On the spectrum and nature of the peculiar Type Ia supernova 1991T

Adam Fisher, David Branch, Kazuhito Hatano and E. Baron

Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019-0225, USA

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ABSTRACT
A parametrized supernova synthetic-spectrum code is used to study line identifications in the photospheric-phase spectra of the peculiar Type Ia SN 1991T, and to extract some constraints on the composition structure of the ejected matter. The inferred composition structure is not like that of any hydrodynamical model for Type Ia supernovae. Evidence that SN 1991T was an overluminous for a SN Ia is presented, and it is suggested that this peculiar event was probably a substantially over-Chandrasekhar explosion that resulted from the merger of two white dwarfs.

Key words: radiative transfer – supernovae: general – supernovae: individual: SN 1991T.

1 INTRODUCTION

SN 1991T was a well-observed and spectroscopically peculiar Type Ia supernova (Filippenko et al. 1992; Phillips et al. 1992; Ruiz-Lapuente et al. 1992; Branch, Fisher & Nugent 1993). Before and around the time of maximum light its optical spectrum showed strong lines of Fe iii rather than the usual SN Ia lines of singly ionized elements of intermediate mass, and although the deep red Si ii absorption that is characteristic of SNe Ia finally did develop after maximum light, it never reached its usual strength.

In this paper we report the results of a study of photospheric-phase spectra of SN 1991T using the parametrized supernova spectrum-synthesis code SYNWOSN (Fisher et al. 1997; Fisher 1999). In Section 2, previous studies of the optical spectra of SN 1991T are briefly summarized. Our method of `direct' spectral analysis is described in Section 3, and results are presented in Section 4. In Section 5 we discuss evidence that SN 1991T was too luminous to be a Chandrasekhar-mass explosion, and suggest that it probably was a substantially over-Chandrasekhar explosion resulting from the merger of two white dwarfs. A general discussion appears in Section 6.

2 PREVIOUS STUDIES OF SN 1991T SPECTRA

Filippenko et al. (1992) presented optical spectra obtained from −12 to +47 d. [Thoughout this paper, epochs are in days with respect to the date of maximum light, 1991 April 28 (Phillips et al. 1992; Lira et al. 1998). Filippenko et al. (1992) used April 26.] They showed that although the pre-maximum optical spectra did not resemble those of any other supernova, beginning near maximum light the usual SN Ia lines of intermediate-mass elements slowly developed, and months after explosion the iron-dominated spectrum appeared almost identical to that of a typical SN Ia. They identified the two strong features in the pre-maximum optical spectrum with the Fe iii λ4404 and λ5129 multiplets, and concluded that the composition of the outer layers of the supernova was dominated by iron-group elements. Given their inferred composition structure of a thin layer of intermediate-mass elements sandwiched between inner and outer regions dominated by iron-peak elements, they favoured a double-detonation model (the nearly complete incineration of a mildly sub-Chandrasekhar-mass white dwarf by detonation waves propagating inward and outward from the base of an accumulated helium layer) for the origin of SN 1991T. They noted that it was odd, then, that in their +6 d spectrum an absorption near 7550 Å that is ordinarily attributed to O i λ7773 seemed to be present at its usual strength.

Ruiz-Lapuente et al. (1992) presented optical spectra obtained on seven consecutive nights from −13 to −7 days. They too identified the Fe iii lines, as well as lines of Ni iii, and they too concluded that the outer layers had undergone complete burning to iron-peak elements. They suggested that conclusion by presenting synthetic spectra based on approximate NLTE calculations, for the time-dependent nickel-cobalt-iron composition that results from the radioactive decay of initially pure 56Ni. As they noted, though, the lines in their synthetic spectra tended to be stronger than the observed lines. Their spectra did not extend late enough in time for them to encounter the oxygen line. They did, however, discuss another puzzle. Their spectra showed no evidence for the high velocities of the outer layers that would follow from complete burning to iron-peak elements. They suggested that the line-forming layers had been decelerated upon encountering a low-density carbon-oxygen envelope associated with a merger of two white dwarfs.

Phillips et al. (1992) presented optical spectra obtained from −13 to +66 d. From the appearance of the spectra they concluded that the abundances of silicon, sulphur, and calcium in the outer layers were unusually low, but they did not specify what was present in their place.

Jeffery et al. (1992) carried out parametrized synthetic-spectrum
calculations, based on the Sobolev approximation, an approximate radiative-equilibrium temperature distribution, and full LTE, including a Planckian rather than a resonance scattering source function. They modified the composition structure of the carbon-deflagration model W7 (Nomoto, Thielemann & Yokoi 1984; Thielemann, Nomoto & Yokoi 1986), by trial and error, to get reasonable fits to observed optical (and some IUE near-ultraviolet) spectra obtained at -9, -3, and +10 d. The adopted composition (displayed in their fig. 7) was complex, and not simply dominated in the outer layers by iron-peak elements. It was like that of model W7 for ejection velocities less than 8500 km s⁻¹; heavily modified between 8500 and 14400 km s⁻¹ in favour of iron-peak elements at the expense of intermediate-mass elements; heavily modified between 14400 and 21000 km s⁻¹ in favour of both intermediate-mass and iron-peak elements at the expense of carbon; and primarily carbon and oxygen above 21000 km s⁻¹. Noting that somewhat weaker Fe iii lines might have gone unrecognized in previous studies of other SNe Ia, they suggested that although the composition structure was unusual, the explosion history of SN 1991T probably was not fundamentally different from that of a normal SN Ia.

Mazzali, Danziger & Turatto (1995) also carried out parameterized spectrum calculations, using a Monte Carlo code and a resonance scattering source function. They were restricted to using a homogeneous composition above the photosphere at each of the eight epochs considered. For each epoch they used a combination of a mixed W7 composition and the time-dependent ⁵⁶Ni-decay composition. They concluded that an unusually high temperature was partly responsible for the weakness of the lines of singly ionized intermediate-mass elements, but also that iron-peak elements dominated the composition above 13000 km s⁻¹. They favoured a 'late-detonation' (Yamaoka et al. 1992) explosion mechanism in a Chandrasekhar-mass white dwarf for the origin of SN 1991T. (Mazzali et al. 1995 referred to it as a 'delayed detonation', but by custom that term is used to refer a class of models that, unlike the late detonations, do not synthesize ⁵⁶Ni in the outer layers; e.g., Khokhlov, Müller & Höflich 1993).

Nugent et al. (1995) calculated detailed NLTE spectra using the PHOENIX code (Hauschildt & Baron 1999, and references therein), for a fixed composition (W7 mixed above 8000 km s⁻¹ with titanium enhanced by a factor of 10) and a series of temperatures. They found that their series of synthetic spectra gave a good account of many of the spectral differences among SNe Ia, from the peculiar, cool, 'weak' SN 1991bg, through the normal SNe Ia, to the peculiar, warm, 'strong' SN 1991T. This showed that to a certain extent the differences between the spectra of SNe Ia are due to temperature differences, and confirmed that in SN 1991T a high temperature can enhance the Fe iii and Si iii lines and weaken the lines of singly ionized elements. Still, the temperature differences among SNe Ia are presumably caused by differences in the amounts of ejected ⁵⁶Ni, and differences in the composition structures certainly are to be expected.

Meikle et al. (1996) displayed and discussed an infrared spectrum obtained at the time of maximum light. They considered the possibility that a P Cygni-like feature having an emission peak near 10800 Å and an absorption near 10500 Å could be attributed to either He i λ10830 or Mg ii λ10926, but found difficulties with both identifications.

3 SPECTRUM SYNTHESIS PROCEDURE

In this paper we use the fast, parameterized, supernova spectrum-synthesis code SYNOW to make a 'direct' analysis (Fisher et al. 1997) of spectra of SN 1991T. The goal is to study line identifications and determine intervals of ejection velocity within which the presence of lines of various ions are detected, without initially adopting any particular composition structure. The composition and velocity constraints that we obtain with SYNOW can then provide guidance to those who compute hydrodynamical explosion models and to those who carry out computationally intensive NLTE spectrum modeling. The SYNOW code was described briefly by Fisher et al. (1997) and in detail by Fisher (1999). In our work on SN 1991T we have made extensive use of the paper by Hatano et al. (1999), which presented plots of LTE Sobolev line optical depths versus temperature for six different compositions that might be expected to be encountered in supernovae, and which presented SYNOW optical spectra for 45 individual ions that can be regarded as candidates for producing identifiable spectral features in supernova spectra.

Fisher et al. (1997) concentrated on a high-quality spectrum of the normal Type Ia SN 1990N that was obtained by Leibundgut et al. (1991) at -14 d. Fisher et al. suggested that at this very early phase an absorption feature observed near 6400 Å, which had previously been attributed to moderately blueshifted Si ii λ6355, actually was produced by highly blueshifted (v > 26000 km s⁻¹) C i i i λ6580, indicating the presence of an outer high-velocity carbon-rich layer in SN 1990N. In this paper we suggest that SN 1991T also contained an outer carbon-rich layer, but extending to lower velocity than in SN 1990N.

We have studied spectra of SN 1991T at seven epochs ranging from -13 days to +59 d. For comparison with each observed spectrum, we have calculated a large number of synthetic spectra with various values of the fitting parameters. These include: T bb, the temperature of the underlying blackbody continuum; T exc, the excitation temperature; v phot, the velocity of matter at the photosphere; and v max, the maximum ejection velocity. For each ion that is introduced, the optical depth of a reference line is also a fitting parameter, with the optical depths of the other lines of the ion calculated assuming Boltzmann excitation at T exc. In addition, we can introduce restrictions on the velocity interval within which an ion is present; when the minimum velocity assigned to an ion is greater than the velocity at the photosphere, the line is said to be detached from the photosphere. The radial dependence of the line optical depths is taken to be exponential with e-folding velocity v e = 3000 km s⁻¹ (with one exception to be discussed in Section 4.2) and the line source function is taken to be that of resonance scattering in the Schuster–Schwarzschild approximation. The most interesting fitting parameters are v phot, which, as expected, decreases with time, and the individual ion velocity restrictions, which constrain the composition structure.

4 SPECTRUM SYNTHESIS RESULTS

In this section we present comparisons of synthetic spectra with observed spectra for four of the seven epochs we studied, to illustrate how we reach our conclusions about the composition structure of the ejecta. The pre-maximum and post-maximum spectra are discussed separately, because the former were so peculiar, while the latter became increasingly normal.

4.1 Pre-maximum

In the pre-maximum spectra only two features have obvious identifications: two strong features produced by the Fe iii λ4404...
and λ5129 multiplets. Fig. 1 compares a −13 d observed spectrum to a synthetic spectrum that has $v_{\text{phot}} = 15000$ km s$^{-1}$ and $T_{\text{exc}} = 13000$ K. Ions responsible for features in the synthetic spectrum are marked. The x-axis is wavelength in Å. The y-axis is $F_{\lambda}$.

Figure 1. A spectrum of SN 1991T obtained at −13 d (Phillips et al. 1992) is compared to a synthetic spectrum that has $v_{\text{phot}} = 15000$ km s$^{-1}$ and $T_{\text{exc}} = 13000$ K. Ions responsible for features in the synthetic spectrum are marked. The x-axis is wavelength in Å. The y-axis is $F_{\lambda}$.

And $\lambda5129$ and $\lambda6580$ can account for this feature, and in spite of searching for a plausible alternative with the help of the plots of Hatano et al. (1999), we have none to offer.

Fig. 2 compares a −4 d observed spectrum to a synthetic spectrum that has $v_{\text{phot}} = 10000$ km s$^{-1}$ and $T_{\text{exc}} = 13000$ K. The two strong Fe III features are fitted reasonably well, and Ni III and Ni II probably account for some of the other observed features. Additional ions of iron-peak elements would need to be introduced to account for the observed flux deficiency at $\lambda < 3500$ Å. The narrow absorption near 4400 Å is well fitted by the Si III λ4560 multiplet, which is the strongest optical multiplet of Si III and was identified in SN 1991T by Jeffery et al. (1992). Note that at this phase, there is a weak absorption near 6200 Å, rather than the 6300-Å absorption of earlier phases. In general, supernova absorption features shift redward as the photosphere recedes with respect to the matter, or they remain unshifted if the line has become detached. A blueward shift of an absorption is generally a sign that a new line is beginning to make a significant contribution. In this case the new line is very likely Si II λ6355, which in normal SNe Ia is very strong at this phase. (In the synthetic spectrum, lines of Ni II and Fe III also are affecting this feature.)

The diagnostic value of a spectral feature is not simply proportional to its strength. A weak feature in the pre-maximum spectra that is of special interest to us is the broad, shallow absorption near 6300 Å, which definitely is a real feature because it can be seen in almost all of the spectra obtained earlier than −6 d by Filipenko et al. (1992), Phillips et al. (1992) and Ruiz-Lapuente et al. (1992); this feature was not mentioned in the previous discussions of the SN 1991T spectra. As shown in Fig. 1, C II λ6580 can account for the presence of Ni III lines in the observed spectrum to be probable.

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Figure 2. A spectrum of SN 1991T obtained at −4 d (Phillips et al. 1992) is compared to a synthetic spectrum that has $v_{\text{phot}} = 10000$ km s$^{-1}$ and $T_{\text{exc}} = 13000$ K. Ions responsible for features in the synthetic spectrum are marked. The x-axis is wavelength in Å. The y-axis is $F_{\lambda}$.

Figure 3. A spectrum of SN 1991T obtained at +6 d (M. M. Phillips et al., unpublished) is compared to synthetic spectra that have $v_{\text{phot}} = 9500$ km s$^{-1}$ and $T_{\text{exc}} = 10000$ K. Ions responsible for features in the synthetic spectrum are marked. In the upper panel, maximum velocities of 12000 and 15000 km s$^{-1}$ have been imposed on S II and Si I, respectively. In the lower panel, these limits have been removed. The x-axis is wavelength in Å. The y-axis is $F_{\lambda}$.
about 15 000 km s\(^{-1}\) to mainly Si ii forming above 10 000 km s\(^{-1}\). A very careful study of a good series of spectra obtained within this time interval might better determine the minimum velocity at which C ii was present. If the C ii line became detached before the Si ii line made its appearance, the observed absorption minimum would have remained constant at the detachment velocity until the development of the Si ii line started to cause a shift to the blue.

### 4.2 Post-maximum

Fig. 3 shows a +6 d observed spectrum. By this time the spectrum had begun to look much less peculiar. The synthetic spectrum has \(v_{\text{phot}} = 9500\) km s\(^{-1}\) and \(T_{\text{exc}} = 10000\) K. The synthetic feature near 5000 Å is now a blend of Fe iii and Fe ii lines. The observed S ii and Si ii features are weaker and narrower than in normal SNe Ia. In the synthetic spectrum of the lower panel, the one feature is produced by Na ii\(^{\text{I}}\) line optical depths, by a factor of 10, has been introduced at 10 000 km s\(^{-1}\). This is inferred to be a measure of the maximum velocity of the iron-peak core. The structure of the synthetic spectrum near 5000 Å is quite sensitive to the velocity of the Fe ii line optical depth discontinuity (Fisher 1999).

The major shortcoming in the upper panel of Fig. 4 is that the broad minimum observed near 7000 Å is not reproduced by the synthetic spectrum. The weak synthetic absorptions in the vicinity of Fe ii would be the Planck function evaluated at the local electron temperature, but instead of introducing a whole new fitting function involving the radial dependence of the electron temperature, we have simply retained the resonance scattering source function. In the lower panel of Fig. 4 the [O ii] feature is calculated with a line optical depth discontinuity, and the velocity limits on [O ii] are from Fe ii. It should be noted that Mazzali et al. (1995) attributed this absorption in a +25 d spectrum to Fe ii lines, but at that epoch other synthetic absorptions produced by Fe ii appear to be much too strong. We too find that the 7000 Å feature cannot be attributed to Fe ii without making other Fe ii features much too strong.

A possible identification for the absorption near 7000 Å is [O ii] \(\lambda\lambda 7320, 7330\) (Fisher 1999; Hatano et al. 1999). For a forbidden transition the natural first approximation to the source function would be the Planck function evaluated at the local electron temperature, but instead of introducing a whole new fitting function involving the radial dependence of the electron temperature, we have simply retained the resonance scattering source function. In the lower panel of Fig. 4 the [O ii] feature is calculated with a line optical depth that is detached at 10 000 km s\(^{-1}\), where \(\tau = 0.5\), and has a shallow radial gradient (\(v_{\text{in}} = 20 000\) km s\(^{-1}\)) such that \(\tau = 0.24\) at the maximum [O ii] velocity of 25 000 km s\(^{-1}\).

**Figure 4.** A spectrum of SN 1991T obtained at +59 d (W. P. S. Meikle et al., unpublished) is compared to synthetic spectra that have \(v_{\text{phot}} = 4000\) km s\(^{-1}\) and \(T_{\text{exc}} = 10000\) K. The upper panel of Fig. 4 shows that resonance scattering by permitted lines of just three ions (Fe ii, Ca ii and Na i) can give a reasonable account of most of the features in the observed spectrum, although the height of the synthetic peaks in the blue indicates that the synthetic spectrum is underblanketed. In the synthetic spectrum Na i and Ca ii are detached at 9000 km s\(^{-1}\), and an abrupt decrease in the Fe ii line optical depths, by a factor of 10, has been introduced at 10 000 km s\(^{-1}\). This is inferred to be a measure of the maximum velocity of the iron-peak core. The structure of the synthetic spectrum near 5000 Å is quite sensitive to the velocity of the Fe ii line optical depth discontinuity (Fisher 1999).
upper panel of Fig. 5, which is like the upper panel of Fig. 4 but with the [O ii] feature included in the synthetic spectrum, looks better than the upper panel of Fig. 4. The lower panel of Fig. 5 shows how the fit degrades when Na i is not detached, the discontinuity in the Fe ii line optical depths is not introduced, and the upper and lower velocity limits on [O ii] are dropped.

From a spectroscopic point of view the [O ii] identification is attractive and plausible. Moreover, Kirshner et al. (1993) discussed the velocity interval in which the O i λ7773 line could be detected in the early spectra of a small sample of well observed SNe Ia. For SN 1991T they estimated that the O i line had a significant optical depth from at least as low as 9000 km s$^{-1}$ to at least as high as $19 \times 10^3$ km s$^{-1}$, which is not inconsistent with what we are using for [O ii]. However, the mass and associated kinetic energy of the oxygen that would be required to produce a significant [O ii] line optical depth, at such high velocities and at this fairly late phase, appear to be high. For this feature, with its very low transition probability, just producing a uniform line optical depth of 0.2 requires

$$M = 0.26 \times 10^5 \times \frac{v_{25}}{77} \times \frac{t_{77}}{f_{01}} \times M_\odot; \quad E_K = 10^{51} \times \frac{v_{25}}{77} \times \frac{t_{77}}{f_{01}} \times \text{erg},$$

where $v_{25}$ is the maximum velocity in units of 25 000 km s$^{-1}$, $t_{77}$ is the time since explosion in units of 77 d (allowing for a rise time to maximum of 18 d), and $f_{01}$ is the fraction of all oxygen that is in the lower level of the transition. It is possible that essentially all of the oxygen is singly ionized at this phase, but $f_{01}$ must be significantly less than unity, because the lower level of the transition is 3.3 eV above the ground level of singly ionized oxygen. (The ground level of the transition is, at least, the metastable lowest level of the doublet, the true ground level of singly ionized oxygen being a quartet.)

We have no plausible alternative to offer for the 7000-Å minimum. If it is not an absorption feature at all, then the continuum must be at a level that is considerably lower than we have adopted to obtain the fits shown in the top panels of Figs 4 and 5. In that case the minimum would be a consequence of a lack of opacity at the relevant wavelength, as has been suggested for flux minima in infrared spectra of SN 1991T (Spyromilio, Pinto & Eastman 1994) and other SNe Ia (Wheeler et al. 1998). We suspect that the [O ii] identification is correct, but in view of the mass and energy problem the maximum [O ii] velocity may need to be somewhat lower than the 25 000 km s$^{-1}$ that we have used.

### 4.3 Summary of the inferred composition structure

Our line identifications in the spectra of SN 1991T are, for the most part, the same as those of Jeffery et al. (1992) and Mazzali et al. (1995), e.g., Fe ii and Fe ii, Ni ii and Ni ii, Ca ii, Si ii, Si ii and Si ii and Na i. In addition, though, we identify C ii $\lambda\lambda 6580$ in the $-13$ d spectrum and, somewhat more tentatively, [O ii] $\lambda\lambda 7320$, 7330 in the $+59$ d spectrum.

In Fisher et al. (1997) we presented evidence for the presence of C ii in SN 1990N at $v > 26000$ km s$^{-1}$. It is thought that when SNe Ia are arranged in a sequence from powerful events like SN 1991T to weak ones like SN 1991bg, SN 1990N belongs on the powerful side (e.g. Phillips et al. 1992; Nugent et al. 1995). One might then expect events that are weaker than SN 1990N to have unburned carbon extending down to velocities lower than 26 000 km s$^{-1}$, and our synow studies of other SNe Ia suggest that this generally is the case (Fisher 1999). Similarly, one might expect events like SN 1991T that are thought to be stronger than SN 1990N to have a minimum velocity of carbon that is higher than


**Figure 6.** The velocity at the photosphere, used in the synthetic spectra, is plotted against time.

26 000 km s$^{-1}$. However, in SN 1991T we find evidence for C ii moving at least as slow as about 15 000 km s$^{-1}$. At the same time, we find evidence that the iron-peak core of SN 1991T extended out to velocities at least as high as in SN 1990N and other SNe Ia. Independently, Mazzali et al. (1998) list outer velocities of the iron core for 14 SNe Ia, inferred from nebular-phase spectra, and they find that SN 1991T has the highest velocity in their sample. Thus SN 1991T seems to have had both slower unburned carbon and a faster iron-peak core than SN 1990N, with its intermediate-mass elements being confined to an unusually narrow velocity interval.

Fig. 6 plots the velocity at the photosphere adopted for our synthetic spectrum fits, as a function of time. The pause in the velocity decrease, around 10 000 km s$^{-1}$, presumably reflects an increase in the density or the opacity near the outer edge of the iron-peak core. It should be noted, however, that such a pause is not evident in fig. 17 of Mazzali et al. (1995). Their adopted values of the velocity at the photosphere are higher than ours before maximum light, lower than ours after maximum light, and they decrease smoothly with time.

Our combined constraints on the composition structure are shown in Fig. 7. The inferred structure is not like that of any hydrodynamical model that has been published. A speculation about the cause of the peculiar composition structure of SN 1991T will be offered in Section 6, after the implication of the high luminosity of SN 1991T is considered in the next section.

### 5 THE LUMINOSITY OF SN 1991T

NGC 4527, the parent galaxy of SN 1991T, is in the southern extension of the Virgo cluster complex. According to the Nearby Galaxies Catalogue (Tully 1988) it is a member of the same small group of galaxies (group 11–4 in Tully’s notation) as NGC 4536 and 4496, the parent galaxies of the normal Type Ia SNe 1981B and 1960F. These three galaxies have similar heliocentric radial velocities of 1730, 1866 and 1738 km s$^{-1}$, respectively, and they are the three brightest galaxies in the group. On the sky, NGC 4527 is 1.9 from NGC 4496 and only 0.6 from NGC 4536. Peletier & Willner
Ruiz-Lapuente et al. (1992), at the redshift of NGC 4527, were detected in the spectra of SN 1991T. Values of the colour excess that have been estimated on the basis of the strengths of the Na i lines include $E(B - V) = 0.34$ by Ruiz-Lapuente et al. (1992) and 0.13–0.23 by Filippenko et al. (1992). Although these estimates are recognized to be uncertain, some significant amount of extinction is to be expected. (4) Mazzali et al. (1995) and Nugent et al. (1995) concluded from its spectral features that SN 1991T was hotter than normal SNe Ia, yet some of the broad-band colours of SN 1991T were observed to be redder than those of normal SNe Ia. Phillips et al. (1992) estimated $E(B - V) = 0.13$ by assuming that the intrinsic $B - V$ colour at maximum light was that of normal SNe Ia. The revised photometry of Lira et al. (1998) makes SN 1991T even redder than had been thought, with $B_{\text{max}} - V_{\text{max}} = 0.19 \pm 0.03$.

For SN 1991T we adopt $E(B - V) = 0.2 \pm 0.1$. For SN 1981B we use $E(B - V) = 0.10 \pm 0.05$ (M. M. Phillips 1995, personal communication), and we assume that the extinction of SN 1960F was negligible (Saha et al. 1996b; Schaefer 1996). It may be worth noting that these estimates are in accord with the galaxy 'dustiness' categories of van den Bergh & Pierce (1990), who put NGC 4496 in category 1 ('some dust visible'), NGC 4536 in category 2 ('dust easily visible') and NGC 4527 in category 3 ('galaxy appears very dusty'); only 12 of the 230 galaxies in their sample were assigned to the very dusty category. With our adopted extinction estimates, the extinction-free apparent $(B + V)$ and absolute $(M_B$ and $M_V$) magnitudes of the normal SNe 1960F and 1981B become similar, while SN 1991T becomes brighter than SNe 1960F and 1981B by 0.7–0.8 mag (see Table 1).

For the bolometric correction, $M_{\text{bol}} - M_V$, of normal SNe Ia such as 1981B and 1960F, we adopt $0.1 \pm 0.1$ (Höflich 1995; Mazzali et al. 1995; Nugent et al. 1995; Branch, Nugent & Fisher 1997). Even before being corrected for extinction, SN 1991T had a larger fraction of its energy in the near-ultraviolet than do normal SNe Ia (Nugent et al. 1995; Schaefer 1995b; Branch et al. 1997); therefore a smaller fraction of its total flux was emitted in the $B$ and $V$ bands, and its $M_{\text{bol}} - M_V$ was more negative than that of normal SNe Ia. For SN 1991T we adopt $M_{\text{bol}} - M_V = -0.1 \pm 0.1$ (not inconsistent with 0.0 $\pm$ 0.1 of Mazzali et al. 1995). The bolometric absolute magnitude of SN 1991T then exceeds that of SN 1981B by 0.95 $\pm$ 0.37 mag (where the uncertainty in the difference between the distance moduli of NGC 4527 and 4536 has been neglected), and the luminosity of SN 1991T exceeds that of SN 1981B by a factor between 1.7 and 3.4, with the best estimate being a factor of 2.4 (see Table 1).

The peak luminosity of a Type Ia supernova can be written (Arnett 1982; Branch 1992)

$$L = \alpha R(t_\text{t}) M_{\text{Ni}},$$

where $R(t_\text{t})$ is the time of maximum light in years and $M_{\text{Ni}}$ is the mass of nickel produced in the explosion. The factor $\alpha$ is usually taken to be 1.0.
where $R$, the instantaneous radioactivity luminosity per unit nickel mass at the time of maximum light, is a known function of the rise time $t_r$, $M_{\text{Ni}^6}$ is the mass of ejected $^{56}\text{Ni}$, and $\alpha$ is dimensionless and of order unity. For normal SNe Ia, such as SN 1981B, characteristic values of $t_r = 0.6 \text{ M}_\odot$, $t_r = 18 \text{ d}$, and $\alpha = 1.2$ (e.g. Höflich & Khokhlov 1996; Branch et al. 1997) give $L = 2.03 \times 10^{43} \text{ erg s}^{-1}$. This corresponds to a bolometric absolute magnitude $M_\text{bol} = -19.57$, a little brighter than, but not inconsistent with, the value implied by the Cepheid distance and the adopted extinction.

At first glance one might think that sufficient overluminosity of SN 1991T with respect to SN 1981B could be achieved with a Chandrasekhar mass, just by allowing the nickel mass to approach the Chandrasekhar mass in SN 1991T (i.e., $1.4/0.6 = 2.33$, and we have estimated that SN 1991T was more luminous than SN 1981B by a factor of 2.4). However, there are severe problems with this simple picture, in which nearly all of the ejected mass of SN 1991T is initially in the form of $^{56}\text{Ni}$. (1) Spectral lines formed by elements other than nickel, cobalt, and iron show that the initial composition of SN 1991T was not just $^{56}\text{Ni}$. (2) No hydrodynamical models of Chandrasekhar-mass explosions produce just $^{56}\text{Ni}$. Even the pure detonation model of Khokhlov et al. (1993) produced only $0.92 \text{ M}_\odot$ of $^{56}\text{Ni}$, with the rest of the mass being in the form of other iron-peak isotopes. (3) A rapid expansion of the ejecta caused by the high kinetic energy per gram, together with the prompt escape of gamma-rays emitted by $^{56}\text{Ni}$ in the outer layers, would make the light curve too fast, and with gamma-rays escaping the value of $\alpha$ would be low. For example, for the detonation model of Khokhlov et al. (1993), Höflich & Khokhlov (1996) calculated $\alpha = 0.76$ (in their notation it is $\eta$). (5) The optical and gamma-ray luminosities depend on distance in the same way. From the optical brightness of SN 1991T and the lack of detection of gamma-rays by Lichiti et al. (1994) and Leising et al. (1995), the latter authors conclude that ‘some way of producing optically brighter but gamma-ray fainter supernovae (compared to SN Ia models in the literature) is required to explain SN 1991T’. A Chandrasekhar-mass explosion that contained nearly a Chandrasekhar mass of $^{56}\text{Ni}$ would have a low ratio of optical to gamma-ray luminosity.

If SN 1991T is at the same distance as SNe 1981B and 1960F, as we assume here, then it is unlikely that its luminosity can be explained in terms of a Chandrasekhar mass ejection.

6 DISCUSSION

If the luminosity of SN 1991T was too high to be explained in terms of a Chandrasekhar mass ejection, the only recourse would seem to be to appeal to the explosion of a super-Chandrasekhar product of the merger of two white dwarfs. The question of whether mergers of white dwarfs actually can produce explosions is not yet settled (e.g. Mochkovitch, Guerrero & Segretain 1997). An attractive recent suggestion was that of Iben (1997), who noted that because tidal torques will spin up the pre-merger white dwarfs to rotate in near synchronism with the orbital motion, huge shear forces will arise at the onset of the merger. If both white dwarfs ignite prior to or during the merger, owing to shear and tidal heating, or if the ignition of one of the white dwarfs then provokes the ignition of the other, this might be a way to get not only a super-Chandrasekhar mass ejection, but even a super-Chandrasekhar mass of $^{56}\text{Ni}$ if such should prove to be required. Getting a super-Chandrasekhar mass of $^{56}\text{Ni}$ out of a thermonuclear explosion was difficult to envisage before Iben’s suggestion. It must be noted, though, that in the first calculations of tidal heating during a merger, it failed by a narrow margin to cause carbon to ignite (Iben, Tutukov & Fedorova 1998).

It is interesting that on the basis of their population-synthesis studies, Tutukov & Yungelson (1994) predict that for ‘young’ mergers, those that occur within 300 Myr of star formation, the average combined mass is substantially super-Chandrasekhar, typically about $2.1 \text{ M}_\odot$ (see their fig. 4). Recall that SN 1991T appears to have occurred near a spiral arm. Preliminary indications are that the several other events resembling SN 1991T that have been discovered in recent years also tend to be associated with star forming regions and/or to be significantly extinguished by dust (A. V. Filippenko 1998, personal communication; P. Garnavich 1998, personal communication). SN 1991T-type events may be from a younger population than most SNe Ia.

It also is interesting that Ruiz-Lapuente et al. (1992) discuss the possible detection of a narrow circumstellar line of O I 8446 in their earliest spectrum of SN 1991T. Searching for narrow circumstellar lines of hydrogen, helium, carbon, or oxygen is one the best ways to probe the composition of the donor star in the binary progenitor system of a SN Ia (Branch et al. 1995). No signs of circumstellar interaction, and no clear detections of narrow circumstellar lines of hydrogen or helium, have been found in any SN Ia.

On the basis of a light-curve study that was based on a constant-opacity approximation, Cappellaro et al. (1997) discussed the possibility that SN 1991T was super-Chandrasekhar, even for their adopted ‘short’ distance of 13.5 Mpc.

In a very general sense, the composition structure expected of a merger explosion might resemble the composition structure that has been inferred for SN 1991T (cf. Ruiz-Lapuente et al. 1992). An unusually strong explosion produces a high-mass, high-velocity iron-peak core surrounded by an unusually small mass of intermediate-mass elements; this encounters a surrounding low-density mass of carbon and oxygen which decelerates the intermediate-mass elements and forces them into a narrow velocity interval.

The proposition that SN 1991T was the result of a super-Chandrasekhar merger may also be consistent with the findings of Höflich & Khokhlov (1996), who calculated light curves for a variety of SN Ia hydrodynamical models and found that the slow light curve of SN 1991T was best fitted by models that have a substantial amount of unburned carbon and oxygen in their outermost layers. The particular models that Höflich & Khokhlov cited as best fitting the light curve have a peak $L_\text{max} = 19.4$, which is not luminous enough for SN 1991T. Khokhlov et al. (1993) constructed super-Chandrasekhar models in which the underlying explosion was the detonation of $1.2 \text{ M}_\odot$, inside low-density carbon-oxygen envelopes of 0.2, 0.4 and 0.6 $\text{M}_\odot$. In these models the minimum velocity of unburned carbon was less than 10000 km s$^{-1}$, a value which is lower than we infer from the spectra. The detonation of a Chandrasekhar mass inside the carbon-oxygen envelopes would give a brighter light curve and a higher minimum velocity of unburned carbon.

None of this explains the presence of iron-peak elements at higher velocity than the intermediate-mass elements, or the possible coexistence in velocity space of iron-peak elements and unburned carbon. Eventually, only multidimensional hydrodynamical studies of the merger process can tell us whether this is possible.

It should be noted that Liu, Jeffery & Schultz (1997b) used a steady-state model of ionization and thermal structure to calculate early nebular-phase spectra for comparison with observed spectra obtained hundreds of days after the explosion. Although they favoured a sub-Chandrasekhar mass ejection for SN 1991T, the mass was higher than they favoured for normal SNe Ia (Liu, Jeffery & Schultz 1997a). Spyromilio et al. (1992) argued on the basis of a
nebular-phase spectrum that SN 1991T ejected an exceptionally high mass of $^{56}\text{Ni}$, around 1 $M_{\odot}$.

The argument that SN 1991T was super-Chandrasekhar depends, of course, on our assumption that SN 1991T is at the same distance as SNe 1981B and 1960F. A Cepheid-based determination of the distance to NGC 4527, though perhaps not easy for such a dusty, inclined galaxy, is vital to check on this assumption.

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