SN 2005cs in M51
I. The first month of evolution of a subluminous SN II plateau

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ABSTRACT
Early time optical observations of supernova (SN) 2005cs in the Whirlpool Galaxy (M51), are reported. Photometric data suggest that SN 2005cs is a moderately under–luminous Type II plateau supernova (SN IIP). The SN was unusually blue at early epochs (U–B ≈ −0.9 about three days after explosion) which indicates very high continuum temperatures. The spectra show relatively narrow P–Cygni features, suggesting ejecta velocities lower than observed in more typical SNe IIP. The earliest spectra show weak absorption features in the blue wing of the He I 5876Å absorption component and, less clearly, of Hβ and Hα. Based on spectral modelling, two different interpretations can be proposed: these features may either be due to high–velocity H and He I components, or (more likely) be produced by different ions (N II, Si II). Analogies with the low–luminosity, 56Ni–poor, low–velocity SNe IIP are also discussed.

While a more extended spectral coverage is necessary in order to determine accurately the properties of the progenitor star, published estimates of the progenitor mass seem not to be consistent with stellar evolution models.

Key words: supernovae: general - supernovae: individual (SN 2005cs) - supernovae: individual (SN 1997D) - supernovae: individual (SN 1999br) - supernovae: individual (SN 2003Z) - galaxies: individual (M51)

1 INTRODUCTION
Type II supernovae (SNe II) are believed to be produced by the explosion following the core–collapse of massive stars that retained most of their H envelope at the time of explosion. Some SNe II spend a period at almost constant luminosity: this phase, lasting sometimes a few months, is called “plateau” (hence the label SN IIP). When the SN enters this phase, the temperature is low enough that the massive H envelope, initially ionized because of the deposition of energy by the shock wave, starts to recombine. After recombination, the light curve of SNe IIP declines steeply, until it settles onto the “radioactive tail”, as do other SN Types. In this phase the luminosity is due mainly to the radioactive decay of 56Ni to 56Co to 56Fe.

Despite the considerable number of SNe IIP studied in recent years (e.g. Patat et al 1993, Hamuy 2003), the physical properties of the progenitor stars are still a matter of debate. Thanks to the direct identification of several SN precursors in deep pre–explosion images, important constraints have been established on the nature of the progenitors of SNe IIP. The first SN with a known progenitor was SN 1987A in the Large Magellanic Cloud. Archival images showed that the supergiant progenitor was unusually blue (e.g. Sonneborn et al 1987). The present ensemble of SNe IIP with detected progenitor includes SN 2003gd (Van Dyk et al...
SN 2005cs was discovered in the famous Whirlpool Galaxy (NGC 5194 or M51) by Kloehr et al. (2005) on 2005 June 28.905 UT. Modjaz et al. (2005) classified it as a young Type II SN. All data were pre-reduced with standard IRAF\textsuperscript{3} procedures, and instrumental SN magnitudes were determined using the point-spread function (PSF) fitting technique performed with the “SNOOPY”\textsuperscript{4} package. Since SN 2005cs is a bright object, this technique provides acceptable results, although the background region of SN 2005cs is extremely complicated, such that the subtraction of the template could be more appropriate when the SN fades.

In order to transform instrumental magnitudes to the standard Johnson–Cousins system, first-order colour corrections were applied with colour terms derived from observations of photometric standard fields (Landolt 1992). The photometric zeropoints were finally determined by comparing the magnitudes of a local sequence of stars in the vicinity of M51 (cf. Fig.\textsuperscript{1}) to the values reported for some of these stars by Richmond et al. (1996) in their study on SN 1994A. A complete definitive photometry (calibrated on a larger sequence of stars, i.e. those labelled by numbers in Fig.\textsuperscript{1}) will be presented in a forthcoming paper (Pastorello et al. in prep.).

The SN magnitudes are reported in Tab.\textsuperscript{1} and in the U, B, V, R, I light curves are shown in Fig.\textsuperscript{2} together with the light curves of SNe 1999br (Hamuy 2001; Pastorello et al. 2004) and 1999em (Hamuy et al. 2001; Leonard et al. 2002; Elmhamdi et al. 2003), shifted arbitrarily in magnitudes (but not in phase) in order to match the light curves of SN 2005cs. The overlap of the B, V, R and I band light curves of the three SNe is very good, while some differences are visible in the U band evolution: the U band light curve of SN 2005cs declines more rapidly than that of SN 1999em.

According to Modjaz et al. (2005), the simultaneous presence in the SN spectrum of narrow Galactic and host galaxy interstellar Na ID lines with analogous equivalent width (0.2 Å) indicates a similar contribution of the two components to the total extinction. The host galaxy extinction can be estimated using the relation of Turatto et al. (2003), while the value provided by Schlegel et al.

\textsuperscript{3} IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc, under contract to the National Science Foundation.

\textsuperscript{4} SNOOPY is a package implemented in IRAF by E. Cappellaro, based on DAOPHOT.
Table 1. UBVRI magnitudes of SN 2005cs and assigned errors. Both measurement errors and uncertainties in the photometric calibration (the most important source of errors) are taken into account. Measurement uncertainties give a minor contribution to the total error because, despite the relatively complex background, the SN was much brighter than any other nearby source.

| Date       | JD (+2400000) | U     | B     | V     | R     | I     | Inst. |
|------------|--------------|-------|-------|-------|-------|-------|-------|
| 05/06/26   | 53548.39     | > 17.3| > 17.7| > 17.6|       |       | NCO   |
| 05/06/30   | 53552.36     | 13.48±0.05| 14.36±0.05| 14.48±0.02| 14.46±0.04| 14.44±0.04| Caha |
| 05/07/01   | 53553.36     | 13.53±0.06| 14.36±0.05| 14.46±0.05| 14.40±0.02| 14.34±0.06| Ekar |
| 05/07/02   | 53554.46     | 13.69±0.10| 14.45±0.04| 14.51±0.03| 14.47±0.03| 14.29±0.10| Ekar |
| 05/07/05   | 53557.42     | 14.52±0.04| 14.54±0.04| 14.42±0.05| 14.29±0.08|         | Ekar |
| 05/07/06   | 53557.84     | 14.02±0.06| 14.60±0.05| 14.55±0.03| 14.36±0.03| 14.40±0.03| Sub  |
| 05/07/07   | 53559.40     | 14.65±0.04| 14.56±0.09| 14.41±0.09| 14.35±0.11|         | TNT  |
| 05/07/11   | 53563.38     | 14.81±0.05| 14.87±0.04| 14.56±0.04| 14.37±0.02| 14.23±0.05| Ekar |
| 05/07/11   | 53563.42     | 14.89±0.04| 14.93±0.04| 14.53±0.04| 14.37±0.03| 14.26±0.03| TNT  |
| 05/07/13   | 53565.38     | 15.27±0.06| 15.04±0.05| 14.64±0.02| 14.37±0.03| 14.29±0.05| LT   |
| 05/07/14   | 53566.36     | 15.29±0.05| 15.11±0.05| 14.68±0.02| 14.44±0.04| 14.23±0.02| Ekar |
| 05/07/14   | 53566.40     | 15.09±0.04| 14.66±0.04| 14.40±0.05| 14.32±0.06|         | TNT  |
| 05/07/17   | 53569.42     | 15.92±0.07| 15.31±0.05| 14.67±0.03| 14.40±0.03| 14.27±0.04| LT   |
| 05/07/19   | 53571.40     | 15.36±0.12| 14.72±0.05| 14.45±0.09| 14.26±0.07|         | TNT  |
| 05/07/20   | 53572.40     | 15.39±0.07| 14.71±0.03| 14.45±0.03| 14.27±0.03|         | TNT  |
| 05/07/25   | 53577.40     | 15.46±0.09| 14.72±0.04| 14.36±0.06| 14.24±0.06|         | TNT  |
| 05/07/27   | 53579.40     | 15.60±0.07| 14.73±0.04| 14.39±0.04| 14.16±0.04|         | TNT  |
| 05/07/31   | 53583.39     | 16.83±0.09| 15.78±0.06| 14.71±0.03| 14.38±0.03| 14.12±0.05| TNT  |
| 05/07/31   | 53583.47     | 16.81±0.11| 15.77±0.06| 14.69±0.03| 14.36±0.03| 14.15±0.04| LT   |

NCO = Osservatorio Cavaglio 40 cm Newton Telescope  
Caha = Calar Alto 2.2 m Telescope + CAFOs  
Ekar = Asiago 1.82 m Copernico Telescope + AFOSC  
Sub = Subaru Telescope 8.2 m + FOCAS  
TNG = Telescopio Nazionale Galileo 3.5 m + Dolores  
LT = Liverpool Telescope 2.0 m + RATCAM  
TNT = Teramo Normale Telescope 72 cm

Figure 2. Early U, B, V, R, I light curves of SN 2005cs, including our limits of June 26 (when the SN was not detected) and the unfiltered limit from IAU Circ. 8853 (asterisk). Also, the light curves of SN 1999br (BVRI) and SN 1999em (UBVR) have been included for comparison, and shifted in magnitude by an arbitrary amount in order to match the corresponding curves of SN 2005cs. The very early B band detections of M. Fiedler (SNWeb) have been also reported (filled pentagons).
extinction $A_B = 0.10$ (Pastorello et al. 2004) for SN 1999br, $\mu = 30.34$ (Leonard et al. 2003) and $A_B = 0.41$ (Baron et al. 2000) for SN 1999em, $\mu = 18.49$ and $A_B = 0.79$ (Arnett et al. 1989) for SN 1987A, and $\mu = 32.87$ and $A_B = 0.29$ (Pastorello 2003) for SN 2002gd. Distance moduli for SNe 1999br and 2002gd were estimated from the recession velocity corrected for the Local Group infall onto the Virgo Cluster ($v_{\text{Vir}}$), adopting a value of $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$.

All typical SNe IIP show a similar colour evolution. Their colour curves become monotonically redder with time. On the other hand, SN 1987A was significantly redder at early epochs (until $\sim 50$ days), but then the colour difference between it and other SNe IIP decreases with time. SN 2005cs follows the behaviour of SNe IIP: the B–V colour increases from $-0.2$ to $1$ during the first month, while the V–R colour increases much more slowly ($0$ to $0.3$) over the same period (Fig. 3 top and middle).

Interestingly, the uvoir light curve of SN 2005cs has an evolution reminiscent of that of normal SNe IIP (Fig. 3 bottom). The uvoir luminosity of SN 2005cs is intermediate between those of the intermediate $^{56}$Ni mass SN 1999em ($M_{^{56}\text{Ni}} \approx 0.05M_\odot$, Leonard et al. 2003) and the low-luminosity, $^{56}$Ni-poor SN 1999br ($M_{^{56}\text{Ni}} \approx 2\times10^{-3}M_\odot$, Zampieri et al. 2003; Pastorello et al. 2004), and is similar to that of the $^{56}$Ni-poor SN 2002gd (see Sect. 4 and Pastorello 2003).

### 3 SPECTROSCOPY

Spectroscopy is available for 10 different epochs, ranging from about 3 to 35 days after the explosion. A summary of all spectroscopic observations is given in Tab. 2.

All raw frames were first bias and flat-field corrected, and then the SN spectra were optimally extracted. Wavelength calibration was obtained with the help of comparison lamp exposures, while the spectra were flux calibrated using standard star spectra obtained on the same night as the SN observations. When no spectro-photometric standard star was observed, a sensitivity func-
tion derived on a different night (close in time) was used. Telluric features were removed from the SN spectra, again using spectrophotometric standard spectra. However, the strong telluric band at 7570–7750 Å is superimposed on the O I λ7774 SN feature, and imperfect removal might significantly affect the profile of this line. Finally all spectra were checked against the quasi-contemporaneous photometry and, where discrepancies occurred (especially during low-transparency or bad-seeing nights), the photometric data were used to derive a scaling factor to apply to the SN spectrum. The relative, final flux calibration was reasonable, and the agreement with photometry within 10%.

3.1 Spectral evolution

We monitored SN 2005cs spectroscopically for about one month. There are only two significant observational gaps, between July 6 and 11 (phase 9–14 days) and between July 19 and 31 (phase 22–34). During the last part of the coverage the spectrum of SN 2005cs evolved significantly. The spectral sequence is shown in Fig. 4.

The first spectra (phase 3–5 days) are characterized by a very blue continuum. The most prominent features are the P–Cygni profiles (Mazzali et al. 1992), but other metal ions may also contribute significantly to the continuum shape. The most prominent lines are now Hα, Ca II H&K and the Ca II IR triplet are not blended, confirming the low ejecta velocity.

In addition to strong lines of Fe II, Ti II and Sc II (e.g. the absorptions at 5250 Å and 5470 Å), Sr II absorptions at 5230 Å and 5580 Å have completely disappeared. The Fe II multiplet 42 lines (λ4924, λ5018, λ5169) begin to be visible to the red side of Hβ. The He I λ5876 Å line becomes dimmer and a strong O I λ7774 line is now visible. Moreover, a very prominent absorption feature is now well developed at ~6300 Å, close to the blue wing of the Hα absorption.

By the times of the last TNG observation, obtained about 34 days after the explosion, the spectrum had noticeably changed. The spectra at phases 14–22 days show redder continua and lines with deeper P–Cygni profiles. In the region below ~5300 Å, together with the Balmer H lines, we identify several metal lines.

3.2 High-velocity H I, He I features or N II, Si II lines?

Fig. 5 shows the early evolution of the spectral region between 4100 Å and 7300 Å. The Hβ, He I λ5876 Å and Hα absorption minima are marked and the corresponding line velocities are reported. The features at λ4580 Å, 5580 Å and near 6300 Å are also marked, with labelled the two alternative identifications: as putative HV H and He I, and as N
II and Si II lines (bottom of Fig. 5), Baron et al. (2000) discuss the identification of the 4580Å and 5580Å features in an early time spectrum of SN 1999em. Using the simple parametrised code SYNOW (Fisher 2000), in which the relative line strengths for each ion are fixed assuming local thermodynamic equilibrium (LTE), Baron et al. (2000) find that these features could be consistent with N II λ4623 and λ5679. However, the non-LTE model atmosphere code PHOENIX provides a synthetic spectrum which leads them to reject this identification, because it would require an overabundance of nitrogen to reproduce these features. Therefore they support the identification of the 4580Å, 5580Å absorptions as secondary features of Hβ and He I 5876Å at high velocity (∼20000 km s⁻¹), produced by complicated and unexplained non-LTE effects. Alternatively, using the model atmosphere code CMFGEN (Hillier & Miller 1998) and assuming a relevant N enrichment, Dessart & Hillier (2005, 2006) reproduce the lines in the blue wings of both of Hβ and He I 5876Å detected in the spectra of SN 1999em as N II.

For SN 2005cs a scenario where two line forming regions exist for hydrogen and helium is not supported by the line velocities measured for the putative HV components. As shown in Fig. 5 these line velocities are inconsistent. In particular, the velocity of the putative HV Hβ component is much larger than that of the HV Hα component. Moreover, the putative HV Hβ and HV He I features disappear simultaneously in the spectrum at ∼8 days. This supports, at least in the case of SN 2005cs, the identification of these two features as both due to N II.

For the same reason, and because of its persistence over
profiles in the spectra of SN 2005cs. Bottom: comparison of the H α evolution for SN 2005cs, SN 1987A, SN 1999em and SN 1999br. See the text for references.

In Fig. 6(top) we show the evolution of the velocity of various absorption spectral lines in SN 2005cs, as derived from the position of their minima. Hα shows the highest velocities, about 1000 km s\(^{-1}\) larger than those of the He I line. The N II and the Si II features appear to have smaller velocities than other lines. In particular, the velocity of the N II lines decreases from about 5600 km s\(^{-1}\) to ~3200 km s\(^{-1}\) between ~3 and 5 days. The velocity of the Si II 6355Å feature decreases from 4300 km s\(^{-1}\) at ~8 days to about 2100 km s\(^{-1}\) one month after the explosion. Over the same time interval, the Hα velocity decreases from 6200 to 3700 km s\(^{-1}\), while the Fe II velocity is ~800 km s\(^{-1}\) faster than that of the Si II line. In Fig. 6(bottom) we compare the Hα velocity evolution in SN 2005cs with that of SN 1987A (Phillips et al. 1988), SN 1999em (Pastorello 2003), and SN 1999br (Hamuy 2001; Pastorello et al. 2004). The Hα velocity curve of SN 2005cs appears to be strikingly similar to that of the low–velocity SN 1999br.

### Table 3. Model parameters for synthetic spectra shown in Fig. 7

| Parameter                  | SN 2005cs | SN 1987A | SN 1999em | SN 1999br |
|----------------------------|-----------|---------|-----------|-----------|
| log(\(L/L_\odot\))        | 7.90      | 7.88    | 7.90      | 7.88      |
| \(v_{\text{ph}}\) [km s\(^{-1}\)] | 3710  | 2580    | 3835  | 4037  |
| log(\(R_{\text{ph}}/R_\odot\)) | 3.894 | 4.037   | 3.894 | 4.037 |
| \(T_{\text{ph}}\) [K]    | 7599      | 6223    | 7599      | 6223      |

3.3 Spectral models: the 17 and 34 days spectra

Some preliminary spectral models have been computed in order to provide basic line identification. The code used for the synthetic spectra was described in more detail by Abbott & Lucy (1985); Mazzali & Lucy (1993); Lucy (1999); Mazzali (2000). The procedure involves a Monte Carlo (MC) simulation of the line transfer based on the Sobolev approximation. The code assumes that all radiative energy is emitted below a sharp lower boundary. The propagation of all energy packets is followed through the spherically symmetric envelope. Processes of interaction for photons taken into account are electron scattering and line transitions. When a photon packet is absorbed by a line transition, it is reemitted at a new frequency corresponding to the branching probabilities for the radiative decays of the excited level. At the end of the MC calculation a formal integral routine derives the emergent spectrum based on the MC estimate of the source functions (see Lucy 1999).

All models were computed assuming solar composition (Grevesse & Sauval 1998). As a starting point for this preliminary analysis we used the density structure of the hydrodynamic explosion model adopted to fit SN 1997D (Turatto et al. 1998). This model was characterised by an outer density profile which can be approximated by a power law \(\rho \propto r^{-40}\) at velocities above 3000 km s\(^{-1}\), and contained less than \(\sim 0.1M_\odot\) of material above this velocity. However, in order to reproduce the relatively narrow absorptions, in particular the well separated lines of the Ca II IR triplet, the density structure was cut above \(v = 6500\ km\ s\(^{-1}\)\) by adopting an even steeper power law \((\rho \sim r^{-40})\) beyond that velocity. This modification leads to an insignificant reduction of the ejected mass. Tab. 3 gives an overview on the model parameters used to derive the synthetic spectra shown in Fig. 7 Input parameters include the total luminosity of the SN and the position of the photosphere in velocity space \(v_{\text{ph}}\). Together with the epoch \(t\) this constrains the photospheric radius \(R\) and, therefore, the temperature at the photosphere via \(T_{\text{ph}}^3 = L/4\pi c R^2 = L/4\pi c r^2 v^2_{\text{ph}}\), where \(c\) is the Stefan–Boltzmann constant. Tab. 3 gives the final temper-

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**Figure 5.** Evolution of the region between 4100 and 7300Å, where the minima of Hβ, He I 5876Å and Hα are marked, as well as the position of the features at ~4580Å, 5580Å and 6300Å.

**Figure 6.** Top: expansion velocities for Hα, Hβ, He I λ5876, Na ID, N II λ5680, Fe II λ5169, Si II λ6355 deduced from the minima of P–Cygni profiles in the spectra of SN 2005cs. Bottom: comparison of the Hα velocity evolution for SN 2005cs, SN 1987A, SN 1999em and SN 1999br. See the text for references.

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a much longer time than the feature at 4580Å, we believe that the feature near 6300Å is Si II 6355Å, rather than HV Hz. The presence of this absorption in the spectra of SN 1999em was claimed by Dessart & Hillier (2003), and not explicitly mentioned by Baron et al. (2000).
Figure 7. Comparison between synthetic spectra and the observed spectra of SN 2005cs at phase 17 (top) and 34 days (bottom). The parameters used to compute the synthetic spectra are reported in Tab. 3.

The synthetic spectra in Fig. 7 are compared with the observed spectra at phases ~17 (top) and 34 days (bottom), respectively. The bottom panel of Fig. 7 also shows the identifications of prominent line features in this spectrum. The synthetic spectra support the identification of the feature near 6300 Å with the Si II 6347, 6371 Å lines. In the region between 5000 and 6400 Å, together with strong Fe II features, prominent lines of Sc II, Ti II, and the Na ID lines are identified.

In the later spectrum we note the increased strength of the Ba II lines compared to earlier epochs. Unfortunately, the 5854 Å line is blended with Na ID and the 6497 Å line with Hα. However, the feature at 6142 Å is relatively unblended and is detected unambiguously. The Ba II lines, as well as those of other s-process elements (Sc, Sr), are particularly prominent in late–photospheric spectra of low–velocity SNe IIP (Pastorello et al. 2004) and of SN 1987A, while are weaker in other SNe IIP (Mazzali et al. 1993, Mazzali & Chugai 1995, Utrobin & Chugai 2005).

The proposed density structure does not seem to be able to
fit the observations in detail. In particular, it is apparent that the proposed density cut, which is required to fit the Ca II IR lines at $t = 17 \text{ d}$, does not provide a good fit for the epoch $t = 34 \text{ d}$. This suggests that a steeper density law with less mass at high velocity is required to reproduce the low–velocity narrow absorptions seen in the observed spectra.

Concerning the total ejected mass, no conclusion can be drawn on the basis of spectral models of early epochs alone. A more detailed analysis of the density structure would also require information on the later spectral evolution as well as a study of the light curve, including the duration of the plateau phase (e.g. Turatto et al. 1998). This will be discussed elsewhere.

### 3.4 Comparison with other SN IIP

In Fig. 8 we compare the spectrum of SN 2005cs at $\sim 4 \text{ days}$ with those of other young SNe IIP: the low–velocity, $^{56}$Ni–poor SN 2002gd (Pastorello 2003), SN 1999em (Hamuy et al. 2001) and SN 1987A (Padova–Asiago SN archive). All spectra have blue continua and show He I $5876\AA$ and the H Balmer lines. Moreover, the features we attribute to N II $4623\AA$ and $5679\AA$ seem common to all SN II spectra except SN 1987A, which has however broader lines.

At $\sim 10 \text{ days}$ after explosion (see Fig. 9), we note a number of significant differences between the spectra of SNe IIP. While the spectrum of SN 1987A shows a red continuum dominated by prominent H and Fe II P–Cygni features, the spectra of more typical SNe IIP are still relatively blue. Although the spectrum of SN 2005cs is slightly redder than that of SN 1999em (Elmhamdi et al. 2003), it is bluer than that of the low–velocity, $^{56}$Ni–poor SN 2003Z (Knop et al. in preparation). The N II features visible in Fig. 8 have now completely disappeared, but the prominent absorption feature at $6300\AA$ is now visible in the spectra of SNe 2003Z, 2005cs and, as a bump in the H$\alpha$ absorption profile, in 1999em (see discussion in Elmhamdi et al. 2003). The identification of this feature as Si II $6355\AA$ is supported by the spectral modelling presented in Sect. 3.3.

In Fig. 10 we compare the spectrum of SN 2005cs at phase $\sim 2 \text{ weeks}$ to those of the $^{56}$Ni–poor SNe 1999br (Hamuy 2001),Pastorello et al. 2004 and 2003Z (Knop et al. in preparation) at a similar epoch. We also include 2 spectra of SN 1999em
Pastorello et al.

days after the explosion. The Si II 6355Å feature is prominent in (Leonard et al. 2002; Hamuy et al. 2001), taken about 17 and 21 1999em, 1999br. For references, see text.

luminosity distribution of SNe IIP (Hamuy 2001; Pastorello 2003; dicative that a very small mass of bottom), provides further support to our idea that SN 2005cs can expect that SN 2005cs will also evolve through a long plateau(3–4 be regarded as another SN 1997D–like event. In analogy to other number of objects belonging to this group. Only SNe with very low report some significant information available in the literature for a lar to SN 1997D (Turatto et al. 1998) are remarkable. In Tab. 4 we not longer visible 4 days later.

4 DISCUSSION

The observational analogies between SN 2005cs and objects similar to SN 1997D Taratto et al.1998 are remarkable. In Tab.4, we report some significant information available in the literature for a number of objects belonging to this group. Only SNe with very low ejecta velocities and/or small ejected 56Ni mass (≤10−2 M⊙) are included in Tab.4. All these objects belong to the faint tail of the luminosity distribution of SNe IIP (Hamuy 2001; Pastorello 2003; Hamuy 2003; Pastorello et al. 2003; Zampieri 2005) and have similarly low expansion velocities. In particular, the good match between the Hα velocity curves of SNe 2005cs and 1999br (Fig.6 bottom), provides further support to our idea that SN 2005cs can be regarded as another SN 1997D–like event. In analogy to other low–luminosity SNe IIP (Pastorello et al. in prep.), we therefore expect that SN 2005cs will also evolve through a long plateau (3–4 months) and reach a faint late–time luminosity. This would be indicative that a very small mass of 56Ni (of the order of ~ 10−2M⊙ or less) was ejected in the explosion, as the other similar SNe of Tab. 4.

The earliest spectra of SN 2005cs are very blue, suggesting a very high continuum temperature (2–3×104 K). In Fig.11 the evolution of the temperature of SN 2005cs derived from a blackbody fit to the spectral continuum is compared with those of SN 1987A Phillips et al. 1988, SN 1999em (as measured in Pastorello 2003 and SN 1999br Pastorello et al. 2004). Again, the continuum temperature evolution of SN 2005cs is not different from that of other SNe IIP. In particular, SN 2005cs has higher continuum temperatures than SN 1999br, but slightly lower than SN 1999em. Independent on the phase, all these long–plateau SNe have significantly higher continuum temperatures than SN 1987A. The temperature of SN 1987A becomes stationary about 3 weeks after the explosion, while for other SNe IIP the same happens 30–40 days past explosion. This indicates that in SN 2005cs (and in the other SNe IIP) the H envelope starts to recombine later than in SN 1987A.

If the faint absolute luminosity and the very well developed plateau should be confirmed by the observational campaign still in progress, they would fit with some difficulty the relatively small mass (MAMS ≈ 9M⊙) progenitor scenario derived from the progenitor detection Maund et al. 2003; Li et al. 2006. As mentioned in Sect. 4, both groups argued that the low luminosity of the progenitor indicates that it had a small mass. Maund et al. 2003 obtained a likely range of bolometric luminosity 4 ≤ L/L⊙ ≤ 4.4 (shaded region of their Fig. 3), and even for conservative errors, 4.6 Li et al. 2006 obtained an even lower value. To compare with the observed luminosity, they used the Geneva evolutionary models. The highest luminosities attained in the Geneva models are log(L/L⊙) = 4.2, 4.5, and 4.8 for M = 7M⊙, 9M⊙, and 12M⊙, respectively. To be consistent with the observed luminosity for the conservative limit, they suggested M = 7–12M⊙ for the progenitor.

However, the Geneva evolutionary models do not reach the pre–supernova stage. They cover the evolution up to the formation of O+Ne+Mg core for M > 9M⊙ and only up to the formation of the C+O core for M = 7M⊙. Stars with M < 8M⊙ form a degenerate C+O core whose mass Mcore increases towards the Chandrasekhar mass, Mch, as the star climbs the AGB. Paczynski 1970. Eventually the stars will either lose their H–rich envelope to form C+O white dwarfs or undergo a thermonuclear explosion (the so–called Type I–1/2 supernovae) when Mcore gets close to Mch (for reviews, see Sugimoto & Nomoto 1980; Nomoto & Hashimoto 1988). The 8–10M⊙ stars form a degenerate O+Ne+Mg core whose Mcore also increases towards Mch on the AGB. Nomoto 1984. Their final fate is either an O+Ne+Mg white dwarf or a core–collapse supernova when Mcore gets close to Mch Nomoto 1984.

The luminosity L of AGB stars with M ≤ 10M⊙ obeys Paczynski’s (1970) M–L relation. If a star with M ≤ 10M⊙ reaches Mcore = 1.4M⊙, the pre–supernova luminosities should be at least log(L/L⊙) = 4.8 for X(He) = 0.7, and even higher if the He abundance is higher (e.g. because of mixing. Hashimoto et al. 1993). If the progenitor was as massive as 12M⊙, the pre–supernova luminosities would be log(L/L⊙) ≥ 4.8. Systematic studies of the progenitor luminosity, including the effect of rotation, would be desirable to obtain a more reliable detailed comparison.

Therefore, the observed luminosity of the putative progenitor of SN 2005cs is inconsistent with the pre–supernova luminosity of 7–12M⊙ stars. If large extinction causes the observed luminosity of the progenitor to be very small, the observed luminosity cannot be used to constrain the progenitor’s mass. One possibility is that the absolute magnitude (and hence the mass) of the progenitor star is underestimated because of dust enshrouding the supergiant progenitor and later swept away by the SN explosion Graham & Meikle 1986. This scenario was ruled out by Maund et al. 2005 because no K band excess in the magnitude of the progenitor was detected in archival images. However, we cannot exclude the possibility that a particular dust composition and an extremely low temperature cause the light to be absorbed at optical wavelengths and re–emitted mostly in the mid– and far–IR bands (see e.g. Pozzo et al. 2004). Dust was observed in the late evolution of another well studied SN IIP, 2003gd Hendry et al. 2004. Despite having a plateau luminosity and an expansion velocity evolution similar to the “normal” SN 1999em, SN 2003gd showed low late time luminosity, indicating the ejection of a small mass of 56Ni (0.015M⊙), only a factor
two more than SN 1997D. Van Dyk et al. (2003) and Smartt et al. (2003) found a moderate–mass progenitor for SN 2003gd (8 M\textsubscript{\odot}). However, an evident light echo was recently detected in HST images of this object (Van Dyk et al. 2003; Sugerman 2005). This was due to SN light scattered by large–grain dust, located 110–180 pc in front of the SN, that survived the initial UV–flash. If this material was present before the SN explosion, it could be responsible for significant extinction of the star light, leading to an underestimate of the luminosity (and hence of the mass) of the progenitor.

As further support to this discussion, most SNe reported in Tab. 1 exploded in late Type galaxies (mainly of morphological Type Sb–Sc, by LEDA\textsuperscript{5}), which would be consistent with massive progenitors.

Finally, there is some ambiguity as regards the location of the putative progenitor of SN 2005cs. Therefore, even if the works of Maund et al. (2005) and Li et al. (2005) seem to support a moderate mass scenario for the precursor star of SN 2005cs, late time observations of the explosion site will probably be required in order to remove the residual uncertainty in the correct identification of the progenitor.

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