Distance estimate and progenitor characteristics of SN 2005cs in M51

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Abstract

Distance to the Whirlpool Galaxy (M51, NGC 5194) is estimated using published photometry and spectroscopy of the Type II-P supernova SN 2005cs. Both the Expanding Photosphere Method (EPM) and the Standard Candle Method (SCM), suitable for SNe II-P, were applied. The average distance (7.1 ± 1.2 Mpc) is in good agreement with earlier SBF- and PNLF-based distances, but slightly longer than the distance obtained by Baron et al. (1996) for SN 1994I via the Spectral Fitting Expanding Atmosphere Method (SEAM). Since SN 2005cs exhibited low expansion velocity during the plateau phase, similarly to SN 1999br, the constants of SCM were re-calibrated including the data of SN 2005cs as well. The new relation is better constrained in the low velocity regime \( v_{ph}(50) \sim 1500 – 2000 \) km s\(^{-1}\), that may result in better distance estimates for such SNe. The physical parameters of SN 2005cs and its progenitor is re-evaluated based on the updated distance. All the available data support the low-mass (\( \sim 9 \) M\(_{\odot}\)) progenitor scenario proposed previously by its direct detection with the Hubble Space Telescope (Maund et al. 2005; Li et al. 2006).

Key words: stars: evolution – supernovae: individual (SN 2005cs) – galaxies: individual (M51)

1 INTRODUCTION

The Type II-P SN 2005cs in M51 was discovered by Kloehr (2005) on June 28.9 2005. The first spectroscopic data (Modjaz et al. 2005) indicated that this SN was caught at very early phase, shortly after explosion. Pastorello et al. (2006) presented high-quality \( UBVRI \) photometry and optical spectroscopy obtained during the first month of the plateau phase. From their data supplemented by amateur observations they could determine a tight constraint on the explosion time. They derived JD 2453549 ± 1 (June 27.5 UT, 2005), which is adopted in this paper, and will be used for the distance determination later. They also collected the available information for the reddening of SN 2005cs, and found \( E(B-V) = 0.11 \pm 0.04 \) mag, which is consistent with the blue colour of SN 2005cs at the early phase (see Pastorello et al., 2006 for discussion). Tsvetkov et al. (2006) published additional photometry extending into the nebular phase, from which they estimated the explosion time very close to that of Pastorello et al. (2006) (within 0.2 day) and a nickel mass \( M_{Ni} \sim 0.018 \) M\(_{\odot}\).

Both teams have detected the possible progenitor, but only in the \( I \) band, which led to the conclusion that the progenitor was probably a red giant. From the \( I \) band flux and the flux upper limits in the other bands the mass of the progenitor turned out to be relatively small: \( M_{ZAMS} = 7 – 9 \) M\(_{\odot}\) (Li et al. 2006) and \( M_{ZAMS} = 7 – 12 \) M\(_{\odot}\) (Maund et al. 2005). The lower limit of these mass estimates are close to the theoretical limit of core collapse (Hillebrandt 2005).

In this paper we present a new distance estimate to M51 based on the published data of SN 2005cs. The application of the distance measurement methods are in Section 2. In Section 3 we compare the SN-based distance to other recent distance estimates and derive an average value that is consistent with the available information. Finally, we update the physical parameters of SN 2005cs based on the new distance.

2 DISTANCE MEASUREMENT

In this section we apply the Expanding Photosphere Method (EPM) and the Standard Candle Method (SCM) for estimating the distance to SN 2005cs.
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Table 1. Quantities determined in EPM. The columns contain the followings: observational epoch (JD-2540000), bolometric flux (in erg s⁻¹ cm⁻²), temperature (in K), velocity at the photosphere (in km s⁻¹), angular size (in 10⁻⁶ km Mpc⁻¹) and θ/ceph (in day Mpc⁻¹). The uncertainties are in parentheses.

| t (JD-2540000) | fbol (erg s⁻¹ cm⁻²) | Teff (K) | vph (km s⁻¹) | θ (10⁶ km Mpc⁻¹) | θ/ceph (day Mpc⁻¹) |
|----------------|----------------------|----------|--------------|------------------|---------------------|
| 3552.36        | 5.11·10⁻¹¹           | 35864 (4207) | 6370(300)    | 0.4158           | 0.0752              |
| 3553.35        | 5.28·10⁻¹¹           | 30183 (1220) | 5900(300)    | 0.6993           | 0.1195              |
| 3554.46        | 5.07·10⁻¹¹           | 23624 (180)  | 5550(300)    | 1.0042           | 0.2079              |
| 3557.42        | 4.94·10⁻¹¹           | 20058 (243)  | 5050(300)    | 1.3997           | 0.3146              |
| 3557.84        | 4.68·10⁻¹¹           | 16836 (2092) | 4900(300)    | 1.9601           | 0.4630              |
| 3559.40        | 4.62·10⁻¹¹           | 15038 (1633) | 4560(300)    | 2.4489           | 0.6095              |
| 3563.38        | 4.46·10⁻¹¹           | 10235 (1417) | 4030(250)    | 4.9404           | 1.4206              |
| 3563.42        | 4.35·10⁻¹¹           | 9385 (1730)  | 4010(250)    | 5.6194           | 1.6199              |
| 3565.38        | 4.11·10⁻¹¹           | 9244 (1468)  | 3725(250)    | 5.5881           | 1.7480              |
| 3566.36        | 4.04·10⁻¹¹           | 8897 (1195)  | 3600(250)    | 5.9649           | 1.9177              |
| 3566.40        | 3.98·10⁻¹¹           | 8999 (1533)  | 3600(250)    | 5.7287           | 1.8469              |
| 3569.42        | 3.81·10⁻¹¹           | 7575 (1568)  | 3330(250)    | 7.0943           | 2.4510              |
| 3571.40        | 3.72·10⁻¹¹           | 7495 (1429)  | 3180(250)    | 7.1004           | 2.5843              |
| 3572.40        | 3.68·10⁻¹¹           | 7341 (1512)  | 3090(250)    | 7.2426           | 2.7040              |
| 3577.40        | 3.72·10⁻¹¹           | 7049 (1479)  | 2730(250)    | 7.6167           | 3.3267              |
| 3579.40        | 3.70·10⁻¹¹           | 6519 (1415)  | 2580(250)    | 8.2323           | 3.8112              |
| 3583.39        | 3.66·10⁻¹¹           | 6023 (1537)  | 2260(250)    | 8.7738           | 4.4152              |
| 3583.47        | 3.64·10⁻¹¹           | 6051 (1630)  | 2260(250)    | 8.7205           | 4.4858              |

2.1 Expanding Photosphere Method

The Expanding Photosphere Method [Kirshner & Kwan 1974] derives distance of an optically thick, homologously expanding SN atmosphere, radiating as a diluted blackbody. These assumptions are expected to be close to the real physical situation in a dense atmosphere of a Type II-P SN at the early plateau phase, when the ejecta is almost fully ionized, and electron scattering dominates the true absorption [Dessart & Hillier 2005]. Since SN 2005cs was observed in the first 30 days of the plateau phase, this is a promising object for the application of EPM.

We have applied the bolometric version of EPM described by Vinkó et al. [2006]. The BVRI photometric data from Pastorello et al. [2006] were dereddened using E(B−V) = 0.11, then transformed into fluxes using the calibration given by Hamuy et al. [2001]:

\[ f_\lambda = \frac{h \cdot c}{\lambda \cdot W_\lambda} \cdot 10^{(m_0 - m)/2.5} \]  

(1)

where \( W_\lambda \) is the FWHM of the given filter, \( m \) is the dereddened magnitude, \( m_0 \) is the zero-point of the magnitude scale.

From these quasi-monochromatic fluxes, the bolometric flux \( f_{bol} \) for each epoch was estimated by numerically integrating \( f_\lambda \) using the effective wavelengths and FWHM values of the BVRI filters. The missing fluxes in lower and greater wavelengths were extrapolated linearly from the B- and I-band fluxes, assuming zero flux at 3400 Å and 23000 Å [Vinkó et al. 2006].

The angular radius was derived from the bolometric light curve as

\[ \theta = \sqrt{\frac{f_{bol}}{\pi \cdot c \cdot T_{eff}^4}} \]  

(2)

where \( f_{bol} \) is the observed bolometric flux, \( T_{eff} \) is the effective temperature and \( \zeta(T) \) is the dilution factor.

The effective temperatures were estimated by fitting a blackbody to the fluxes in B, V and I bands. The R band was omitted because of the presence of the Hα emission line. Vinkó et al. [2004] has recently demonstrated that the total flux of the blackbody corresponding to temperature \( T_{BVRI} \) produces a reasonable distance estimate, although the spectral flux distribution of the SN is, of course, not exactly Planckian. Fortunately, the deviation from the blackbody curve is not so severe at the early phases, when SN 2005cs was observed, but becomes more and more pronounced after \( t > 20 \) days, when the lines of ionized metals appear in the spectrum.

The dilution factor \( \zeta(T) \) comes from model atmospheres. We have applied the dilution factors derived recently by Dessart & Hillier [2005]. They determined \( \zeta \) for the first 30 days of the plateau. They also argued that EPM should be applied for phases earlier than 30 days, because of the failure of the blackbody assumption at later phases, when metallic lines dominate the photospheric spectrum. Note that their model atmospheres had \( T_{eff} < 20000 \) K, thus, the dilution factors are valid only in the range of \( 4000 < T_{eff} < 20000 \) K (see Fig. 1 of Dessart & Hillier [2005]).

The dilution factors of Dessart & Hillier [2005] are systematically higher than those of Eastman et al. [1996]. This has the consequence that the distances computed from the Dessart & Hillier [2005] dilution factors are systematically longer than those from the Eastman et al. [1996] dilution factors. It is not clear why these two sets of model atmospheres give different dilution factors, but Dessart & Hillier [2006] provided a convincing evidence that their data result in a distance to SN 1999em, which is in good agreement with the cepheid-based distance to the host galaxy, while the calculation based on the earlier set of dilution factors give a distance that differs by 50 % (Leonard et al. 2003).
We have calculated the distance by applying the linear equation

$$ t = t_0 + D \frac{\theta}{v_{ph}} $$

(3)

where $t_0$ is the moment of the explosion, $v_{ph}$ is the photospheric expansion velocity at epoch $t$ and $D$ is the distance.

The velocity data were selected from Pastorello et al. (2006) and were interpolated to the epochs of the photometric data. In the first days, when there are no metallic lines in the spectrum, we used the velocities inferred from the He I $\lambda$5876 line. This line is a good indicator of the photospheric velocity at the early phases. According to our parametrized model spectra of Type II-P SNe (Vinkó, in preparation), the velocities from He I $\lambda$5876 match the input photospheric velocities of the model spectra within $\pm 2 \%$. After $JD = 2453557$ the Fe II $\lambda$5169 line was used, which is the standard one for computing photospheric velocities in SNe II-P atmospheres (Dessart & Hillier 2003).

The derived parameters for SN 2005cs are listed in Table I. Note that the first 6 points were omitted from the fitting, due to the following reasons. The estimated temperature of the first 4 data is over 20000 K, outside the temperature range of the dilution factors (see above). The next two points have the highest errorbars of their fitted $T_{eff}$, and the theoretical dilution factors of Dessart & Hillier (2003) also show large scatter around these temperatures. Moreover, our approach for computing the bolometric fluxes has been tested to work well only for $T < 10000$ K (Vinkó et al. 2006). The bolometric fluxes are underestimated above this temperature, due to the very approximative treatment of the UV flux, which has significant contribution at high temperatures.

Because the moment of the explosion of SN 2005cs could be determined with very small uncertainty ($JD = 2453549 \pm 1$ Pastorello et al. (2006)), at first, we kept this parameter fixed and derived only the distance. This resulted in $D = 6.37 \pm 0.12$ Mpc (Fig. I). The $\pm 1$ day uncertainty of the explosion epoch changes the distance with $\pm 0.34$ Mpc.

Secondly, when $t_0$ was treated as a free parameter, the distance decreased to $D = 6.84 \pm 0.18$ Mpc. The explosion epoch turned out to be $t_0 = 2453553.39 \pm 0.52$ JD. This is 4 days later than the one coming from the photometric data, and clearly inconsistent with the observations (the discovery date is 2 days earlier). However, the slightly lower distance describes the observed data better, than the previous one (see Fig. I).

It is difficult to explain why the two EPM solutions give different distances by $\sim 20 \%$. The inclusion of the first 6 data that were disregarded before (see above) does not change either solution significantly. In the first case, they are too close to the explosion epoch which is fixed, thus, the slope of the fitted line remains unchanged. In the second case, when the explosion epoch is also fitted, surprisingly, the first 6 points lie nicely close to the line fitted to the other data. Thus, the varying uncertainties of our bolometric fluxes, although undoubtedly present, cannot fully explain the $\sim 20 \%$ inconsistency between the EPM solutions of fixed and variable explosion epoch.

Another possible reason is the systematic error in the measurement of the photospheric velocity. Since we are using published velocities, and the original spectra are not at our disposal, we cannot quantify the amount of their potential systematic error better than estimating the errorbars according to the resolution of the spectra given by Pastorello et al. (2006). Then, as a test, we have systematically increased all velocities in Table I by $1 \sigma$ and refitted $t_0$ and $D$. As a result, the distance increased to $7.5 \pm 0.2$ Mpc, but the explosion epoch remained the same, $t_0 = 2453535.37 \pm 0.4$ JD. Thus, systematic underestimate of the velocities may result in the underestimate of the distance, but it does not solve the problem of the computed explosion epoch that is still too late.

The most problematic part of EPM is, of course, the issue of the dilution factors that are computed from complex models of SNe atmospheres (Dessart & Hillier 2003). Despite the continuous efforts for improving them, they may still contain some sort of systematic uncertainty, beside the statistical errors that are $\sim 5 \%$ between $4000 < T_{BV,I} < 8000$ K, but increase up to $\sim 20 - 30 \%$ for $T_{BV,I} > 12000$ K (see Fig. 1 of Dessart & Hillier (2003)). For comparison, the whole analysis was repeated with the use of the dilution factors by Eastman et al. (1994) that are systematically lower at a given temperature (see above). As expected, this resulted in significantly lower distances: $D = 6.37 \pm 0.12$ Mpc (with $t_0 = 2453549$ fixed) and $D = 5.40 \pm 0.13$ Mpc (with $t_0 = 2453535.8 \pm 0.4$ fitted). Their average, $5.88$ Mpc is below the other M51 distances determined independently (see Sect. 3), similarly to the case of SN 1999em mentioned above. These results suggest that the Dessart & Hillier (2005) dilution factors provide a better EPM-distance when applied to data obtained during the first month of the photospheric phase, at least in the case of SN 2005cs. However, regardless of the dilution factors, there seems to be a persistent problem with the explosion date, i.e. the best-fitting EPM solution predicts an explosion epoch which is clearly too late with respect to the earliest observations. This is a warning sign that the assumptions of EPM, for example the spherically symmetric ejecta, may be incorrect.

Nevertheless, we decided to consider the average of the two original EPM-solutions in estimating the final distance (see Section 3). Therefore, $D = 7.59 \pm 1.02$ Mpc has been adopted as the best EPM-distance to SN 2005cs.

Note that Eq. 3 was derived by neglecting the radius of the progenitor with respect to the term $v_{ph}(t - t_0)$, as usual. Taking into account the progenitor radius $R_0$ in $\theta = (R_0 + v_{ph}(t - t_0))/D$ increases the EPM-distance. In the case of SN 2005cs, setting $R_0 = 500 \, R_\odot$ results in a $6 \%$ increase of the distance. However, it is shown in Sect. 3 that SN 2005cs probably had a smaller initial radius of $\sim 180 \, R_\odot$, which has negligible effect on the distance (about $2 \%$).

### 2.2 Standard Candle Method

The Standard Candle Method (SCM) is based on a luminosity-velocity relation at 50 days after explosion, approximately in the middle of the plateau phase. This method was calibrated using 24 SNe (Hamuy 2003). More recently, Nugent et al. (2006) refined the relation by adding two local SNe to the calibrating sample, re-formulated and extended the method to cosmological distances.

We tried to apply SCM for SN 2005cs in two ways. First, the original relation by Hamuy (2003) was considered. For
this purpose, one needs the $V$ and $I$ magnitudes and the expansion velocity obtained on the 50th day after explosion. Since the data of Pastorello et al. (2006) do not reach this phase, we used the photometry of Tsvetkov et al. (2006), which is in good agreement with the data of Pastorello et al. (2006). $V(50) = 14.69 \pm 0.1$ mag and $I(50) = 13.96 \pm 0.1$ mag was determined by linear interpolation. Unfortunately, there are no published velocity data of SN 2005cs extending into day $+50$, so we had to estimate this parameter.

First, the velocity curves of SN 2005cs and the other low-velocity SN 1999br (Hamuy 2003) was matched, and the combined curve was used to estimate the velocity at day 50. Secondly, the velocity curves of SN 2005cs and the other low-velocity Type II-P SN 1999br (Hamuy 2003) was matched, and the combined curve was used to estimate the velocity at day 50. Secondly, we applied the formula by Nugent et al. (2004) $v_{ph}(50) = v_{ph}(t) \cdot (t/50)^{0.464}$ for the last two published velocities of SN 2005cs (Pastorello et al. 2006). The first method gave $v_{ph} \sim 2020$ km s$^{-1}$, while in the second case the average of the predicted velocities was $\sim 2047$ km s$^{-1}$. Finally, $v_{ph}(50) = 2030 \pm 300$ km s$^{-1}$ was adopted as an average.

Substituting these values into the formulae of Hamuy (2003), $D_V = 6.13 \pm 0.8$ Mpc and $D_I = 6.55 \pm 0.9$ Mpc was derived for the distance of SN 2005cs (Table 2).

Because SN 2005cs was a low-velocity SN, and such Type II-P SNe are represented only by SN 1999br in the calibrating sample, we decided to recalibrate the SCM including SN 2005cs as well. This new relation is expected to be better constrained in the low velocity regime, thus, it may predict more accurate distances for such SNe.

Of course, one needs independent distances for such calibration. Hamuy (2003) used the Hubble-flow velocities for computing the distances. However, the host galaxy of SN 2005cs, M51, is too close to get reasonable estimates of its distance from redshift.

Therefore, we have adopted the weighted average of all the distances of M51 except the value from SCM, using the reciprocal of the errorbars as weights (see Table 3 in Section 3.1). This resulted in $D = 7.25 \pm 1.21$ Mpc, which is slightly less than the average EPM-distance ($7.59 \pm 1.02$ Mpc) determined above. Fig. 2 shows SN 2005cs on the absolute magnitude – velocity diagram with the other calibrating SNe (26 in $V$- and 19 in $I$-band) from Hamuy (2003) and Nugent et al. (2006). It is seen that most of them have a velocity greater than 3000 km/s. Only SN 1999br and SN 2005cs are in the low velocity regime. They have similar velocities, but SN 2005cs is brighter by almost 2 magnitudes.

The calibrating sample was fitted by the following equation of SCM:

$$m = A + a \cdot \log \left( \frac{v_{50}}{5000} \right) = 5 \cdot \log(H_0D) - b$$

where $m$ is the observed magnitude (in $V$ or $I$), $A$ is the extinction, $H_0 = 73$ km (s Mpc)$^{-1}$ (Riess et al. 2004) is the Hubble-constant, $D$ is the distance, $a$ and $b$ are the fitted constants.

The results of the fit are seen in Fig. 3 ($V$) and in Fig. 4 ($I$). The fitted constants $a$ and $b$ are collected in Table 2. The inclusion of SN 2005cs changed mainly the constant $a$, the slope of the luminosity-velocity relation.

With the new constants the distance of SN 2005cs was re-evaluated. These values are also seen in Table 2. All of them are lower than the EPM-distance with fixed explosion epoch. The agreement is better with the EPM-distance with fitted $t_0$ (see the previous section). However, we stress that the present application of SCM is only preliminary, because...
Table 2. The derived constants a and b of Eq. 3 in V and I bands and the same data from Hamuy (2005). The obtained distances of SN 2005cs (in Mpc) are also shown in the last column.

| Method | a            | b            | D      |
|--------|--------------|--------------|--------|
| V      | 6.564 (0.68) | 1.478 (0.11) | 6.13 (0.8) |
|        | Hamuy (2005) | this paper   |        |
| I      | 5.869 (0.68) | 1.926 (0.09) | 6.55 (0.9) |
|        | Hamuy (2005) | this paper   |        |

3 DISCUSSION

3.1 The average distance to M51

M51 is a very well-known galaxy, but its distance was determined only a few times between 1974 and 2005. Sandage & Tammann (1974) derived 9.6 Mpc using sizes of H II regions. Although they did not specify the errorbar of their result, it is probably more uncertain than the other, more recent distance estimates. Georgiev et al. (1990) got 6.91 ± 0.67 Mpc from the photometric properties of young stellar associations (YSA). Feldmeier & Ciardullo (1997) determined 8.39 ± 0.60 Mpc using planetary nebulae luminosity function (PNLF), but later they revised it as 7.62 ± 0.60 Mpc using improved reddening (Ciardullo et al. 2002). From surface brightness fluctuation (SBF) Tonry et al. (2001) obtained 7.66 ± 1.01 Mpc.

The Type Ic SN 1994I also gave a chance for distance determination to M51. By fitting theoretical light curves to observations Iwamoto et al. (1994) got D = 6.92±1.02 Mpc. With the spectral-fitting expanding atmosphere method (SEAM) Baron et al. (1996) derived 6.02 ± 1.92 Mpc.

Table 3 contains the various M51 distances (except that of Sandage & Tammann (1974), which deviates mostly from all the other ones) together with our results based on SN 2005cs. Adopting their average, the final distance to M51 turns out to be

\[ D_{M51} = 7.1 \pm 1.2 \text{ Mpc}. \]

3.2 The physical properties of SN 2005cs

The physical parameters of SN 2005cs are sensitive to the distance used to derive these parameters. All the previous studies (Li et al. 2001; Maund et al. 2003; Pastorello et al. 2003; Tsvetkov et al. 2006) adopted the SBF-distance D = 8.39 Mpc by Feldmeier & Ciardullo (1997), which was actually shortened to 7.62 Mpc by the same authors in a subsequent paper (Ciardullo et al. 2002). Thus, the published parameters of SN 2005cs may need some revision based on the updated M51 distance.

We have calculated some of the physical parameters adopting the average M51 distance (D = 7.1 Mpc) from the previous section. Using the light curves of Tsvetkov et al. (2006), the middle-plateau absolute magnitudes (corrected for reddening with \( E(B - V) = 0.11 \)) are \( M_V(50) = -14.88 \pm 0.3 \) and \( M_I(50) = -15.46 \pm 0.3 \). For comparison, Tsvetkov et al. (2003) determined \( M_V(50) = -15.33 \), which...
Table 4. The inferred physical parameters of SN 2005cs, based on $D = 7.1$ Mpc and $E(B-V) = 0.11$ mag. See text for explanation. The errors are in parentheses.

| Parameter | $M_V(50)$ (mag) | $M_I(50)$ (mag) | $M_{I pb}^{loop}$ (km s$^{-1}$) | $v_{ph}(50)$ (km s$^{-1}$) | $M_{Ni}(51)$ ($M_{\odot}$) | $E_{expl}(51)$ erg | $M_{ej}(51)$ ($M_{\odot}$) | $R_{ini}(10)$ R$_{\odot}$ | $M_{prog}(51)$ ($M_{\odot}$) |
|-----------|-----------------|-----------------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $-14.88$  | $-15.46$         | $-5.5$          | $2030$           | $0.009$         | $0.19$          | $8.3$           | $177$           | $(0.3)$         | $(0.3)$         |
| $(0.3)$   | $(0.3)$          | $(0.7)$         | $(300)$          | $(0.003)$       | $(0.15)$        | $(5.3)$         | $(150)$         | $(5.3)$         |}

is $\sim 0.4$ mag brighter, because of their longer adopted distance. From the correlation between the Ni-mass and $M_V$ ($Hammuy$ 2003), the calculated Ni-mass is $M_{Ni} \approx 0.009 \pm 0.003 M_{\odot}$. Again, this is somewhat less than the value given by Tsvetkov et al. (2006) ($\approx 0.018 M_{\odot}$). However, this less amount of synthesized Ni is in better agreement with the relation of Hammuy (2003) between the Ni-mass and the middle-plateau photospheric velocity. For $M_{Ni} \sim 0.009 M_{\odot}$ this relation predicts $v_{ph}(50) \approx 2200$ km s$^{-1}$, which is in good agreement with $\sim 2030$ km s$^{-1}$ determined in Sect. 2.2. Tsvetkov et al. (2006) estimated $v_{ph}(50) \sim 2600$ km s$^{-1}$, which is too high, since the observed velocity is already $\sim 2200$ km s$^{-1}$ at day +35 (see Table I).

The physical parameters for the progenitor star have been derived from the formulae given by Nadyozhin (2003). These equations relate the explosion energy, ejected envelope mass and initial radius to the plateau absolute magnitude. Explosion velocity and plateau duration. Using $M_V \sim -14.88$ mag, $v_{ph} \sim 2030$ km s$^{-1}$ estimated above, and $\Delta m_B \sim 86$ days from the light curves of Tsvetkov et al. (2006), $E_{expl} = 0.19 \times 10^{51}$ erg, $M_{ej} = 8.3 \pm 0.8 M_{\odot}$ and $R_{ini} = 177^{+258}_{-115} R_{\odot}$ has been calculated for the explosion energy, envelope mass and radius, respectively. These are in good agreement with the ones given by Tsvetkov et al. (2006), despite the somewhat shorter distance applied in this paper. The absolute magnitude of the progenitor was also updated using the magnitude estimates from HST-photometry. For the observed brightness of the likely progenitor star, Li et al. (2006) reported $I = 24.15 \pm 0.2$ mag, while Maund et al. (2005) got $I \approx 23.3$ mag, about 1 mag brighter. The average of these is $\sim 23.7 \pm 0.6$ mag, which is adopted here. Using the 7.1 Mpc distance, the absolute $I$-band magnitude is $M_I^{loop} \approx -5.5 \pm 0.7$ mag, which is the same as the result of Li et al. (2006). Although their progenitor brightness is fainter than the average value used here, they adopted a longer distance to M51, leading to the same absolute magnitude.

The inferred physical parameters of SN 2005cs and its progenitor are summarized in Table I.

From the envelope mass of $\sim 8 M_{\odot}$, the progenitor mass $M_{prog}$ can be calculated by adding the estimated mass of the compact remnant of the core-collapse process. Assuming that it is a neutron star, its mass is estimated as $\sim 1.3 \pm 0.5 M_{\odot}$ (Ferrier & Kalogera 2001). The progenitor mass is then $M_{prog} = 9.6 \pm 5.3 M_{\odot}$, which is in good agreement with the mass of $7 - 9 M_{\odot}$ estimated from the direct detection of the progenitor (Li et al. 2006; Maund et al. 2005), as it was also found by Tsvetkov et al. (2006). On the other hand, it seems to be in contrast with the theoretical prediction by Zampieri et al. (2003) that low-luminosity SNe II-P, such as SN 1999br and SN 1997D may occur from a peculiar, low-energy explosion of a more massive supergiant star of $\sim 15 - 20 M_{\odot}$. SN 2005cs was definitely such a low-energy, low-luminosity SN, as it is also indicated by its low expansion velocity (Pastorello et al. 2006), because the explosion energy derived above is the lowest among the energies of other SNe II-P determined in similar way (see Table 2 of Nadyozhin 2003). It is even lower than the one inferred by Zampieri et al. (2003) for SN 1999br ($\sim 0.6 \cdot 10^{51}$ erg), which had lower expansion velocity than SN 2005cs. Although Pastorello et al. (2006) argued that the mass of the progenitor may be underestimated from its observed $I$-band flux, the explosion characteristics of SN 2005cs are in better agreement with the low-mass progenitor scenario proposed by Li et al. (2006) and Maund et al. (2005).

The consistency of the inferred progenitor mass and radius can be tested with the prediction of the evolutionary tracks. We have applied the Padova evolutionary models Bressan et al. (1993) with $Z = 0.02$ and $Z = 0.008$. For both metallicities, the $M = 7 M_{\odot}$ models have $R \sim 180 R_{\odot}$ radius at K3 - K4 spectral type ($T_{eff} \sim 4000$ K), near the end of their calculated evolutionary track. This is also in good agreement with the K - M spectral type estimated from the HST flux limits Li et al. (2006; Maund et al. 2003). The $M > 9 M_{\odot}$ models have $R > 300 R_{\odot}$ in this spectral type regime, regardless of metallicity. Note, however, that the progenitor parameters estimated above are quite uncertain, therefore the larger, more massive progenitor scenario cannot be ruled out from these data alone. It is concluded that the available information may suggest a consistent picture for SN 2005cs and its progenitor, namely a low-mass, $(M \sim 9 M_{\odot})$ K3 - K4 spectral type supergiant that showed a low-energy explosion ($E_{expl} \sim 0.2 \cdot 10^{51}$ erg) producing an underluminous ($M_V(50) \sim -15$ mag), slowly expanding ($v_{ph}(50) \sim 2000$ km s$^{-1}$) Type II-Plateau SN.

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REFERENCES

Baron, E., Hauschildt Branch, D., Kirshner, R. P., Filippenko, A. V. 1996, MNRAS 279, 799
Bressan, A., Fagotto, F., Bertelli, G., Chiosi, C. 1993, A&A S 100, 647
Ciardullo, R., Feldmeier, J. J., Jacoby, G. H., De Naray, R. K., Laychak, M. B., Darrell, T. R. 2002, ApJ 577, 31
Dessart, L., Hillier, D. J. 2005, A&A 439, 617
Dessart, L., Hillier D. J., 2006, A&A 447, 691
Eastman, R. G., Schmidt, B. P., Kirshner, R. 1996, ApJ, 466, 911
Feldmeier, J. J., Ciardullo, R. 1997, ApJ, 479, 231
Fryer, C. L., Kalogera, V. 2001, ApJ, 554, 548
Georgiev, Ts. V., Zamanova, V. I., Ivanov, G. R. 1990, P. Astron. Zh. 16, 979
Hamuy, M. 2001, PhD Thesis, Univ. of Arizona
Hamuy, M. 2003, ApJ 582, 905
Hamuy, M., 2005, in: "Cosmic Explosions" Springer Proceedings in Physics No. 99. Eds. J. M. Merciaide, K. W. Weiler, p. 535
Hamuy, M. et al. 2001, ApJ 558, 615
Hillebrandt, W. 2005 in: "Cosmic Explosions" Springer Proceedings in Physics No. 99. Eds. J. M. Merciaide, K. W. Weiler, p. 241
Iwamoto, K. et al. 1994, ApJ 437, 115
Kirshner, R. P., Kwan, J. 1974, ApJ 193, 27
Kloehr, W., 2005, IAUC, 8553
Leonard D. C., Kanbur S. M., Ngeow C. C., Tanvir N. R., 2003, ApJ 594, 247
Li, W., Van Dyk, S. D., F A. V., Cuillandre J., Jha, S., Bloom, J. S., Riess, A. G., Livio, M. 2006, ApJ 641, 1060
Maund, J. R., Smartt, S. J., Danziger, I. J. 2005, MNRAS 364, L33
Modjaz, M., Kirshner, R., Challis, P., 2005 IAU Circ. 8555
Nadyozhin, D. K., 2003, MNRAS 346, 97
Nugent, P. et al., 2006, preprint (astro-ph/0603535)
Pastorello, A. et al., 2006, preprint (astro-ph/0605700)
Riess, A. G. et al. 2005, ApJ 627, 579
Sandage, A., Tammann, G. A. 1974, ApJ 194, 559
Tonry, J. L., Dress Blakeslee, J. P., Ajhar, E. A., Fletcher, A. B., Luppino, G. A., Metzger, M. R., Moore, C. B. 2001, ApJ 546, 681
Tsvetkov D. Yu. et al., 2006, preprint (astro-ph/0605184)
Vinkó, J. et al. 2006, MNRAS 369, 1780
Zampieri, L., Pastorello, A., Turatto, M., Capellaro, M., Benetti, S., Altavilla, G., Mazzali, P., Hamuy, M., 2003, MNRAS 338, 711