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THE TYPE Ic (HELIUM-POOR Ib) SUPERNOVA 1987M: TRANSITION TO THE SUPERNEBULAR PHASE

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ABSTRACT

We discuss a series of spectra of the Type Ic (helium-poor Ib) supernova (SN) 1987M in the Sc galaxy NGC 2715, obtained over a 6 month interval following its discovery. Two spectra of SNe Ia, SN 1987L in NGC 2336 and SN 1987N in NGC 7606, are also illustrated for comparison. Near maximum brightness, SN 1987M showed all the spectroscopic characteristics of the "helium-poor" variety of SNe Ib identified in 1987 by Wheeler and collaborators, but it may have been subluminous by only 0.6 mag (B) instead of the average value of 1.5 mag. The possible presence of very weak Hα must be verified through spectral synthesis. Strong P Cygni profiles of O I λ 7774 and Ca II are visible at early times in the near-infrared spectrum, as previously predicted. The Type IIb SN 1987K, by contrast, exhibits prominent Hα but no O I λ 7774, although the two objects appear quite similar at blue and visual wavelengths. Strong Co II and Fe II absorption may be present at near-ultraviolet wavelengths in SN 1987M, as in SNe Ia. The data clearly reveal, for the first time, the remarkable transition to the "supernebular phase" of SNe Ib and Ic. Unambiguous [O I] and [Ca II] lines begin to appear less than two months past maximum. The ejected mass is estimated to be small, $M \lesssim 1\ M_\odot$, although this number is highly uncertain. Multicolor light curves of SN 1987M, derived from CCD images and spectra, show a rapid decline from maximum brightness, perhaps even steeper than that of typical SNe I. This also suggests a relatively low ejected mass. Furthermore, unlike many SNe Ib, SN 1987M was not superposed on a luminous H II region. It is possible that SNe Ic, such as SN 1987M, have different progenitors or explosion mechanisms than SNe Ib. Specifically, we postulate that SNe Ic result from explosions of white dwarfs, while core collapse in massive, hydrogen-deficient stars produces SNe Ib.

I. INTRODUCTION

One of the strongest absorption lines visible in the spectra of most Type I supernovae (SNe I) during the first month past maximum brightness is near 6150 Å. Generally believed to be produced by blueshifted Si II $\lambda\lambda$ 6347, 6371, it provides a convenient way of measuring the photospheric expansion velocity. Long ago, however, Bertola and collaborators (Bertola 1964; Bertola, Mammano, and Perinotto 1965) noticed that the spectra of SNe 1962L and 1964L resemble those of classical SNe I, except that this line was absent near maximum. Originally referred to as "peculiar SNe I" (SNe Ip), these objects were largely forgotten until additional examples were noticed in the 1980s. Especially important were SN 1983N in NGC 5236 and SN 1984L in NGC 991 (Sramek, Panagia, and Weiler 1984; Elias *et al.* 1985; Uomoto and Kirshner 1985; Wheeler and Levreault 1985; Graham *et al.* 1986; Panagia, Sramek, and Weiler 1986).

As summarized by Porter and Filippenko (1987), SNe Ip seemed to constitute a distinct subclass, characterized by their (a) lack of the 6150 Å absorption trough, (b) preference for galaxies having Hubble types Sbc or later, (c) proximity to H II regions, (d) rather low luminosity, typically 1.5 mag fainter than classical SNe I, (e) distinct IR light curves having no secondary maximum around 1 month past primary maximum, (f) reddish colors, and (g) emission of radio radiation within a year past maximum. The subclass was renamed "Type Ib" (Elias *et al.* 1985) to distinguish it from classical SNe I, now called SNe Ia. There were strong suspicions (Wheeler and Levreault 1985) that the explosion mechanism might be more closely related to that of SNe II than to SNe Ia, but it was difficult to be certain because the spectroscopic appearance of SNe Ib near maximum resembled that of somewhat *older* (t = 1–2 months) SNe Ia. This resemblance led to the catchy phrase that SNe Ib are Type I supernovae that are "born old."

An important step in the study of SNe Ib was made when Gaskell *et al.* (1986) realized that the spectrum of SN 1983N, taken about eight months after maximum, closely resembled that of the newly discovered "unique" SN 1985F (Filippenko and Sargent 1985b; Filippenko and Sargent 1986). Similarly, Kirshner (quoted in Chevalier 1986) found that a late-time spectrum of SN 1984L, now published in Schlegel and Kirshner (1989), also resembled that of SN 1985F. Specifically, the late-time spectra of SNe Ib were found to exhibit strong, broad emission lines of [O I] $\lambda\lambda$ 6300, 6364, [Ca II] $\lambda\lambda$ 7291, 7324, Mg I] λ 4571, and Na I D $\lambda\lambda$ 5890, 5896, as did the discovery spectra of SN

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1985F. Such characteristics were very different from those of old SNe Ia, and they greatly supported the conclusion that SNe Ib constitute a physically separate subclass of SNe Ia, possibly having a fundamentally different explosion mechanism. Indeed, several papers (Cahen, Schaeffer, and Cassé 1986; Begelman and Sarazin 1986; Filippenko and Sargent 1986; but also see Branch and Nomoto 1986) had previously suggested that SN 1985F resulted from core collapse in a hydrogen-deficient massive star such as a Wolf–Rayet star, and Chugai (1986) had already pointed out that SN 1985F might be a SN Ib discovered long after maximum. The late-time discovery of SN 1985F was confirmed by Tsvetkov (1986), who inspected prediscovery plates taken at the Crimean Station of the Sternberg State Astronomical Institute.

Another major development occurred when Harkness *et al.* (1987) unambiguously identified lines of He I in the spectra of SN 1983N and SN 1984L, the two prototypical SNe Ib. The helium lines were so strong that they could not be reproduced under conditions of local thermodynamic equilibrium (LTE), even in a pure helium atmosphere. Large departures from the normal helium-level populations were required. Some SNe Ib, on the other hand, do not exhibit prominent helium lines; these were dubbed "SNe Ic" (Wheeler and Harkness 1986). Moreover, a comparison of published spectra obtained near maximum brightness suggests that the optical and near-IR continua of SNe Ic are redder (cooler) than those of SNe Ib. However, Wheeler *et al.* (1987) subsequently argued that SNe Ib and SNe Ic are closely related objects, differing primarily in the relative abundances of helium, oxygen, and carbon in their outer layers. Thus, SNe Ic might actually be "helium-poor" SNe Ib, while the prototypical SNe Ib were "helium-rich" objects.

More recently, Harkness and Wheeler (1990; see also Wheeler and Harkness 1990) have advocated the use of their earlier terminology (Ib and Ic). There appear to be empirical differences between SNe Ib and Ic, and it is possible that the explosion mechanisms may differ. On the other hand, we do not yet know whether two distinct subtypes exist. There may, instead, be a continuous distribution of He I strengths in SNe Ib. Furthermore, no obvious differences in the late-time spectra of SNe Ib and Ic have been found in the few objects studied so far. The terminology we adopt in this paper, therefore, is a compromise. When sufficiently good early time spectra are available, we will distinguish between SNe Ib and Ic, but the term Ib will be used whenever only late-time spectra exist (as for SN 1985F).

To determine the explosion mechanisms and physical properties of SNe Ib and Ic, it is of great importance to follow the IR spectroscopic evolution. The early time behavior of SN 1983N (Harkness *et al.* 1987; Panagia *et al.* 1991) and SN 1984L (Harkness *et al.* 1987) were well covered, as was the late-time spectrum of SN 1985F (Filippenko and Sargent 1986; Schlegel and Kirshner 1989). It has been difficult, however, to obtain data at intermediate times. Especially interesting is the transition to the spectacular "supernebular phase" (Wheeler *et al.* 1986) dominated by [O I], [Ca II], and Ca II. The manner in which this occurs should, in principle, tell us whether the progenitor is massive (e.g., a Wolf–Rayet star) or has low mass (a white dwarf), but the spectroscopic observations must be combined with accurate photometry and with detailed numerical models for a proper analysis.

In this paper we discuss spectra of the Type Ic SN 1987M, starting from near maximum brightness and ending about 6 months past maximum, well into the supernebular phase. This provides the best coverage to date of the behavior of SNe Ic at intermediate stages of their evolution. We also derive multiband light curves from CCD images and spectra of the supernova. We have already discussed portions of this study in previous papers and conferences (Filippenko 1988a, b; Porter, Filippenko, and Sargent 1988; Porter 1990; Filippenko 1990a).

II. OBSERVATIONS

a) Discovery and Classification

Supernova 1987M, in the Sc galaxy NGC 2715 ($\alpha_{1950} = 9^h1^m52.5^s$, $\delta_{1950} = 78°17'15''$; Dressel and Condon 1976), was discovered (Szeidl and Lovas 1987) on 21 September 1987 UT by M. Lovas of Konkoly Observatory. He reported its photographic magnitude as 15.0, and its position as 2″ E and 20″ N of the nucleus. Filippenko (1987) used the Shane 3 m reflector at Lick Observatory to obtain CCD spectra of the object on 28 and 29 September. Based on the overall resemblance to the spectrum of SNe I, and on the absence of the usual absorption trough near 6150 Å, he classified SN 1987M as a SN Ib. Unlike most SNe Ib, however, this object was not superposed on a luminous H II region.

Porter *et al.* (1987) used a CCD spectrum obtained on 2 October with the Hale 5m reflector at Palomar Observatory to confirm the Type Ib classification. They also noted that the spectrum more closely resembled those of SNe Ib 1983I and 1983V than those of SNe 1983N and 1984L, suggesting that SN 1987M was a "helium-poor" SN Ib as defined by Wheeler *et al.* (1987). Strong, narrow Na I D absorption due to gas in NGC 2715 was visible in the spectrum, implying some degree of reddening and extinction. Their quoted offset from the nucleus was 5″ E and 17″ N, rather different from that reported by Szeidl and Lovas (1987). Uomoto (1987) gave nearly the same offset, 4″ E and 18″ N. Both Uomoto (1987) and Filippenko and Schachter (1988) mentioned that SN 1987M was well on its way to becoming a supernebula in November and December 1987.

Observations of SN 1987M by our group continued through March 1988, as documented in Tables I and II. The image taken on 21 December 1987 is shown in Fig. 1 [Plate 152]; the supernova's red magnitude at that time was 18.47. The disk of the galaxy has many H II regions, and SN 1987M appears to be superposed on, or close to, a spiral arm.

b) Spectroscopy

Most of the spectra of SN 1987M were obtained with the Cassegrain CCD spectrograph (Miller and Stone 1987) attached to the Shane 3m reflector at Lick Observatory. A Texas Instruments (TI) 3-phase 800×800 pixel chip was used. Several additional spectra were obtained with the Double Spectrograph (Oke and Gunn 1982) at the Cassegrain focus of the Hale 5 m reflector at Palomar Observatory. A journal of observations is given in Table I. Also included are observations of SNe Ia 1987L (NGC 2336) and 1987N (NGC 7606), which will be useful for comparison purposes.

With one exception, the slit was aligned close to the parallactic angle, to minimize differential light losses produced by atmospheric dispersion (Filippenko 1982). Some near-ultraviolet and blue light may have been preferentially lost in the spectrum of SN 1987M obtained on 2 October 1987 UT; the position angle of the narrow slit (1″) differed from the

TABLE I. Journal of observations: spectroscopy.[a]

UT Date	Time[b]	Exp.(s)	Tel.[c]	Slit (″×″)[d]	P.A.[e]	Δλ (Å)[f]	Res. (Å)[g]	sec z[h]	See[i]	Obs.[j]
09–28–87	12:44	400	L3	3.2 × 130	71°	3100–6285	16–18	1.5	1.5″	1
09–28–87	12:56	500	L3	3.2 × 130	71	5895–7520	8–9	1.5	1.5	1
09–29–87	12:44	800	L3	3.2 × 130	71	6835–10050	16–18	1.5	1–1.5	1
10–02–87	12:13	930	P5	1.0 × 120	90[k]	3750–7750	5–7	1.6	1–1.5	2,3
10–20–87	12:29	1200	P5	1.0 × 120	46	3150–7015	5–7	1.5	1	4,5
11–22–87	11:29	1500	L3	3.2 × 130	32	5935–9145	16–18	1.3	2–3	1,6
11–22–87	11:59	1800	L3	3.2 × 130	20	4560–6180	7–9	1.3	2–3	1,6
11–23–87	12:29	1500	L3	2.0 × 130	2	3110–4720	5–7	1.3	1.5–2	1,6
12–25–87[l]	03:08	600	L3	4.0 × 130	30	6130–9340	18–21	1.7	4–5	1
12–25–87[l]	05:08	1800	L3	4.0 × 130	47	3210–6400	18–21	3.7	4–8	1
12–26–87[m]	09:55	2700	L3	2.0 × 130	167	5910–9110	13–15	1.4	2	1
12–26–87[m]	10:56	3000	L3	2.0 × 130	146	3190–6370	10–12	1.4	2	1
12–26–87	11:57	2700	L3	2.0 × 130	155	3190–6370	10–12	1.3	1–1.5	1
12–26–87	12:47	2700	L3	2.0 × 130	140	5910–9110	13–15	1.4	1–1.5	1
02–09–88	05:18	3600	P5	2.0 × 120	34	3760–10020	8–15	1.5	1.5	1,4
02–25–88	07:06	3000	L3	2.0 × 130	170	6050–9260	13–15	1.3	1	1,6
02–25–88	08:02	3600	L3	2.0 × 130	157	3105–6280	9–11	1.3	1	1,6
03–26–88	07:13	4000	L3	3.0 × 130	135	6045–9255	15–17	1.4	3–4	1

[a] All observations are of SN 1987M in NGC 2715, unless stated otherwise.
[b] UT at beginning of observation.
[c] Telescope. L3 = Lick 3 m, P5 = Palomar 5 m.
[d] Slit width and length (seconds of arc).
[e] Position angle (degrees) of slit. This was generally very close to the parallactic angle.
[f] Observed wavelength range of spectrum. In some cases, the extreme ends are very noisy, and are not shown in the figures.
[g] Spectral resolution (full width at half-maximum intensity).
[h] Secant of zenith angle (approximate air mass) at midpoint of observation.
[i] Seeing disk (FWHM, seconds of arc), visually estimated on acquisition screen.
[j] Observers: (1) A. V. Filippenko, (2) J. R. Mould, (3) I. N. Reid, (4) W. L. W. Sargent, (5) C. C. Steidel, (6) J. Schachter.
[k] Parallactic angle = 65°.
[l] SN 1987N in NGC 7606.
[m] SN 1987L in NGC 2336.

parallactic angle by 25°, and the observation was made at a relatively high airmass (1.6).

Routine methods were used to calibrate the data (e.g., Filippenko and Sargent 1985a). A swath of length 3–4″ was generally used for the spectral extractions. The background sky was subtracted, along with some light from the outer portions of the parent galaxy. We attempted to exclude H II regions from the composite sky spectrum, to minimize effects on the narrow emission lines at the position of the supernova. However, since the slit was oriented along many different position angles, the amount of subtracted background starlight varied considerably from spectrum to spectrum, depending on the location of H II regions along the slit. Thus, the continuum flux cannot be trusted in our spectra when the SNe were faint.

Absolute and relative fluxes for the spectra were obtained

TABLE II. Journal of observations: imaging of SN 1987M.[a]

UT Date	Time[b]	Exp.(s)[c]	Filters[d]	CCD[e]	sec z[f]	See[g]	Clear?[h]	Obs.[i]
10–03–87	12:58, 13:04	200, 100	*r*, *g*	TI4	1.5	1.4″	Y	1
10–16–87	10:56	90	*r*	TI4	1.6	1.1	N	2
10–17–87	10:48, 11:07	300, 300	*g*, *r*	PFUEI	1.6	2.4	N	3
10–26–87	12:22, 12:35	300, 300	*r*, *g*	TI4	1.5	1.6	Y	4
10–28–87	10:49, 11:00	300, 600	*r*, *g*	TI4	1.6	1.8	N	3
12–21–87	11:29, 11:36	300, 300	*r*, *g*	TI4	1.4	0.9	Y	4
02–12–88	08:19, 08:26	300, 300	*r*, *g*	TI4	1.4	1.4	Y	1
09–08–88[j]	11:54, 12:00	300, 300	*g*, *r*	TI8	1.8	1.5	Y	3

[a] All images obtained with the 1.5-m reflector at Palomar Observatory.
[b] UT at beginning of each observation.
[c] Length of each observation (seconds).
[d] Thuan and Gunn (1976) filters used for each observation.
[e] Type of charge-coupled device used; see text for details.
[f] Secant of zenith angle (approximate air mass) during observations.
[g] Seeing disk (FWHM, seconds of arc), measured from images.
[h] Y = photometric conditions, N = not photometric.
[i] Observers: (1) S. Djorgovski, (2) J. Schombert, (3) A. Picard, (4) D. Padgett.
[j] Template images.

by comparison with secondary standard stars (Oke and Gunn 1983; Massey *et al.* 1988). The spectra of standard stars were also employed to remove, by division, telluric absorption bands at wavelengths longer than 6200 Å. Measurements made in photometric conditions with good atmospheric seeing gave results reasonably consistent with those derived from the direct images, even though a narrow slit was used. In some cases the nights were not photometric, but the relative spectrophotometry should be largely unaffected.

c) Photometry

CCD photometry of SN 1987M in the *g* and *r* passbands of the Thuan and Gunn (1976) photometric system was contributed by several observers at the Oscar Mayer 1.5 m reflector at Palomar Observatory (Table II). The CCD labeled TI4 is an 800×800 pixel device whose natural image scale at the Cassegrain focus is 0.23″ pixel^{-1}. It can be used with scale-reducing optics to obtain 0.46″ pixel^{-1}, or in a 2×2 binning mode to obtain 0.35″ pixel^{-1}. The PFUEI (Gunn and Westphal 1981) uses a different TI chip in a different optical configuration. TI8, used for the template image (discussed below), is yet another Texas Instruments chip with a slightly different optical configuration. Since data for the light curve were not taken with the same chip as the template image, the color curve is likely to be nonstandard, given the different wavelength-sensitivity curves of the chips.

The images were processed with the software package FIGARO, written by Keith Shortridge. Standard operations such as bias level subtraction, flatfielding, and calculation of photometric transformation coefficients were performed using normal procedures. Photometry of the supernova was then performed using the scaling and template subtraction technique described by Filippenko *et al.* (1986). The images were all rebinned to 0.46″ pixel^{-1}, and sky brightness was measured from a region 1′ SE of the nucleus, well outside the disk of NGC 2715 along its apparent minor axis. Next, 1′×1′ windows, centered on the supernova, were excised from the images. Galaxy and foreground star intensities were scaled to the 12 February 1988 images, and the 8 September 1988 templates were subtracted. The aperture used for supernova photometry was 10″.

The images from 3 October 1987 were reduced differently. They were taken in such bright twilight that the galaxy was essentially invisible, and the scaling method could not be used. Fortunately, that night was photometric, and good magnitudes could be obtained independently.

We were also able to derive broadband magnitudes of SN 1987M from a few spectra having high photometric quality, as outlined by Filippenko *et al.* (1986). This was only possible during the first few months; incomplete removal of the underlying starlight leads to an overestimate of the object's brightness at late times. [The danger of using late-time spectra to construct light curves is demonstrated by SN 1987K: the last two points in Filippenko's (1988a) red light curve are at least 1 mag too bright, according to the photometry of Turatto *et al.* (1990).] Moreover, the early time spectra allowed us to synthesize Johnson (1955) *V* and *B* magnitudes, useful for direct comparison with the average SN light curves published by Doggett and Branch (1985). In all cases, the published spectrum of the standard star BD + 17 4708 (Oke and Gunn 1982) was used to calibrate the spectroscopically derived magnitudes of SN 1987M.

III. RESULTS

a) Spectroscopy

The montage in Fig. 2 illustrates the spectrum of SN 1987M on various dates from 28 September 1987 to 25 February 1988. A spectrum obtained on 25 March 1988 was very noisy, but qualitatively similar to the last one shown. An offset was added to each spectrum except the first, for clarity. The redshift ($cz = 1339$ km s^{-1}; Sandage and Tammann 1987) of the parent galaxy, NGC 2715, was removed in all cases.

The 28 September spectrum, probably obtained one week after maximum brightness, establishes the event as Type I by the absence of hydrogen lines, and as Type Ib by the absence of the 6150 Å trough. The most prominent absorption lines can be identified with Ca II H and K (~3800 Å), O I λ 7774, the Ca II near-IR triplet at ~8200 Å (which shows a distinct P Cygni profile), and blends of Fe II (near 4400, 4800, and 5000 Å). Lacking He I λ 5876 and λ 6678 absorption lines, SN 1987M more closely resembles the helium-poor (Ic) SNe 1983I and 1983V (Wheeler *et al.* 1987) than the prototypical (helium-rich) SNe Ib 1983N and 1984L; thus, SN 1987M can be classified as a SN Ic (Harkness and Wheeler 1990).

The Type Ib/Ic classification is confirmed by the emergence of strong, broad, reasonably unblended emission lines of intermediate-mass elements (O, Ca, Mg, Na) several months later. As shown in Fig. 3, the late-time spectrum of SNe Ia and Ib differ dramatically; SNe Ia are dominated by a strongly blended "forest" consisting mainly of [Fe II], [Fe III], and [Co III] emission lines (Axelrod 1980; Weaver, Axelrod, and Woosley 1980).

The early and rapid onset of the supernebular phase in SNe Ic is quite evident in Fig. 2. This is somewhat surprising, but Harkness *et al.* (1987) had previously noted the emergence of [O I] λλ 6300, 6364 in the SN Ib 1984L about 2 months after maximum. In SN 1987M, no [O I] λλ 6300, 6364 emission is visible on 20 October (1 month past maximum), but it is clearly present a month later on 22 November. We do not know the strength of [Ca II] λλ 7291, 7324 on 20 October, but by 22 November it is already very prominent, even more so than the [O I] doublet. It is interesting that on 20 October, [O I] λ 6364 appears approximately as strong as [O I] λ 6300, because both lines are near the intensity of the Planck function at the appropriate temperature. Note that a supernebular phase dominated by [O I] was actually predicted for SNe Ib by Chugai (1986).

Harkness *et al.* (1987) claim that [O I] λ 5577 is present as early as ten days and 18 days past maximum in spectra of SNe Ib 1983N and 1984L, respectively, but this line falls in a complicated region and its presence must be verified with synthetic spectra. It is almost certainly visible in SN 1984L by 2 months past maximum, and probably by 1.5 months past maximum. Wheeler and Harkness (1990) state that [O I] λ 5577 is present in the 22 November spectrum of SN 1987M, about 2 months past maximum, but the observed and predicted wavelengths do not agree very well. In our opinion, the features over the range 5300–5600 Å in the 22 November spectrum are slightly modified versions of those in the 20 October spectrum, and do not strongly support the [O I] λ 5577 identification. Thus, there is no overwhelming evidence at relatively early times that SNe Ic are more oxygen rich than SNe Ib.

Of the first three spectra of SN 1987M shown in Fig. 2, the one obtained on 2 October 1987 looks most similar to the

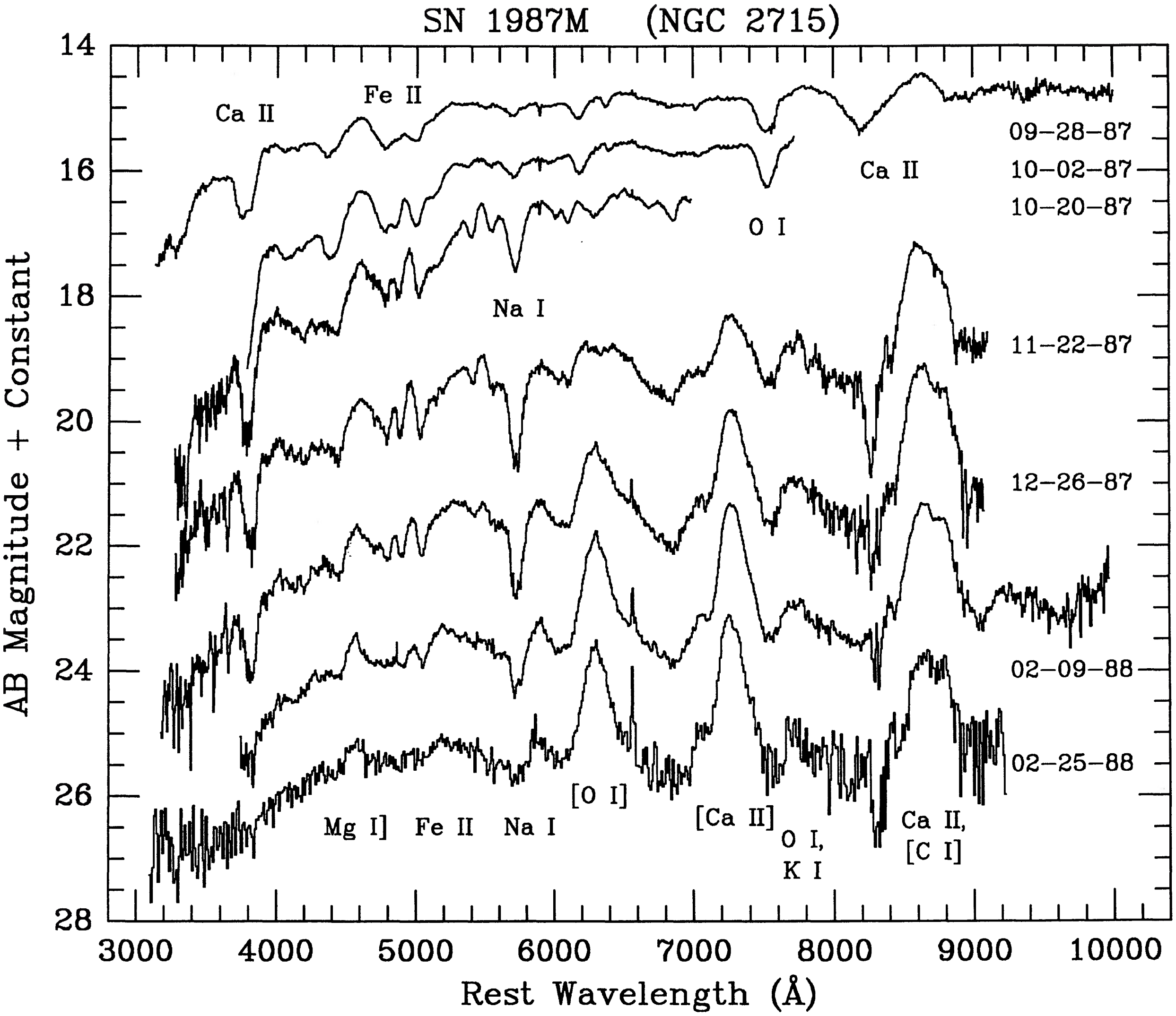

FIG. 2. Spectra of SN 1987M, obtained with the Shane 3 m reflector at Lick Observatory and the Hale 5 m reflector at Palomar Observatory. The redshift of the parent galaxy (1339 km s^{-1}) has been removed in all cases. The ordinate scale is given by AB $= -2.5\log f_\nu - 48.6$, where the units of f_ν are ergs s^{-1} cm^{-2} Hz^{-1} (Oke and Gunn 1983). From top to bottom, the additive constants are 0.0, 0.6, 0.0, 1.4, 3.0, 4.1, and 5.4 mag. All dates are UT, but the 28 September 1987 spectrum is a combination of data from 28 and 29 September (photometrically calibrated on 28 September 1987), and the 22 November 1987 spectrum is a combination of data from 22 and 23 November (photometrically calibrated on 22 November 1987). A very noisy spectrum obtained on 26 March 1988 is qualitatively similar to that of 25 February 1988. Some prominent emission and absorption lines are marked. Na I D might be contaminated by He I λ 5876, especially at early times. Narrow Hα emission is due to a low-luminosity H II region surrounding SN 1987M. Narrow Na I D absorption from the interstellar medium of NGC 2715 is clearly visible near 5890 Å in the top three spectra.

composite spectrum of the SNe Ic 1983I and 1983V published by Wheeler *et al.* (1987). Specifically, as also pointed out by Wheeler and Harkness (1990), there is a small peak at 4900 Å between Fe II absorption lines in the composite spectrum whose relative strength nicely matches that in SN 1987M on 2 October. On 28 September this peak is too weak in SN 1987M, whereas on 20 October it is too strong. Moreover, by 20 October a cluster of narrow Fe II lines is present near 5500 Å in SN 1987M, yet it is absent in the composite spectrum of SNe 1983I and 1983V. The spectroscopically determined phase of SN 1987M, together with optical and IR photometry of SNe 1983I and 1983V, lead Wheeler and Harkness (1990) to conclude that SN 1987M achieved maximum *V* brightness somewhere in the range 17–25 September. Thus, its discovery on 21 September probably occurred near maximum, consistent with our own estimate in Sec. III*b*.

Wheeler *et al.* (1987) predicted that O I λ 7774 should be strong in the spectra of (helium-poor) SNe Ic, but slightly weaker relative to several other features in (helium-rich) SNe Ib. A quick glance at the top two spectra in Fig. 2 shows that O I absorption is indeed very strong in SN 1987M. Unfortunately, high-quality near-IR spectra of SNe Ib have not yet been published. Furthermore, the O I line should be reasonably prominent even in SNe Ib (Wheeler *et al.* 1987). By far the main observational difference between the early time

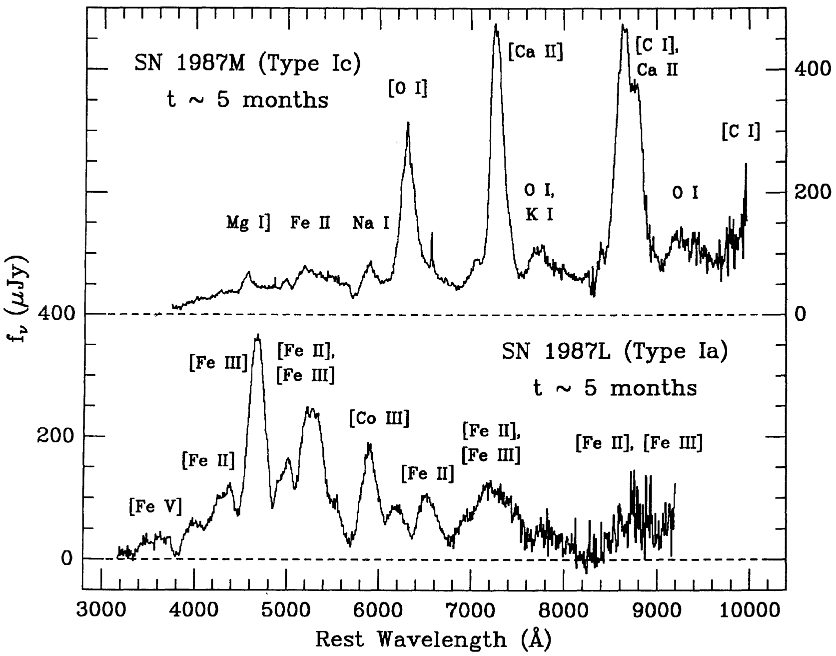

FIG. 3. Spectra of SN 1987L (Type Ia) and SN 1987M (Type Ic), both about 5 months past maximum brightness. The ordinate has been shifted by 400 μJy for SN 1987M, as indicated by the scale on the right-hand side. The spectra of SN 1987L and SN 1987M were obtained on 26 December 1987 UT and on 9 February 1988 UT, respectively. Despite the rough overall similarity of SNe Ia and Ic near maximum brightness, the late-time spectra of these two objects are astoundingly different. Prominent features in SNe Ia are generally complicated blends of iron and cobalt lines, whereas those in SNe Ic and Ib are reasonably unblended lines from intermediate-mass elements, primarily oxygen and calcium. In SN 1987L, the prominent [Fe II], [Fe III], and [Co III] blends are also contaminated to some extent by Fe I, Fe II, [Fe V], [Fe VI], and [Fe VII] (Weaver, Axelrod, and Woosley 1980).

spectra of SNe Ib and Ic lies in the strength of the He I absorption lines.

The rapid decrease in density of the ejecta with time is traced by the increasing strength of forbidden relative to permitted calcium emission. It also appears that the Ca II H and K (permitted) absorption trough may be filled in by emission in the last spectrum, although by this time the star was becoming difficult to observe. We can make a rough estimate of the density by noting that in the 9 February 1988 spectrum, the [Ca II] intensity is comparable to that of the Ca II infrared triplet. (Here, we have assumed that part of the Ca II profile actually consists of [C I] λ 8727, and that the blue wing of the [Ca II] profile is contaminated by other lines, probably [Fe II].) Figure 2 in Ferland and Persson (1989) then yields $n_e \approx 10^9$–10^{10} cm^{-3} if $T_e = 3000$–5500 K, a plausible range of temperatures. Since the general late-time spectral characteristics of SN 1987M resembled those of SN 1987A (with an absence of hydrogen, of course), it is reasonable to assume that the late-time behavior of its photospheric temperature was also similar. Thus, at an age of 130 days we have $T_e \approx 4700$ K (Catchpole *et al.* 1987), and $n_e \approx 1.6 \times 10^9$ cm^{-3} if the photospheric temperature is adopted for the Ca II emitting gas.

Figure 4 shows spectra of SN 1987M and SN 1985F roughly 5 and 10 months past maximum brightness, respectively. It is clear that the same basic features are present, although SN 1987M is at a considerably earlier stage of its supernebular phase. SN 1987M still exhibits prominent P Cygni absorption components of Na I D and the Ca II near-IR triplet, and the emission-line intensity ratios are different in the two objects. Comparison with Fig. 2, however, shows that the strengths of absorption lines steadily decrease at late times. Furthermore, the intensity of [O I] rises relative to that of [Ca II], and [Ca II]/Ca II also increases. It is quite plausible, therefore, that the spectrum of SN 1987M eventually looked very similar to that of SN 1985F. Unfortunately, lacking early-time spectra, we do not know whether SN 1985F was a SN Ib, a SN Ic, or perhaps even a SN II which later metamorphosed into a SN Ib (as did SN 1987K; Filippenko 1988a). Judging from its rather broad light curve (Filippenko *et al.* 1986; Ensman and Woosley 1988; Schlegel and Kirshner 1989), though, it seems unlikely that SN 1985F would have been spectroscopically classified as a SN Ic near maximum; see Sec. III*b*.

Fransson and Chevalier (1989) successfully modeled the late-time emission-line spectrum of SN 1985F by assuming that the progenitor was a massive star that underwent core collapse. The great strength of the [O I], [Ca II], and Ca II lines is largely due to enrichment of oxygen and calcium in the core of the progenitor. Considerable mixing of the ejecta was invoked to reproduce the observed line profiles, which are quite broad. In a study of SN 1987A, on the other hand, Swartz, Harkness, and Wheeler (1989) showed that small (nearly solar) abundances of oxygen and calcium in the outer envelope may account for the strong lines seen in the late-time spectra of SNe II. If their calculations are correct, it is possible that the [O I] and [Ca II] lines in SN 1987M do not imply extremely large overabundances of intermediate-mass elements.

b) Photometry

In Table III we list the measured magnitudes of SN 1987M. Figure 5 shows the supernova's *B*, *g*, *V*, and *r* light curves, superposed on the average *B* and *V* light curves of SN I constructed by Doggett and Branch (1985). The zero point of the time axis is taken to be 21 September 1987 UT, the date of discovery. Although the data are sparse, the light curves are consistent with maximum brightness near the discovery date and an inflection point about 30 days later. However, SN 1987M seems to have had a steeper initial decline (at *B* and *V*) than the average SN I. The Pskovskii (1984)

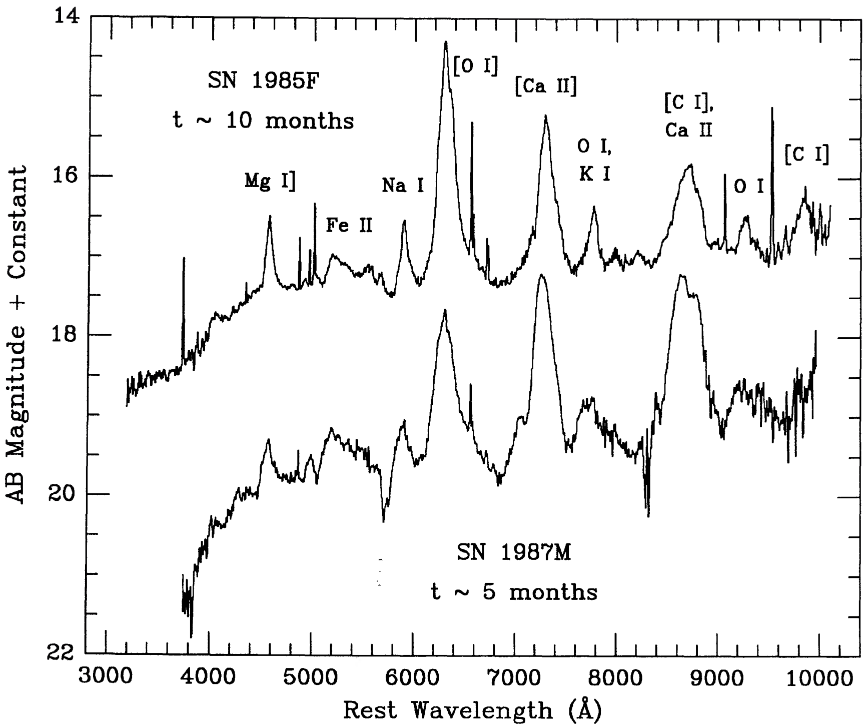

FIG. 4. Comparison of late-time spectra of SN 1985F and SN 1987M. The spectrum of SN 1985F is taken from Filippenko and Sargent (1986). Long after maximum SN 1985F had the defining characteristics of SNe Ib/Ic, but whether it was helium rich or helium poor is not known; it may have even started out as a SN II. All of the major features appear in both objects. The absorption lines are stronger in SN 1987M than in SN 1985F, and the emission-line intensity ratios are not the same, but these discrepancies are probably due to the different ages of the two objects. Owing to differences in atmospheric seeing, the narrow [S III] lines beyond 9000 Å in SN 1985F appear too strong, relative to other narrow lines.

parameter β, for example, is about 12 mag $(100\ \mathrm{d})^{-1}$, whereas the typical value is 8-9 mag $(100\ \mathrm{d})^{-1}$ (e.g., Filippenko 1989b). In this way, SN 1987M resembles the well-studied SNe Ia 1986G in Centaurus A (Phillips *et al.* 1987). More significantly, it appears as though other SNe Ic (e.g., SN 1983V) also have steeper light curves than SNe Ib (Wheeler and Harkness 1990). One simple interpretation is that the ejected mass is smaller in SNe Ic than in SNe Ib.

It should also be noticed, from Table III, that SN 1987M reddened very quickly during its first few weeks. Unfortunately, only two B magnitudes are available over this time interval, and both were determined from spectra rather than images. The rapid blue fading, however, is qualitatively consistent with the original estimate of $m_{pg} = 15.0$ given by Szeidl and Lovas (1987) for 21 September 1987, if we transform to an approximate B magnitude of 15.3 using the relation $B \approx m_{pg} + 0.3$ (Branch and Bettis 1978; Cadonau 1987).

TABLE III. Photometry of SN 1987M.[a]

UT Date	Day[b]	B[c]	g[d]	V[e]	r[f]
09–21–87	0	...	...	...	...
09–28–87[g]	7	16.25	15.20	15.02	14.92
10–02–87[g,h]	11	17.06	15.68	15.39	15.10
10–03–87	12	...	15.60	...	15.20
10–16–87	25	...	...	...	16.16
10–17–87	26	...	17.00	...	16.28
10–20–87[g]	29	18.84	17.32	16.98	16.51
10–26–87	35	...	17.29	...	16.65
10–28–87	37	...	17.68	...	16.95
11–22–87[g]	62	19.53	18.20	17.98	17.67
12–21–87	91	...	19.40	...	18.47
02–12–88	144	...	...	...	19.77

[a] All measurements given in magnitudes.
[b] Day since discovery of SN 1987M.
[c] Johnson (1955) B.
[d] Thuan and Gunn (1976) g.
[e] Johnson (1955) V.
[f] Thuan and Gunn (1976) r.
[g] Magnitudes derived from spectra.
[h] B may be too faint, due to atmospheric dispersion.

Like SN 1986G, SN 1987M was substantially obscured by dust; moderately strong Na I D absorption at the redshift of NGC 2715 is visible in the early-time spectra of SN 1987M, with equivalent width $EW \approx 2.1$ Å. Rich (1987) found an equivalent width of 3.6 Å for the redshifted Na I absorption line in the spectrum of SN 1986G, and used high-resolution spectra to obtain the sodium column density and velocity width of each of four components. The measured column density corresponds to an internal color excess of $E_{B-V} = 0.76 \pm 0.1$ mag. Together with the Galactic reddening of $E_{B-V} = 0.12$ mag (Burstein and Heiles 1984), the total reddening is 0.88 mag, in close agreement with the value $E_{B-V} = 0.90$ mag derived by Phillips *et al.* (1987) from a comparison of light-curve shapes. Lacking high-resolution spectra of SN 1987M, we cannot do a detailed analysis similar to that of Rich (1987). Nevertheless, if we adopt a conversion factor of $E_{B-V}/\mathrm{EW} = 0.21$ mag Å^{-1}, as implied by the Na I D absorption in SN 1986G, and apply it to our measured value of EW ≈ 2.1 Å for SN 1987M, we find that $E_{B-V} \approx 0.44$ mag. The Galactic reddening of NGC 2715 is only 0.005 mag (Burstein and Heiles 1984). Thus, adopting the usual conversion $A_V = 3.0\ E_{B-V}$, we derive a total visual extinction of ~ 1.3 mag for SN 1987M. Also, with $A_B = 4.0\ E_{B-V}$, we find $A_B \approx 1.8$ mag.

We have tried to determine whether SN 1987M was subluminous, as are most SNe Ib and Ic. Tully (1988) gives a distance modulus of 31.65 mag for NGC 2715, with $H_0 = 75$

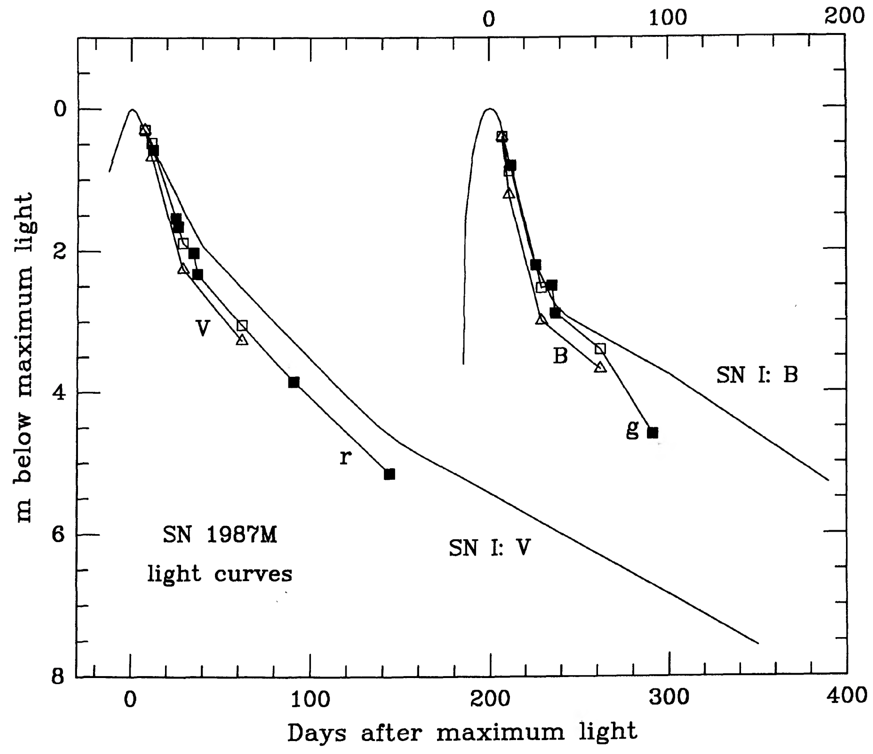

FIG. 5. Photometric measurements of SN 1987M, derived from CCD images (solid symbols) and spectra (open symbols). Maximum brightness (day 0) is assumed to have occurred on 21 September 1987, but we did not begin to obtain data until 28 September (day 7). To compensate for this, an offset of 0.4 mag has been added to all *B* and *g* points; the corresponding offset for all *V* and *r* points is 0.3 mag. The *B* and *g* light curves have been shifted by 200 days relative to the *V* and *r* curves, as indicated by the upper abscissa scale. Also shown are average SN I *B* and *V* light curves, from Doggett and Branch (1985).

km s^{-1} Mpc^{-1}. However, this appears to be based on the redshift given by Humason, Mayall, and Sandage (1956), which has been superseded by the value $cz = 1339$ km s^{-1} (van der Kruit and Bosma 1978). Correcting for Galactic rotation and Virgo infall, as done by Tully (1988), we obtain $m - M = 31.9$ mag. Hence, with $B \approx 15.3$ mag at maximum, we have $M_B \approx -16.6$ mag, so $M_B^0 \approx -18.4$ mag. For comparison, typical SNe Ia at maximum have $M_B^0 = -19.0$ mag (Miller and Branch 1990). We conclude that SN 1987M was probably only about 0.6 mag fainter in *B* than average SNe Ia. This is marginally consistent with previous estimates (0.9–1.9 mag) of the amount by which SNe Ib are subluminous in *B* (Uomoto and Kirshner 1985; Branch 1986). Nevertheless, given the uncertainties in the conversion from Na I D equivalent width to E_{B-V}, it is conceivable that SN 1987M was not subluminous.

IV. DISCUSSION

a) Progenitors

At this time, two very different types of progenitors are being considered for SNe Ib/Ic. Probably the most favored progenitors are massive stars that have shed their outer layer of hydrogen, either through winds or by mass loss onto a companion star. The explosion mechanism, core collapse with subsequent ejection, is essentially the same as that of SNe II. There are many general and specific scenarios (e.g., Wheeler and Levreault 1985; Begelman and Sarazin 1986; Uomoto 1986; Chevalier 1986; Schaeffer, Cassé, and Cahen 1987; Harkness *et al.* 1987; van den Bergh 1988; Fransson and Chevalier 1989), but in general only the details differ among them. The other possible type of progenitor is a white dwarf. Branch and Nomoto (1986), for example, suggest that a detonation begins at the boundary layer between the He shell and the C-O core, whereas Woosley (1990) advocates a slow-flame carbon deflagration. Other possibilities are discussed by Khokhlov and Ergma (1986) and by Iben *et al.* (1987); see also Tornambè and Matteucci (1987).

The similarity of the *shape* of the light curve of SN 1987M to that of average SNe Ia poses the most severe problem for models invoking massive progenitors. Ensman and Woosley (1988), as well as Nomoto, Shigeyama, and Hashimoto (1988; see also Nomoto *et al.* 1988), point out that the light curves of exploding Wolf–Rayet stars should have broader, shallower peaks than those of most SNe Ib. Although both large-scale mixing and clumping of the ejecta can lead to smaller gamma-ray deposition, to our knowledge it has not been possible to make the resulting light curves as narrow as that of SN 1987M, which appears to be even *steeper* than normal. However, recent calculations of evolving stars by Langer (1989) suggest that the final helium core of a very massive star can be substantially smaller than that predicted in earlier studies, if mass loss is properly taken into account. Perhaps mixing and clumping, combined with these new calculations, will produce light curves that resemble that of SN 1987M.

The general problem with white dwarf detonation models of SNe Ib/Ic, on the other hand, is that they are either too luminous to be SNe Ib/Ic, or fade away *more* rapidly than typical SNe Ib (Branch 1988). The rapid brightness decline of a white dwarf that undergoes an off-center detonation at the base of the helium layer (Branch and Nomoto 1986), for example, occurs because the detonation is confined to the outer few tenths of a solar mass of material. In addition, the predicted late-time spectrum (Fransson 1988; Fransson and Chevalier 1989) does not exhibit sufficiently strong emission lines of intermediate-mass elements, and the relative intensities of certain lines (such as [C I] λ 8727 and [O I] $\lambda\lambda$ 6300, 6364) differ from the observations. More recently, though, Woosley (1990) has suggested that a slow-flame carbon deflagration in a white dwarf may explain some SNe Ib; the light curve is fainter and broader than in previous models, and the late-time spectrum may be consistent with observations. With a light curve that is only slightly steeper than that of typical SNe Ia, SN 1987M may well have had a white dwarf progenitor.

To further explore this possibility, it is instructive to derive an approximate mass for the ejecta in SN 1987M, despite large uncertainties in the density structure of the expanding envelope. If we assume that (a) the expansion is spherically symmetric, (b) the density, given by the [Ca II] to Ca II line ratio, is constant throughout the ejecta at a given time, and (c) the number of free electrons contributed by each atom is constant throughout the ejecta at a given time, we can calculate the ejected mass by using the relation $\mathscr{M} \approx (4/3)\ \pi m n_e v^3 t^3 x^{-1}$. Here v is the typical velocity of the [Ca II] emitting gas, m is the mean mass per atom (neutral or ionized), t is the time since the explosion, and $x = n_e/n$ is the ratio of the free-electron number density to the atom number density. As an example, on 9 February 1988 we use $t \approx$ 130 days, $v \approx 2500$ km s^{-1} (the measured half width at half-maximum intensity of [Ca II]), and $n_e \approx 1.6\times10^9$ cm^{-3} (Sec. III*a*). Given the predominance of emission lines of neutral and singly ionized species in the spectrum, we assume $x \approx 0.5$—that is, one out of every two atoms contributes a free electron. The exact composition of the ejecta is not known, but intermediate-mass elements such as oxygen probably contribute a large fraction; hence, we adopt $m \approx 20 m_p \approx 3.3\times10^{-23}$ g. This number could be incorrect by as much as a factor of 2, depending on the mass fraction of helium, iron, and other important elements. Under these assumptions, the ejected mass turns out to be $\mathscr{M} \approx 5.0\ \mathscr{M}_\odot$, suggesting that the progenitor was quite massive.

Filippenko (1989a) used nearly the same method to determine an ejected mass of $\gtrsim$ 5–30 $\mathscr{M}_\odot$ in SN 1987F. As mentioned by Filippenko (1990b), however, this calculation neglected clumping of the ejecta. Clumping was definitely present in the ejecta of SN 1987A (e.g., Arnett *et al.* 1989), and some evidence for clumping has been found in the SN 1985F (Filippenko and Sargent 1989). In SN 1987F, the derived filling factor of clumps is ~ 0.01 (Filippenko 1990b). If a comparable number applies to SN 1987M, then the above mass estimate must be revised to ~ 0.05 $\mathscr{M}_\odot$, a very small value. However, this mass is actually a lower limit; there is certainly low-density gas between the high-density clumps, and the average density must increase with decreasing radius in the ejecta (rather than being constant, as assumed). Perhaps a more reasonable, yet highly uncertain, estimate of the ejected mass is ~ 0.5–1 $\mathscr{M}_\odot$.

The flux of the [O I] $\lambda\lambda$ 6300, 6364 emission can also be used to calculate the ejected mass, but only of oxygen. In the high-density limit ($n_e \gtrsim 2\times10^6$ cm^{-3}, certainly satisfied here), Uomoto (1986) notes that $\mathscr{M}_{\rm O} = 10^8 f([{\rm O\ I}])\ D^2 \exp(2.28/T_4)\ \mathscr{M}_\odot$, where $\mathscr{M}_{\rm O}$ is the mass ($\mathscr{M}_\odot$) of ejected oxygen, D is the distance (Mpc) of the supernova, $10^4\ T_4$ is the temperature (K) of the oxygen-emitting gas, and $f([{\rm O\ I}])$ is the flux (ergs s^{-1}cm^{-2}) of [O I] emission. On 9 February 1988, we measure $f([{\rm O\ I}]) = 3.5\times10^{-14}$ ergs s^{-1} cm^{-2}. (We use this particular spectrum because at earlier times the [O I] emission was more blended with other lines, and at later times the quality of the spectra was lower.) Correcting for extinction by a factor of 2.8, corresponding to $E_{B-V} = 0.44$ mag, gives $f([{\rm O\ I}]) = 9.8\times10^{-14}$ ergs s^{-1} cm^{-2}. Adopting the probable photospheric temperature of 4700 K on 9 February, we find $\mathscr{M}_{\rm O} \approx 0.4\ M_\odot$, again suggesting that the progenitor mass is not extremely large. Unfortunately, the exponential dependence of $\mathscr{M}_{\rm O}$ on temperature makes the result highly uncertain; for $T_4 = 0.6, 0.5, 0.4$, and 0.3 we find that $\mathscr{M}_{\rm O}$ $(M_\odot) = 0.14, 0.30, 0.94$, and 6.3, respectively. In principle, an accurate value of T_4 could be derived from the intensity ratio [O I] $\lambda\lambda$ 6300, 6364/[O I] λ 5577, but the weak λ 5577 line is severely blended with emission lines of Fe II and other species.

Another factor relevant to our discussion of the progenitor mass is the environment of SN 1987M. Traditionally, one of the arguments used in favor of the massive progenitor hypothesis has been the occurrence of SNe Ib/Ic in galaxies of Hubble type later than Sb, and especially their proximity to luminous H II regions (Porter and Filippenko 1987). NGC 2715 is an Sc galaxy, but SN 1987M was *not* superposed on a luminous H II region. This is evident from the template image of NGC 2715, and from the weakness of the narrow Hα emission in the late-time spectra (Fig. 2). Indeed, Panagia and Laidler (1989) have argued that SNe Ib are generally less closely associated with H II/OB complexes than are SNe II, and that they therefore have less massive progenitors—as also suggested by their light curves.

It is also useful to compare in detail the early-time spectrum of SN 1987M with that of SN 1987K (Filippenko 1988a), a SN II whose spectrum eventually metamorphosed into that of a SN Ib. (Such an object might reasonably be called a SN IIb; Woosley *et al.* 1987.) Figure 6 illustrates the spectra on the same wavelength scale; the redshift of the parent galaxies has been removed. The spectroscopic similarity at wavelengths in the range 3800–6000 Å is striking, but overall there are two or three major differences. The first is that SN 1987K exhibits a prominent Hα P Cygni profile, whereas SN 1987M does not. As mentioned by Filippenko (1988a), the local maximum near 6500 Å in SN 1987M might actually be Hα emission, but it is considerably weaker than in SN 1987K. The corresponding absorption line is either absent or largely obscured by an emission line at ~ 6300 Å; the weak absorption near 6360 Å and/or 6190 Å may be all that remains. The second difference is that SN 1987M shows strong O I λ 7774 absorption, unlike SN 1987K. Another difference is that SN 1987M has a well-defined peak blueward of Ca II H and K absorption, whereas the flux density of SN 1987K continues to decline in the near-UV region. The spectroscopic appearance at these wavelengths, however, may be a strong function of time due to the blanketing effect of many lines; hence, a slight mismatch in the phases at which the data were obtained might be responsible for the discrepancy.

If the O I λ 7774 line is produced by an oxygen-rich layer in a massive star (Harkness *et al.* 1987), it might be possible to hide it in SN 1987K if the progenitor had a thin, essentially unenriched hydrogen envelope, as proposed by Filippenko (1988a). In this case, the absorption features between 3800 and 6000 Å also cannot be attributed to an overabundance of heavy elements. The same conclusion therefore holds for SN 1987M, since the features in SN 1987M and SN

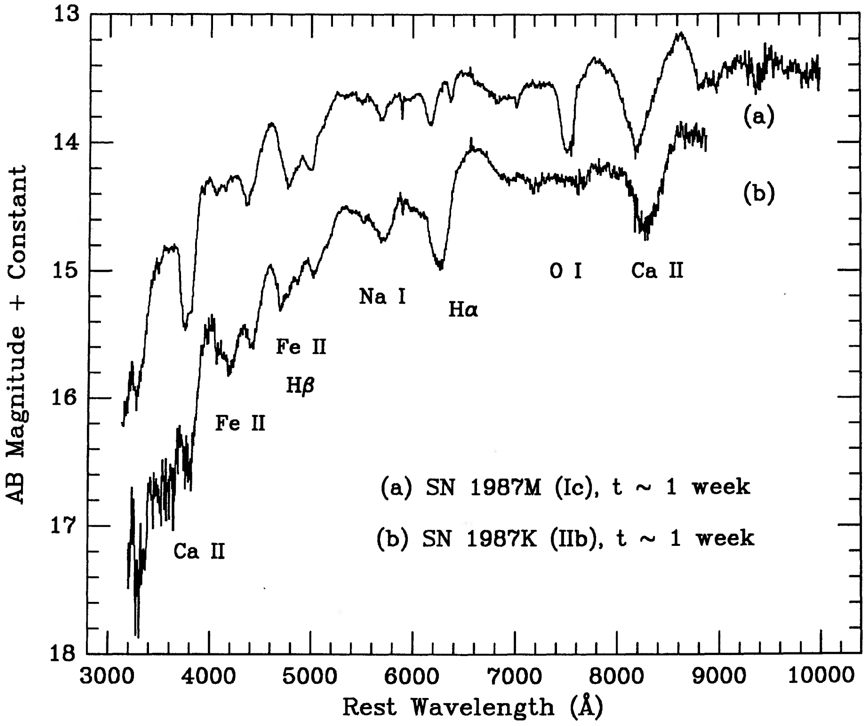

FIG. 6. Spectral comparison between SN 1987K (Type II at early times, Type Ib at late times) and SN 1987M (Type Ic), roughly one week past maximum brightness. The data for SN 1987K and SN 1987M were obtained on 7 August 1987 UT (Filippenko 1988a) and on 28 September 1987 UT, respectively. An offset of -1.3 mag has been added to the SN 1987M spectrum. Several prominent features are marked. He I λ 5876 may contaminate Na I D absorption to some extent. The appearance of SN 1987M is quite similar to that of SN 1987K, except Hα is weak or absent in SN 1987M while O I λ 7774 is absent in SN 1987K. Another possible difference is the shape of the continuum blueward of the Ca II H and K lines.

1987K appear so similar over this wavelength range. This, perhaps, is somewhat hard to understand, given the evidence for mixing in SN 1987A (e.g., Arnett *et al.* 1989) and in SN 1985F (Fransson and Chevalier 1989). On the other hand, it is also not clear how to interpret the difference in O I λ 7774 strengths under the assumption of a white dwarf progenitor. Despite their similarities, SN 1987K and SN 1987M may have actually come from very different types of stars or explosion mechanisms.

b) Peculiar IR Light Curves

Elias *et al.* (1981, 1985) have shown that SNe Ia exhibit very red and rapidly changing $J-H$ colors. There is a local minimum in J (and, to a lesser extent, in H and K) 15–20 days after primary maximum, followed by a secondary maximum ~ 15 days later. The $J-H$ color is reddest about 20 days past primary maximum. SNe Ib/Ic, by contrast, have significantly bluer $J-K$ colors; moreover, their J, H, and K light curves decline monotonically from primary maximum, showing no secondary maxima. Noting the great strength of Si II λ 6355 in SNe Ia, as well as the evolution of the strength of the Na I D absorption, Graham (1986) suggests that the absorption at J in SNe Ia is produced by a dense array of strong Si I lines near 1.2 μm. He attributes the absence of the deep Si II feature in SNe Ib/Ic to a real deficiency of silicon, rather than to an excitation effect.

As a test of his hypothesis, Graham (1986) states that a comparison of SNe Ia and Ib/Ic should be made below 4000 Å. The P Cygni profile whose absorption minimum is near 3700 Å is usually attributed to Ca II, but it might be partially produced by Si I λ 3905 in SNe Ia. If so, it is expected to be considerably stronger in SNe Ia than in SNe Ib/Ic at the same phase. Figure 7 illustrates spectra of SN 1987M (Ic) and SN 1987N (Ia), both observed roughly 1 week past maximum brightness. It can be seen that the strength and profile of the 3700 Å absorption are strikingly similar in the two SNe. Specifically, in both objects the absorption minimum is 1.2 mag deep when measured from the peak near 3950 Å, and 0.6 mag deep in SN 1987N (compared with 0.7 mag in SN 1987M) when measured from the peak near 3600 Å. Since the Ca II near-IR triplet lines are also of similar strength in the two SNe, Si I is unlikely to contribute appreciably to the near-UV absorption.

It might be argued that the spectra in Fig. 7 were obtained too early, before the Si I absorption line became very strong. However, spectra of SN 1981B published by Branch *et al.* (1983) show that the strength of the 3700–3800 Å absorption trough changes very little in SNe Ia during the first two months past maximum. According to Fig. 2, by contrast, this absorption becomes substantially stronger in the SN Ic 1987M over the same time interval. Hence, there is certainly no evidence for enhanced Si I absorption in the near-UV spectra of SNe Ia, relative to SNe Ib/Ic. We conclude that transient Si I absorption is therefore unlikely to produce the observed minimum in the J light curve of SNe Ia. Harkness and Wheeler (1990) came to the same conclusion, arguing that the IR minimum is visible over a broad range (J, H, and K). Most convincing of all, of course, are the IR spectra of SN 1986G (Cen A) obtained by Frogel *et al.* (1987); lines of Si I were not present at a detectable strength. The nature of the broad J-band absorption remains unknown.

c) Si II and Co II in SN 1987M

During the first month past maximum, the property that distinguishes SNe Ib/Ic from SNe Ia at optical wavelengths is that the latter exhibit a strong 6150 Å absorption trough, thought to be produced by blueshifted Si II λ 6355. Figure 7,

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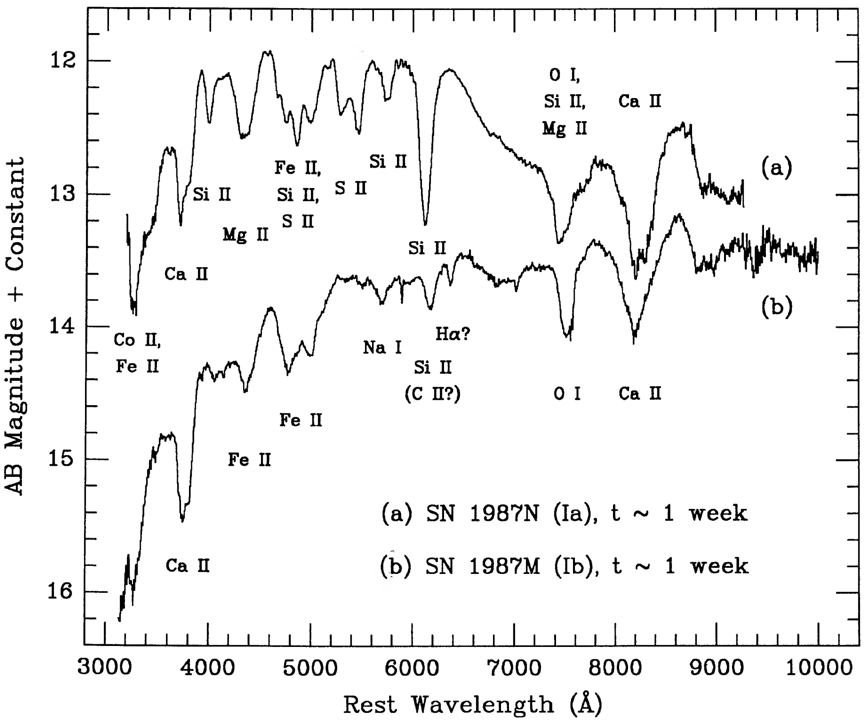

FIG. 7. Spectral comparison between SN 1987N (Type Ia) and SN 1987M (Type Ic), roughly one week past maximum brightness. An offset of − 1.2 mag has been added to the SN 1987N data. Part of the reason SN 1987N appears so much bluer than SN 1987M is that the latter object is heavily reddened ($E_{B-V} \approx 0.44$ mag), while the former is essentially unreddened. Plausible identifications of the absorption lines are given next to each spectrum. The trough at 3250 Å may be due to Co II and Fe II in both objects. Si II λ 6355 absorption is identified for the first time in a SN Ic, but an alternative choice is C II λ 6580 (Wheeler *et al.* 1987) or even Hα. The weak dip near 6360 Å might also be attributed to Hα.

however, shows that Si II absorption might be weakly present in the spectrum of SN 1987M. Although the measured wavelength of the line is ~ 6190 Å in SN 1987M, compared with ~ 6110 Å in SN 1987N, a similar shift is seen in the O I λ 7774 absorption. (However, the shift seems to be in the opposite direction in the Ca II near-IR absorption line.) The presence of weak Si II λ 6355 absorption in SN 1987M is not entirely unexpected. Branch (1989), in fact, notes that the *absence* of this line in SNe II is difficult to understand unless silicon has an abundance significantly below solar. Wheeler *et al.* (1987), on the other hand, identify the 6190 Å absorption feature with blueshifted C II λ 6580; a non-LTE contribution from Ne I λ 6402 also cannot be ruled out (Harkness *et al.* 1987). Another possibility is Hα absorption, as mentioned in Sec. IV*a*. Detailed spectral modeling will be necessary to see whether Si II provides the best fit to the spectrum and is physically most realistic.

Most of the identifications given in Fig. 7 are taken from Branch *et al.* (1985), as well as from the reviews by Harkness and Wheeler (1990) and by Wheeler and Harkness (1990). Of particular interest is the absorption trough near 3250 Å, which Branch and Venkatakrishna (1986; see also Harkness 1985) attribute to newly synthesized Co II and Fe II in SNe Ia such as SN 1987N. If the same trough in the premaximum *IUE* spectrum of the SN Ib 1983N (Panagia 1985) indicates an overabundance of iron and cobalt, Branch and Venkatakrishna (1986) suggest that white-dwarf models of SNe Ib might be more attractive than massive-star models. The UV deficit in the SN Ic 1987M may be even greater than that of SNe Ia, but spectra of higher quality are necessary to confirm this.

The cause of the strong UV blanketing, however, is controversial. Harkness and Wheeler (1990) obtain good fits to the near-UV spectrum of SN 1983N with a helium-rich envelope having a *solar* abundance of iron. Moreover, SN 1987A exhibited a strong UV deficit, yet it too is well modeled with nearly normal abundances of iron-group elements. It is also quite easy to produce the prominent Fe II lines in the optical spectrum of objects such as SN 1987M without resorting to peculiar abundances. More work in this area is clearly warranted.

V. CONCLUSIONS

A qualitative examination of the spectra and light curves does not allow us to reach a firm conclusion regarding the nature of the progenitor of SN 1987M. Although SN 1987M may have come from a reasonably high-mass star, overall the evidence appears to favor a low-mass progenitor. The small ejected mass ($\lesssim 1\ \mathscr{M}_\odot$), albeit very poorly determined, does not imply a massive progenitor. Stronger evidence for a low-mass progenitor is provided by the light curve, which might decline even more rapidly than that of typical SNe I. In addition, SN 1987M did not occur in a luminous H II region; it was, however, superposed on (or close to) a spiral arm of NGC 2715.

Nevertheless, as discussed previously in this paper, several lines of evidence do suggest that many SNe Ib/Ic have high-mass progenitors. Hence, given the currently available data, we believe that SNe Ib/Ic may constitute a physically heterogeneous class, with two distinct types of progenitors possibly having two different explosion mechanisms. For example, SNe Ib (helium rich) may fall into one physically distinct subclass, while SNe Ic (helium poor) fall into a separate subclass. This is a more extreme point of view than that of Harkness *et al.* (1987), who conjecture that all SN Ib/Ic progenitors are massive but suffer different amounts of mass loss prior to exploding.

In principle, the simplest way to choose between the proposed models of SNe Ib/Ic when studying a particular supernova might be to determine the mass of the ejected oxygen from the measured luminosity of the [O I] emission. This, unfortunately, is very difficult in practice because one needs an accurate temperature, and the requisite [O I] λ 5577 line is both weak and highly blended with other features. Instead, it will probably be necessary to compare high-quality observations with synthetic light curves and multiepoch spectra obtained with sophisticated supernova calculations.

For statistical samples of SNe, on the other hand, considerable progress can be made if many light curves are obtained on *uniform* photometric systems, and especially if the measurements at many colors are combined to obtain bolometric light curves. A long series of high-quality spectra, with frequent sampling at early times, is also necessary. Careful astrometry of SNe and their nearest H II regions is also desirable, to more thoroughly address the issues raised by Panagia and Laidler (1989). Finally, photometry and spectroscopy of the H II regions themselves should tell us much about the environments in which SNe Ib and Ic occur.

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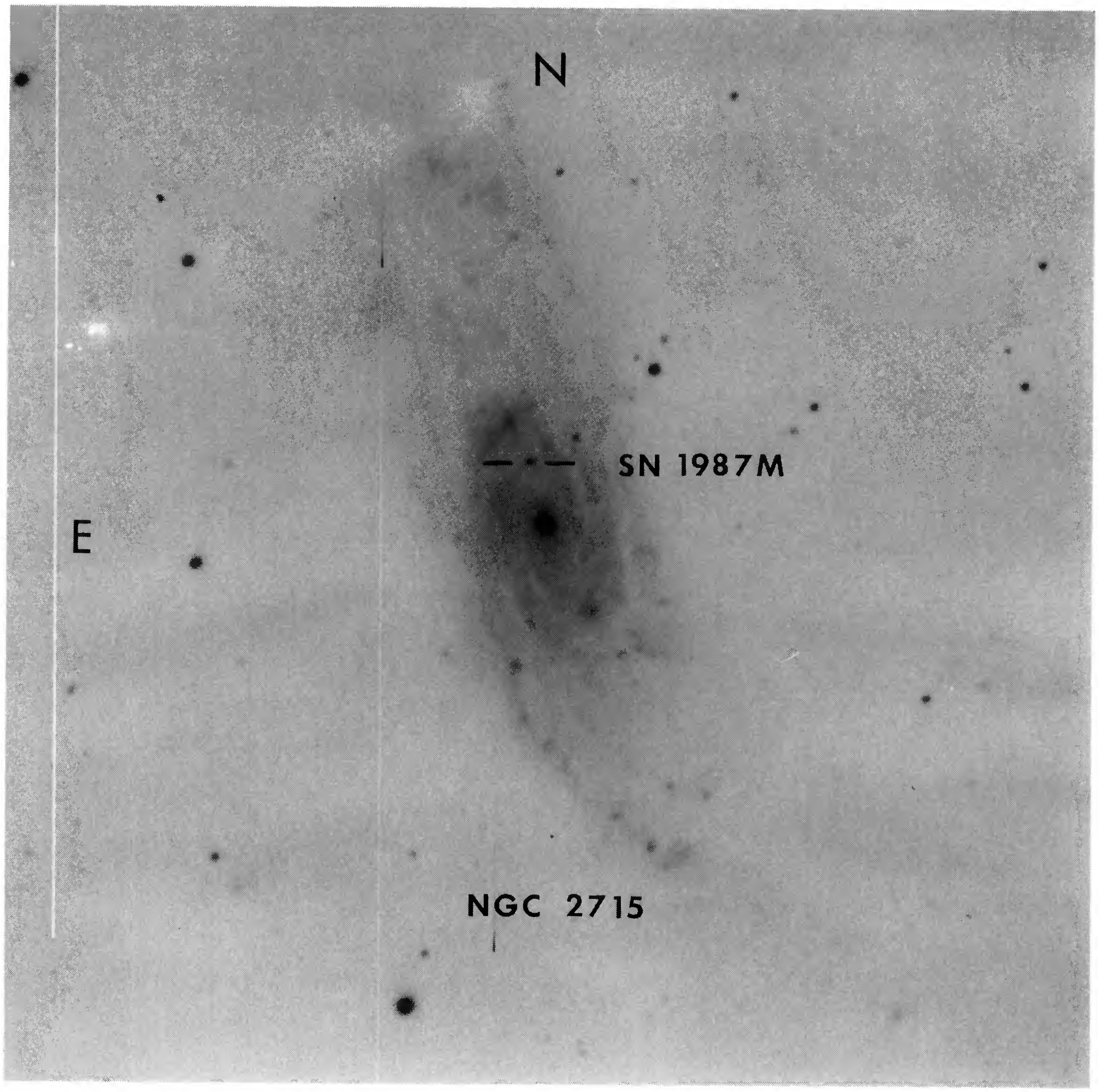

FIG. 1. CCD image (*r* filter) of NGC 2715 and SN 1987M, obtained on 21 December 1987 UT. Exposure time was 5 min with the Oscar Mayer 1.5 m reflector at Palomar Observatory. North is up, east to the left. The few vertical stripes are partially blocked columns of the CCD. SN 1987M is 4.5″ E and 17.5″ N of the nucleus, ± 1″ in each coordinate. It appears close to a spiral arm, but not on a luminous H II region.

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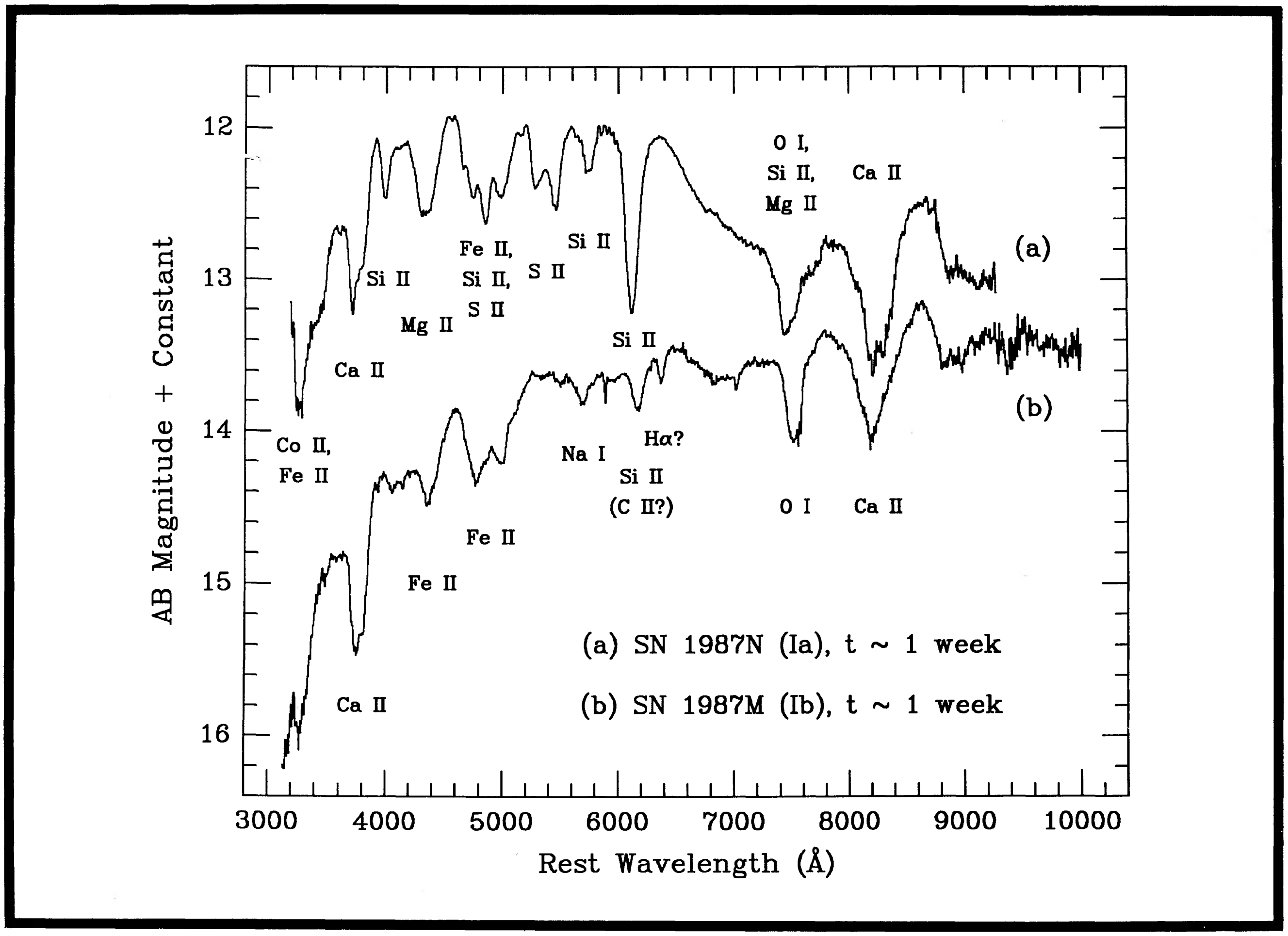

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