The peculiar Type II Supernova 1997 D: A case for a very low ^{56}Ni mass [0]

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ABSTRACT

SN 1997D in NGC 1536 is possibly the least luminous and energetic Type II supernova discovered to date. The entire light curve is subluminous, never reaching $M_V = -14.65$. The radioactive tail follows the ^{56}Co decay slope. In the case of nearly complete trapping of the γ-rays, the ^{56}Ni mass derived from the tail brightness is extremely small, ~ 0.002 $M_\odot$. At discovery the spectra showed a red continuum and line velocities of the order of 1000 km s^{-1}. The luminosity and the photospheric expansion velocity suggest that the explosion occurred about 50 days before discovery, and that a plateau probably followed. Model light curves and spectra of the explosion of a 26 $M_\odot$ star successfully fit the observations. Low mass models are inconsistent with the observations. The radius of the progenitor, constrained by the prediscovery upper limits, is $R_0 \lesssim 300$ $R_\odot$. A low explosion energy of $\sim 4 \times 10^{50}$ ergs is then required in the modeling. The strong Ba II lines in the photospheric spectra are reproduced with a solar abundance and low $T_{\rm eff}$. A scenario in which the low ^{56}Ni mass observed in SN 1997D is due to fall–back of material onto the collapsed remnant of the explosion of a 25–40 $M_\odot$ star appears to be favored over the case of the explosion of an 8–10 $M_\odot$ star with low ^{56}Ni production.

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1. Introduction

SN 1997D was serendipitously discovered on Jan. 14.15 U.T. (De Mello & Benetti 1997) in NGC 1536, a morphologically disturbed spiral galaxy belonging to a high density group (Maia et al. 1994). Although NGC 1536 ($v_{\rm helio}$ = 1296 km s^{-1}, RC3) is one of the galaxies patrolled visually by Rev. Evans for his SN search (private communication), he missed the SN because its brightness apparently never exceeded his detection limit.

The first spectrum showed the main features of type II SNe, but also revealed peculiarities which make this object unique. Particularly noteworthy were the extremely slow expansion velocities, the red color and the strong Ba II lines (Turatto et al. 1998). A campaign of photometric and spectroscopic observations was therefore promptly started at ESO and CTIO. The complete data set will be presented elsewhere.

2. Properties and evolution

The SN was intrinsically faint compared to other SNe II. If we assume a distance modulus of $\mu = 30.64$ mag for NGC 1536 (H_0 = 75 km s^{-1} Mpc^{-1}; Tully 1988), and $A_B = 0.00$ (RC3), a set of closely spaced non-detections by Evans sets an upper limit to the SN luminosity of $M_{\rm V}({\rm max}) \gtrsim -14.65$. This is about 2 magnitudes fainter than regular SNe II at maximum (Patat et al. 1994).

In Fig. 1 we compare the absolute V light curve of SN 1997D with those of other SNe II: the double–peaked SN 1987A, the prototypical SNIIb 1993J and the linear SN 1979C. Even with the uncertainties on the epoch of maximum and in the distance modulus, SN 1997D was definitely fainter than all of these objects. The decline rates in the V, R and I bands after J.D. 2450520 are close to the ^{56}Co decay rate.

The color of SN 1997D at discovery was unusually red. No sign of interstellar absorption lines, which are expected in case of strong extinction, is present in the spectra. SN 1997D reddened rapidly over the first few weeks after discovery, reaching a maximum (B−V)= 2.5 in mid-February, and then turned gradually bluer. The analogy with the color curves of other SNe II, which reach the red-most point between 40 and 80 days after peak luminosity, indicates that maximum light should have occurred around J.D. 2450430 (±20d).

A bolometric light curve is needed for a proper analysis of the energetics. Unfortunately, most of our observations only cover the optical domain. Only at one phase are nearly simultaneous optical (Jan.31) and IR (Jan.27) spectra available. The overall luminosity between 0.35 and 2.3 μ in the combined spectrum is $\log(L_{\rm bol})$ = 40.83 erg s^{-1}. At that epoch the color is still sufficiently blue that Schmidt's (1998) empirical bolometric corrections to V can be used. One then obtains $\log(L_{\rm bol})$ = 40.96 erg s^{-1}, in good agreement with the spectrophotometry. At later phases the color of SN 1997D was so red that Schmidt's correction cannot be applied. However, the available spectra show that at all epochs most of the energy was radiated in the V and R bands and that the color evolution is mostly due to variations in the B band, where the flux is much smaller. Therefore, during the photospheric phase we assumed that the bolometric light curve can be described reasonably well by applying a constant bolometric correction to the V magnitudes. The bolometric light curve thus derived is shown in the insert of Fig. 1. The last point has been obtained adopting for SN 1997D the same $L_{\rm bol}/L_{\rm BVRI}$ ratio as for SN 1987A in the nebular epoch (Schmidt 1998).

Although in SN 1987A the γ–rays from the ^{56}Co decay were not completely deposited (Pinto et al. 1992), the late time decline of SN 1987A was close to the decay rate of ^{56}Co. The mass of ^{56}Ni ejected by SN 1987A was $\sim 0.075\ M_\odot$ (Bouchet et al. 1991a, Bouchet et al. 1991b, Bouchet & Danziger 1993, Danziger et al. 1991, Nomoto et al. 1994). Assuming for SN 1997D the same γ–ray deposition as in SN 1987A, the ratio of the luminosities on the tail of the light curves can be used to determine the mass of ^{56}Ni synthesized in the explosion of SN 1997D. We then obtain a ratio $M_{^{56}{\rm Ni}}(87{\rm A})/M_{^{56}{\rm Ni}}(97{\rm D}) \sim 40$. Taking into account the uncertainties in the determination of the epoch of maximum and of the bolometric luminosity, the mass of ^{56}Ni ejected by SN 1997D is very small, between 0.001 and 0.004 $M_\odot$.

A comparison with SN 1987A (Fig. 2) shows general similarities with respect to P-Cygni lines of H I, Ca II, Na I and Ba II, and more subtle differences. These latter are emphasized by the strengths of the Ba II absorption lines and possibly those of other s–process elements. SN 1987A showed strong lines of Ba II, the analysis of which (Williams 1987, Lucy 1988, Höflich 1988, Mazzali & Chugai 1995) suggested an enhanced abundance of barium. SN 1997D shows even stronger lines of Ba II, with the identification of an array of multiplets, but, as we shall discuss later, an overabundance of barium is not required because a lower temperature prevails in the envelope.

Strong lines of Sr II, also an s–process element, were also observed in the IR spectrum taken on Jan.27 (Clocchiatti et al. 1998). In this spectrum the He I 10830 line, which is the dominant feature in the IR spectra of other SNe II, is not clearly detected, although it might affect the blue wing of Sr II 10914.

Finally, one of the most striking peculiarities of SN 1997D is the low expansion velocity of the ejecta, approximately 1200 km s^{-1}, as measured from the line absorption minima. Only the strong Ba II lines show somewhat higher velocities, but it is well known that strong lines may form in outer parts of the envelope and that stratification effects may also be present. As we will discuss later (Sect. 3.2), the small velocity constrains the epoch of the first spectrum to be ~ 50 days.

3. Model Light Curve and Spectra

The light curve of SN 1997D is unique because the luminosity is low, both at 'maximum light' and on the radioactive tail. These properties, along with the narrowness of the lines and the redness of the continuum, can be used to deduce the physical characteristics of the progenitor and of the explosion.

The progenitor model used here is that of a 26 $M_{\odot}$ star with an 8 $M_{\odot}$ He core at the beginning of collapse (Nomoto & Hashimoto 1988) and an 18 $M_{\odot}$ H-rich envelope. The stellar radius is $R_0 = 300\ R_{\odot}$, which is 3 - 5 times smaller than typical red supergiants. The explosion was simulated using a 1-D Lagrangian hydrodynamical code (Young et al. 1995) with an energy of $E = 4 \times 10^{50}$ ergs and the ejection of 0.002 $M_{\odot}$ of ^{56}Ni. In order to eject a small amount of ^{56}Ni, most of the material of the innermost region where Si is burned to Ni has to fall back on the degenerate neutron core where it is photodisintegrated before emitting $\gamma-$rays in forming the compact remnant. This is used to place the mass cut, resulting in a collapsing core of 1.8 $M_{\odot}$, and ejecta mass of 24.2 $M_{\odot}$.

3.1. Light Curves

Our model light curve (Fig. 3) successfully reproduces the main characteristics of the observations. The model parameters are constrained as follows. The early light curve is powered by shock heating, i.e., the gradual release of deposited shock energy. After the peak, the model light curve enters a slight plateau phase lasting about 40 days (Fig. 3); during this period, the recombination wave moves inwards in mass through the H envelope down to the He core. The peak luminosity ($M_V \gtrsim$ –14.65) depends on R_0, M, and E. In order to achieve a consistent model, the progenitor radius cannot exceed 300 $R_{\odot}$. For larger radii, the SN would have been too bright at shock breakout.

After the plateau the light curve drops over 2 magnitudes to the radioactive tail. The luminosity and shape of the tail depend on the ^{56}Ni mass and on E/M. The ^{56}Ni mass determines the absolute magnitude and E/M determines the decline rate. The tail of SN 1997D follows the ^{56}Co decay rate as in SN 1987A. For the SN 1997D model, $E/M = 1.7 \times 10^{49}$ ergs ${M_{\odot}}^{-1}$. This is $\sim$ 10 times smaller than in SN 1987A, and gives the low velocity and the complete trapping of the γ-rays. The low luminosity tail is reproduced with the low ^{56}Ni mass of 0.002 $M_{\odot}$.

We have selected the current model through an elimination process involving 7 models, which we will discuss in a subsequent paper. For models with a small ejected mass (M $< 20\ M_{\odot}$) the plateau is too short, giving a time from explosion to discovery of $<$ 50 days, inconsistent with the spectra. The tail of SN 1997D falls at the ^{56}Co decay rate, which suggests two possibilities: 1) the ejecta is optically thick to the γ-rays and the tail reflects the total ^{56}Ni mass ejected; or 2) the ejecta is optically thin to the γ-rays and the tail is powered by annihilation of the trapped positrons. Since the positrons carry only 3.7% of the decay energy, this latter case would imply a normal ^{56}Ni production. This can only be true if the opacity to γ-rays is less than one, i.e. if the total mass of the ejecta is $M_{ej} < \frac{4\pi(vt)^2}{3\kappa_\gamma}$. A simple estimate shows that for this to be the case the mass of the ejecta would have to be less than the mass of ejected ^{56}Ni alone. Using for the tail the values: γ-ray opacity, $\kappa_\gamma = 0.03\ cm^2/g$, velocity, $v = 700$ km/s and time, t = 70 days, we get $M_{ej} < \frac{1}{80} M_{\odot}$. Thus the tail cannot be powered by positron annihilation and we therefore explore models in which the ejecta is optically thick to γ-rays. Models with larger energies give higher material velocities and broader spectral lines, which is again inconsistent with the observations. For models with larger E/M the light curve is too bright and the plateau is too short. Models with smaller progenitor radii have plateaus that are too short. To attain the same final kinetic energy, the shock, in a more compact star, expands the ejecta, and thus cools it, much more rapidly than for a star with a larger radius. The result is that the photosphere moves inward faster, and the plateau is shorter.

3.2. Spectra

We used the explosion model described above to compute synthetic spectra for two epochs with a Monte Carlo spectrum synthesis code, which is based on that described in Mazzali & Lucy (1993) but has been improved to include photon cascades (Mazzali & Lucy 1998, in preparation).

On Jan. 17 the red continuum indicates a photospheric temperature $T_{\rm eff} \sim 6400$ K. The other input parameters are the expansion velocity ($v_{\rm ph} = 970$ km s^{-1}) and the epoch of explosion. Given the luminosity as deduced in Sect. 2, the required temperature can only be achieved with a rather large radius of about 6000 $R_\odot$. Since $R_{\rm ph} = v_{\rm ph} t$, this implies $t \sim 50$ days for the first spectrum. Therefore, we deduce that the peak was missed by about 50 days, that a plateau followed, and that the SN was first observed on the decline to the tail.

The model spectrum (Fig. 4) matches the observed one well with the exception of some features in the red, where the model continuum is also somewhat too high, and of the Hβ absorption. Most of the narrow absorption lines are well reproduced. In particular, Ba II 6497 is stronger than Hα. Since solar abundances were used, this is just a temperature effect, and no overabundance of Ba is required. The temperature is low enough for the Ba III/Ba II ratio to be small, which results in strong Ba II lines, while the same low temperature makes Hα weak. The narrow lines are clearly the result of a low explosion energy. The fact that the lines are so narrow allows a reasonably accurate determination of the mass above the photosphere. Values ranging between 10 and 20M$_\odot$ give acceptable spectra. The model adopted here has 14.5M$_\odot$ above 970 km s^{-1}. Models with a smaller mass give lines too shallow if $v_{\rm ph} = 970$ km s^{-1}.

Synthetic spectra show that the requirement that $t \sim 50$ days on 17 Jan. is a rather strong one. If the explosion took place closer to discovery, i.e. $t < 50$ days, the observed expansion velocity implies a small radius. Together with the derived luminosity, this results in a higher $T_{\rm eff}$ than required. In this case, the Ba III/Ba II ratio increases and the Ba II line intensities decrease. If on the other hand the explosion occurred earlier, so that $t > 50$ days, the radius is too large and the temperature becomes too low. When the temperature drops below 5000K, lines of Ti I and Fe I absorb most of the radiation below 4500 and the synthetic spectrum changes dramatically.

We also computed a synthetic spectrum of our selected explosion model evolved to match the 6 Feb. data. The fitting was satisfactory using an epoch consistent with $t = 50$ days on Jan.17.

4. Discussion

SN 1997D is among the least luminous Type II supernovae known to date. The low luminosity persists also in the tail, where the decline rate is close to that of a ^{56}Co-powered tail. SN 1997D is also characterized by a low temperature and a very low expansion velocity. These features are well reproduced by an explosion model with a relatively small progenitor radius (300 $R_\odot$), massive ejecta ($\sim$ 24 $M_\odot$), low explosion energy (4×10^{50} ergs), and small ejected ^{56}Ni mass ($\sim$ 0.002 $M_\odot$).

A similarly small amount of ^{56}Ni has recently been proposed for another SN II, SN 1994W (Sollerman et al. 1998), but this object was rather luminous and its tail declined faster than the ^{56}Co slope.

The neutrino-heating mechanism of massive star explosions is not well understood, so the explosion energy and the amount of ^{56}Ni ejected as a function of progenitor mass are difficult to predict from the hydrodynamical models. According to pre-supernova model calculations, stars more massive than $\sim$ 25 $M_\odot$ form an Fe core in a greater gravitational potential because of the significantly smaller C/O ratio and the consequently weak carbon shell burning (Nomoto et al. 1993; Woosley & Weaver 1995). Therefore, if the efficiency of neutrino heating does not change with exploding mass, more massive stars tend to produce lower explosion energies, and they suffer from more fall-back of material onto the collapsed remnant. The mass cut is then placed further out. However, the progenitor must be less massive than the Wolf-Rayet progenitors (i.e., $\lesssim$ 30 - 40 $M_\odot$) because of the presence of an envelope with a mass of at least 15 $M_\odot$ above the photosphere at day 50.

Stars in the range $\sim$ 10 - 25 $M_\odot$ are likely to explode with typical explosion energies of $\sim 1 \times 10^{51}$

ergs, and to produce 0.07 - 0.15 $M_\odot$ of ^{56}Ni, as indicated by the brightness and light curve shapes of SN 1993J, SN 1987A and of Type Ibc supernovae (Nomoto et al. 1995; Young et al. 1995). Stars of 8 - 10 $M_\odot$ are predicted to produce little ^{56}Ni and other heavy elements (Nomoto 1984; Mayle & Wilson 1988). However, these stars are at the top of the AGB in the pre-supernova stages (Hashimoto et al. 1993), which is inconsistent with the small radius of SN 1997D. Also, synthetic spectra obtained from the low mass models have shallow absorption lines compared to the observations.

In conclusion, the progenitor of SN 1997D was probably as massive as 25 - 40 $M_\odot$. Our 26 $M_\odot$ model is in this mass range, thus being consistent with the low E/M and the small ^{56}Ni mass. The presupernova radius depends on many parameters, and the reason for its being rather small in SN 1997D is an open question. Spectral models appear to rule out the case of low metallicity and He enhancement. A possible scenario involves a close binary system in which the companion star spiraled in to make the envelope more massive (Podsiadlowski 1992).

The ejection of a small mass of ^{56}Ni provides a constraint on the mass of the collapsed remnant, $M_{\rm rem}$ (Nomoto et al. 1993; Thielemann et al. 1996). In our 26 $M_\odot$ model, is $M_{\rm rem} = 1.8\ M_\odot$. If $M_{\rm rem}$ were assumed to be smaller, more ^{56}Ni would be ejected: e.g. if $M_{\rm rem} = 1.7\ M_\odot$, then M(^{56}Ni) = 0.1 $M_\odot$. For more massive progenitor models, $M_{\rm rem}$ would be larger than 1.8 $M_\odot$. If the equation of state of nuclear matter is relatively soft, the maximum (gravitational) mass of a cold neutron star is $\sim$ 1.5 $M_\odot$ (Brown & Bethe 1994). If this is the case, the remnant of SN 1997D must be a small-mass black hole, and the low luminosity tail of SN 1997D might be a signature of the formation of such an object.

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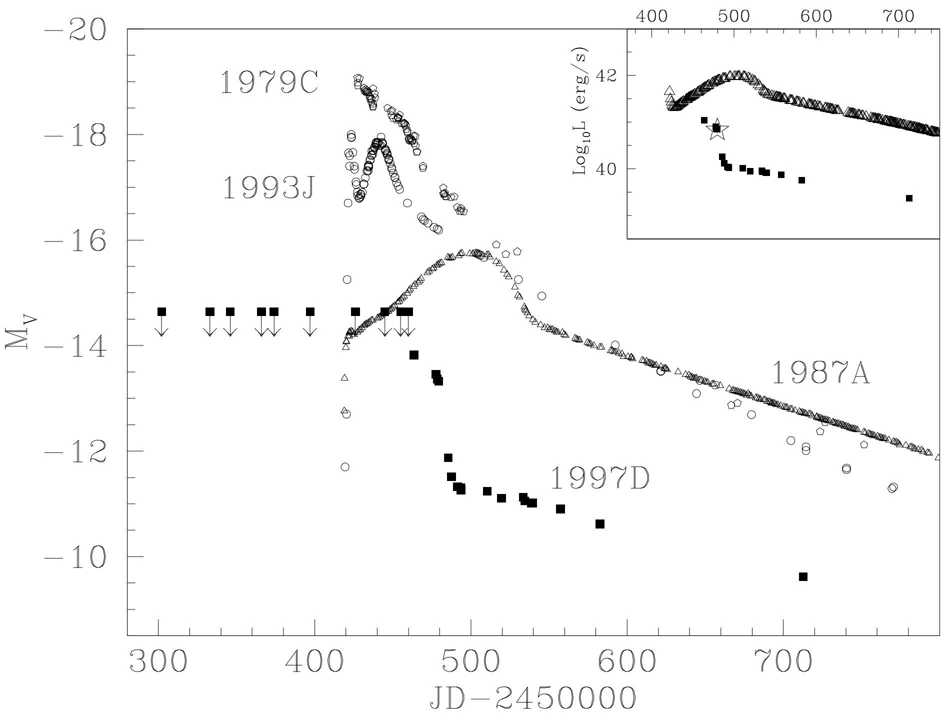
Fig. 1.— Comparison of the absolute V light curve of SN 1997D with those of SNe 1987A, 1993J and 1979C. The epochs of maxima have been corrected to J.D. 24500420. Only galactic absorption has been considered. The upper limits from the negative observations of Rev. Evans (private communication) have been also plotted. The insert shows the bolometric light curves of SN 1997D and SN 1987A (Catchpole et al. 1987, 1988). The star marks the optical+IR spectrophotometric observation of Jan.30.

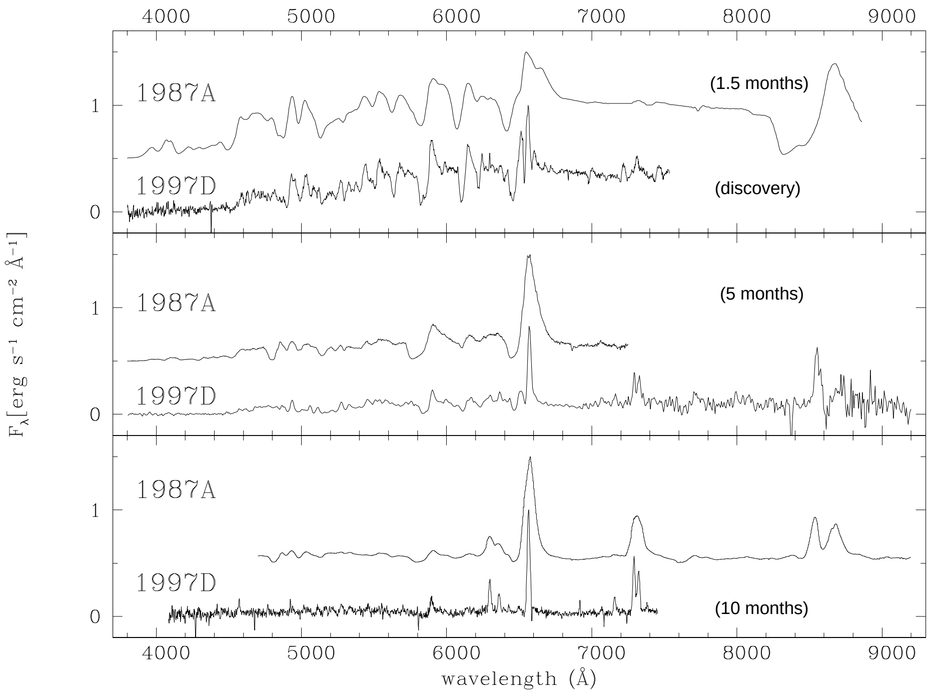
Fig. 2.— Comparison of the spectra of SN 1997D and SN 1987A. Top: the spectrum of SN 1997D at discovery is compared with that of 1987A 1.5 months past explosion. Middle: spectra taken 100 days later. The spectrum of SN 1997D is the result of the merging of two spectra with different resolutions and signal–to–noise ratios. Bottom: spectra taken 10 months past maximum. All spectra have been normalized to the peak of the Hα emission and corrected for redshift.

Fig. 3.— The observed absolute V photometry of SN 1997D compared to the model light curve (mass = 24 $M_\odot$; radius = $300 R_\odot$; mass of ^{56}Ni= 0.002 $M_\odot$; energy= 4×10^{50} ergs).

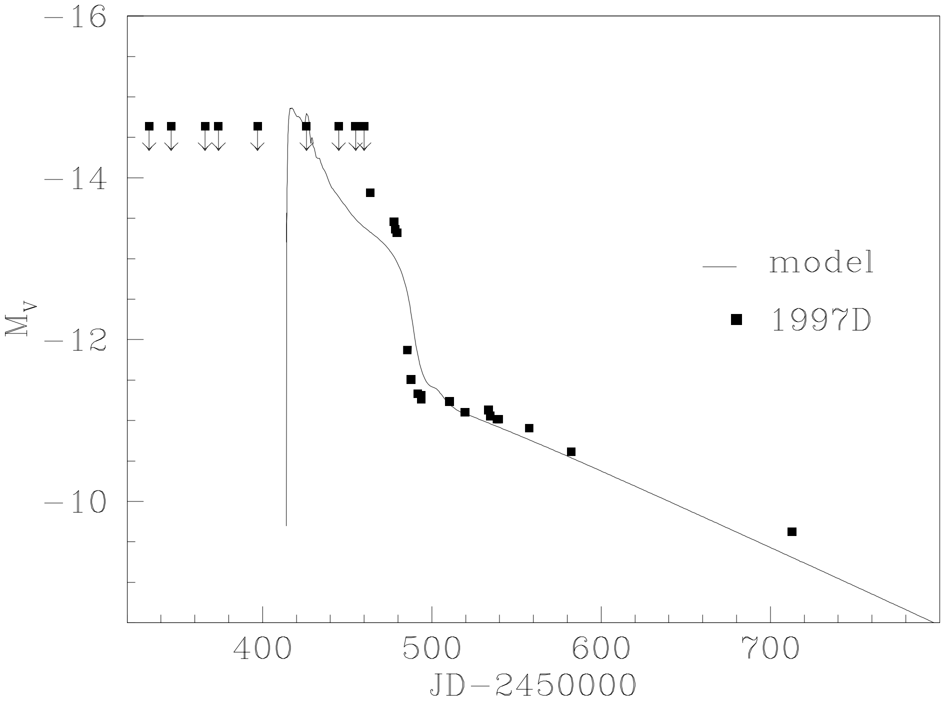
Fig. 4.— The observed spectrum of SN 1997D on Jan.17 (continuous line) and the synthetic spectrum computed from the explosion model (dashed line). The parameters of the model are: $v_{\rm ph}$ = 970 km s^{-1}; radius= 6000 $R_\odot$; $T_{\rm eff}$ = 6400 K; mass above the photosphere M = 14.5 $M_\odot$; epoch=50 days; solar abundances.



1979C
1993J
1987A
1997D
M_V
JD−2450000
$Log_{10}L$ (erg/s)



1987A
(1.5 months)
1997D
(discovery)
1987A
(5 months)
1997D
1987A
1997D
(10 months)
F_λ[erg s^{-1} cm^{-2} Å^{-1}]
wavelength (Å)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M_V
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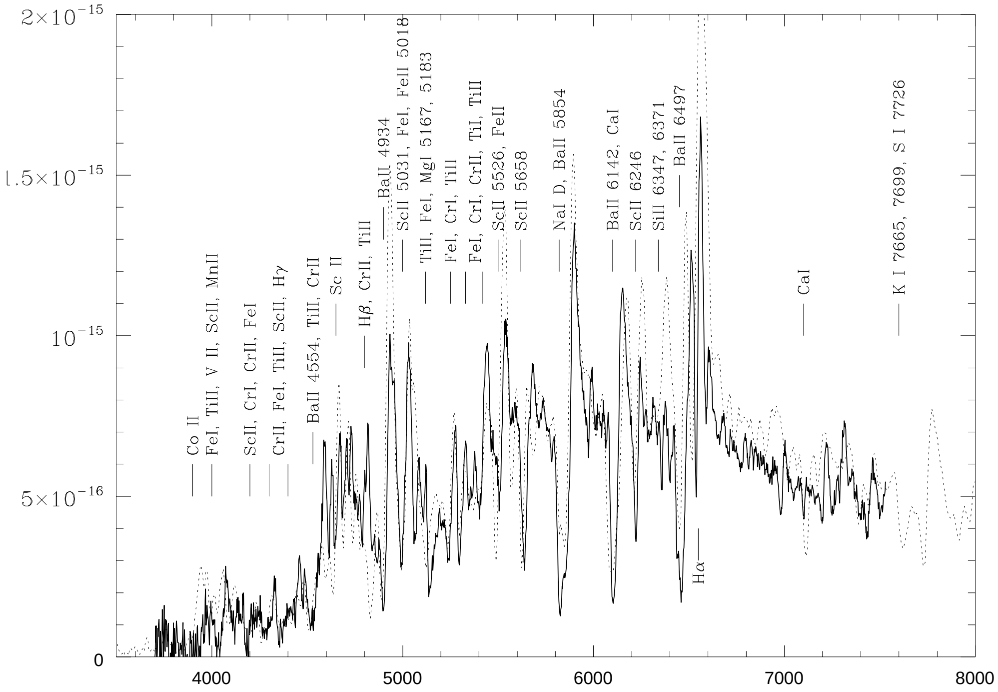
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1.5×10−15
10−15
5×10−16
0
4000
5000
6000
7000
8000
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FeI, TiII, V II, ScII, MnII
ScII, CrI, CrII, FeI
CrII, FeI, TiII, ScII, Hγ
BaII 4554, TiII, CrII
Sc II
Hβ, CrII, TiII
BaII 4934
ScII 5031, FeI, FeII 5018
TiII, FeI, MgI 5167, 5183
FeI, CrI, TiII
FeI, CrI, CrII, TiI, TiII
ScII 5526, FeII
ScII 5658
NaI D, BaII 5854
BaII 6142, CaI
ScII 6246
SiII 6347, 6371
BaII 6497
Hα
CaI
K I 7665, 7699, S I 7726