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THE SUPERNOVA 1983k IN NGC 4699: CLUES TO THE NATURE OF TYPE II PROGENITORS

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ABSTRACT

Optical spectrographic and photometric observations of the Type II supernova 1983k in NGC 4699 are presented. For the first time, high quality spectra have been obtained of a Type II supernova before it reached maximum light. The first of these, taken nearly 10 days before maximum, showed high-ionization N III and He II emission lines atop a strong blue continuum. Near maximum, the emission lines disappeared, leaving weak H I, He I, and Ca II absorption lines. By a month after maximum, the spectra were dominated by P Cygni–like emission lines of H I, again consistent with a Type II classification.

The light curve, which showed a very extended peak, and the absorption lines seen at maximum provide independent evidence that the progenitor of this supernova had an extensive, preexisting circumstellar shell. The strong nitrogen lines seen before maximum imply that the surface layers of the progenitor were significantly overabundant in this element. Both of these characteristics are consistent with the progenitor having been an exploding Wolf-Rayet star or a red supergiant.

Subject headings: galaxies: individual — stars: supernovae

I. INTRODUCTION

Although considerable data have been amassed over the years covering the postmaximum phases of supernovae, by the very nature of these objects, observations at premaximum and maximum have proved much more elusive. This is particularly true for Type II supernovae where virtually nothing is known of the premaximum properties, and only a handful of low-dispersion spectra have ever been obtained at maximum. The payoff of actually catching a Type II supernova on the rise is potentially very big. For example, from the behavior of the light curve at these earliest epochs, it is possible to learn much about the structure of the progenitor star before it exploded. Lacking such data, the evidence to date regarding the nature of Type II supernova progenitors has been largely indirect and circumstantial.

The discovery in mid-1983 of a Type II supernova in the outer regions (3′.3 NE of the nucleus) of the Sab galaxy NGC 4699 more than 2 weeks before it finally reached maximum offered an unprecedented opportunity to study a member of this class of objects at such an early stage. The supernova, designated SN 1983k, was found by M. Wischnjewsky on 1983 June 6 (UT) on a plate taken during the supernova search program of the Cerro Calan Observatory (see Maza *et al.* 1981). The magnitude on the discovery plate was approximately 17, and a subsequent plate taken on June 10 (UT) showed the supernova to have brightened to approximately 13th magnitude (Maza 1983). We obtained our first spectrum on June 14 and followed the object almost nightly through maximum, which did not occur for nearly 10 more days.

In this paper, we present these unique spectra along with the light curve obtained of SN 1983k through the first three months after discovery. The premaximum spectrum was dominated by intense H I, He II, and N III emission lines which abruptly gave way to a continuous spectrum with weak H I, He I, and Ca II absorption lines. Possible interpretations of these features are discussed, and the nature of the progenitor star in the light of these new data is considered.

II. OBSERVATIONS

The first three spectra of SN 1983k were obtained on the nights of June 14, 16, and 17 (UT) by M. T. R. with a SIT Vidicon detector (see Atwood *et al.* 1979) on the Cassegrain spectrograph of the Cerro Tololo Inter-American Observatory (CTIO) 1.5 m telescope. These observations covered the approximate wavelength range $\lambda\lambda$4000–7000 at a resolution of 8.5 Å. A slit width of 3″.7 was employed. Two postmaximum spectra were acquired a month later by M. M. P. on the nights of July 16 and 18 (UT) with the same telescope and equipment. Slit widths of 3″.7 and 9″.2 were used this time, with the wider one allowing more accurate spectrophotometry.

Between June 17 and 27 (UT), V. S. N. obtained eight blue photographic spectra with the Cassegrain spectrograph plus image tube attached to the 1 m Yale telescope at CTIO. Two additional blue spectra of the supernova, and one also of the nucleus of NGC 4699, were taken during a later run by V. S. N. on August 1 and 2 (UT). These spectra, which had a reciprocal dispersion of 45 Å mm^{-1}, were widened to 1 mm and recorded on Kodak IIIa-J emulsion baked with forming gas.The plates were developed together with a spot sensitometer intensity calibration plate in D-19.

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The SIT Vidicon spectra were reduced and calibrated using the CTIO La Serena computing facilities. The flux scale was determined from standard star observations made the same night. The photographic spectra were measured for the determination of radial velocities at the Instituto de Astronomia y Fisica del Espacio, Buenos Aires, with a Grant oscilloscope display engine, with which digitized intensity tracings were also made.

A light curve in B was obtained for SN 1983k through photographic observations made with the Cerro Roble 70 cm Maksutov and the CTIO 60 cm Curtis Schmidt telescopes, photoelectric measurements made with the CTIO 60 cm Lowell telescope, and CCD images taken at the prime focus of the CTIO 4 m telescope. A fewer number of measurements were obtained in V. These data will be presented in more detail in a later paper (Maza *et al.*, in preparation).

III. RESULTS

The blue light curve of supernova SN 1983k covering the period during which our spectra were obtained is displayed in Figure 1. Shown in the same figure are the $B-V$ color measurements acquired over the same dates. The plateau in the B light curve after maximum identifies the supernova as most likely belonging to the so-called P (plateau) class of Type II supernova (Barbon, Ciatti, and Rosino 1979). Indeed, the overall shapes of both the B and $B-V$ curves are in excellent agreement with the mean curves for this class. Maximum light occurred on 1983 June 23 ± 2 (UT) when the brightness reached an estimated value of $B = 12.4 \pm 0.1$ mag. As SN 1983k was located far outside the main body of NGC 4699 (see Fig. 5 and § IV), the correction to this magnitude due to extinction within NGC 4699 itself is likely to be negligible. The foreground reddening due to our own Galaxy estimated from the neutral hydrogen column density in the same direction is $A_B = 0.09$ mag (Burstein and Heiles 1984). Hence, for a corrected distance modulus of 30.4 mag for NGC 4699 (de Vaucouleurs 1975), which is a member of the southern extension (Virgo II) of the Virgo cluster, SN 1983k reached an absolute magnitude of $M_{B_0} \approx -18.1$ mag. This value is brighter than the mean for Type II supernovae (Barbon, Ciatti, and Rosino 1979), but is not without precedent (e.g., see de Vaucouleurs *et al.* 1981; Buta 1982).

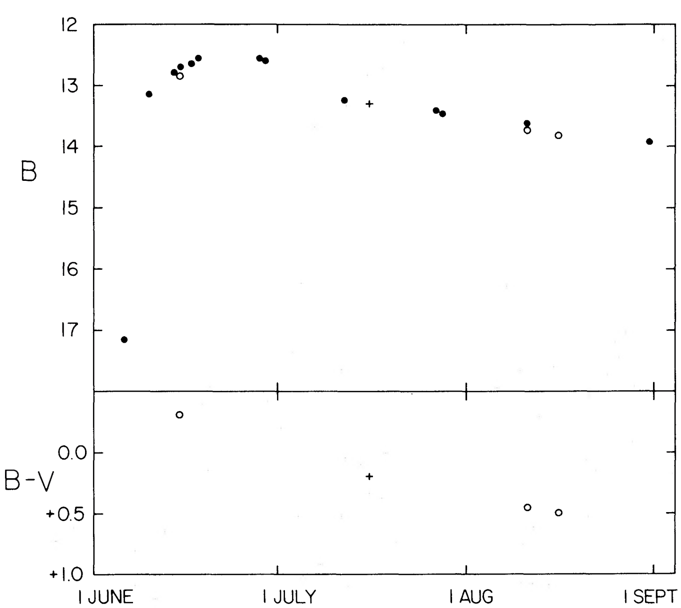

FIG. 1.—*(above)* B light curve of SN 1983k from 1983 June 6 to August 31. Filled circles are photographic measurements, open circles, photoelectric or CCD photometry, and the cross, a value derived from SIT Vidicon spectrophotometry. *(below)* Evolution of the $B-V$ color. Symbols are the same as for the light curve measurements.

The first four spectra of SN 1983k, taken more than a week before maximum light, show several strong, broad emission lines atop a very blue continuum (see Figs. 2 and 3). The most prominent lines are readily identified with He II λ4686 and λ5411, the H I Balmer series (plus a contribution of He II emission), and the N III $\lambda\lambda$4634, 4640, 4641 blend, and the overall character is one of quite high excitation, strikingly similar to that observed in Wolf-Rayet stars of type WN6–7. The higher dispersion 1 m telescope spectrum taken on June 17 shows, in addition, weak and relatively narrow blueshifted absorption present in the H I Balmer lines. There is definite evidence in the SIT Vidicon spectra for changes in the relative intensities of these lines from night to night, especially in the case of the N III λ4640 blend when compared to He II λ4686. The very blue continuum at this early epoch is consistent with a blackbody temperature somewhat in excess of 20,000 K.

Measurement of the peak of the He II λ4686 emission line in the 1 m spectrum of June 17 yields a helicentric radial velocity of $+577$ km s^{-1}. The N III $\lambda\lambda$4634, 4640, 4641 blend gives a value of $+890$ km s^{-1} if the wavelength of the strongest member of the multiplet, λ4640, is assumed to correspond to the measured peak. The velocity for the Hγ peak was measured to be $+1116$ km s^{-1}, but the position of this feature is affected by the absorption to the blue. Giving both the N III blend and Hγ half weight, we infer a mean radial velocity for the emission lines of $+790$ km s^{-1}. The heliocentric radial velocity of the nucleus of NGC 4699 as measured from the 1 m spectra is $+1318 \pm 15$ km s^{-1}. This yields a mean velocity for the emission lines with respect to the nucleus of approximately -530 km s^{-1}. However, the supernova was located almost exactly on the major axis of the galaxy, at a projected radius of 11.5 kpc, and so this value must include a substantial component due to galactic rotation. The observations of Mayall and Lindblad (1970) indicate that the NE half of NGC 4699, where the supernova was discovered, has a positive radial velocity with respect to the nucleus, but unfortunately these authors did not publish a complete rotation curve. However, from the observed inclination of NGC 4699 and published rotation curves of other Sa and Sb galaxies (Rubin 1983), we estimate this amount to 160 ± 50 km s^{-1}. Hence, the final radial velocity of the emission lines with respect to the supernova is likely approximately -700 km s^{-1}.

The next six spectra, all taken with the image-tube spectrograph on the 1 m telescope, nicely straddle the maximum of the light curve. By this time the Wolf-Rayet–like emission lines had dramatically disappeared, leaving a strong and still very blue continuum with weak absorption features not unlike those of a B0 star (see Fig. 3). Most of these absorptions can be identified with the H I Balmer series and He I, although there is definite evidence of Ca II H and K as well. The profiles of the H I lines show evidence of P Cygni–like structure, with the overall strengths increasing slowly with time. This phase is consistent with descriptions of the few previous spectra obtained of Type II supernovae at maximum (e.g., see Minkowski 1964), except for the presence of the narrow absorption lines. However, none of the previous spectra were obtained at sufficient wavelength resolution to detect such weak features.

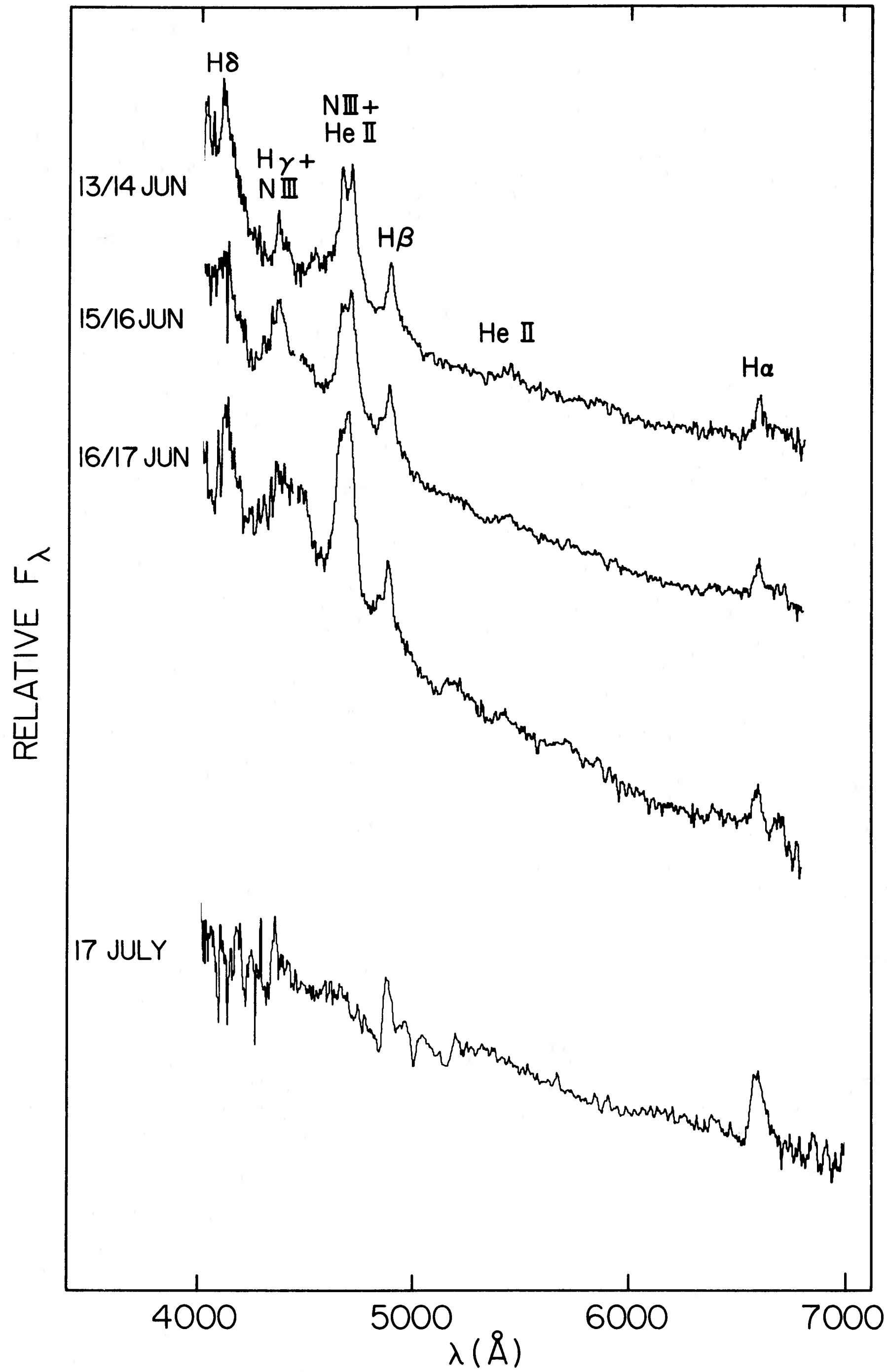

FIG. 2.—SIT Vidicon spectra of SN 1983k obtained with the CTIO 1.5 m telescope in 1983 June and July. The July spectrum is the average of observations made on 16 and 18 July (UT).

It seems likely that the H I absorption lines observed at this phase are related to the weak blueshifted absorptions seen in the first 1 m spectrum when the Wolf-Rayet–like emission lines were still present. This is supported by the radial velocity measurements, which show a steadily increasing blueshift of these features over the 11 day period from premaximum to maximum covered by the 1 m spectra. The mean of the Hγ and Hδ measurements are plotted as a function of time relative to the nuclear velocity of NGC 4699 (and corrected for the assumed contribution of galactic rotation) in Figure 4, and indicate an approximately linear acceleration rate of 40 km s^{-1} day^{-1}. The velocities for this absorption are quite low and the line profiles much narrower in comparison with the absorption lines observed in the postmaximum spectra of August 1 and 2 (see below), and those seen in other Type II supernovae at comparably late epochs (e.g., see Kirshner and Kwan 1974).

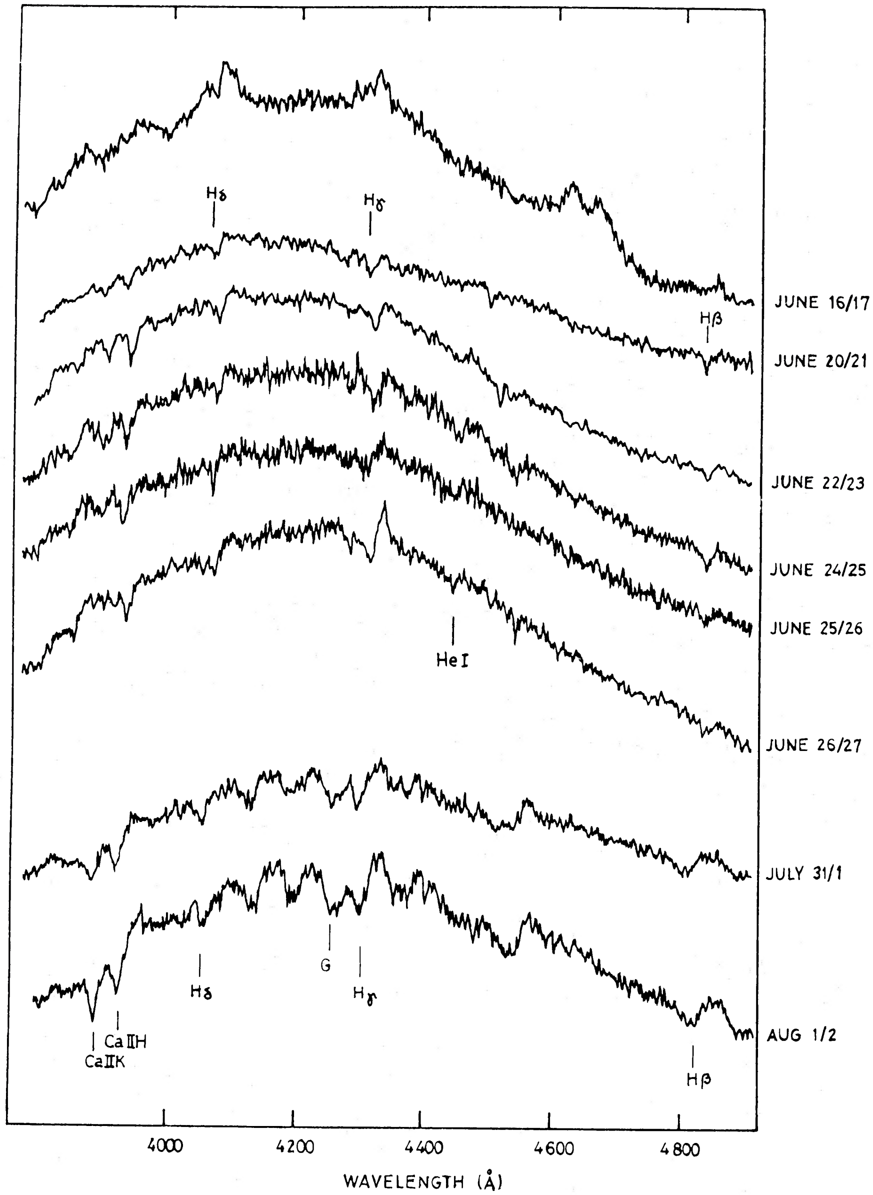

FIG. 3.—Intensity tracings of photographic image-tube spectra of SN 1983k taken with the CTIO 1 m telescope from 1983 June 17 to August 2

However, similar weak, narrow H I absorption lines were observed just after maximum in the Type II supernovae 1979c in M100 (Branch *et al.* 1981).

By the time of the July SIT Vidicon observations (24 days after maximum), the overall appearance of the spectrum of SN 1983k closely resembled that of many other Type II supernovae at the same stage (see Fig. 2). A number of absorption lines are seen, which are due both to H I and probably Fe II. However, the most striking feature is the Hα emission which, like that of the Type II supernova 1979c in M100, had developed a notable red asymmetry with little evidence of the P Cygni–like absorption seen at Hγ and Hβ. The total blue extent of the Hα emission line profile is of the order of 4500 km s^{-1}. The continuum by this time had grown considerably redder and was consistent with a blackbody of temperature of approximately 9000 K.

The final spectra obtained on August 1 and 2 (roughly 40 days after maximum) with the 1 m telescope show still further development of the absorption and emission features in the blue (see Fig. 3). The spectrum at this epoch again compares well with those of other Type II supernovae such as 1969l and 1970g (Kirshner and Kwan 1974). Besides the aforementioned H I and Fe II lines, our spectra clearly show strong Ca II H and K absorption as well as a prominent feature at an observed wavelength of λ4289. From comparison of this spectrum with that of the nucleus of NGC 4699 (shifted to the supernova radial velocity), the latter absorption is best identified with the G band. The P Cygni–like troughs of the H I Balmer lines have become somewhat broader, and yield expansion velocities at this phase of approximately 2700 km s^{-1} at the absorption minimum (see Fig. 4).

IV. DISCUSSION

The light curve and postmaximum spectra of SN 1983k in NGC 4699 show this to have been a fairly typical Type II event. Type II supernovae are strongly correlated with the

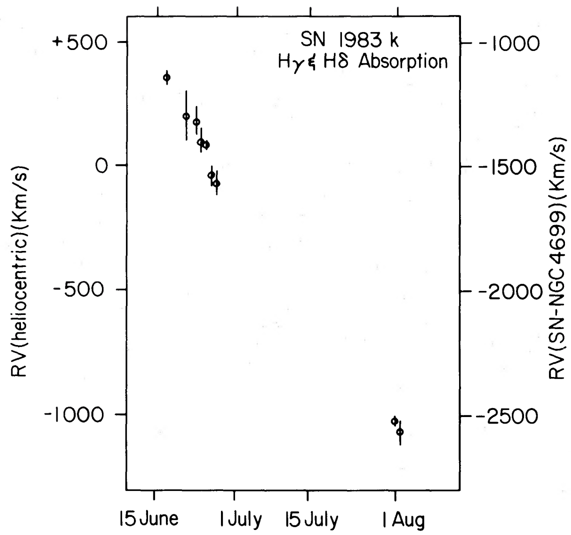

FIG. 4.—Heliocentric radial velocity measurements of the Hδ and Hγ absorption lines. The right-hand scale gives the velocities corrected for the measured redshift of the nucleus of NGC 4699 (+1318 km s^{-1}) plus a component due to the rotation of NGC 4699 at the position of the supernova (assumed to be +160 km s^{-1}).

arms of spiral galaxies (Maza and van den Bergh 1976) and, more specifically, with the nebulous knots which outline the spiral arms (Huang, Dame, and Thaddeus 1984). Based on this fact, it is generally believed that the progenitors of Type II supernovae are massive stars ($M > 8\ M_{\odot}$) that evolve so rapidly that they never appear far from sites of star formation. This belief has been strengthened over the years by the theoretical studies of a number of authors (see Falk and Arnett 1977, and references therein) which have shown that the gross characteristics of the postmaximum light curve and kinematics of Type II supernovae can be succesfully explained by models in which a shock wave generated by core collapse traverses the envelope of a red supergiant.

Our observations of SN 1983k provide new and important constraints on the nature of the progenitor stars of at least some Type II supernovae. The fact that the light curve agrees well with the shock models strongly suggests that the progenitor was indeed a massive star with a highly extended envelope ($R \approx 3 \times 10^{13}$–$10^{14}$ cm). Moreover, both the light curve and spectra at maximum show clear evidence for a preexisting circumstellar shell of material, implying that the progenitor of SN 1983k had undergone significant mass loss. Figure 1 shows that the B light curve was characterized by a well-defined and broad peak, with maximum light having taken more than 2 weeks to reach after discovery. It should be emphasized that this is the first clear-cut observation of such an extended light peak in a Type II supernova. As discussed by Falk and Arnett (1973, 1977) in the context of shock wave models, this type of behavior at maximum light requires the presence of an extended circumstellar shell ($R \approx 10^{15}$ cm) since models with a red giant–like envelope and *no* circumstellar shell produce an unacceptably narrow light peak. Likewise, the weak H I Balmer and He I absorption-line spectrum observed at maximum light almost certainly was produced in a preexisting circumstellar shell. The narrow starlike profiles of these absorption features, their initially low blueshift (~ -1000 km s^{-1}), and apparently accelerating velocities (see Fig. 4) are inconsistent with the expected rapid expansion of the progenitor star envelope deduced from both the $B-V$ colors and the Hα emission line profile in the postmaximum spectra. The acceleration of these absorption lines can perhaps be understood as an interaction between the shell material and the radiation emerging from the supernova photosphere or may be merely an effect produced by rapidly changing optical depths in a previously expanding circumstellar shell.

The broadness and asymmetry of the Hα emission in the July SIT spectra is presumably due in large part to the expansion of the supernova envelope. In this respect, it is interesting to note that the width of the emission line profile in 1983k is roughly half that observed in SN 1979c in M100 at a corresponding phase (Branch *et al.* 1981), which suggests that the expansion velocity of the photosphere was less by a similar factor. This is supported by the velocities of the P Cygni–like absorption lines in the August 1 and 2 postmaximum spectra of SN 1983k which are considerably lower than measurements of the SN 1979c lines at a similar epoch. Further corroborating evidence is found in the B and V light curves of both supernovae. Under the assumption that the observed continuum is well represented by a blackbody, these data can be used to derive the evolution of the angular radius of the photosphere (see Kirshner and Kwan 1974). Since M100 (which lies in the main Virgo cluster), and NGC 4699 are probably at comparable distances, any differences between the observed rate of increase of the angular radius should directly reflect a difference in expansion velocities. In fact, we find that the rate of increase of the angular radius of SN 1983k over the first two months of observation was approximately 30% smaller than that measured for SN 1979c (Branch *et al.* 1981).

The strong Wolf-Rayet–like spectra seen in the first premaximum observations represent a hitherto unobserved phase in the development of Type II supernovae. Although detailed knowledge of physical conditions is required to accurately determine abundances, the prominent nitrogen lines very likely imply that at least some of the gas in the progenitor star was significantly nitrogen enriched. This spectrum abruptly disappeared at the approach of maximum light, which is the point at which the shock wave most likely emerged at the photosphere (Falk and Arnett 1977). Thus, it seems probable that the nitrogen-rich material lay either at the surface or perhaps in the circumstellar shell of the progenitor. This is supported by the blueshift of the emission-line peaks at this stage, which is most readily explained if the emission-line region was at or near the outer surface of the expanding progenitor envelope. *We conclude that SN 1983k most likely resulted from a massive star with an extended envelope, which had undergone significant mass loss prior to exploding and whose surface layers contained nitrogen-enriched material.*

Of course, the Wolf-Rayet–like premaximum spectrum raises the obvious question of whether the progenitor could have been a Wolf-Rayet star. Maeder and Lequeux (1982) have concluded that the evolution of many such stars is likely to culminate in a supernovae explosion, and that one of every three to seven supernovae in our Galaxy had Wolf-Rayet progenitors. However, it is equally possible that the Wolf-Rayet–like spectrum resulted from the physical conditions produced by the supernova explosion, and was not a property of the progenitor. Many authors have considered the most likely progenitors of type II supernovae to be massive red supergiants. In fact, the values of the radial velocities measured from the premaximum and maximum absorption, and later from the postmaximum Hα emission line width agree surprisingly well with the photospheric velocities predicted by model F of Falk and Arnett (1977) for a 7 $M_\odot$ red supergiant with a 1.7 $M_\odot$ circumstellar shell. Also, the properties of the light curve of SN 1983k are consistent with a red supergiant progenitor, particularly since there is now considerable evidence that the envelopes of such stars do have significant overabundances of nitrogen with respect to other metals (Luck 1978). A Wolf-Rayet star probably would not have a sufficiently large envelope to produce light curve peculiarities such as an extended peak, although the high mass loss rates should produce a considerable circumstellar shell. Certainly it would be interesting to calculate shock models with the envelope and shell structures predicted for Wolf-Rayet stars to see whether the light curves could be made to resemble that of SN 1983k.

Finally, it is worth mentioning that the location of SN 1983k in NGC 4699 was somewhat unusual considering that this supernova was unquestionably a Type II event. As already stated, Type II supernovae are rarely found very far from spiral arms, yet SN 1983k occurred in the outermost reaches of NGC 4699 at a projected distance of 11.5 kpc (or 23 kpc if the Sandage and Tammann [1976] value of the distance modulus for the Virgo cluster is assumed). As shown in Figure 5 (Plate 1), deep CCD images obtained with the CTIO 4 m telescope show no evidence of either H II regions or spiral arms at this distance. This location is even more extreme than that of the Type II supernova 1969l, which was singled out for attention by Tammann (1974) because of its position in the outskirts of NGC 1058. However, it should be remembered that in our own Galaxy, at least a few red supergiants and Wolf-Rayet stars are observed out to distances as great as 15 kpc (e.g., see Maeder and Lequeux 1982). Supernova 1983k serves to emphasize, therefore, that star formation in disk galaxies is not entirely restricted to the environs of spiral arms.

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REFERENCES

Atwood, B., Ingerson, T., Lasker, B. M., and Osmer, P. S. 1979, *Pub. A.S.P.*, **91**, 120.
Barbon, R., Ciatti, F., and Rosino, L. 1979, *Astr. Ap.*, **72**, 287.
Branch, D., Falk, S. W., McCall, M. L., Rybski, P., Uomoto, A. K., and Wills, B. J. 1981, *Ap. J.*, **244**, 780.
Burstein, D., and Heiles, C. 1984, *Ap. J. Suppl.*, **54**, 33.
Buta, R. J. 1982, *Pub. A.S.P.*, **94**, 578.
de Vaucouleurs, G. 1975, in *Stars and Stellar Systems*, Vol. **9**, *Galaxies and the Universe*, ed. A. Sandage, M. Sandage, and J. Kristian (Chicago: University of Chicago Press), p. 557.
de Vaucouleurs, G., de Vaucouleurs, A., Buta, R., Ables, H. D., and Hewitt, A. V. 1981, *Pub. A.S.P.*, **93**, 36.
Falk, S. W., and Arnett, W. D. 1973, *Ap. J. (Letters)*, **180**, L65.
———. 1977, *Ap. J. Suppl.*, **33**, 515.
Huang, Y.-L., Dame, T. M., and Thaddeus, P. 1983, *Bull. AAS*, **15**, 965.
Kirshner, R. P., and Kwan, J. 1974, *Ap. J.*, **193**, 27.
Luck, R. E. 1978, *Ap. J.*, **219**, 148.
Maeder, A., and Lequeux, J. 1982, *Astr. Ap.*, **114**, 409.
Mayall, N. U., and Linblad, P. O. 1970, *Astr. Ap.*, **8**, 364.
Maza, J. 1983, *IAU Circ.*, No. 3827.
Maza, J., and van den Bergh, S. 1976, *Ap. J.*, **204**, 519.
Maza, J., Wischnjewsky, M., Torres, C., Gonzalez, I., Costa, E., and Wroblewski, H. 1981, *Pub. A.S.P.*, **93**, 239.
Minkowski, R. 1964, *Ann. Rev. Astr. Ap.*, **2**, 247.
Rubin, V. C. 1983, in *IAU Symposium 100, Internal Kinematics and Dynamics of Galaxies*, ed. E. Athanassoula (Dordrecht: Reidel), p. 3.
Sandage, A., and Tammann, G. A. 1976, *Ap. J.*, **210**, 7.
Tammann, G. A. 1974, in *Supernovae and Supernova Remnants*, ed. C. B. Cosmovici (Dordrecht: Reidel), p. 215.

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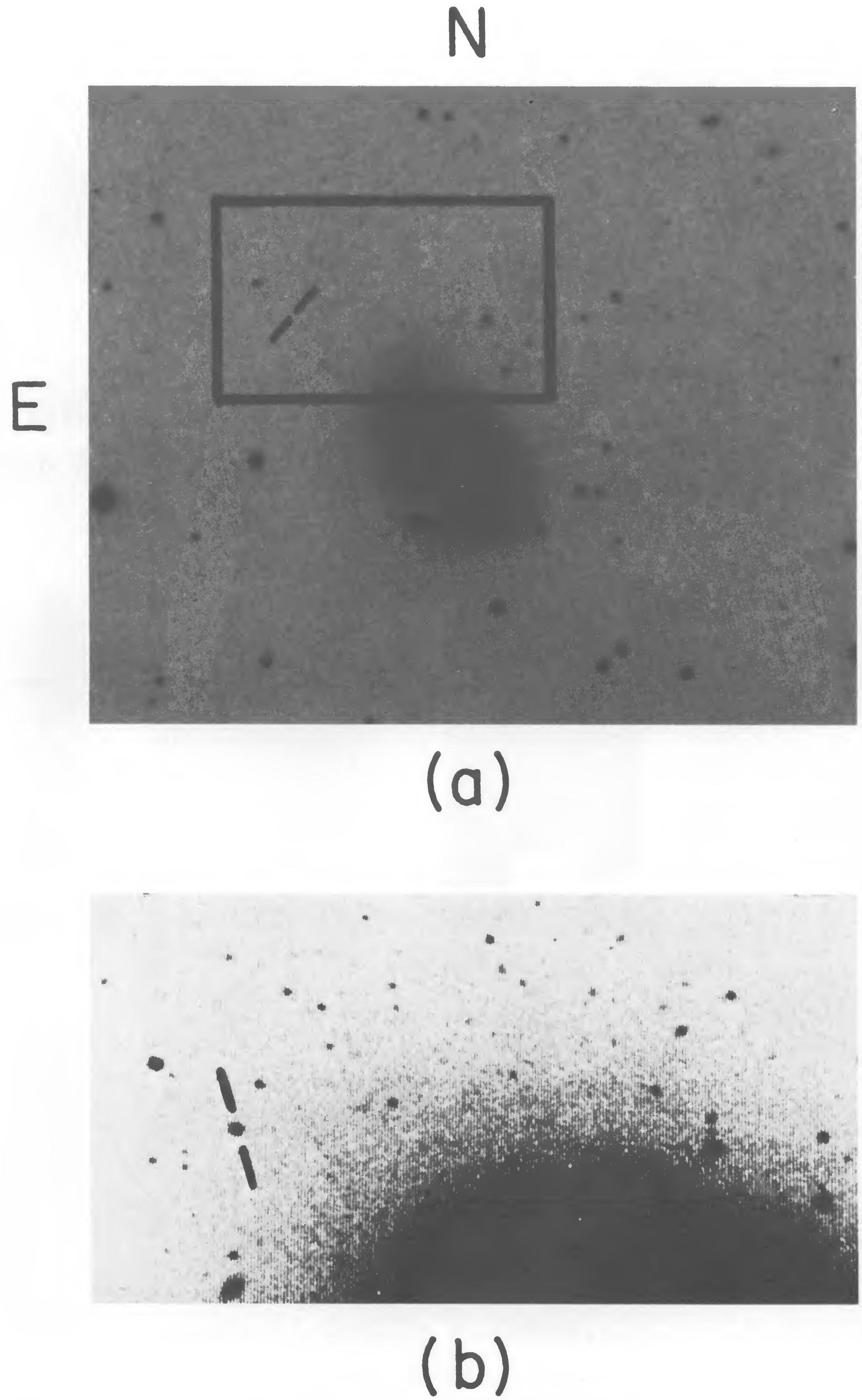

FIG. 5.—(*a*) Reproduction of the O print of the National Geographic-Palomar Sky Survey plate showing the field of NGC 4699. The position of SN 1983k has been indicated, along with a rectangle showing the area covered by the CCD image shown in Fig. 5*b*. The distance from the supernova to the galaxy nucleus is 3$'$.3. (*b*) Deep *B* image of SN 1983k obtained with an RCA CCD at the prime focus of the CTIO 4 m telescope on 1983 December 11. Exposure time was 10 minutes, and the magnitude of the supernova was $B = 18.8$ mag.

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