THE ASTROPHYSICAL JOURNAL, 252:L61–L64, 1982 January 15

INTERPRETATION OF THE MAXIMUM LIGHT SPECTRUM OF A TYPE I SUPERNOVA

D. BRANCH
Department of Physics and Astronomy, University of Oklahoma

AND

R. BUTA, S. W. FALK, M. L. MCCALL, P. G. SUTHERLAND,[1] A. UOMOTO, J. C. WHEELER, AND B. J. WILLS
Department of Astronomy and McDonald Observatory, University of Texas at Austin
Received 1981 August 10; accepted 1981 September 28

ABSTRACT

A high quality optical spectrum of the 1981 Type I supernova in NGC 4536 at maximum light is well represented by a synthetic spectrum consisting of resonance scattering lines of Ca II, Si II, S II, Mg II, and O I, superposed on a continuum. The assumption of LTE at the photosphere leads to relative abundances of Ca, Si, S, Mg, and O that are consistent with solar abundances for a range of continuum temperatures. The spectrum is inconsistent with models such as the "double-detonation" model in which material with $v = (12–15) \times 10^3$ km s^{-1} is burned completely to Ni^{56}.

Subject heading: stars: supernovae

I. INTRODUCTION

On 1981 March 2, a 12th magnitude Type I supernova (SN I) was discovered by Tsvetkov (see Aksenov 1981) in NGC 4536, an SAB(rs)bc galaxy in the southern extension of the Virgo cluster complex. Optical spectrophotometry and *UBV* photometry were begun at McDonald Observatory on March 6, about 1 day before maximum light. Observations made between March 6 and March 9 with the intensified dissector scanner (IDS) spectrograph on the 2.7 m telescope provide the best spectrum ever obtained for an SN I near maximum light and the opportunity to interpret the spectral features in some detail. We find that simple synthetic spectra consisting of resonance scattering features on a blackbody continuum match the observed spectrum very well.

II. OBSERVATIONS

Photometry with the 0.9 m telescope, which will be reported in full elsewhere, shows that the light curve was typical of an SN I and that maximum light occurred on March 7 ± 1 day. Fitting the $B - V$ curve to the reddening-free composite $B - V$ curve for SN I (Pskovskii 1971) gives a color excess $E(B - V) = 0.16 \pm 0.03$, or an extinction of $A_V = 0.5 \pm 0.1$. According to de Vaucouleurs, de Vaucouleurs, and Corwin (1976), the extinction due to our Galaxy combined with the expected internal extinction for the morphological type and inclination of NGC 4536 is $A_V \sim 0.35$.

All of the spectra obtained at McDonald will be shown and discussed in a later paper. Here we discuss only a composite spectrum which refers to the time of maximum light (Fig. 1). The composite was made by combining the spectra of March 6, 7, 8, and 9 to achieve full coverage of the interval 3200–8500 Å. The overlapping parts of the spectra are practically identical, and little information has been lost in the superposition. The spectral features are very similar to those of other SN I's that have been observed at maximum light, e.g., SN 1974g in NGC 4414 (Patchett and Wood 1976; Iye *et al.* 1975), although the unusual narrow absorption features seen in SN 1974g are not seen in this spectrum.

III. INTERPRETATION

We interpret most of the spectral features as lines of singly ionized metals (Pskovskii 1969; Branch and Tull 1979) formed by resonance scattering above a photosphere that emits a thermal continuum (Kirshner *et al.* 1973). The assumptions and approximations underlying the synthetic spectrum calculations have been discussed by Branch (1980). Line formation is treated in the escape probability approximation (Sobolev 1960; Castor 1970); the line source function is that of resonance scattering; the optical depth of every line is taken to vary as r^{-7}, consistent with hydrodynamical calculations; and velocity is proportional to radius. The composition and ionization of the material above the photosphere are assumed to be homogeneous. For each ion the optical depth at the photosphere of one line is a fitting parameter, and the optical depths of the other

[1]Alfred P. Sloan Foundation Fellow. On leave from Department of Physics, McMaster University, 1980–1981.

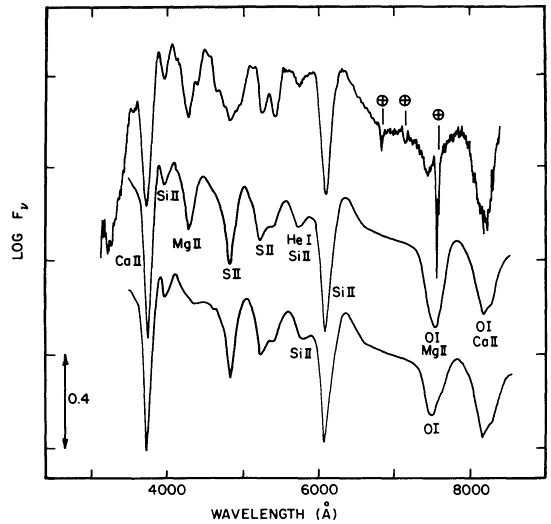

FIG. 1.—The spectrum at the top is a composite of spectra obtained 1981 March 6–9. Terrestrial absorptions are marked. The spectrum in the middle is a synthetic spectrum having $T = 17{,}000$ K and $v = 12{,}000$ km s^{-1}. Ions responsible for the major absorption features are shown. The synthetic spectrum at the bottom has the Mg II and He I lines removed. Interstellar reddening has been applied to the synthetic spectra, with $A_V = 0.3$.

lines are fixed by assuming that the relative level populations are given by the Boltzmann rule.

In Figure 1, the observed spectrum is compared with a synthetic spectrum having a color temperature $T = 17{,}000$ K and a velocity at the photosphere of 12,000 km s^{-1}. Line identifications do not depend sensitively on the choice of continuum temperature. Lines of Ca II, Si II, S II, Mg II, O I, and He I are used, with those responsible for the major absorption features identified in the figure. Considering the approximations that have been made in the calculations, the agreement is quite good.

The synthetic spectrum at the bottom of Figure 1, with the Mg II and He I lines removed, serves two purposes. The first is to show that the O I λ7773 triplet alone accounts nicely for an observed feature, whereas when Mg II is included to account for a feature in the blue at λ4481, λ7896 of Mg II detracts from the O I fit. The observed feature is probably due to O I, and the assumption of LTE excitation in Mg II probably overestimates the strength of λ7896 relative to λ4481. The second purpose is to show that when He I λ5876 is removed, a weak absorption feature still appears near 5760 Å due to λ5979 of Si II. In a recent paper on the interpretation of the premaximum spectra of an SN I, Gordon (1980) identifies the absorption feature as Si II, but she does identify He I in emission. We have included He I to show that the observed feature can be well represented, but whether He I really contributes to the spectrum remains an important open question. Neutral Na might also contribute at this wavelength.

Wavelengths, identifications, optical depths in the synthetic spectrum, and blueshifts of the observed absorption minima are given in Table 1. As expected (Branch 1980), there is a correlation between blueshift and optical depth. We draw particular attention to the strong Ca II λ3945 feature: its minimum is formed well above the photosphere even though this ion is presumed to be distributed homogeneously. This interplay of line optical depth, blueshift of absorption minima, and blending with nearby features makes it difficult to assess the assumption of homogeneity. There may be a hint of stratification in order of atomic number—the O I blueshift is somewhat high and that of S II somewhat low—but stratification of excitation and ionization rather than abundance could be responsible. We estimate from the line profiles that Ca, Si, S, Mg, and O probably coexist at least in the velocity interval 12,000–15,000 km s^{-1}. Complete composition stratification seems unlikely, but abundance gradients cannot be excluded.

The optical depths needed for the synthetic spectrum can be used to make rough estimates of abundance ratios if LTE at the photosphere is assumed. Despite the low density, gross departures from LTE are not expected if the radiation field at the photosphere is Planckian. If the ultraviolet deficiency of the SN I is due to enhanced opacity at short wavelengths, the optical photosphere occurs beneath the UV photosphere, and the UV radiation field, which drives the level populations, should be nearly Planckian at the optical photosphere.

The electron density at the photosphere is given by $N_e = (n-1)\tau_e/R\sigma_e$, if $N_e(r) \propto r^{-n}$. With $n = 7$, $\tau_e = 1$,

TABLE 1

ABSORPTION IDENTIFICATIONS AND VELOCITIES

λ[a]	ID	τ_e	V	λ[a]	ID	τ_e	V
3743 ...	Ca II λ3945	12.0	15,400	5271 ...	S II λ5454	1.3	10,100
3983 ...	Si II λ4129	2.5	10,600	5441 ...	S II λ5640	0.8	10,600
4290 ...	Mg II λ4481	2.5	12,800	6103 ...	Si II λ6355	6.0	11,900
4838 ...	Si II λ5051	2.2	12,700	7450 ...	O I λ7773	1.5	12,500

[a] In the rest frame of NGC 4536.

and $R = 1.6 \times 10^{15}$ cm (12,000 km s^{-1} for 15 days), we have $N_e = 5.6 \times 10^9$ cm^{-3}. For this electron density, Figure 2 shows abundance ratios implied by the optical depths used in the synthetic spectrum as functions of temperature. (Changing τ_e/R by factors $\lesssim 2$ leads to changes in relative abundances $\lesssim 2$.) Several points are worth mentioning: (1) The relative abundances derived from lines of Ca II, Si II, S II, Mg II, and O I are strikingly similar to solar abundances for temperatures in the range 8000–15,000 K. Lines of Fe II were not used in the synthetic spectrum. Figure 2 shows that the upper limit is consistent with a solar abundance of iron, relative to the other elements seen. (2) The optical depths of the Si II and O I lines, together with the upper limits to the Si III and O II lines, imply $T \lesssim 11{,}000$ K. The difference between this temperature and the color temperature of 17,000 K could be due to departures from LTE, or it may reflect a strong temperature gradient above the photosphere. The temperature gradient would cause the optical depths of the high excitation (~ 20 eV) Si III and O II lines to fall off rapidly with radius, which would in turn cause weak lines. (3) If He I λ5876 contributes to the observed feature near 5760 Å, LTE gives [He/Si] $\lesssim -2$ for $T \gtrsim 11{,}000$ K; but this line also is a 20 eV line, so a higher He abundance, even as high as solar, cannot be excluded. (4) No evidence of C is seen, but no useful limit to its abundance can be set because it is subject to the same restrictions as He. (5) The LTE upper limit to the hydrogen abundance is [H/Si] $\lesssim -4$. (6) Inclusion of a significant amount of Co II, as predicted in some models, causes unacceptable changes in the synthetic spectrum.

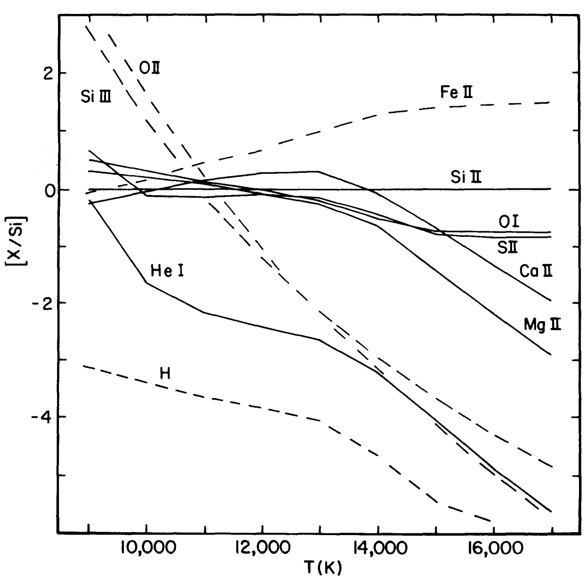

FIG. 2.—Abundance is plotted against temperature for $N_e = 5.6 \times 10^9$ cm^{-3}. Abundances derived from ions used in the synthetic spectrum are shown as solid lines, and upper limits to abundances based on ions not used in the synthetic spectrum are shown as broken lines. $[X/\mathrm{Si}] = \log X/\mathrm{Si}$ (supernova) $- \log X/\mathrm{Si}$ (Sun).

IV. IMPLICATIONS

If the total density and the electron density both vary as r^{-n}, the mass and kinetic energy above the photosphere are given by

$$M_{\mathrm{ph}} = 0.064\, M_\odot (n-1)/(n-3)(\mu_e/4)\tau_e R_{15}^2,$$

$$E_{\mathrm{ph}} = 0.64 \times 10^{50} \text{ ergs } (n-1)/(n-5)(\mu_e/4)\tau_e R_{15}^2 v_9^2, \tag{1}$$

where μ_e is the mean molecular weight per electron. If helium (singly ionized) is the most abundant element, then $\mu_e \sim 4$ and $\tau_e \sim 1$. Then with $n = 7$ and $R_{15} = 1.6$, we have $M_{\mathrm{ph}} = 0.23$ $M_\odot$, and $E_{\mathrm{ph}} = 6.6 \times 10^{50}$ ergs. These values, which apply only to the material above the photosphere, are substantial. If the helium abundance is low, then $\mu_e > 4$; but electron scattering may make only a small contribution to the total opacity. Thus the values of τ_e at the photosphere and, concomitantly, M_{ph} and E_{ph} are uncertain.

Further constraints on SN I models arise from consideration of the velocity of the material above the photosphere and its composition. The existence of elements other than Ni, Co, and Fe in the material moving at 12,000 km s^{-1} is incompatible with the bare "double-detonation" or "edge-lit" accreting white dwarfs that ignite degenerate helium at the He-C interface (Nomoto 1980; Woosley, Weaver, and Taam 1980): the elements we identify could only have existed near the surface of the white dwarf, but the explosion accelerates such material to velocities much higher than 12,000 km s^{-1}. Given the spectroscopic homogeneity of SN I's, it appears that such events rarely, if ever, occur. Such rarity may suggest that nova explosions prevent the necessary conditions from developing (Nomoto 1982). Alternatively, the assumption of ignition in a spherical shell may give misleading results.

Completely detonated helium white dwarfs (Mazurek 1973; Nomoto and Sugimoto 1977) may also be ruled out by our interpretation of the spectrum, since these do not have the elements we identify at velocities ~ 12,000 km s^{-1}. Further discussion of these and other detonation/deflagration models is given by Wheeler (1982).

The partial deflagration of an accreting C-O white dwarf that has reached the Chandrasekhar mass might lead to a composition of the outer layers consistent with our interpretation of the spectrum (Nomoto 1980), as well as a reasonable light curve (Chevalier 1981; Arnett 1981). A potential difficulty for this model is that, since the total mass and density structure are fixed, it may produce too tightly defined an event, with no ready explanation for the small but real differences among

SN I's (Branch 1981). Whether the carbon, oxygen, and their burning products can be produced in approximately solar ratios in this model and distributed homogeneously requires further investigation.

The chemical composition inferred here might also be consistent with core collapse in a helium star (Arnett 1980; Weaver, Axelrod, and Woosley 1980). This model may eject too little Ni to account for the late time spectra and light curves (Axelrod 1980), and it demands a neutron star remnant. In the remnants of the Tycho, Kepler, and 1006 supernovae, there is no positive evidence for neutron stars and weak evidence against their presence. The failure of the *Einstein Observatory* to detect pointlike thermal X-ray sources in these remnants may mean no neutron stars are present, although the theory of cooling neutron stars is not definitive (Glen and Sutherland 1980; Van Riper and Lamb 1981; Nomoto and Tsuruta 1981). These remnants also fail to show synchrotron nebulosity commonly associated with pulsars (Helfand 1981).

Another possibility is the deflagration of a white dwarf that is embedded in a helium envelope (Weaver, Axelrod, and Woosley 1980; Nomoto, Sutherland, and Wheeler 1982). The abundances of the intermediate mass elements are a very important discriminant for this model. If they are solar, the helium must dominate by mass and the envelope must be optically thick at maximum light. On the other hand, if the helium at the photosphere is underabundant, then the intermediate mass elements must be recently synthesized and the helium envelope must be optically thin at maximum light. Its role would be to provide the needed variety in light-curve shape and velocity at the photosphere. The evolutionary origin of such a configuration is unclear.

We are grateful to Jeff Brown, Russell Levreault, and Ken'ichi Nomoto for helpful discussions and to Derek Wills for assistance with the observations. This research was supported in part by the National Science Foundation through grants AST 78-08672 (D. B.), AST 79-16335 (R. B.), AST 79-01182 (A. U. and B. J. W.); a Benfield Fellowship (M. L. M.); and the Natural Sciences and Engineering Research Council of Canada (P. G. S.).

REFERENCES

Aksenov, E. P. 1981, *IAU Circ.*, No. 3580.
Arnett, W. D. 1980, *Ap. J.*, **240**, 105.
______. 1981, preprint.
Axelrod, T. S. 1980, in *Proc. Texas Workshop on Type I Supernovae*, ed. J. C. Wheeler (Austin: University of Texas Press), p. 80.
Branch, D. 1980, in *Supernova Spectra*, ed. R. Meyerott and G. H. Gillespie (New York: American Institute of Physics), p. 39.
______. 1981, *Ap. J.*, **248**, 1076.
Branch, D., and Tull, R. G. 1979, *A.J.*, **84**, 1837.
Castor, J. I. 1970, *M.N.R.A.S.*, **149**, 111.
Chevalier, R. A. 1981, *Ap. J.*, **246**, 267.
de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H. G. 1976, *Second Reference Catalogue of Bright Galaxies* (Austin: University of Texas Press).
Glen, G., and Sutherland, P. G. 1980, *Ap. J.*, **239**, 671.
Gordon, C. 1980, *Astr. Ap.*, **81**, 43.
Helfand, D. J. 1981, private communication.
Iye, M., Kodaira, K., Kikuchi, K., and Ohtani, H. 1975, *Pub. Astr. Soc. Japan*, **27**, 571.
Kirshner, R. P., Oke, J. B., Penston, M. V., and Searle, L. 1973, *Ap. J.*, **185**, 303.
Mazurek, T. J. 1973, *Ap. Space Sci.*, **23**, 365.
Nomoto, K. 1980, in *Proc. Texas Workshop on Type I Supernovae*, ed. J. C. Wheeler (Austin: University of Texas Press), p. 164.
______. 1982, *Ap. J.*, **253**, in press.
Nomoto, K., and Sugimoto, D. 1977, *Pub. Astr. Soc. Japan*, **29**, 765.
Nomoto, K., Sutherland, P. G., and Wheeler, J. C. 1982, in preparation.
Nomoto, K., and Tsuruta, S. 1981, *Ap. J.* (*Letters*), **250**, L19.
Patchett, B., and Wood, R. 1976, *M.N.R.A.S.*, **175**, 595.
Pskovskii, V. P. 1969, *Soviet Astr.—AJ*, **12**, 750.
______. 1971, *Soviet Astr.—AJ*, **14**, 798.
Sobolev, V. V. 1960, *Moving Envelopes of Stars* (Cambridge: Harvard University Press).
Van Riper, K., and Lamb, D. Q. 1981, *Ap. J.* (*Letters*), **244**, L13.
Weaver, T. A., Axelrod, T. S., and Woosley, S. E. 1980, in *Proc. Texas Workshop on Type I Supernovae*, ed. J. C. Wheeler (Austin: University of Texas Press), p. 113.
Wheeler, J. C. 1982, in *Proc. NATO Advanced Studies Institute on Supernovae* (Cambridge: Institute of Astronomy), in press.
Woosley, S. E., Weaver, T. A., and Taam, R. E. 1980, in *Proc. Texas Workshop on Type I Supernovae*, ed. J. C. Wheeler (Austin: University of Texas Press), p. 96.

D. BRANCH: Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019

R. BUTA, S. W. FALK, M. L. MCCALL, A. UOMOTO, J. C. WHEELER, and B. J. WILLS: Department of Astronomy, University of Texas, Austin, TX 78712

P. G. SUTHERLAND: Department of Physics, McMaster University, Hamilton, Ontario L8S 4M1, Canada