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THE NEAR–MAXIMUM-LIGHT SPECTRUM OF THE TYPE Ic SUPERNOVA 1987M

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ABSTRACT

An analysis of the near–maximum-light optical and near-UV spectrum of the Type Ic supernova 1987M is presented. In the spectrum, in addition to the fairly certain identifications of O I, Ca II, and optical Fe II lines, we identify a weak Hα line, a moderately weak Si II λ6355 doublet, and the He I λ5876 line. The near-UV region of the spectrum is found to result from a blend of iron peak ion lines, with only solar abundances of the iron peak elements required in the supernova atmosphere. It is concluded that hydrogen is underabundant relative to solar composition in the supernova atmosphere by at least a factor of 10; no lower limit on hydrogen abundance has been determined. It is also concluded that a helium star model for Type Ic supernovae is adequate and slightly favored for explaining the analyzed spectrum. The implications of the spectrum analysis for explosion models of Types Ib and Ic supernovae are discussed.

Subject heading: stars: supernovae

1. INTRODUCTION

The early optical spectra of Type Ic supernovae, near the time of the light-curve maximum, lack the conspicuous hydrogen lines of Type II supernovae, the conspicuous red Si II absorption feature of Type Ia and the conspicuous He I lines of Type Ib supernovae (Harkness & Wheeler 1990). To date, only a few Type Ic supernovae have been observed spectroscopically, and some of the line identifications remain uncertain. More importantly, the key issue of Type Ic atmosphere composition has not yet been settled.

Line identifications in Type Ic supernovae have been discussed by Wheeler et al. (1987) and by Filippenko, Porter, & Sargent (1990, hereafter FPS). Wheeler et al. compared observed spectra of SN 1983I in NGC 4051 and SN 1983V in NGC 1365 to synthetic spectra computed for an oxygen-rich atmosphere (He:C:O = 1:1:8 by mass, with solar mass fractions of heavier elements). They attributed observed spectral features to lines of O I, Ca II, and Fe II and tentatively associated weak absorptions near 5700 and 6200 Å with He I λ5876 and C II λ6580, respectively. Wheeler et al. suggested that SN 1983I and SN 1983V may have been explosions of the oxygen-rich cores of massive stars that had lost their hydrogen and most of their helium; the loss mechanism may be either stellar winds or binary mass transfer. FPS presented a series of spectra of SN 1987M in NGC 2715 and identified lines of O I, Na I (perhaps incorrect for the earliest spectrum; see below), Ca II, and Fe II. They also called attention to the possibility that weak emission and absorption features occurring in the range 6000–6600 Å might be produced by the Si II λ6355 line that is so strong in Type Ia supernovae and by Hα. In this *Letter*, we analyze the near–maximum-light spectrum of SN 1987M (§ 2) and discuss the implications of this analysis for current ideas about the origins of Types Ib and Ic supernovae (§ 3).

2. SPECTRUM ANALYSIS

Figure 1 displays the first SN 1987M spectrum (1987 September 28; estimated to be 7 days after maximum light) obtained by FPS and a fitted synthetic spectrum. The observed spectrum has been corrected for the redshift of NGC 2715 ($cz = 1339$ km s^{-1}; van der Kruit & Bosma 1978) and normalized to the highest flux value. From the strength of the interstellar sodium absorption lines FPS estimated $E(B-V) = 0.45$ mag and concluded that after correction for extinction SN 1987M was ~0.5–1 mag brighter in the B band than has generally been estimated for Types Ib and Ic supernovae. We find, however, that this much reddening implies an intrinsic color temperature, which if used as the characteristic atomic excitation temperature of the atmosphere, is much too high ($T \approx 12{,}000$ K) to give acceptable LTE fits to the Fe II lines we identify in the observed spectrum (see below). Therefore we have assumed $E(B-V) = 0.25$ mag, which leads to a "normal" Type Ib/c B-band peak brightness, and have reddened the synthetic spectrum using this $E(B-V)$ value.

The synthetic spectrum was calculated using the elementary LTE supernova model described in detail by Jeffery & Branch (1990). This model consists of a photosphere that emits a blackbody continuum and a line-scattering atmosphere. The model is in uniform-motion homologous expansion. Over 1600 lines belonging to the most relevant ions are included in the calculations; no continuous opacity is included. The radiative transfer is treated using the Sobolev method. The photospheric Sobolev line optical depths are calculated assuming a characteristic electron density and atomic excitation temperature. The Sobolev line optical depths above the photosphere (i.e., in the atmosphere) are obtained by scaling the photospheric values using an assumed density distribution. For SN 1987M, simple line-fitting experimentation suggested that an inverse power-law density distribution with index 10 would ade-

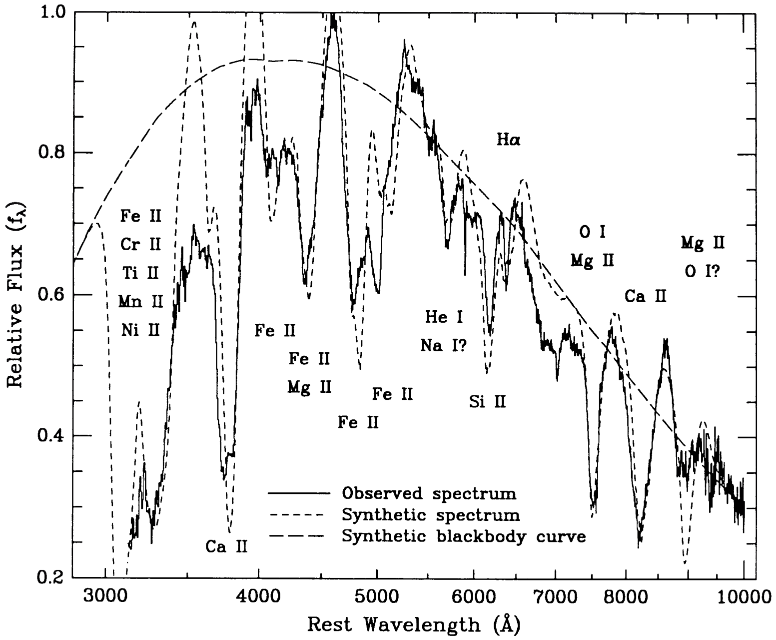

FIG. 1.—Comparison of the spectrum of SN 1987M observed on 1987 September 28 and a synthetic spectrum

quately reproduce the line profiles, and so this distribution has been adopted. The line source functions are calculated with the assumption of pure resonance scattering. The appropriate model photospheric velocity for SN 1987M was determined from experimental fitting to be 11,000 km s^{-1}. The temperature of the blackbody continuum (the color temperature) is another parameter of the model. With the adoption of $E(B-V) = 0.25$ mag, it was found that a color temperature of 8500 K gave roughly the right continuum shape for SN 1987M. The overall scale of the synthetic spectrum was set by demanding that the integrated fluxes of the observed and synthetic spectra be equal for the range 5000–6200 Å which is approximately the V band.

To fit the SN 1987M spectrum using the model, a helium star composition was adopted with, initially, solar metal abundances. Three parameters, characteristic atomic excitation temperature, characteristic electron density, and hydrogen abundance (while conserving H/He mass fraction), were then varied for the fit. The fitting criteria used were that the lines due to iron peak elements (which turned out to be most important for the overall spectrum formation) and the 6370 Å absorption should be well fitted. The 6370 Å absorption is the feature tentatively identified by FPS as due to Hα; therefore, fitting this feature has considerable importance. In narrowing down the range of parameter space to examine, considerable weight was given to the estimated electron density of 5×10^9 cm^{-3} obtained using the rough prescription given by Jeffery & Branch (1990, eq. [64]), an electron-scattering continuum opacity optical depth to the photosphere of 1, and an estimated time since explosion of the supernova of 27 days: 20 days from the explosion to maximum light plus 7 days. (The light curve of SN Ib 1983N suggests that 20 days may be an upper limit for the rise time of Types Ib and Ic supernovae; see Panagia 1985, Fig. 8). It is thought that a characteristic electron density lower than $\sim 5 \times 10^8$ cm^{-3} or higher than $\sim 15 \times 10^9$ cm^{-3} would be implausible; thus, these values were adopted as lower and upper bounds for the characteristic electron density parameter.

The estimated color temperatures for the spectrum for $E(B-V) = 0.0$ mag and $E(B-V) = 0.45$ mag [FPS's $E(B-V)$ estimate] were 6000 and 12,000 K, respectively; assuming a fairly close connection between color and characteristic excitation temperature, these color temperature estimates were adopted as lower and upper bounds for the excitation temperature parameter. Given the fitting criteria and bounds, a path of acceptable fits through the three-parameter space was located. The overall most plausible fits were obtained for excitation temperatures ~ 8500 K and electron densities $\sim 5 \times 10^9$ cm^{-3}. Excitation temperatures greater than ~ 9500 K seem to be ruled out, since the Fe II lines, which are very prominent in the observed spectrum, cannot be fitted for these excitation temperatures given our adopted electron density bounds even when the criterion of fitting the 6370 Å absorption is dropped.

In our most plausible fits with solar metal abundances, the line optical depth of the Si II λ6355 doublet was a factor of a few too strong and the line optical depth of the O I λ7773 line was a factor of ~ 10 too weak to give nice fits to the profiles attributed to these lines. Discrepancies of this size are attributable to gradient effects and NLTE effects (e.g., Branch et al. 1991). However, given the necessity for illustrative reasons of displaying a fit to the 6370 Å absorption (which would be impossible if the synthetic Si λ6355 emission feature were too strong) and desiring to show that a fit to the 7510 Å absorption with the O I λ7773 line can be obtained, the abundances of silicon and oxygen were adjusted to give reasonably nice fits to these absorptions. The synthetic spectrum displayed in Figure 1 is a representative example of our most plausible fits. The parameters of this synthetic spectrum are electron density 5×10^9 cm^{-3}, excitation temperature 8500 K (the same as the color temperature), hydrogen abundance a factor of 800 below solar, oxygen abundance a factor of 10 above solar, and silicon abundance a factor of 4 below solar. It is notable that the

TABLE 1

LINES IN THE SN 1987M SPECTRUM

Identification	Absorption Minimum (Å)	Line Velocity (km s^{-1})
Iron peak blend	3270 ± 10	...
Ca II λ3945 doublet....	3770	13600 ± 800
Fe II blend	4350	...
Fe II λ4924	4770	9500
Fe II λ5169	4990	10600
He I λ5876	5690	9600
Si II λ6355 doublet.....	6170	8900
H I λ6563..............	6370	8900
O I λ7773..............	7510	10300
Ca II λ8579 triplet	8190	13900

NOTE.—The uncertainties are only rough estimates.

synthetic spectrum shows excess flux in the ranges 3400–3600 Å and 6500–7300 Å, and at the Ca II H and K lines' emission feature. These discrepancies may be due to a lack in our line list of weak lines that have cumulative importance in those wavelength regions.

Based on the synthetic spectrum, we favor the line identifications shown in Figure 1; more detailed specifications for some of the identified lines are given in Table 1. The identifications of the Ca II and the optical Fe II lines are straightforward. In the range ~3200–3700 Å, the line features are due principally to the iron peak ions identified in the figure; the Fe II lines are dominant near 3200 Å, but otherwise the identified iron peak ions contribute roughly equally. Blueward of 3160 Å, no lines were included in the calculations, and this explains the sudden rise of the synthetic spectrum to the synthetic blackbody curve near 3100 Å. The Fe II (P Cygni profile) absorption in the synthetic spectrum near 4100 Å does not correspond to any distinct feature in the observed spectrum; this lack of clear correspondence may be due to an absence of some significant lines in the calculations. The synthetic absorption at 4350 Å is due to a blend of Fe II lines of roughly comparable strengths having rest wavelengths in the range 4500–4600 Å; the Mg II λ4481 line also contributes to this absorption.

The observed absorption at 5690 Å is reproduced in the synthetic spectrum by He I λ5876. However, for plausible LTE fits at temperatures significantly lower than 8500 K, this helium line is predicted by LTE to be much too weak. For such temperatures, a NLTE Na I λ5892 doublet may be invoked to account for the 5690 Å absorption; a NLTE Na I λ5892 doublet has been found to account for a similarly located absorption in SN II spectra (e.g., Höflich 1988). Since the presence or absence of helium in Type Ic supernovae is critical for deciding between progenitor models, it is important to check the helium line identification we have made. An observational check would be to attempt to find the He I λ10830 line, which should be very strong if the He I λ5876 line is present, in Type Ic spectra.

The observed absorption at 6170 Å is nicely accounted for by the Si II λ6355 doublet. As mentioned above, solar abundance silicon makes the Si λ6355 doublet too strong in the synthetic spectrum, and so the silicon abundance was reduced in the calculations. More plausibly, gradient or NLTE effects should be invoked to weaken the silicon doublet. The weak narrow absorption at 6370 Å is fitted reasonably well by the Hα line, with a weaker contribution from the C II λ6580 line. The Hα identification is not definite, however, since we are not able to identify the weaker Hβ and Hγ lines in the complex line blends mainly due to Fe II. In principle, the identification of Si II and Hα in SN Ic 1987M might raise a classification issue. The Si II and Hα features in SN 1987M are, however, much weaker relative to other features than they are in Type Ia and Type II supernovae. Thus SN 1987M presents no serious classification ambiguity.

The absorption minimum wavelengths and line velocities (i.e., the velocities corresponding to the blueshifts of the absorption minimum wavelengths) for some of our identified lines are given in Table 1. The high blueshifts of the Ca II absorptions are probably due to the tendency for strong lines to have greater absorption blueshifts than weaker lines whose blueshifts more closely reflect the velocity at the photosphere (see, e.g., Jeffery & Branch 1990). The observed absorptions at 6170 and 6370 Å, attributed by us to Si II λ6355 and Hα, respectively, give velocities that are a little slow compared to the other weak lines. However, the differences (which are within, or almost within, measurement uncertainty) may not be significant, or may be due to observational noise, line blending, or some other modulating physical effect in the supernova atmosphere.

As remarked above, the synthetic spectrum shown in Figure 1 is only a representative example of our most plausible fits. Only somewhat less plausible fits can be obtained for rather different conditions. From the analysis of all our plausible fits, we conclude that hydrogen must be underabundant compared to solar composition by at least a factor of 10. Because the C II λ6580 line, which is nearly coincident with the Hα line, can be strong enough in some of the higher excitation temperature fits (excitation temperature $\gtrsim$8500 K) to account by itself for the 6370 Å absorption, no lower limit on hydrogen abundance can be set. There is, however, other evidence for hydrogen in Type Ib and Type Ic supernovae. A strong P Cygni line possibly due to Hα is present in a spectrum of SN Ib 1954A (Branch 1972). Supernova 1987K, which was clearly a Type II at maximum light, metamorphosized into a Type Ib/c in its nebular phase (Filippenko 1988), dramatically establishing a connection between significant hydrogen abundance and Type Ib and Type Ic supernovae. (Type Ib and Type Ic supernovae are not, so far, distinguishable in the nebular phase; Harkness & Wheeler 1990.) Recently, Filippenko (1991) has reported that SN Ic 1991A in its photospheric phase shows evidence for an Hα emission feature without a P Cygni trough; only hydrogen lines in Type II supernovae have been known to show such early pure emission lines. Thus, the bulk of the evidence favors a conclusion that SN 1987M had significant hydrogen, although at much less than solar abundance. The presence of significant, though underabundant, hydrogen strongly suggests that helium should be the dominant element. Since our helium star composition produces plausible fits to the SN 1987M spectrum, we conclude that helium stars are plausible progenitors for Type Ic supernovae. However, a solar composition with all hydrogen and helium converted to carbon and oxygen can also give plausible fits if one allows for somewhat greater gradient and NLTE effects. Thus, a preference for a helium star composition is only weakly supported by our spectrum analysis.

3. THE ORIGINS OF TYPE Ib AND Ic SUPERNOVAE

Nomoto, Filippenko, & Shigeyama (1990) propose, mainly on the basis of the light curve, that SN 1987M resulted from the core collapse of a 3–3.6 $M_\odot$ helium star descended from a 12–15 $M_\odot$ star that lost its hydrogen to a binary companion. More generally, Hachisu et al. (1991) propose that both Type Ic and Type Ib supernovae result from the collapse of helium stars having masses in the ranges ~3–4 $M_\odot$ and ~4–6 $M_\odot$, respectively. The zero-age main-sequence masses of the helium stars for the lower and upper mass ranges are presumed to be ~12–15 $M_\odot$ and ~15–20 $M_\odot$, respectively (Shigeyama et al. 1990). The exploding helium stars in the lower mass range were found to produce more ^{56}Ni (Shigeyama et al. 1990) and to mix their ^{56}Ni more extensively toward the surface layers than the exploding helium stars in the upper mass range (Hachisu et al. 1991). The latter result was obtained from two-dimensional numerical simulations including Rayleigh-Taylor instabilities and is dependent on the initial models. The more extensive mixing of ^{56}Ni toward the surface enhances the escape of the radioactive decay products, speeds up the optical light curve, and can increase the maximum light luminosity (Shigeyama et al. 1990). From the facts that Type Ic supernovae appear to have, on average, narrower light curve peaks than Type Ib supernovae (Shigeyama et al. 1990; Wheeler & Harkness 1990), and that SN 1987M, at least, may have been bright, the different mass ranges for the Type Ib and Type Ic progenitors in the Hachisu et al. scenario naturally followed.

The different mass range assignment for the progenitors in the Hachisu et al. scenario may be consistent with the light curve data, but its consistency with the spectra is not clear. It has been speculated (e.g., Branch 1988) that nonthermal excitation of helium by the products of nickel-cobalt decay may be responsible for the appearance of He I lines in Type Ib supernovae. (In the SN II 1987A, such a nonthermal process may be responsible for the appearance of He I λ10830 [Graham 1988] and perhaps He I λ5876 [Jeffery & Branch 1990].) If helium is present in Type Ic supernovae as well as in Type Ib supernovae (as this *Letter* suggests may be the case; see § 2), and Type Ic supernovae experience more extensive mixing of ^{56}Ni toward the surface than Type Ib supernovae because Type Ic progenitors have lower mass, and there is nonthermal excitation of the He I lines, then the He I lines should be stronger in Type Ic than in Type Ib supernovae, contrary to observations. The question of the difference between the Type Ic and Type Ib progenitors cannot be considered to be settled until this spectroscopic dilemma is resolved.

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REFERENCES

Branch, D. 1972, A&A, 16, 247
———. 1988, in Atmospheric Diagnostics of Stellar Evolution: Chemical Peculiarity, Mass Loss, and Explosions, ed. K. Nomoto (Berlin: Springer), 281
Branch, D., Pauldrach, A. W. A., Puls, J., Jeffery, D. J., & Kudritzki, R. P. 1991, in ESO Workshop on SN 1987A and Other Supernovae (Garching: ESO), in press
Filippenko, A. V. 1988, AJ, 96, 1941
———. 1991, IAU Circ., No. 5169
Filippenko, A. V., Porter, A. C., & Sargent, W. L. W. 1990, AJ, 100, 1575 (FPS)
Graham, J. R. 1988, ApJ, 335, L53
Hachisu, I., Matsuda, T., Nomoto, K., & Shigeyama, T. 1991, ApJ, 368, L27
Harkness, R. P., & Wheeler, J. C. 1990, in Supernovae, ed. A. G. Petschek (New York: Springer), 1
Höflich, P. 1988, in Atmospheric Diagnostics of Stellar Evolution: Chemical Peculiarity, Mass Loss, and Explosions, ed. K. Nomoto (Berlin: Springer), 288
Jeffery, D. J., & Branch, D. 1990, in Jerusalem Winter School for Theoretical Physics, Vol. 6, Supernovae, ed. J. C. Wheeler, T. Piran, & S. Weinberg (Singapore: World Scientific), 149
Nomoto, K., Filippenko, A. V., & Shigeyama, T. 1990, A&A, 240, L1
Panagia, N. 1985, in Supernovae as Distance Indicators, ed. N Bartel (Berlin: Springer), 14
Shigeyama, T., Nomoto, K., Tsujimoto, T., & Hashimoto, M. 1990, ApJ, 361, L23
van der Kruit, P. C., & Bosma, A. 1978, A&AS, 34, 259
Wheeler, J. C., & Harkness, R. P. 1990, Rep. Progr. Phys., 53, 1467
Wheeler, J. C., Harkness, R. P., Barker, E. S., Cochran, A. L., & Wills, D. 1987, ApJ, 313, L69