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FORBIDDEN LINES OF Si I: AN ALTERNATE INTERPRETATION FOR AN INFRARED EMISSION FEATURE IN THE SPECTRUM OF SN 1983N (M83)

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ABSTRACT

An alternate interpretation for the IR spectral feature observed in SN 1983N is presented and analyzed. The low-resolution, CVF spectrum published by Graham *et al.* in 1986 around 1.644 μm, originally interpreted in terms of [Fe II] lines, can be fitted assuming pure [Si I] emission (1.6454 μm and 1.6068 μm lines) obtaining a result as good as that of a synthetic [Fe II] spectrum ($\chi^2_{\rm RED} \approx 1$ in both cases).

The mass of silicon inferred from the observed flux of [Si I] 1.6454 μm is consistent with carbon deflagration models. The Si/O relative abundance is significantly lower than the standard solar value, in agreement with current ideas concerning Type Ib supernovae.

As optical lines ($\lambda < 8000$ Å) of both [Si I] and [Fe II] are intrinsically faint, no evidence capable of distinguishing between the two hypotheses can be found in the existing observational data. Future ground-based IR spectral observations should, therefore, include the 1.10 μm and 1.26 μm spectral regions where bright and clean lines of [Si I] and [Fe II], respectively, lie.

Subject headings: stars: supernovae — infrared: spectra

I. INTRODUCTION

The main peculiarity of Type I supernovae (SN I) is the very slow, exponential decay of their light curve. The generally accepted explanations for this phenomenon, unexpected in an object where adiabatic cooling of the expanding material is quite rapid, postulates the production and expulsion of about one solar mass of ^{56}Ni at the SN outburst. The radioactive decay of ^{56}Ni into ^{56}Fe through ^{56}Co can supply the required energy input to heat the ejecta well after the explosion in form of gamma rays and positrons. Following the work of Colgate and McKee (1969), a self-consistent model for "classical" type I supernovae (SN Ia) has been developed. Mass accretion onto a white dwarf from a companion star ignites the carbon degenerate core of the WD as it approaches the Chandrasekhar limit producing an explosive nucleosynthesis (carbon deflagration or detonation) where a large part of the material is transformed into ^{56}Ni and which completely destroys the WD (e.g., Woosley, Arnett, and Clayton 1973; Nomoto, Thielemann, and Yokoi 1984; Woosley, Taam, and Weaver 1986). The heating and the energy transfer inside the ejecta of a SN Ia have been studied in some detail by a number of authors (e.g., Arnett 1979; Axelrod 1980*a*, *b*; Weaver, Axelrod, and Woosley 1980; Meyerott 1980; Chevalier 1981; Branch *et al.* 1985) with results in good agreement with both the observed light curves and spectra.

The nature of the "peculiar Type I supernovae" (SN Ib) is less clear. These objects, of which SN 1983N is a prototype, have in common with SN Ia a slowly decaying light curve and no hydrogen lines in their spectra. Their main peculiarities are as follows:

1. A peak luminosity about 1.5 mag lower than SN Ia (e.g., Uomoto and Kirshner 1985).
2. Prominant emission lines of neutral oxygen in their late time spectra (Gaskell *et al.* 1986; Filippenko and Sargent 1986).
3. The $J - H$ color index of Type Ia supernovae changes significantly (0.5 mag) between 20 and 60 days after the explosion. This "J depression" is not observed in SN Ib (Elias *et al.* 1985).
4. The prominent absorption feature at about 6150 Å, normally observed in early time spectra of Type Ia supernovae and generally interpreted as a blueshifted absorption wing of Si II 6347, is not seen in SN Ib (e.g., Uomoto and Kirshner 1985; Branch 1986).

Graham (1986) has suggested that SN Ib are silicon deficient with respect to SN Ia to explain the absence of both the 6150 Å feature and of the J depression. Based on the strength of the observed oxygen lines, models where the progenitor of a SN Ib is a massive Wolf-Rayet (WO) star have been proposed (Begelman and Sarazin 1986; Gaskell *et al.* 1986). Even though the physical processes leading to a Type Ib supernova seem to be totally different from those of a SN Ia, it is generally accepted that a similar amount of ^{56}Ni must be produced in both cases to account for the similarity of their light curves (e.g., Gaskell *et al.* 1986; Begelman and Sarazin 1986).

Observationally, strong Fe II absorption features can be recognized in optical spectra of SN I's (e.g., Branch *et al.* 1983) and a large number of Fe II and Co II lines provides the best fit to early time UV spectra (Branch and Venkatakrishna 1986). However, as the optical depth in these lines is quite large and since most of the iron and cobalt are, according to the models, confined in the inner, low-velocity regions of the envelope, only a small fraction of these elements contributes to the observed spectral features (e.g., Branch *et al.* 1985).

TABLE 1

[Si I] Lines at Optical and Near-IR Wavelengths

				Relative Line Intensities[b]					
				T = 5000 K			T = 10,000 K		
Transition	$\lambda(\mu m)$	$A_{RAD}(s^{-1})$[a]	$n_{CRIT}(cm^{-3})$[b]	$n = 10^5$	10^6	10^7	$n = 10^5$	10^6	10^7
${}^1D_2-{}^3P_1$	1.6068	7.93×10^{-4}	2×10^5	0.36	0.36	0.36	0.36	0.36	0.36
${}^1D_2-{}^3P_2$	1.6454	2.25×10^{-3}	2×10^5	1.0	1.0	1.0	1.0	1.0	1.0
${}^1S_0-{}^3P_1$	0.65268	3.13×10^{-2}	1×10^7	0.02	0.09	0.32	0.04	0.24	1.1
${}^1S_0-{}^1D_2$	1.0991	1.14×10^0	1×10^7	0.51	1.9	7.0	0.95	5.2	24.0

[a] Mendoza 1983.

[b] Computed assuming $\Omega = 1$ for all the transitions, as no reliable computation of Si I collision strengths is available in the literature (Mendoza 1983). For different values of Ω, n_{crit} scales as Ω^{-1}.

Therefore, no quantitative results can be derived easily from these data. The recent detection by Graham *et al.* (1986, hereafter G86) of an emission feature in the IR spectrum of SN 1983N at about 1.644 μm is the most convincing observational evidence of the presence of a large mass of iron in the envelope of a Type I supernova. This feature, once interpreted as [Fe II] emission, implies that at least 0.02 solar masses of Fe^+ (corresponding to about 0.3 solar masses of iron), must be present in the envelope of the supernova.

In this *Letter* I discuss the possibility that the features observed by G86 are misidentified [Si I] transitions. In § II the IR spectrum of [Si I] is analyzed and compared with the data of G86. The implications on the silicon abundance are then discussed in § III. As both [Si I] and [Fe II] have clean transitions in the IR and red wavelength regions, some suggestions for future observations are made in § IV.

II. THE [Si I] SPECTRUM

The ground-state level structure of neutral silicon (electron configuration 3 p^2) is similar to that of O III, but with a smaller energy spacing between the P, D, and S levels.

In Table 1 the [Si I] transitions are listed together with the associated wavelengths, transition probabilities (Mendoza 1983), and additional information. The two lines of interest here are those at 1.6068 μm and 1.6454 μm, which are the equivalent of the [O III] 4959 Å and 5007 Å transitions, respectively.

The brightest of these [Si I] lines lies very close to the more famous [Fe II] $a^4D_{7/2}-a^4F_{9/2}$ transition at 1.6435 μm and only by using an instrument with resolution $R = \lambda/\Delta\lambda > 2000$ can one clearly distinguish one from the other, provided that the line widths are smaller than 300 km s^{-1}. The second line lies relatively close to another important [Fe II] transition, $a^4D_{3/2}-a^4F_{7/2}$ at 1.5994 μm, which is marginally detected in the low-resolution spectrum ($R \approx 100$) of G86. To complicate the scenario further, the expected intensity ratio between the two [Fe II] lines in the high-density limit, $I(1.5994\ \mu m)/I(1.6435\ \mu m) \approx 0.3$ (Nussbaumer 1987), is similar to that between the [Si I] lines, $I(1.6068\ \mu m)/I(1.6454\ \mu m) = 0.36$ (cf. Table 1).

All these considerations can be visualized in Figure 1 where the data taken from Figure 2 of G86 are fitted using the [Si I] lines just described. The free parameters of the fit are the level of the continuum, assumed to be flat; the width of the Gaussian line profile, assumed to be the same for both lines; the amplitude of the principal line; and the redshift, z.

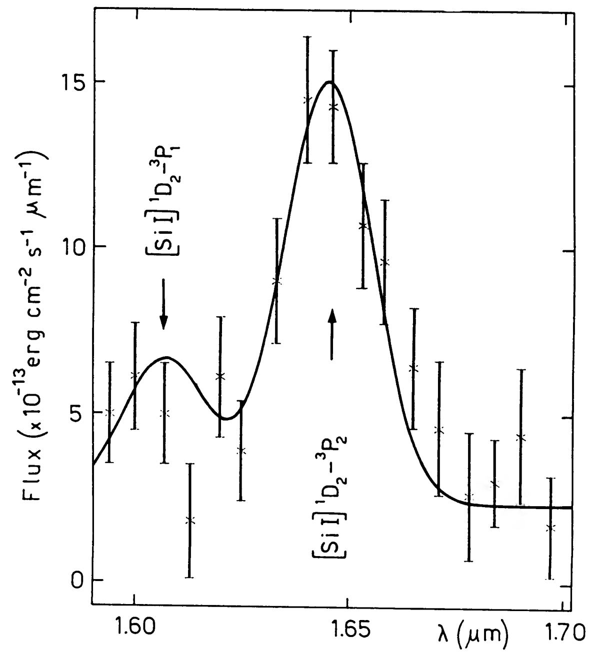

FIG. 1.—The 1.644 μm spectrum of SN 1983N, adapted from Fig. 2 of Graham *et al.* (1986), is displayed together with the fitted [Si I] emission profile. The positions of the two [Si I] transitions, arising from the same upper level, are marked. See text, § II, for details.

The resulting best-fit parameters are as follows:

1. Continuum level = 2.3 ± 0.5 10^{-13} ergs cm^{-2} s^{-1} μm^{-1}.
2. Gaussian line width = 0.015 ± 0.002 μm.
3. Amplitude of the 1.6454 μm line = 1.3 ± 0.15 10^{-12} ergs cm^{-2} s^{-1} μm^{-1}.
4. $z < 0.001$.
5. Reduced $\chi^2 = 1.2$.
6. Intensity of the 1.6454 μm line = 3.5 ± 0.6 10^{-14} ergs cm^{-2} s^{-1}.

The result is as good as that obtained in G86 by fitting a synthetic [Fe II] spectrum to the data and obtaining a reduced χ^2 of about 1.1, as deduced from Figure 2 of their paper.

In principle, as both [Fe II] and [Si I] have transitions falling at optical wavelengths, existing optical spectra of

SN 1983N could be used to decide which interpretation of the IR spectrum is correct. In practice, however, the expected intensity of the optical lines, as derived from the 1.644 μm transitions, are below the detection limits. In particular, all the [Fe II] optical lines ($\lambda < 8000$ Å) are typically an order of magnitude fainter than the 1.6435 μm transition (Graham, Wright, and Longmore 1987). The [Si I] 6527 Å transition is the only optical line which, at temperatures around 10,000 K and large enough densities, is expected to have an intensity comparable to that of 1.6454 μm (cf. Table 1). This intensity corresponds to about 2–3 times the noise level in the Gaskell *et al.* (1986) spectrum of SN 1983N, as deduced from Figure 1 of their paper (this spectrum was taken 4 months before the IR spectrum). However, since the ratio of optical to infrared line intensities depends strongly on the values of gas density and temperature (cf. Table 1), the failure to detect the optical transition is probably not significant.

As discussed in § IV, measurements of the [Si I] 1.0991 μm and [Fe II] 1.2567 μm lines would give a more definite answer in favor of one hypothesis or the other.

III. THE SILICON ABUNDANCE IN SN 1983N

We now discuss the silicon abundance derived from the [Si I] line flux in view of the existing models of Type I supernovae to check whether one can find any "a posteriori" evidence against the Si I interpretation of the observed IR spectral feature.

Quite generally, the flux of an observed line can be related to the mass of the emitting ion by:

$$F = \frac{M}{mW4\pi d^2}\left(\frac{n_u}{n_{\rm ion}}\right) h\nu_{ul} A_{ul} \exp\left(-\tau_L - \tau_R\right),$$

where F is the observed line flux, M is the mass of the emitting ion, m is the proton mass, W is the atomic weight of the ion, d is the distance to the source, $(n_u/n_{\rm ion})$ is the fraction of the ions in the level "u," A_{ul} is the transition probability, τ_L is the optical depth of the line, and τ_R is the extinction coefficient. An upper limit to, and a reasonable estimation for, the optical depth of the line can be obtained using:

$$\tau_L \approx n_{\rm ion}(g_u/g_l)(\lambda^3/8\pi) A_{ul}(L/\Delta v),$$

where L is typical dimension of the SN ($L \approx v_{\rm exp}\, t$) and Δv is the line width in cm^{-1}. For the [Si I] line of interest here one finds:

$$\begin{aligned}\tau(1.6454\mu{\rm m}) &\approx 10^{-8}\, n({\rm Si\,I})\,(L/0.01\ {\rm pc})(\Delta v/10^3\ {\rm km\ s^{-1}})^{-1}\\ &\approx 10^{-2}\left[M({\rm Si\,I})/M_\odot\right]\left(v_{\rm exp}/10^4\ {\rm km\ s^{-1}}\right)^{-2}\\ &\quad\times(t/1\ {\rm yr})^{-2}(\Delta v/10^3\ {\rm km\ s^{-1}})^{-1},\end{aligned}$$

where in the last relationship $W\, m\, n$(Si I) $L^3 = M$(Si I) has been assumed. As the data of G86 were collected about 1 yr after the explosion and the measured line width was about 2500 km s^{-1}, the optical depth of the envelope of SN 1983N in the 1.6454 μm line is totally negligible. The visual extinction toward SN 1983N is estimated to be about 1.5 mag, corresponding to an extinction at 1.644 μm of about 0.2 mag (G86 and references therein). The relative population of the ^1D level of Si I can be computed as follows. At densities larger than the critical density ($n_e \gg 10^5$ cm^{-3}; cf. Table 1), the level population is in thermodynamical equilibrium and therefore depends only on the gas temperature:

$$\begin{aligned}\left[n(^1D)/n({\rm Si\,I})\right]_{\rm TE} &= 5/U(T)\exp\left[-E(^1D)/KT\right]\\ &\approx 0.44\exp(-9100/T),\end{aligned}$$

where $U(T)$ is the partition function. At densities lower than the critical density the relative level population decreases because the radiative decay rate from the upper level becomes larger than the collisional depopulation rate. In particular, for $n_e \ll n_{\rm crit}$ the population of the upper level decreases linearly with the gas density ($n_u \propto n_e q_{lu}(T)/A_{ul}$). In first approximation one can therefore write:

$$\begin{aligned}\left[n(^1D)/n({\rm Si\,I})\right] &= \left[n(^1D)/n({\rm Si\,I})\right]_{\rm TE} && \text{if } n_e > n_{\rm crit}\\ &= \left[n(^1D)/n({\rm Si\,I})\right]_{\rm TE}(n_e/n_{\rm crit}) && \text{if } n_e < n_{\rm crit}\end{aligned}$$

The mass of neutral silicon required to account for the observed flux of the [Si I] line is therefore:

$$\begin{aligned}M({\rm Si\,I}) &\approx 1.7\times10^{-3}\exp(9100/T)\\ &\quad\times\left(\frac{F(1.6454\ \mu{\rm m})}{4\times10^{-14}\ {\rm ergs\ cm^{-2}\,s^{-1}}}\right)(d/4\ {\rm Mpc})^2\ M_\odot.\end{aligned}$$

At densities lower than the critical density the required mass must be increased by a factor $(n_{\rm crit}/n_e)$. Computed models of Type Ia supernovae predict, ~ 1 yr after the explosion, $T \approx 6000$ K and $n_e \approx 10^5$–10^6 cm^{-3} (Axelrod 1980*a*; Meyerott 1980). Gaskell *et al.* (1986) deduced from their optical spectrum of SN 1983N $T \approx 3900$ K and $n_e \approx 2\times10^8$. As the critical density of the 1.6454 μm line is probably smaller than 2×10^6 [assuming $\Omega(^1D-^3P) > 0.1$; cf. Table 1], radiative depopulation of the ^1D level can be neglected, and its population depends therefore only on the gas temperature. For an electron temperature ranging between 4000 and 7000 K, one finds: M(Si I) $\approx 6\times10^{-3}$–1.7×10^{-2} $M_\odot$. Adopting the values predicted in theoretical models for electron temperature ($T \approx 6000$ K) and ionization degree (Si/Si^0 ≈ 20, Axelrod 1980*a*; Meyerott 1980) the derived silicon mass is 0.15 $M_\odot$. This number is close to that predicted by carbon deflagration models [M(Si) ~ 0.13–0.16 $M_\odot$, Nomoto, Thielemann, and Yokoi 1984] but much larger than that expected in a carbon detonation nucleosynthesis [M(Si) $\approx 10^{-3}$ $M_\odot$; Woosley, Taam, and Weaver 1986].

Even though the above-mentioned models refer to classical Type Ia supernovae and cannot be directly applied to

SN 1983N, they indicate that the required mass of silicon is not unreasonable if the explosion is produced by carbon deflagration. Also, one can expect to find larger amounts of neutron silicon in the envelope of a Type Ib supernova for the following reasons:

1. The progenitor of a SN Ib is probably a WR star of $\sim 50\ M_\odot$ (Begelman and Sarazin 1986; Gaskell *et al.* 1986) which already contains a considerable amount of silicon inside its envelope.

2. The ionization degree of the envelope, which scales with the square root of the SN luminosity (Meyerott 1980), is lower for a Type Ib supernova because it is subluminous.

3. The shock wave produced by the SN can interact with the material deposited by the stellar wind from the progenitor star. In such a case, all the dust grains where most of the silicon is hidden are destroyed and the silicon is returned to the gas phase (e.g., Seab and Shull 1983). This contribution may become important if the progenitor star was surrounded by a thick envelope. More precisely, one needs to have $\sim 0.1\ M_\odot$ of dust (equivalent to $\sim 10\ M_\odot$ of material) within 0.01 pc of the star to produce the observed $0.01\ M_\odot$ of neutral silicon. However, simple considerations on the absorption produced by such an envelope rule out this hypothesis in the case of SN 1983N.

Another independent piece of information on the silicon abundance can be derived by comparing the observed fluxes of [Si I] 1.6454 μm (G86) and [O I] 6300 + 6364 Å (Gaskell *et al.* 1986). Following the same procedure described above one can easily find:

$$M(\text{Si I})/M(\text{O I}) \approx 20 \exp(-13500/T) \times F(1.6454\ \mu\text{m})/F(6300+6363\ \text{Å}) \quad (1)$$

which is valid when the level population of both O I and Si I is in TE, i.e., at electron densities larger than the critical density of the two transitions. Adopting $\Omega([\text{Si I}]^1D-^3P) = 0.02$, the two critical densities are both equal to $10^7\ \text{cm}^{-3}$ and equation (1) holds for any value of density. For larger values of the collisional cross section of neutral silicon and for the densities lower than $10^7\ \text{cm}^{-3}$ the relative abundance ratio deduced from equation (1) is larger than the true value. The ionization correction to be applied to obtain the Si/O abundance ratio is poorly known. Computed models of Type Ia supernovae assume that the ionization degree is the same for all the species (Meyerott 1980). However, one can expect that Si^0 (ionization potential = 8.2 eV) is more easily ionized than O^0 (ionization potential = 13.6 eV). The Si/O abundance ratio derived using equation (1) might be, therefore, underestimated. Keeping in mind the uncertainties just mentioned, for an electron temperature in the range 4000–7000 K one finds in SN 1983N:

$$M(\text{Si})/M(\text{O}) \approx 3\times10^{-3}\ \text{to}\ 1\times10^{-2}.$$

When compared to a solar value of 8×10^{-2}, this result indicates a consistent underabundance of silicon with respect to oxygen. This result is not surprising since the progenitor of SN 1983N is probably an oxygen-rich WR (Begelman and Sarazin 1986), and it is in agreement with the suggestion of Graham (1986).

IV. FUTURE OBSERVATIONS

In the last section we have seen that one can expect to observe relatively bright lines of [Si I] in the spectrum of a Type I supernova. In particular, these lines can be used to discriminate between carbon deflagration and carbon detonation models as the amount of silicon produced in the first case is much larger than the second one (Nomoto, Thielemann, and Yokoi 1984; Woosley, Taam, and Weaver 1986). It is important to note that the other ionization stages of silicon cannot be easily studied using forbidden lines because [Si II] 34.8 μm is not observable from ground-based telescopes and Si III, Si IV do not have important forbidden transitions.

To avoid the confusion between the [Si I] and [Fe II] lines around 1.644 μm discussed in § II one might try to use a high-resolution IR spectrometer. This approach, however, would not help very much as the two lines are only 19 Å ($= 350\ \text{km s}^{-1}$) apart, less than the typical width of the lines observed in supernovae. One must therefore search for other bright lines of [Si I] in [Fe II]. Good candidates in the IR are the [Si I] 1.0991 μm and the [Fe II] 1.2567 μm transitions which both lie in spectral regions clear from atmospheric absorption and are as bright as the lines around 1.644 μm (cf. Table 1 and Nussbaumer 1987). At optical wavelengths the strongest transitions are [Fe II] 8617 Å and [Si I] 6527 Å. The first line has an intensity comparable to [Fe II] 1.2567 μm (see below) whereas the optical transition of [Si I] is intrinsically 22 times fainter than [Si I] 1.0991 μm (cf. Table 1). Considering the difference in sensitivity between optical and IR spectrometers the optical line of [Fe II] should be much more favourable and comparable S/N ratios should be achieved for the optical and IR lines of [Si I]. However, the optical lines might suffer severe blending problems as in the case of SN 1985F where the [Fe II] 8617 Å line is lost in the broad feature at ~ 8700 Å produced by blended lines of O I, Ca II, N I, and [C I] (Filippenko and Sargent 1986). Curiously enough, the [Fe II] line is not mentioned in the above paper.

Other lines of interest are, in the optical, [Fe II] 9268 Å and, in the IR, [Fe II] 1.2788 μm and [Si I] 1.6068 μm. These transitions are at least 5 times fainter than the main lines listed above and can be observed only in bright supernovae. In case all these lines can be measured, physical parameters of the envelope of the supernova can be deduced from the line intensity ratios.

Electron density.—Both the [Fe II] $I(9268\ \text{Å})/I(8617\ \text{Å})$ and [Fe II] $I(1.2788\ \mu\text{m})/I(1.2567\ \mu\text{m})$ line ratios are sensitive mainly to the gas density (Nussbaumer 1987).

Electron temperature.—The line ratios [Fe II] $I(8617\ \text{Å})/I(1.2567\ \mu\text{m})$ and [Si I] $I(1.0991\ \mu\text{m})/I(1.6068\ \mu\text{m})$ are good "thermometers." At large enough densities one finds:

$$I(8617\ \text{Å})/I(1.2567\ \mu\text{m}) = 6.18 \exp(-7941/T), \quad n_e > 10^6$$

$$I(1.0991\ \mu\text{m})/I(1.6068\ \mu\text{m}) = 420 \exp(-13087/T), \quad n_e > 10^7/\Omega(^1S-^3P).$$

At densities lower than 10^3 cm^{-3} a similar relationship can be found for the [Fe II] line ratio:

$$I(8617\ \text{Å})/I(1.2567\ \mu\text{m}) = 0.44\exp(-7941/T),$$

$$n_e < 10^3$$

The low-density limit cannot be computed for the [Si I] lines because no reliable computation of the collision strengths exists in the literature (Mendoza 1983).

V. CONCLUSION

An alternate interpretation for the 1.644 μm spectrum of SN 1983N has been presented. The original data of G86 can be fitted adopting pure [Si I] emission obtaining a result as good as that using [Fe II] lines in the original paper. On the basis of the existing data, both interpretations are equally acceptable.

To avoid confusion future IR spectra of Type I supernovae should include the [Fe II] 1.2567 μm and [Si I] 1.0991 μm lines which are as bright as the transitions around 1.644 μm and lie in spectral regions clear of atmospheric absorption.

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