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THE PECULIAR TYPE Ia SN 1991T: DETONATION OF A WHITE DWARF?

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ABSTRACT

SN 1991T was a peculiar object whose premaximum optical spectrum did not resemble that of any known supernova; it appears to have been dominated by lines of iron-group elements. Near maximum brightness, however, lines of intermediate-mass elements slowly appeared, and the spectrum began to resemble that of Type Ia supernovae (SNs Ia). With time, the spectral similarity to classical SNs Ia grew progressively stronger. Two months after the explosion, the spectrum was once again dominated by iron-group elements and appeared almost identical to that of typical SNs Ia. At visual wavelengths, SN 1991T was probably $\gtrsim$0.6 mag more luminous than classical SNs Ia, but the shape of its light curve was reasonably normal. We suggest that SN 1991T was a double detonation of a white dwarf, initiated at the boundary layer between the carbon-oxygen core and the helium envelope. Alternatively, the explosion may have been the result of a delayed detonation in a carbon-oxygen white dwarf.

Subject headings: stars: individual (SN 1991T) — supernovae: individual (SN 1991T) — white dwarfs

1. INTRODUCTION

The optical spectra of classical Type Ia supernovae (SNs Ia) are characterized by the absence of hydrogen, and by the presence of a deep absorption trough near 6150 Å during the first 5–6 weeks after the explosion. This trough is thought to be produced by blueshifted Si II λ6355. In general, the light curves and spectra of SNs Ia are very homogeneous (e.g., Branch et al. 1983; Leibundgut 1991). A few genuine photometric differences have been reported (Phillips et al. 1987), and there are unambiguous variations in the observed wavelengths of absorption features at a given phase (Branch 1987; Branch, Drucker, & Jeffery 1988), but the overall similarity of different SNs Ia remains extremely striking. The observed homogeneity of SNs Ia is understood, at least to first order, on theoretical grounds; it is thought that SNs Ia represent the deflagration of a carbon-oxygen white dwarf that has reached the Chandrasekhar limit due to mass transfer from a (possibly disrupted) companion star (e.g., Nomoto, Thielemann, & Yokoi 1984; Iben & Tutukov 1984).

A dramatic exception to the homogeneity of SNs Ia was recently provided by SN 1991T, which occurred in the outskirts of the nearby, highly inclined Sb galaxy NGC 4527 (Fig. 1 [Pl. L1]; $cz = 1740$ km s^{-1}). The early-time spectrum and the spectral evolution of SN 1991T were unprecedented, and the visual luminosity was unusually high, suggesting the possibility of a new variety of SNs Ia having a physically distinct explosion mechanism. Here we present a representative sample of the data collected during the first 3 months after discovery, to illustrate the peculiar nature of SN 1991T. A detailed account of the observations, reductions, and interpretations will be given elsewhere.

2. VISUAL LIGHT CURVE AND LUMINOSITY

SN 1991T was independently discovered by four groups (Waagen *et al.* 1991). The earliest known detection was on 1991 April 13.17 UT by S. Knight, with a visual magnitude of $\sim$14. By April 15.9 the object had brightened to $m_V = 13.0$ mag (M. Villi & G. Contini). Useful upper limits of 15 mag on April 4.48 and April 9.9 are provided by R. Evans and by Villi & Contini, respectively. The most restrictive upper limit, however, comes from a deep IVN + RG9 plate (effective wavelength 8000 Å) obtained at Palomar Observatory during the interval April 10.26–10.32 UT; the limiting near-infrared magnitude is 19.5 (Waagen, *et al.* 1991; J. Mueller 1991, private communication). Thus, the time interval between the explosion and the discovery was $\lesssim$3 days, assuming the Palomar observations preceded the explosion.

The early-time visual light curve of SN 1991T, determined primarily from visual observations made by amateur astronomers, is shown in Figure 2. Despite slight differences in the bandpasses (Allen 1976), the visual observations are generally consistent with the photoelectric measurements, as expected in view of the object's spectral shape during its first month (§ 3). We estimate that the explosion was on 1991 April 11 $\pm$ 1 UT, and that visual maximum ($m_V \approx 11.3$ mag) occurred on April 27 $\pm$ 1; thus, the rise time was probably 16 days, although extreme values of 14 and 18 days cannot be excluded. In normal SNs Ia, the rise time at blue wavelengths is 1–2 days shorter than at visual wavelengths (Leibundgut 1988), but with the present data set we are unable to test whether this was the

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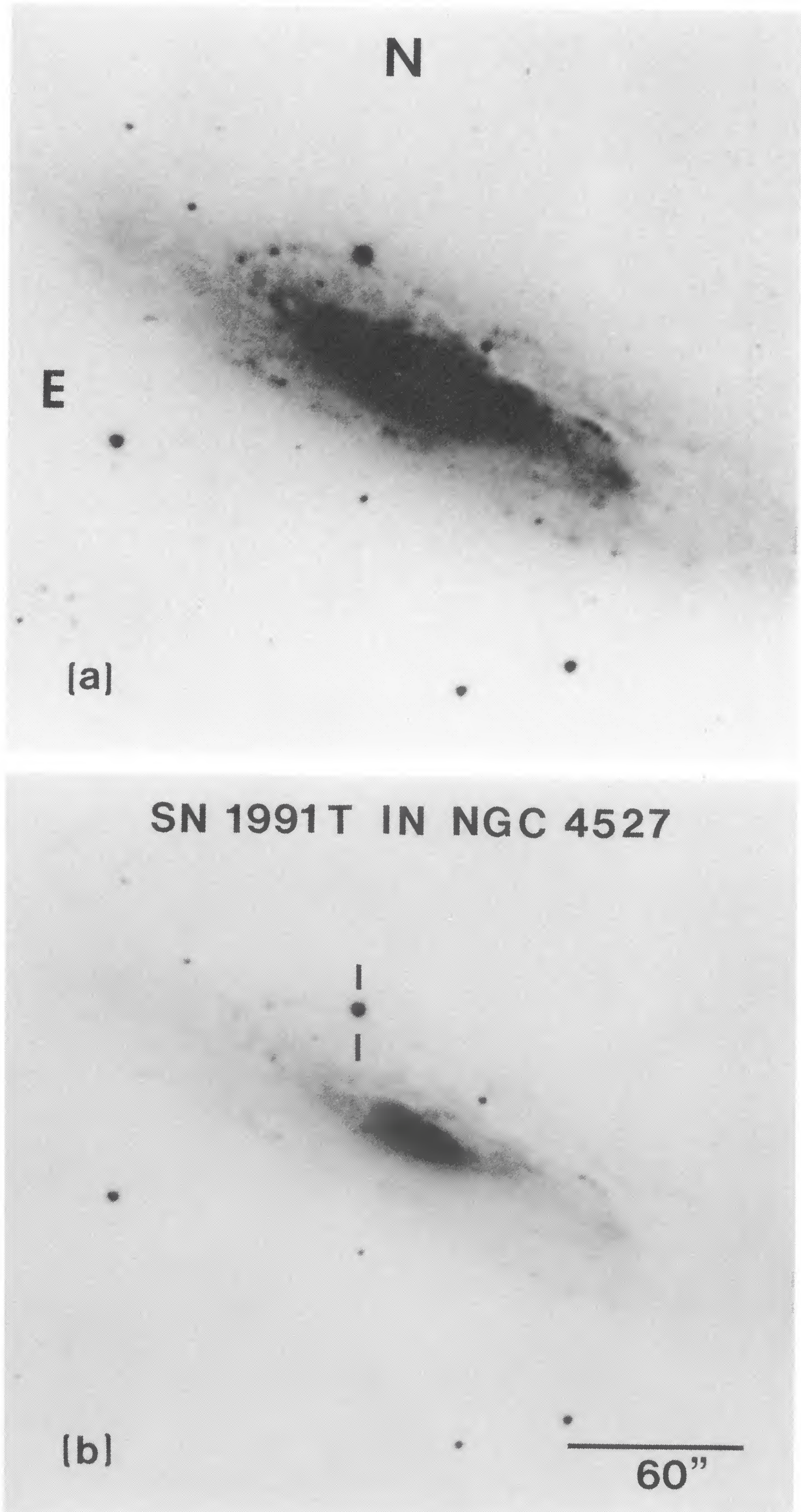

FIG. 1.—CCD image of SN 1991T in NGC 4527, displayed at two different contrast levels. The image was obtained through a red filter on 1991 June 12 UT, with the 1 m Nickel reflector at Lick Observatory. As shown in (*a*), SN 1991T was superposed on the outer part of a spiral arm, probably on the near side of the galaxy. The object is 25".7 east and 44".4 north of the galactic nucleus (IAU Circ., No. 5239).

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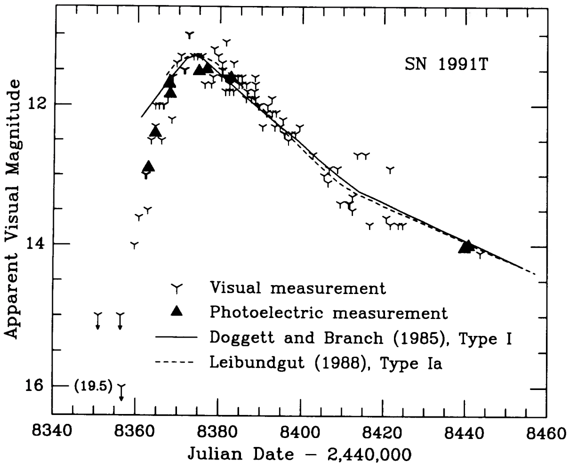

FIG. 2.—Light curve of SN 1991T, at visual wavelengths, compared with average V light curves of normal SNs I. The upper limit of 19.5 mag at JD 2,448,356.8 is at an effective wavelength of ~8000 Å.

case for SN 1991T. We will simply assume that blue maximum (defined to be $t = 0$ d) occurred on April 26 UT, with a rise time of 15 ± 2 days. This may be shorter than the 17–20 day rise time of SN Ia 1990N (Leibundgut et al. 1991), although the uncertainties do not preclude essentially identical values.

Figure 2 also shows the average visual light curves determined by Doggett & Branch (1985; SNs I) and by Leibundgut (1988; SNs Ia). These are based on few observations; in the past, most photometric observations of SNs were made at blue wavelengths. Evidently, the visual light curve of SN 1991T had a normal shape. As mentioned above, it is possible that the premaximum rise was slightly more rapid than usual. Similarly, the postmaximum decline *might* have been somewhat steeper and deeper than average, but this result should be viewed with caution.

The maximum visual *luminosity* of SN 1991T was almost certainly larger than that of typical SNs Ia. Leibundgut & Tammann (1990) found that the average apparent visual magnitude of five normal, well-observed SNs Ia in the Virgo cluster was 12.02 ± 0.29 mag at maximum. Essentially the same value, $m_V = 12.04 \pm 0.34$ mag, was obtained by Leibundgut (1991) for 18 SNs Ia whose distances were artificially converted to that of the Virgo cluster by using a Virgocentric infall model. According to Tully, Shaya, & Pierce (1992), the distance modulus of the Virgo cluster is 30.96 mag, while that of NGC 4527 is 30.57 mag. Thus, SN 1991T is on the *near* side of the Virgo cluster. It would have had an apparent visual magnitude of 11.69 (rather than 11.3) had it been at the distance of the Virgo cluster—0.35 mag *brighter* than the average SN Ia.

Leibundgut & Tammann (1990) state that the SNs Ia used in their study do not suffer appreciably from Galactic or internal extinction; a reasonable estimate is $A_V \lesssim 0.1$–0.2 mag in most cases. Extinction of SN 1991T due to dust in our galaxy is negligible. Internal extinction of SN 1991T, on the other hand, may be substantial. The measured equivalent width of the redshifted (~5927 Å) narrow Na I D absorption line in the spectra (§ 3) is 1.15 Å. Adopting the prescription discussed by Filippenko, Porter, & Sargent (1990) for SN 1987M, we derive a visual extinction of ~0.7 mag, 0.5–0.6 mag larger than in the typical SNs Ia studied by Leibundgut & Tammann (1990). Combining this with the apparent brightness derived above, we find that SN 1991T may have been ~0.9 mag more luminous than classical SNs Ia.

Unfortunately, the extinction estimate of 0.7 mag is uncertain by at least 0.4 mag. For Galactic stars, uncertainty in the relationship between the Na D equivalent width and $E(B-V)$ is large (e.g., Hobbs 1978), although the conversion factor adopted by Filippenko et al. (1990) generally appears to *underestimate* the extinction. On the other hand, according to Jeffery et al. (1991), this approach may actually overestimate the visual extinction; they find that $A_V \approx 0.8$ mag, rather than 1.4 mag, for SN 1987M. Applying a correction factor to SN 1991T, we deduce $A_V \approx 0.4$ mag, roughly 0.2–0.3 mag larger than that of average SNs Ia. We therefore conclude that SN 1991T was probably at least 0.6 mag more luminous than typical SNs Ia. If the canonical SN Ia is powered by 0.6–0.8 $M_\odot$ of radioactive $_{28}Ni^{56}$, SN 1991T may have synthesized 1.0–1.4 $M_\odot$ of nickel, assuming the visual luminosity scales linearly with the nickel mass (e.g., Wheeler & Harkness 1990). Despite being very uncertain, values in this range are suggestively close to the Chandrasekhar limit. It should be possible to derive a more accurate mass for the iron-group elements from detailed studies of the late-time optical light curve and spectra.

3. EARLY-TIME SPECTRAL AND SPECTROSCOPIC EVOLUTION

A set of early-time spectra of SN 1991T, obtained with CCD spectrographs at the Cassegrain focus of the Shane 3 m reflector at Lick Observatory, is shown in Figure 3. Spectrum (*b*), covering a broad wavelength range (3000–9600 Å), was taken on 19 April UT, about 7 days prior to blue maximum ($t = -7$ d). The continuum is quite blue and nearly featureless. Only three deep absorption lines are seen, at approximate wavelengths of 3200, 4200, and 4900 Å. Spectrum (*d*), taken on May 5 ($t = 9$ d), reveals the presence of the red Si II absorption line near 6150 Å which is the defining characteristic of SNs Ia. It was first visible, at a weak level, in spectra obtained on April 24 and 25 (Hamuy & Phillips 1991; Sivaraman, Prabhu, & Anupama 1991), at $t = -2$ to -1 d.

This is not the typical behavior of SNs Ia, as illustrated in Figure 4. The spectrum of the normal, well-observed SN Ia

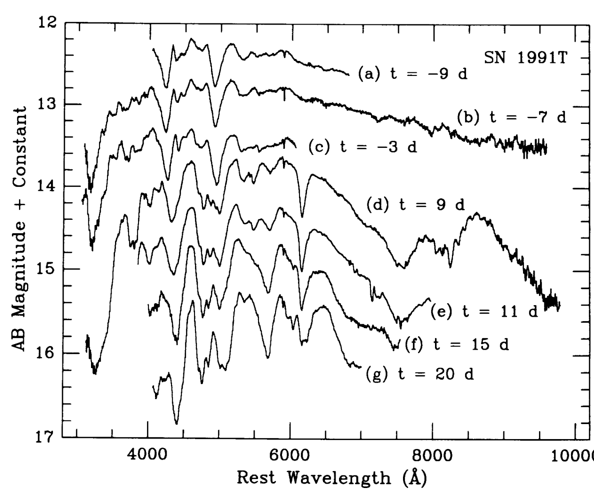

FIG. 3.—Montage of early-time spectra of SN 1991T. AB magnitude = $-2.5 \log f_\nu - 48.6$, where the units of f_ν are ergs s^{-1} cm^{-2} Hz^{-1} (Oke & Gunn 1983). Days are indicated relative to blue maximum, which occurred on 1991 April 26 UT. A few residual atmospheric absorption bands remain near 7200 Å in spectrum (*e*).

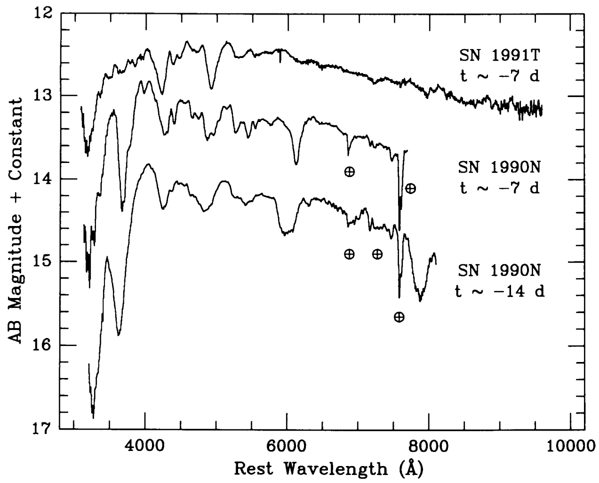

FIG. 4.—Premaximum spectrum of SN 1991T, compared with spectra of the normal SN Ia 1990N (from Leibundgut et al. 1991). Note the striking absence of the 6150 and 3700 Å absorption troughs in SN 1991T. Telluric absorption lines in the spectra of SN 1990N are marked.

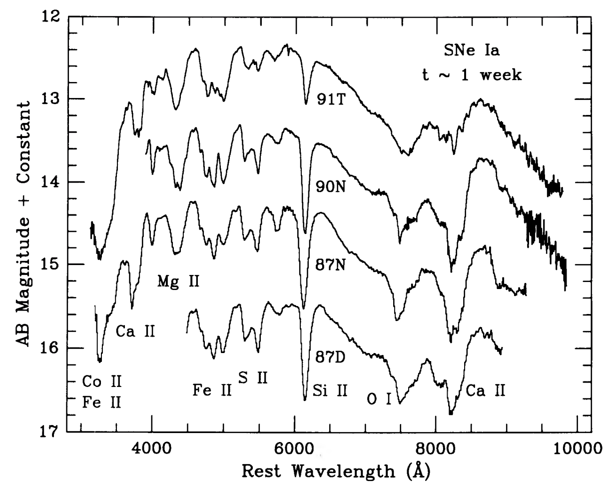

FIG. 5.—Spectrum of SN 1991T, obtained ~1 week past maximum, compared with spectra of normal SNs Ia at comparable phases. Lines of intermediate-mass elements (e.g., Si II, at 6150 Å) are present, but unusually weak, in SN 1991T.

1990N (Leibundgut et al. 1991) showed strong Si II absorption at $t = -7$ d. Lines of other intermediate-mass elements, notably Ca II H + K, were also present. These features were very broad, but nevertheless easily visible, in SN 1990N at considerably earlier times ($t = -14$ d); thus, their absence in SN 1991T cannot be the result of an incorrect estimate of the epoch of maximum brightness. Since the shape of the continuum of SN 1991T is similar to that of SN 1990N at $t = -7$ d, the temperature of the photosphere was close to normal. This suggests that the absence of Si II and Ca II lines in SN 1991T reflects low abundances of intermediate-mass elements rather than an excitation effect. The deep absorption trough near 3200 Å is probably due to Co II $\lambda\lambda$3502, 3446, as in SN 1990N (Leibundgut et al. 1991). Thus, it appears that the outer layers of SN 1991T experienced complete silicon burning, as expected in a detonation. Given these considerations, we suggest that the absorption lines near 4220 and 4920 Å are produced by blends of Fe III lines having rest wavelengths of 4400 and 5100 Å, respectively, with perhaps some contribution from Co II, Co III, and Ni III.

As mentioned above, lines of intermediate-mass elements began to appear when SN 1991T was near maximum brightness, but they were less prominent than usual. This is illustrated in Figure 5, which compares the spectrum of SN 1991T at $t \approx 1$ week with the corresponding spectra of the normal SNs Ia 1987D, 1987N, and 1990N. Relative to the complex blend centered on 4850 Å, which consists primarily of Fe II lines, observed lines of Si II (4000 and 6150 Å), Ca II (3780 and 8220 Å), and S II (5400 Å) are weak. Curiously, lines near 4320 and 7550 Å, generally attributed to Mg II and to O I at this phase (e.g., Branch et al. 1982), seem to have their normal strengths. The relatively late appearance of the Si, Ca, and S lines in SN 1991T shows that the intermediate-mass elements are severely depleted in its outermost layers, unlike the case in normal SNs Ia. Note, however, that the observed velocity of the silicon layer in SN 1991T is essentially identical to that of other SNs Ia.

With time, the spectral resemblance between SN 1991T and typical SNs Ia progressively increased. Figure 6 shows spectra of SN 1991T and SN 1990N obtained at $t \approx 3$ weeks. The Si II line near 6150 Å is stronger in SN 1990N, but other differences are relatively minor. By this stage, lines of Fe II begin to dominate in classical SNs Ia (Axelrod 1980), indicating that the central regions of the star are burned to nuclear statistical equilibrium. Apparently the same was true in SN 1991T. This is confirmed in Figure 7, which compares spectra of SN 1991T and SN 1990N obtained at $t \approx 51$ d. Differences in the spectra, which consist largely of Fe II and Fe III blends, are minor. Thus, had SN 1991T been discovered a month or more past maximum, it would have been classified as a spectroscopically *normal* SN Ia, rather than a peculiar SN Ia ("SN Ia-pec"). Such a transformation of spectral characteristics has never previously been seen in SNs Ia.

4. INTERPRETATION

The observations discussed above indicate that SN 1991T was dominated by iron-group elements in the outermost layers as well as in the core. On the other hand, a thin layer of intermediate-mass elements was present between these two regions, probably close to the surface. Evidently, most of the star was converted to Ni^{56}, perhaps as a result of a double detonation (or double deflagration?) initiated at an intermediate layer in the progenitor white dwarf. This layer could have been at the boundary between the C-O core and the He

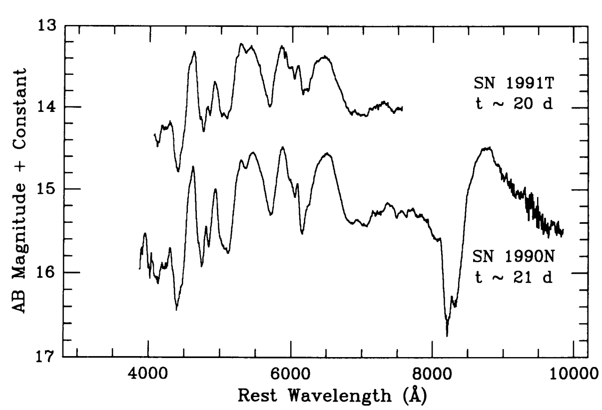

FIG. 6.—Comparison of SN 1991T and the normal SN Ia 1990N, roughly 3 weeks past maximum. The two spectra are quite similar.

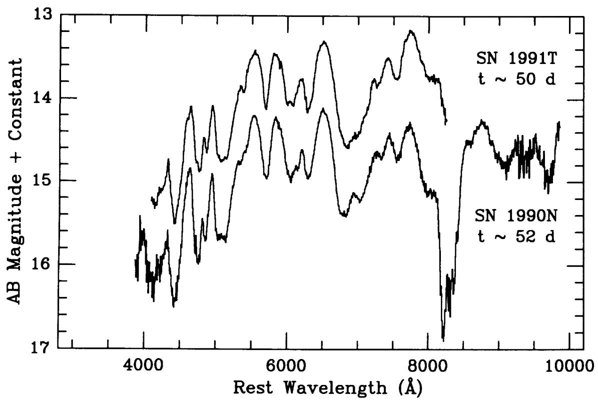

FIG. 7.—Comparison of SN 1991T and the normal SN Ia 1990N, roughly 7 weeks past maximum. The two spectra are nearly indistinguishable.

envelope of the progenitor (Nomoto 1982; Woosley Taam, & Weaver 1986). The layer of intermediate-mass elements, exterior to the fully burned 1.1 $M_\odot$ core, could have experienced only partial burning if the detonation waves required some time (and space) to materialize. The large amount of Ni^{56} (1.2–1.3 $M_\odot$?) expected to be synthesized during the detonation is in good agreement with the maximum luminosity of SN 1991T derived in § 2. On the other hand, the apparent absence of He lines in the premaximum spectrum may be inconsistent with the Ni-He composition resulting from detonations. Also, it is not clear whether a sufficient quantity of partially burned material would remain in the layer which initiated the double detonation.

An alternative is that SN 1991T was the result of a delayed detonation. In this scenario, the central regions experience an outward-moving deflagration, synthesizing Ni^{56} in the core and intermediate-mass elements at larger radii. If the deflagration eventually turns into a detonation, complete burning to Ni^{56} and other iron-group elements could occur in the outermost layers of the star. Khokhlov (1991a, b) and Woosley & Weaver (1991) have recently shown that delayed detonation models seem consistent with many observed properties of *normal* SNs Ia. Thus, to explain SN 1991T, certain details of these models would have to be different.

These possibilities must, of course, be thoroughly tested with numerical models and spectral synthesis codes. Useful constraints are provided by the shape of the light curve of SN 1991T, which appeared similar to that of typical SNs Ia during the first 3 months. The detailed abundances of the intermediate-mass elements also need to be computed and compared with observations. In particular, do O and Mg (and perhaps, by extension, Ne?) have normal abundances relative to Fe, while Si, S, and Ca are significantly depleted? Other models should also be explored. For example, some deflagration models produce detonations in the outermost layers (Nomoto et al. 1984; Woosley & Weaver 1991). It is important to determine whether the progenitor and explosion mechanism of this maverick SN Ia deviate widely from, or are closely related to, those of classical SNs Ia.

Finally, the unusually high luminosity of SN 1991T is relevant to the question of whether SNs Ia are useful as "standard candles" for the determination of cosmologically interesting distances (e.g., Kirshner 1990). If objects such as SN 1991T are common, they will preferentially be discovered in searches for very faint, distant SNs; failure to recognize such objects could lead to serious underestimates of the distances of the parent galaxies. Thus far, studies of nearby SNs indicate that SNs Ia-pec are very rare objects. However, we must also consider the possibility that some factor, such as the lower metal abundances at early epochs, may alter the distribution of SN subtypes at moderate redshifts. A detailed study of the environment of SN 1991T will be made to see whether it has any unusual characteristics.

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Note added in proof.—As discussed by A. Burrows, A. Shankar, & K. A. Van Riper (ApJ, 379, L1 [1991]) and by E. Müller, P. Höflich, & A. Khokhlov (A&A, 249, L1 [1991]), detection of SN 1991T with the *Gamma Ray Observatory* would help determine the explosion mechanism and the mass of newly synthesized nickel.