A Determination of the Properties of the Peculiar SNIa 1991T through Models of its Early-time Spectra

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A series of early-time optical spectra of the peculiar SNIa 1991T, obtained from 2 weeks before to 4 weeks after maximum, have been computed with our Monte Carlo code.

The earlier spectra can be successfully modelled if ^{56}Ni and its decay products, ^{56}Co and ^{56}Fe, dominate the composition of the outer part of the ejecta. This atypical distribution confirms that the explosion mechanism in SN 1991T was different from a simple deflagration wave, the model usually adopted for SNe Ia.

As the photosphere moves further into the ejecta the Ni Co Fe fraction drops, while intermediate mass elements become more abundant. The spectra obtained 3–4 weeks after maximum look very much like those of the standard SN Ia 1990N. A mixed W7 composition produces good fits to these spectra, although Ca and Si are underabundant. Thus, in the inner parts of the progenitor white dwarf the explosion mechanism must have been similar to the standard deflagration model.

The fits were obtained adopting a reddening $E(B-V) = 0.13$. A Tully-Fisher distance modulus $\mu = 30.65$ to NGC 4527 implies that SN 1991T was about 0.5 mag brighter than SN 1990N. At comparable epochs, the photosphere of SN 1991T was thus hotter than that of SN 1990N. The high temperature, together with the anomalous composition stratification, explains the unusual aspect of the earliest spectra of SN 1991T.

The model results allow us to follow the abundances as a function of mass. In particular, spectroscopic evidence is found that about $0.6 M_{\odot}$ of ^{56}Ni must have been synthesized in the outermost $1 M_{\odot}$ of the exploding white dwarf. This implies that almost twice as much ^{56}Ni was produced in SN 1991T than in normal SNe Ia, and explains the unusual brightness of this SN.

1. Introduction

SN 1991 T in NGC4527 constitutes a peculiar case among recent, well observed SNe Ia. Although it was classified as a SN Ia from the light curve and the presence of the Si II 6135Åline at maximum (Filippenko et al. 1992), SN 1991T was peculiar in many respects. First, it was brighter ($V(Max) = 11.50$ on 30 Apr, $B(Max) = 11.64$ on 28 Apr; Phillips et al. 1992) than the average Virgo SNe Ia. The spectrum before maximum light was also peculiar, since the typical Si II and Ca II lines were not present. Only two major features appeared in the earliest spectra, identified as Fe III lines (Ruiz-Lapuente et al. 1992). Later, the Si II and Ca II lines, and lines of other intermediate mass elements typical of SNe Ia (S II) also appeared, but they were weaker than in normal SNe Ia. The expansion velocities were also unusually high. A possible explanation is that SN 1991T suffered a delayed detonation, which caused burning to NSE in its outer layers (Yamaoka et al. 1992).

We have gathered a complete set of SN 1991T spectra, obtained from ESO, CTIO and Lick Observatory from -2 weeks to +4 weeks of maximum light and modelled the most interesting ones with our Monte Carlo code (Mazzali & Lucy 1993), in an effort to

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determine the evolution of L and v_{ph} and the abundances in the envelope as a function of time, and therefore of radius and mass.

2. Basic model features

We used the code described in Mazzali & Lucy (1993), based on the Schuster-Schwarzschild approximation. The SN envelope is assumed to be in homologous expansion. Excitation and ionization are dealt with in the nebular approximation, but corrections are introduced to account for the line and continuum blocking of the radiation field in the UV.

Since the explosion models devised to explain SN 1991T usually yield density structures quite similar to that of the standard W7 model (Nomoto et al. 1984), we retained a W7 density structure and a Chandrasekhar exploding mass. We adopted a Tully-Fisher distance to NGC 4527 of 13.5 Mpc, i.e. $m - M = 30.65$ (Tully 1988), since a TF distance allowed a good fit to SN 1990N (Mazzali et al. 1993). SN 1991T differs from other Virgo SNe Ia in that its light suffered considerable extinction. We adopted the value $E(B-V) = 0.13$ (Phillips et al. 1992), since the even higher value 0.35 suggested by Ruiz-Lapuente et al. (1991) makes it almost impossible to fit the still quite blue color of SN 1991T. We chose a reference time $t_{Max} = 18$ days.

3. Model fitting

We have modelled 8 optical spectra, covering a period of almost 6 weeks, from 16 April ($t = 6$ d, $t_{Max} - 12$d) to 23 May 1991 ($t = 43$ d, $t_{Max} + 25$d), trying to sample that time interval as evenly as possible. All the spectra have been flux-calibrated in B and V. For some of the spectra the original flux calibration could not be recovered, and two different correction factors had to be adopted for the two bands. Space limitation prohibits a thorough description of the fits, which shall be presented elsewhere (Mazzali & Danziger 1993, in preparation), so here we only give a brief account of our results.

Although we tested several abundance combinations, it turned out that two extremes can be defined, which constitute firm upper and lower boundaries. These are on the one hand a composition based on Ni and its subsequent decay into Co (e-folding time 8.8 days) and hence to Fe (113 days), and, on the other hand, a mixed W7 composition, where Ni decay is also considered, but where Ni and its daughter nuclei represent only a small fraction (about 12% by number at early times).

We found that the abundances that give the best fits to the observed spectra are a combination of these two cases, so that the composition is a mixture of IME (C, O, Si, S, Ca, Na, Al, Mg) in a W7 ratio and of Ni, Co, Fe in amounts determined by the initial Ni fraction and the assumed epoch. The IME fraction is smaller than in W7, while the Ni Co Fe fraction is higher, but this difference tends to decrease with time, implying that the peculiar abundances are confined to the outer layers.

In all successful models the luminosity is higher by about 0.5 mag than in the 'standard' SN Ia 1990N (Mazzali et al. 1993). At the earliest epochs the presence of Fe III lines and the absence of both Si II and Ca II lines is due both to the composition, with Ni, Co and Fe dominating in the outermost layers, and to the high temperature, caused by the high luminosity, which reduces the number of Si II and Ca II ions through ionization. In Fig.1 we show our fit to the 16 Apr (t = 6d) spectrum. Near maximum light the IME abundance is higher, and the Si II, Ca II and S II lines begin to appear. The lines observed at this epoch are the same as those in SN 1990N at comparable epochs. In fact, SN 1991T has both a higher luminosity and a higher photospheric velocity than

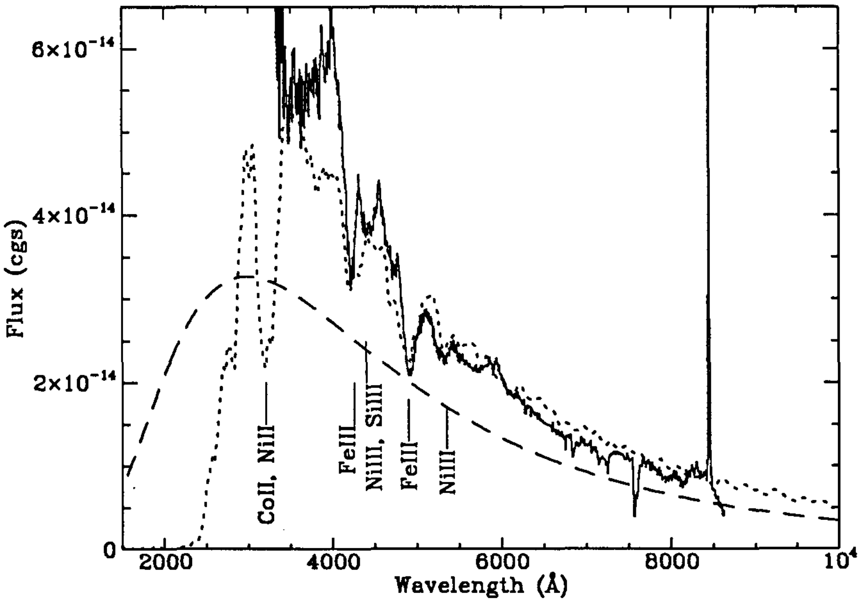

FIGURE 1. The 16 April (t=6 *d*) spectrum (solid line), the best fit (dots) and the photospheric black body (dashed)

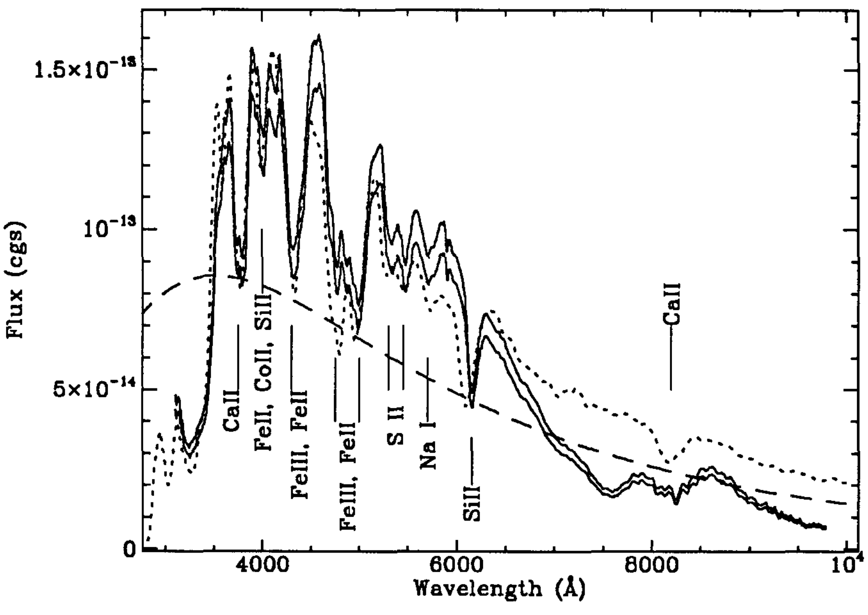

FIGURE 2. The 5 May (t=25 *d*) spectrum: upper solid line – B correction; lower solid line – V correction, the best fit (dots) and the photospheric black body(dashed)

SN 1990N (this is true for all but the very first spectrum we fitted), thus the photospheric temperature is similar in the two SNe, and so are their spectral lines. A higher ejecta velocity in SN 1991T was confirmed also by the nebular lines (Danziger 1993, private communication), and is consistent with the higher explosion energy implied by the higher luminosity and the higher Ni abundance. In Fig. 2 we show the fits for the 5 May ($t = 25$d) spectrum.

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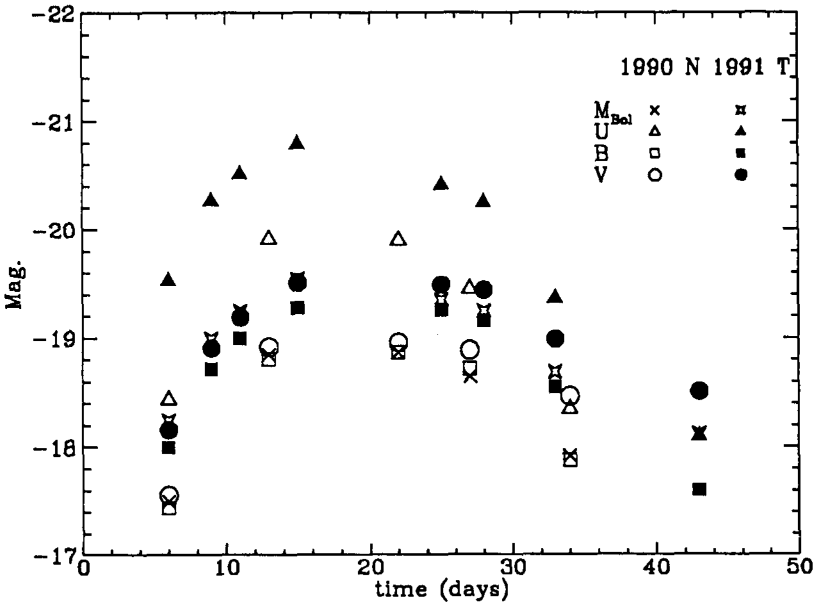

FIGURE 3. Model light curves for SNe 1991T and 1990N

The trend towards an increasing IME abundance continues after maximum, as the photosphere moves deeper into the ejecta. The composition at these epochs is essentially W7, but Si and Ca are underabundant with respect to the other IME, by up to a factor 10 in the innermost shells considered, as already noted by Jeffery et al. (1992). That Si and Ca behave differently from other IME like O and Mg is conceivable, given the nature of the delayed detonation burning. In the post-maximum spectra the Na I D line appears, as it did in SN 1990N, but this is probably a NLTE effect (Mazzali et al. 1993).

4. The global properties of SN 1991T

Fitting a series of spectra of SN 1991T allows us to determine two important properties of this object: the bolometric light curve and the abundance distribution as a function of envelope mass.

The validity of the bolometric light curve obtained from the Monte Carlo model rests on the assumption that our fits are good also in those parts of the spectrum where no data is available, namely the UV and the IR. The value of L_{Bol} obviously also depends on the adopted distance. If this were largely incorrect the model lines would be misplaced in wavelength. An incorrect estimate of the explosion epoch would have a similar effect. In Fig.3 we show the U, B, V and L_{Bol} curves for both SN 1990N and 1991T. The latter is on average 0.5 mag brighter.

The abundance of radioactive Ni in SN 1991T can be determined assuming that the position of the photosphere at each epoch modelled defines a shell in the ejecta, and that the composition adopted to fit the spectrum applies to that shell. The total Ni, Co, Fe abundance in the shell reflects the initial Ni abundance. In this respect modelling a series of spectra is equivalent to analyzing the stratification of the elements synthesized in the explosion. The distribution of Ni in the ejecta as derived from our models is summarized in Table 1. The main conclusion is that in the outermost $1M_{\odot}$ of ejecta about $0.6M_{\odot}$ were ^{56}Ni. We remark that this value was derived from spectroscopy only. If the innermost part of the white dwarf underwent a nuclear deflagration, as suggested

TABLE 1. *Model parameters and radioactive Ni fraction*

t days	v_{ph} km/s	$M_{above}(sh)$ $M_\odot$	$M_{above}(tot)$ $M_\odot$	Ni mass fraction	$M_{Ni}(sh)$ $M_\odot$	$M_{Ni}(tot)$ $M_\odot$
6	17000	0.039	0.039	0.97	0.038	0.038
9	15500	0.090	0.051	0.93	0.047	0.085
11	15000	0.125	0.035	0.89	0.031	0.116
15	13250	0.261	0.136	0.65	0.088	0.204
25	9500	0.558	0.297	0.59	0.175	0.379
28	8500	0.655	0.097	0.57	0.055	0.434
33	6250	0.884	0.229	0.37	0.084	0.518
43	5000	1.034	0.150	0.38	0.057	0.575

by the fact that the composition becomes very similar to W7 there, then most of the innermost $0.4M_\odot$ of the white dwarf must also have been turned into ^{56}Ni (Nomoto et al. 1984).

The total Ni mass produced in the SN 1991T event should thus be close to $1M_\odot$. This agrees with the result obtained by Spyromilio et al. (1992) from fits of the nebular spectrum, and is also in excellent agreement with the high luminosity required to fit the spectra: a Ni mass (and hence L) ratio 1.7 between SN 1991T and SN 1990N implies that the former was brighter by 0.6 mag.

Our models thus confirm that the explosion mechanism at work in SN 1991T was peculiar, making this object brighter than normal SNe Ia. The presence of such deviant events should be considered when using SNe Ia as standard candles. Only a spectroscopic analysis can verify that a SN Ia is 'normal', since an object like SN 1991T differs only marginally from the other SNe Ia as far as the light curve is concerned. The incidence of 'peculiar' SNe Ia may be higher than expected, since several of the recent, well observed SNe Ia (e.g., SN 1986 G, SN 1991bg) are peculiar.

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