature of the spectrum and now with a normal absorption shape, shows an expansion velocity (∼5000 km s\(^{-1}\)), lower than that of other SNe Ib/c (∼7000 km s\(^{-1}\), cf. Fig. 5). The nebular lines of [O I] λλ6300, 6364 look normal, with the emission peak at ∼6544Å. The [O I] λ5577 emission may be present as in SN 1999dn, the peak occurs at 5544Å. At about 6537Å there is a weak but definitely real emission feature with a boxy profile having FWZI ∼98Å (deconvolved by the spectral resolution), which could be tentatively identified as Hα with a maximum expansion velocity of about 4500 km s\(^{-1}\). This emission was already visible in the noisier +47d and +74d spectra with rest frame peaks at 6523Å and 6543Å, respectively. This feature is not normally seen in SNe Ib/c (see Fig. 4) and could be a sign of circumstellar interaction. The overall displacement of the main emission

Figure 3. My light curve of SN 1991D compared with those of the Type Ib SN 1990I (+0.2 mag) and 1999dn (+3.0 mag, Benetti et al 2002b, in preparation), and with that of the Type Ic SN 1990I (+2.1 mag) (Richmond et al. 1996). The absorption (AV) used are: 1.55 mag for SN 1994I (Ho & Filippenko, 1995); 0.43 mag and 0.40 mag for SNe 1999dn and 1990I respectively (Benetti et al 2002b, in preparation). H\(_0\) of 65 km s\(^{-1}\)Mpc\(^{-1}\) is assumed.

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features toward the blue might be an indication of an asymmetry in the ejecta (dust formation in the ejecta being less probable).

Fig. 6 shows that the ratios of the depths of the He I absorption features in SN 1991D follow the general trend shown by the SN Ib sample presented in M01, even though the SN 1991D He I lines are weaker than in normal SNe Ib.

3 SYNTHETIC SPECTRA

The synthetic spectra shown in Figs. 7 and 8 were computed with the parameterized supernova synthetic-spectrum code SYNOW. For a discussion of the physical assumptions and the fitting parameters see B02.

Fig. 7 compares the (smoothed) +10d spectrum of SN 1991D with a synthetic spectrum that has a velocity at the photosphere \( v_{\text{phot}} = 5000 \text{ km s}^{-1} \) and a blackbody continuum temperature \( T_{\text{bb}} = 8500 \text{ K} \), and contains lines of Ca II, Fe II, He I, all undetached (i.e., having non-zero optical depths beginning at the photospheric velocity of 5000 \( \text{km s}^{-1} \)). The value of \( v_{\text{phot}} \), as determined from the Fe II features, is significantly lower than that of the SNe Ib of the B02 sample at the same epoch. For that sample, the characteristic value of \( v_{\text{phot}} \) at +10d was 8000 \( \text{km s}^{-1} \). Also, in the B02 sample, at +10d the He I lines had to be detached; i.e., the optical depths of the He I lines were non-zero only above velocities higher than \( v_{\text{phot}} \). The detachment velocities ranged from about 8000 to 12,000 \( \text{km s}^{-1} \) at +10d.

In the synthetic spectrum of Fig. 7, hydrogen lines also are included, detached at 12,000 \( \text{km s}^{-1} \) so that the Hα absorption is sufficiently blueshifted to match the observed absorption near 6280 Å (the “6300 Å absorption” of B02). The mismatch of the shapes of the observed and synthetic Hα features is not disturbing given our simplifying assumption that the hydrogen line optical depths rise discontinuously from zero at 12,000 \( \text{km s}^{-1} \). The optical depth of the Hα line is sufficiently low that the identification can not be checked by means of Hβ. Note that the synthetic spectrum of Fig. 7 provides no identification for the observed absorption near 6065 Å.

Figure 8 is like Fig. 7 except that in the synthetic spectrum the hydrogen lines are removed and undetached lines of Ne I are included. Now the strongest line of Ne I, \( \lambda 6402 \), accounts for the 6285 Å absorption, and some other Ne I lines account for the observed absorption near 6065 Å, which was unaccounted for in Fig. 7. Ne I lines also slightly improve the fit to the observed feature near 6590 Å, which in Fig. 7
Figure 5. Top panel: The +19d spectrum of SN 1991D is compared with spectra of similar phase of the Type Ic SN 1994I and the Type Ib SNe 1990I and 1999dn. Bottom panel: the +78d spectrum is compared with spectra of the same supernovae at similar phases. The wavelengths are in the rest frame of the parent galaxies. The main He I lines have been labelled. The vertical lines mark the positions of the He I lines for an expansion velocity of 13,500 km s$^{-1}$.

was accounted for by He I $\lambda 6678$ alone. Given that the Ne I lines are undetached, and therefore do not require a separate free parameter such as the detachment velocity that is required for H$\alpha$, the possibility of the presence of Ne I lines in SN 1991D must be taken seriously.

If Ne I lines are present they would need to be nonthermally excited, as are the He I lines in SNe Ib (Lucy 1991; Swartz et al. 1993). In the synthetic spectrum of Fig. 8 the optical depth at the photosphere of Ne I $\lambda 6402$ is 2, while Fig. 4 of Hatano et al. (1999) shows that for a helium-rich composition in LTE the optical depth of this line peaks at 0.1 at T$\approx 8000$ K and decreases steeply at lower temperatures. Thus the departure coefficient required of nonthermal excitation is at least 20, and may be much higher. Detailed spectrum modeling of a well observed SN 1991D–like event would be required to determine the departure coefficient.

In the sample of B02, three SNe Ib — SNe 2000H, 1999di, and 1954A — showed deep H$\alpha$ absorptions accompanied by weak H$\beta$ absorptions. For these three events, B02 rejected the Ne I alternative to H$\alpha$. However, the other events of the B02 sample had weaker “H$\alpha$” absorptions that, as in SN 1991D, could not be checked by means of H$\beta$. Thus Ne I remains a possible alternative identification in these other events.

Figure 6. Temporal evolution of fractional line depths of He I $\lambda 5876$ and $\lambda 7065$ normalized to the fractional line depth of He I $\lambda 6678$, as plotted by Matheson et al. 2001. Open symbols refer to M01 data of SNe Ib, filled symbols refer to SN 1991D.

Figure 7. The +10d spectrum of SN 1991D (solid line) is compared with a synthetic spectrum (dotted line) that has $v_{\text{phot}} = 5000$ km s$^{-1}$ and $T_{\text{bb}} = 8500$ K, and contains lines of Ca II, Fe II, He I, and hydrogen. The hydrogen lines are detached at 12,000 km s$^{-1}$.

4 RESULTS AND DISCUSSION

SN 1991D shows He I lines in the spectrum that classify it as a Type Ib. However, it was a peculiar supernova. Photometrically, it was unusually bright, reaching at least $M_V = -19.0$ and more likely $M_V = -20.2$. Spectroscopically, helium lines were significantly weaker than in typical SNe Ib (cf. B02) and the inferred velocity at the photosphere was rather low. In addition He I lines had non–zero optical depth down to an unusually low velocity and some of the spectral features may be attributed to Ne I.

In order to obtain some information on the progenitor and the explosion scenario of this peculiar event we used as diagnostic tool a semi-analytic model originally developed...
it to compute the light curve and line velocity profile of Type II supernovae (Zampieri et al. 2002, in preparation). The model has been adapted to Type Ib/c supernovae including an approximate treatment of the leakage of the gamma-rays produced by radioactive decay of $^{56}$Co. Despite adopting a number of simplifying assumptions, such as uniform density, homologous expansion and constant opacity, comparison with the results of radiation-hydrodynamic computations has shown that the model is able to capture the essential physical information and to produce reliable parameter estimates.

The astonishingly high luminosity of SN 1991D during the first $\sim$ 20 days ($L_V > 10^{43}$ erg s$^{-1}$) and the large luminosity in the tail ($L_V \approx 10^{42}$ erg s$^{-1}$ at $\sim$ 80 days) are not typical of Type Ib supernovae and are large even for Type Ia supernovae. In particular, the first two photometric points of the discovery the SN impose $L_V \approx 5 \times 10^{43}$ erg s$^{-1}$. This poses serious problems for modeling the light curve with a C+O or He core of a massive progenitor star that has lost its outer H envelope. Even if the very high early luminosity may be associated with emission at or immediately after shock break-out it still requires a very large initial radius.

Because emission from shock break-out is not included in our model, to bracket possible uncertainties in the parameter estimate, we calculated semi-analytic models of SN 1991D including (case A), and neglecting (case B), the first two uncertain photometric points in the fit. The results of the fit of the light curve and line velocity profile of SN 1991D are displayed in Table 3 and Figure 9. The main difference between the two cases is the value of the initial radius. Fitting the light curve in case A requires a progenitor with an extremely large initial radius ($\geq 10^{14}$ cm). Yet, in this case the total explosion energy ($E \sim 1.4 \times 10^{51}$ erg) is about one half that required in case B, essentially because of the lower envelope mass.

In both cases, to account for the high luminosity in the tail, the explosion that originated the supernova must have been capable of producing a large amount of radioactive $^{56}$Ni ($\sim 0.7M_\odot$). This is about 5–10 times larger than the typical yield of a Type Ib/c supernova (Young, Baron & Branch 1993).

We emphasize that the rapid evolution of the early light curve and the relatively low expansion velocity demand that the ejected envelope mass be small ($\sim 1 - 2M_\odot$). This fact lends support to the possibility that the progenitor of SN 1991D was a star in a close binary system (Iwamoto et al. 1994), rather than an isolated very massive star stripped of its outer H envelope.

We suggest a rather speculative scenario which may explain the main properties of SN 1991D: a binary system consisting of a white dwarf and a low mass helium companion ($< 2M_\odot$). Systems of this type have been proposed in other contexts to explain the origin and properties of the emission of cataclysmic variables, supersoft X-rays sources, and some supernovae (Tutukov & Yungelson 1996, Iben and Tutukov 1994). Concerning supernovae, two possibilities have been considered: either the WD accretes matter from the companion and exceeds the Chandrasekar mass exploding as a type Ia SN (Hachisu et al. 1999); or the C+O core of the helium star collapses to produce a SN Ib, if a substantial fraction of the He envelope is left, or a SN Ic, if it is lost (Nomoto et al. 1995).

What if the WD ignites while it is hidden inside a He envelope, that is during a common envelope phase (Tutukov & Yungelson 1996), or while it is spiraling into the giant companion (cf. Sparks & Stecher 1974)? Qualitatively, we would expect that because of the large radius of the helium envelope, the SN would exhibit a high peak luminosity. Yet, since the envelope mass is small, the luminosity decline would be very fast. Though camouflaged, this is essentially a type Ia SN and therefore the mass of radioactive $^{56}$Ni is expected
Table 3. Parameters from the semi-analytic model

|          | radius (cm) | ejected mass (M\(_{\odot}\)) | 56Ni mass (M\(_{\odot}\)) | V\(_{0}\) (cm s\(^{-1}\)) | explosion energy (10\(^{51}\) erg) | \(f_0\) opacity (cm\(^2\) g\(^{-1}\)) | \(t_{rec,i}\) (days) |
|----------|-------------|-------------------------------|--------------------------|--------------------------|-------------------------------------|--------------------------------------|----------------------|
| case A   | 10\(^{14}\) | 1.2                           | 0.7                      | 10\(^{9}\)                | 1.4                                 | 0.5                                  | 0.1                  | 21                   |
| case B   | < 10\(^{12}\)| 2.5                           | 0.7                      | 10\(^{9}\)                | 3                                   | 0.5                                  | 0.15                 | 5                    |

\(V_0\) is the velocity of the outermost envelope material

\(f_0\) is the fraction of the total initial energy that goes into thermal energy

\(t_{rec,i}\) is the time when the bulk of the envelope starts to recombine

...to be large and the radioactive tail quite luminous. Again, because of the low ejected mass, gamma-rays from radioactive decays would not be completely trapped and the late decline of the light curve would also be fast. In this respect, we emphasize that the M\(_V\) light curve of SN 1991D is intriguingly similar to that of SN 1994D both in shape and luminosity, except for the first two brighter points (see Fig. 3). In these assumptions, the early spectrum is expected to show strong He lines but, because in the composition structure of a helium star the second most abundant element after He is Ne (cf. Habets, 1986), the presence of Ne lines in the spectra would not be surprising. Even the narrow Ho lines observed in the late spectra may be the fingerprint of the H envelope lost during the first non-conservative mass transfer/loss episode.

Eventually, when the SN enters the nebular phase, strong [FeII] and [FeIII] lines should emerge in the spectrum. Unfortunately, the last spectrum of SN 1991D has been obtained only 78 days after maximum and is not decisive in this respect. However we note that spectra of this type have already been observed in some type Ib/c supernovae. In fact, SN 1993R and SN 1990aj, two supernovae discovered in the nebular phase, showed peculiar type Ib/c spectra with very intense iron lines similar to those seen in the nebular phase of SNIa (Turatto 2002).

The fine tuning of the proposed scenario would naturally account for the rarity of these type of events, which are so luminous that they are observationally favored in SN searches.

Clearly, to confirm if the proposed scenario is really viable, detailed numerical radiation-hydrodynamic calculations should be performed, and detailed non-local-thermodynamic-equilibrium spectral calculations, including nonthermal ionization (e.g., Baron et al. 2000), should be carried out. In particular, these calculations will show whether Ne I can produce lines of the appropriate strength. From the observational point of view, the fortuitous circumstance that a similar object will be discovered in the future, an effort should be made to secure spectra in the nebular phase.

The very existence of peculiar SNe like SN 1991D naturally leads to other issues. Bright SNe of this type might contaminate the sample of high-z objects used for the determination of the geometry of the Universe. Although, as speculated above, they might originate from thermonuclear explosions and share some photometric properties typical of SNIa, on the other side they would lead to misinterpretation of the observed data. In the recent past another bright atypical SN, the peculiar type Ic SN 1992ar, has been pointed out as a possible contaminator of the SNIa high-z sample (Clocchiatti et al. 2001). Although the rate of such events in the local Universe seems relatively small, their frequency at high-z remains to be determined.

**ACKNOWLEDGMENTS** We acknowledge support from the Italian Ministry for Education, University and Research (MIUR) through grant Cofin MM02095817. This work has been also supported in part by NSF grant AST-9906965 and NASA grant NAG5-3505. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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