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MODELING THE IRON-DOMINATED SPECTRA OF THE TYPE Ia SUPERNOVA SN 1991T AT PREMAXIMUM[1]

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ABSTRACT

SN 1991T in NGC 4527, a galaxy of the Virgo Cluster, has been an unusual Type Ia supernova, being at least one magnitude brighter at maximum than other SN Ia's in Virgo. Unlike SN 1990N, another recent Type Ia SN observed also at premaximum, this supernova has not shown in this phase lines of Si II or Ca II. To study the composition of the ejecta an approximate NLTE treatment of excitation and ionization based on the Sobolev escape probability concept has been developed and incorporated in the Monte Carlo transfer code of Lucy. This spectral synthesis method has been applied to analyze the premaximum observations taken at ESO–La Silla, which are also presented and discussed in this work. The analysis of the optical spectra indicates that the outermost layers of SN 1991T have undergone complete burning, giving a composition rich in Fe-peak elements (Fe is clearly detected and Ni seems to be present as well), without any evidence of intermediate-mass elements such as Si, Ca, or O. This can be interpreted in terms of a fast deflagration that induced a detonation near the surface of the star that burned the outermost layers into nuclear statistical equilibrium (NSE). Comparison of the observations with delayed-detonation models show significant differences in chemical composition from that predicted.

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

1. INTRODUCTION

Very few Type Ia supernovae have been observed before maximum light. Early observations are of great interest, as they reveal the chemical composition of the outermost layers of the supernova and can thus help to discriminate between different models for the explosions. They can also provide clues to the evolutionary scenario leading to Type Ia SN events.

The already long debate on the dynamics of explosive burning in SN Ia's has been revived by recent models: delayed detonation models due to Khokhlov (1991) and Woosley & Weaver (1991), which assume that the initial subsonic burning (deflagration) will turn into supersonic burning (detonation) and incinerate the star almost completely. Larger kinetic energies for the ejecta and also larger ^{56}Ni masses can be obtained, as compared with standard deflagration models (Nomoto, Thielemann, & Yokoi 1984; Sutherland & Wheeler 1984; Woosley, Axelrod, & Weaver 1984). In deflagration models, where burning propagates always subsonically, about 0.4 $M_{\odot}$ of intermediate-mass elements and 0.1 $M_{\odot}$ of unburned material are ejected (Thielemann, Nomoto, & Yokoi 1986). In the delayed detonation models of Khokhlov (1991) and of Woosley & Weaver (1991), intermediate-mass elements are produced in the outer layers of the exploding white dwarf, coexisting over a wide range of expansion velocities with Fe-peak elements. Premaximum observations of Type Ia SNe can thus be used as a test of the models.

The best case of a Type Ia SN monitored long before maximum has been SN 1990N (Leibundgut et al. 1991), which was first observed 2 weeks before maximum light. At the Workshop on Standard Candles held in Trani in 1991 August, a preliminary analysis of the premaximum spectra of SN 1991T was presented by the authors of this *Letter*. This already suggested a composition enhanced in iron-peak elements and revealed significant differences from the spectra of SN 1990N at similar phases (Leibundgut et al. 1991). In this *Letter*, the full set of premaximum observations carried out at La Silla in the framework of the ESO Key Programme on Supernovae (Turatto et al. 1991) is presented, and the method used to generate synthetic spectra is described and applied to reproduce the observations. Finally a discussion on the results of the spectral analysis is made in view of different models of deflagration, detonation, and delayed detonation of white dwarfs.

2. OBSERVATIONS AND IDENTIFICATIONS

SN 1991T was discovered on April 13.17 UT by S. Knight (IAU Circ., No. 5239) and later, independently by other groups of observers. It is located 52″ NE from the nucleus of NGC 4527, a nearly edge-on Sb galaxy member of the Virgo Cluster. Prior to the discovery, no object was seen down to magnitude 15 on April 4.48 and April 9.9 (IAU Circ., 5239). An IVN plate taken on April 10 with the Oschin Schmidt telescope (IAU Circ., 5239) failed also to show the supernova. This sets, therefore, a very restrictive limit to the date of the explosion. From the published photometry it is possible to draw a preliminary light curve. The supernova reached a visual magnitude of about 11.4 ± 0.1 at maximum (April 27. ± 2^d). Moreover, as inferred from the presence of a strong Na I D absorption, the supernova suffers a significant interstellar extinction. The comparison of the $(B-V)$ color at maximum with the average value of SN Ia's at maximum suggests a color excess $E(B-V) \simeq 0.25$. The spectroscopic observations, however,

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show that SN 1991T is not a typical SN Ia, and this estimate of the color excess has to be used with caution. Barbon et al. (1990) have suggested an independent method for determining the interstellar extinction for supernovae based on the relation $E(B-V)$ versus equivalent width (EW) (Na I D). We have measured the EW (Na I D) = 1.37 Å on all our spectra. This gives $E(B-V) = 0.34$. Therefore the mean of the previous estimates $E(B-V) = 0.3$ would imply a visual extinction of $A_v \simeq 1$ mag, thus giving this supernova a corrected visual magnitude of 10.4 in the Virgo Cluster! This value is 1.6 mag brighter than the mean visual magnitude at maximum for SN Ia's in the Virgo Cluster which is about $V = 12.0$ (Leibundgut 1991; Capaccioli et al. 1990). If we take into account the dispersion in magnitude due to depth of the Virgo Cluster, this gives in the most conservative case a result 1.1 mag brighter than the mean value quoted before. Some inferences can be drawn from this fact if the shape of the light curve and the rise time to maximum is similar to the "standard" case. The luminosity at maximum is proportional to the amount of ^{56}Ni synthesized in the explosion. It also depends on the opacity of the material and its expansion velocity, these last two factors being combined in the so-called expansion opacity as a factor that also affects the rise time to maximum (Shigeyama et al. 1991). If we disregard the possibility of a very different expansion opacity than in the "normal" case, then a conservative estimate of the luminosity of SN 1991T with respect to the normal Type Ia supernova in the Virgo Cluster would impose a maximum value on the mass of ^{56}Ni synthesized in normal Type Ia events: 0.5 $M_\odot$ (that is $10^{-0.44}$ times the maximum possible amount: 1.4 $M_\odot$). Because of the importance of such a conclusion for chemical evolution of galaxies and for the use of SN Ia's as distance indicators, this matter should be addressed in the framework of careful modeling of light curves.

Our earliest spectrum at premaximum phase was taken on April 16.07 UT, which is 11 ± 2 days before the V maximum. Therefore, taking into account the uncertainty in the extrapolation of this light curve and the lack of detection on date April 10 at infrared wavelengths, our first observation would correspond to 4–6 days after explosion. Table 1 reports the journal of observations and expansion velocities measured from Fe III line blends in the spectra. The series of flux-calibrated spectra are shown in Figure 1. Difficulties involved in the calibration defining the flux for the violet edge of the spectrum (from 3200 to 3500 Å) make this part of the spectra less reliable. Therefore, we will discuss the chemical composition of the ejecta on the basis of the features observed redwards of 3500 Å.

The features at 4240 Å and 4940 Å in the spectra correspond to strong absorptions of Fe III, as discussed below. Lines of

TABLE 1

JOURNAL OF THE SPECTROSCOPIC OBSERVATIONS AND EXPANSION VELOCITIES AS DEDUCED FROM DIFFERENT Fe III LINE BLENDS[a]

Date (1991)	UT	Equipment[b]	$\lambda_0 = 4417.7$	$\lambda_0 = 5117.1$
Apr 16	01.35	2.2 m + B&C	13200	11710
Apr 17	03.29	2.2 m + EFOSC2	13170	11840
Apr 18	03.38	2.2 m + EFOSC2	12820	11010
Apr 19	03.19	1.5 m + B&C	...	10826
Apr 20	03.37	3.6 m + EFOSC1	12170	10710
Apr 21	02.46	3.6 m + EFOSC1	11480	10250
Apr 22	04.22	3.6 m + EFOSC1	11150	10030

[a] Corrected for redshift of the parent galaxy.

[b] B&C: Bolder & Chievens spectrograph; EFOSC2 and ESOFC1: ESO Faint Object Spectrograph & Camera (2.1).

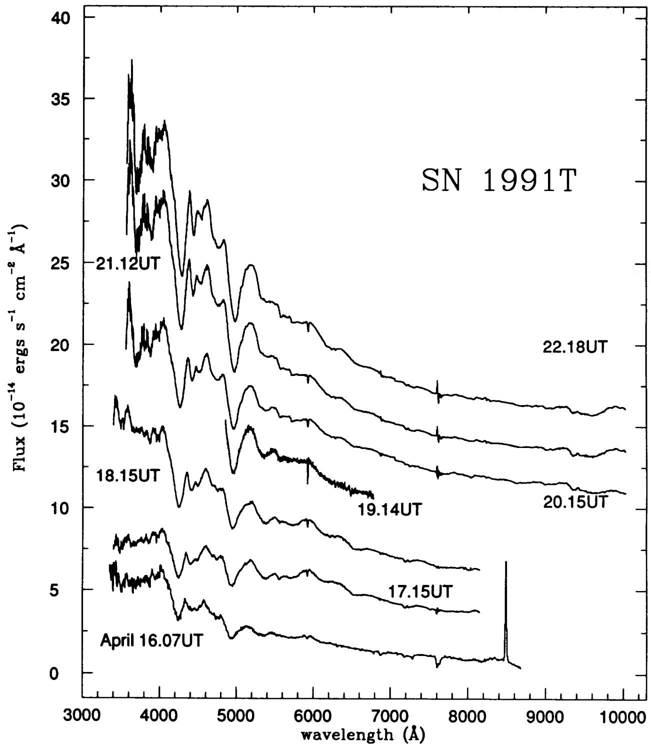

FIG. 1.—Spectra of SN 1991T (uncorrected for reddening and in the parent galaxy rest frame) during the first week after the discovery, in chronological order bottom to top. The flux scale is relative to the first spectrum. Each other tracing has been shifted upward by 2.5×10^{-14} ergs s^{-1} cm^{-2} Å^{-1} with respect to the previous one. The telluric absorption bands visible in the first spectrum have been removed in others.

intermediate-mass elements are not detected in the spectra at these times. Among others, the typical feature due to the Si II λ6355 doublet, the Ca II H and K lines, and the Ca II IR triplet are lacking in all these premaximum spectra. It seems that near maximum the features around 4300 and 4900 Å remain and other features of Fe II appear (IAU Circ., 5255). The first ones are identified by Hamuy & Phillips (IAU Circ., 5251) as Mg II and Fe II lines. However, in the premaximum spectra the main contribution to these features comes from Fe III while no Mg is required to reproduce the spectra (see § 3). In fact, blends of Fe III lines: λλ5127.59, 5128.86, 5088.16, 5075.36, 4432.3, 4420.87, 4391.00, and 4383.78 seem to account fairly well for the strongest features observed, with contributions of Fe II lines probably growing with time.

The earliest spectrum (April 16) shows, in addition to the Fe III features, a narrow unresolved line at 8488 Å (8437 Å in the rest frame of the galaxy), possibly, of circumstellar origin. It is not consistent with a cosmic-ray event because of the number of pixels over which the line extends and its precise centering on the spectrum of the supernova. The integrated flux of this feature is 1.03×10^{-12} ergs s^{-1} cm^{-2}. No certain identification can be made of this unusual feature. But a possible identification is the O I 8446 line. As discussed by Grandi (1975), this line can appear much stronger than the other O I lines if it is excited by Lyβ fluorescence. Continuum fluorescence is another possibility although this normally produces other weaker O I lines that ought to be visible. Discussion of this and others possibilities is beyond the scope of this work. Four days later the emission at 8437 Å is no longer seen.

A model has been constructed to test the Fe III identifications and the hypothesis that the Fe seen is coming from the decay chain $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$, the former nuclide being synthesized at the time of the explosion.

3. RESULTS AND DISCUSSION

An approximate NLTE treatment of excitation and ionization has been developed for use in combination with the previously described Monte Carlo transfer code of Lucy (1987a, b). The solution of the rate equations is carried out using the Sobolev escape probability concept for estimating the scattering integrals in the rate equations (Klein & Castor 1978).

As a first step we treat the ionization for the five five ions of Fe. We obtain the number density of electrons and calculate the continuum opacity (taken to be pure Thompson scattering). For every ion relevant to the spectrum (in our case Fe II and Fe III), a detailed model of the ion + continuum is established, taking into account 119 levels for Fe II and 128 levels for Fe III, which are necessary to cover the energy levels from which the observed transitions in the spectra arise. The results of our analysis show that most of the lines observed in the spectra covering these 7 days are due to Fe III, which is the dominant ion of Fe because the intense radiation field is able to ionize the major fraction of Fe twice. The lines observed in the spectra arise from upper levels, which are mainly populated by radiative excitation. Populations close to LTE are found in the regions where the lines are formed. In the outer atmospheric layers, of low density, depopulation of the upper levels of the ions is found, but that does not have a very significant effect on the spectra.

The envelope is modeled with a density gradient of index $n = -7$, which reproduces the structure of the external layers of the W7 model (Branch et al. 1985). The synthetic spectra are reddened taking $E(B-V) = 0.3$ mag (§ 2). For April 16, a temperature gradient going from 14,000 to 10,000 K is adopted (linearly decreasing with radius). Blackbody emission at 15,000 K is assumed at the lower boundary of the model atmosphere. The photosphere is located at $R_{ph} \simeq v_{ph} \times t$ (t being the time after explosion, here assumed to be 6 days and v_{ph} taken to be 13,200 km s^{-1}). The density of the photosphere is log (ρ_{ph}) = -12.3 (density in g cm^{-3}). The atmosphere model goes from a lower boundary velocity of 13,200 km s^{-1} to an upper boundary velocity of 21,300 km s^{-1}. The atmosphere contains here about 0.22 $M_{\odot}$, although the spectrum can be compatible with some other boundary density and atmosphere mass.

If Fe is coming from the decay chain $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$, a significant amount of Ni should be present in the interval of our observations. In fact Ni III should be the most abundant ion at the radiation temperature of the innermost layers of the envelope. Figure 2*a* compares the spectrum observed on April 16.07 UT with a theoretical spectrum calculated for the abovementioned atmosphere model containing only Ni, Fe, and Co in relative abundances corresponding to 6 days after explosion. The relative strengths of the Fe III and Ni III lines are well fitted. With these relative abundances, Ni III absorptions are found in the predicted spectrum that consistently fit observed lines. These Ni III lines are $\lambda\lambda$5569.8, 5424.13, 4932.5, 4876.3, 4613.9. In particular, the first two Ni III lines are the only contribution to the absorption observed at 5200 Å, thus confirming the presence of this ion in the spectra. Lines of Ni II $\lambda\lambda$3849.6 and 3769.5 appear also in the synthetic spectrum which do not correspond to features in the observed spectrum. The Fe III line appearing at 3800 Å seems too strong in comparison with the observed one. A weak line of Co II at λ4160.65 appears also in the theoretical spectrum.

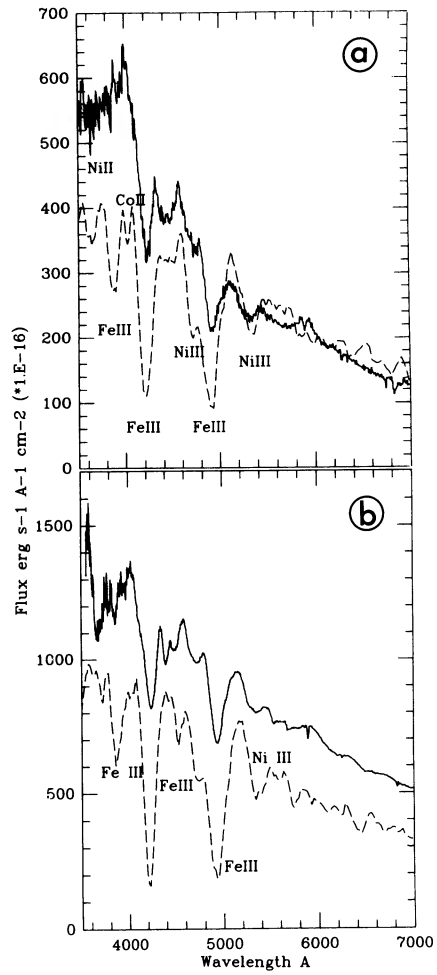

FIG. 2.—(*a*) Comparison of the optical spectrum of SN 1991T on April 16 with a synthetic spectrum corresponding to a mixture of Fe and Co in the proportions resulting from the decay of pure ^{56}Ni into ^{56}Co, followed by that of ^{56}Co into ^{56}Fe assuming that the explosion happened on April 10. The spectra are in the parent galaxy rest frame. The agreement in absolute flux between models and observed spectra has been imposed on the models through the assumption of the appropriate luminosity. (*b*) Same as 2*a* but for date April 20 (10 days after explosion). The observed spectrum has been shifted upward by 2. × 10^{-14} ergs s^{-1} cm^{-2} Å^{-1}.

Figure 2*b* is a comparison for April 20. The photosphere is now located at log (R_{ph}) ≃ 15.02. The density of the photosphere is log (ρ_{ph}) = -12.7. The atmosphere model goes from a lower boundary velocity of 12,200 km s^{-1} to an upper boundary velocity of 20,000 km s^{-1}. The atmosphere contains here about 0.31 $M_{\odot}$. The radial distribution of the temperature of the previous date is conserved. The inner boundary temperature is around 13,800 K. The most significant change in the observed spectrum appears in the wavelength range blueward of 4000 Å. At this date, absorptions at about 3600 Å and 3800 Å appear that were not evident in earlier spectra. In our synthetic spectrum at 3800 Å a Fe III feature appears that could correspond to the one seen in the observed spectrum although the match of the spectrum is not so good as at longer wavelengths.

Finally, the existence of some amount of unburned material is constrained by these observations. If a mass fraction $X_C \simeq 0.02$ of C were left in the external layers of the ejecta, this should give an observable C II line at 6900 Å (λλ7231.4, 7236) which is not seen in the spectra. Upper limits of 0.03 and 0.007 for the mass fractions of S and Si, respectively, in the 0.3 external $M_\odot$ can be derived from the lack of the S III lines λλ4332.73, 4285.01, and 4253.62 and the Si II λ6355 Å (for the temperatures of the atmosphere model). From the lack of the λ7879 line of Mg II, an upper limit on the mass fraction of Mg of 0.03 can be placed. This limit can be lowered if this line is still absent when the temperature drops. The fact that no lines of intermediate-mass elements are present in the early stages of SN 1991T suggests that the material in the outermost layers has undergone complete Si burning. In contrast, in SN 1990N the spectra taken 14 days before maximum already showed the features that are usually observed at maximum in other SN Ia's: the typical features of Co II, Ca II, Mg II, Si II were present (Leibundgut et al. 1991), indicating that burning was partially quenched before reaching the outer layers. However, on the basis of the identifications herein proposed for SN 1991T, we believe that features due to Fe III may be already apparent in the first spectrum of SN 1990N and possibly preclude Mg II as an identification. In SN 1991T, Ca II features seem to be absent in the premaximum spectrum and to be weak if present at all near maximum (IAU Circ., 5251). A Fe-rich spectrum appears to be dominated first by Fe III lines at earlier phases, as is found from our analysis, and later by stronger Fe II lines or perhaps still Fe III lines and possibly also the characteristic Si II feature (IAU Circ., 5251).

The lack of a well-determined date of explosion implies some uncertainty on the phase of our observations. Nevertheless, our calculations are consistent with the Fe observed in the spectra coming from the decay of ^{56}Co which in turn results from the decay of ^{56}Ni. The fact that Si was detected in the spectra of April 25 (IAU Circ., 5251), 4 days after the last spectrum shown here, reveals that a composition richer in intermediate-mass elements is present below the outer layers. The composition enriched in Si inward could be revealing the "inversion" of composition found in models where a fast deflagration induces a detonation in the outermost layers of the star. This possibility resulting in a composition dominated in the outer layers by ^{56}Ni was found by Nomoto et al. (1984) in their model C8 (K. Nomoto 1991, private communication). Another early "delayed detonation" model where such an "inversion" of composition is found is model 3 of Woosley & Weaver (1986), later on called F7 (Harkness 1991). When the shock wave propagates through the outer layers in this model, it produces a detonation that burns the matter into NSE and imparts velocities $v > 17{,}000$ km s^{-1}. The intermediate-mass elements appear "sandwiched" between a core in NSE and an outer region also in NSE. The intermediate-mass elements, concentrated in a thin region spanning the velocity range 15,000–17,000 km s^{-1}, are O, Si, and S.

In model F7, the kinetic energy is larger than inferred for SN 1991T. In fact, SN 1991T did not show very high velocities at premaximum (see Table 1). At maximum light, several lines have an average velocity of 10,000 km s^{-1} (Sivaraman et al., IAU Circ., No. 5255). This would seem to contradict the idea of a large ^{56}Ni mass being synthesized. A possibility, however, is that the material would have been decelerated by an external shell around the supernova, coming from the disruption of the companion star as predicted by the double-degenerate scenario (Iben & Tutukov 1984).

To conclude, SN 1991T seems to correspond to a delayed detonation in a white dwarf that failed to produce intermediate-mass elements in the outermost layers and did not impart much kinetic energy to them. Current delayed detonation models (Khokhlov 1991; Woosley & Weaver 1991) predict amounts of intermediate-mass elements near the surface that seem incompatible with what is observed in SN 1991T. This event is different from the other Type Ia SN well observed at premaximum, SN 1990N, and from other SN Ia's such as SN 1981B and SN 1986G. Thus, SN 1991T is very relevant to the debate concerning the uniqueness of the dynamics of the explosion among SN Ia's: different burning velocities and ignition densities could be responsible for the spectroscopic differences seen at premaximum.

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