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SUPERNOVA 1987A IN THE LARGE MAGELLANIC CLOUD: INITIAL OBSERVATIONS AT CERRO TOLOLO

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ABSTRACT

Optical and infrared observations of SN 1987A in the Large Magellanic Cloud (LMC) covering the first 7 weeks after discovery are presented. Over this period, the spectra were dominated by strong P Cygni emission lines of hydrogen, making this supernova a Type II event. Nevertheless, nearly all aspects of the behavior of SN 1987A have been unusual. The optical spectral and color evolution, while closely resembling that of a normal "plateau" Type II supernova, took place at a rate that was ~ 10 times faster than normal. The expansion velocity of the photosphere, which was unusually high at first, decreased more rapidly than usual by a similar factor. Measurements of several presupernova plates and an objective-prism spectrum of the suspected progenitor, Sanduleak −69°202, rule out the presence of a previously undetected luminous red supergiant, but do suggest the existence of a less luminous red star.

In spite of its very rapid spectral, color, and velocity evolution, SN 1987A continues to brighten slowly at visual wavelengths. This behavior suggests an additional source of energy input, with the most obvious candidate being the radioactive decay of ^{56}Co.

Subject headings: galaxies: Magellanic Clouds — infrared: spectra — photometry — spectrophotometry — stars: supernovae

I. INTRODUCTION

Immediately following the announcement of the outburst of SN 1987A in the LMC (Shelton 1987), Cerro Tololo Inter-American Observatory (CTIO) began a program of systematic observations of the supernova. Because of our situation in which certain instruments are permanently mounted on different telescopes, we have concentrated on obtaining nightly *UBVRI* photometry and low-resolution (~ 5 Å) optical spectrophotometry. Limited spectroscopic observations at infrared wavelengths have also been made. Although SN 1987A is only 7 weeks past outburst at this point, it is already clear that many of its characteristics are unlike those of any other previously observed supernova. As a result of the extraordinary interest generated by this event, we are presenting the following initial summary of our observations. A more detailed presentation and analysis of the data will be given in future papers.

II. SPECTROPHOTOMETRY

The first spectrum of SN 1987A obtained at CTIO is shown at the top of Figure 1. This observation was made on February 25.1 UT with a coated GEC CCD on the 1.5 m telescope ~ 24 hr after discovery, and 40 hr after the supernova was first noticed to have brightened (McNaught 1987). By this time, the spectrum had already developed strong P Cygni emission lines in the H I Balmer series and He I λ5876. The presence of hydrogen makes this supernova, by definition, a Type II event.

Nightly spectrophotometry was begun on February 27 covering the wavelength range λλ3700–7200 with the 2D-Frutti two-dimensional photon counting detector on the 1 m telescope. Sample spectra, spaced at ~ 1 week intervals, are displayed in Figure 1. The evolution of the line spectrum can be described in general terms as one of decreasing excitation, consistent with the changes in the continuum. During the first week, the absorption lines originated from moderately highly excited levels, with $\chi > 10$ eV, at a time when the continuum colors were similar to those of earlier type stars. With each day, however, the H I Balmer and He I line strengths decreased, the continuum reddened, until by the end of the second week, strong lines were also being produced by very

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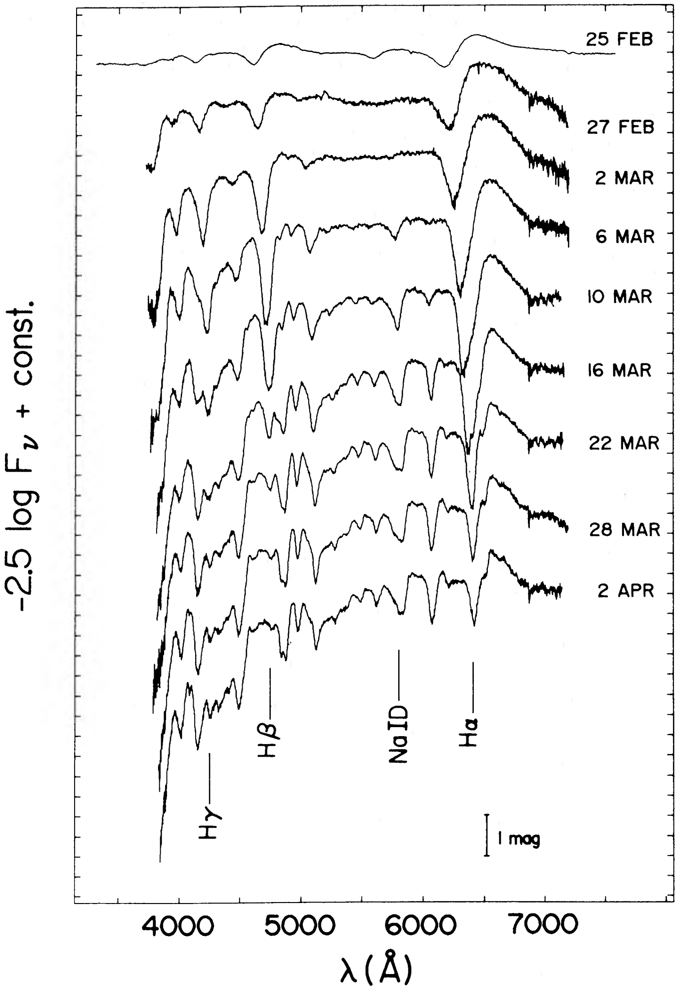

FIG. 1.—Spectral scans of SN 1987A obtained at regular intervals during the 6 weeks following outburst. Initially, the Balmer lines were very strong, but had weakened by mid-March. The low-excitation lines which appeared after that time, and eventually dominated the spectrum in early April, are mostly Fe II multiplets.

low excitation ($\chi < 3$ eV) transitions of the heavy elements. By April 2, the Balmer lines had essentially disappeared except for Hα, and the entire absorption line spectrum was characterized by a low excitation temperature, $T \leq 5000$ K, since all of the lines originate near the ground states. The ionization state of the gas was higher than one would expect for this temperature, with singly ionized metals prevalent, because the rapidly decreasing density causes a non–LTE situation which retards recombination.

In somewhat more detail, the major spectral changes from February 25 to April 2 can be summarized as follows:

February 25.—Strong P Cygni emission lines in the H I Balmer series and He I λ5876 are observed. The continuum energy distribution is quite blue.

March 2.—The H I Balmer emission and absorption lines have grown stronger and narrower, while He I λ5876 has disappeared. Strong Ca II H and K absorption is apparent, as are several weaker Fe II absorption features. The continuum has become noticeably redder.

March 10–16.—The P Cygni Hα absorption has reached maximum depth, whereas the Hβ and Hγ absorption have already begun to decrease in strength. Many absorption features, virtually all due to Fe II, are now visible. The Na I D lines have increased substantially in strength and the continuum has grown still redder.

March 22–28.—Blends of P Cygni emission lines of H I, Na I, Ca II, and Fe II cover virtually the entire optical spectrum. The depth of the P Cygni Hα absorption is now clearly decreasing with time. A weak bump at ~ 6470 Å has developed in the Hα profile. This may be an indication that distortions in the gas outflow are developing due to dynamical instabilities. However, no corresponding structure is apparent at Hβ, so that alternative identifications such as the λ6456 transition of Fe II multiplet 74 cannot be discarded.

March 28–April 2.—The spectrum is essentially identical to that of March 22–28, except in the vicinity of Hα. The emission feature at ~ 6470 Å has grown stronger, and a second bump has appeared at ~ 6670 Å.

The P Cygni absorption components of the spectral lines showed progressive nightly drifts toward redder wavelengths, as did the peak of the Hα emission (see Fig. 1). Although such shifts are characteristic of Type II supernovae, the time scale for change was, once again, much more rapid than normal. Expansion velocities inferred from the absorption minima of Hα, Hβ, Hγ, Na I D, and Fe II λλ5018, 5169 are plotted as a function of time in Figure 2. The value of $-18{,}000$ km s^{-1} measured for Hα in the first spectrum (February 25) is extreme, and to our knowledge has not been equaled by any other Type II supernova. Note that the wings of the Hα emission and absorption in the same spectrum extend to nearly $\pm 30{,}000$ km s^{-1}.

Figure 2 shows that, for any given night, the Hα, Hβ, and Hγ minima yielded progressively lower velocities, and still smaller values were derived from the Na I D and Fe II lines. This effect is most likely due to differences in opacity. The lower the opacity, the deeper one is looking into the supernova envelope where the expansion velocity is less. Such pronounced "stratification" in the spectral line formation must be corrected for in any attempt to determine the distance to SN 1987A via the modified Baade-Wesselink method (Kirshner and Kwan 1974).

Spectra in the wavelength range of 1–3 μm were obtained on March 9 and 10 at the 1.5 m telescope with the IR 8-channel cooled grating spectrometer at a resolution of $\lambda/\Delta\lambda = 1{,}000$. The summed data from these observations are shown in Figure 3. The IR spectrum is fairly simple, consisting of a continuum and the lower members of the Paschen and Brackett series of hydrogen. No lines of elements other than H I are identifiable. As noted by others (Allen and Bailey 1987; Meikle, Graham, and Gregory 1987), the blueshifted minima of the P Cygni profiles of these lines yield velocities that are considerably lower than those observed for the Balmer series on the same date. This is consistent with the fact that the IR lines arise from higher energy levels and, hence, should have lower opacities.

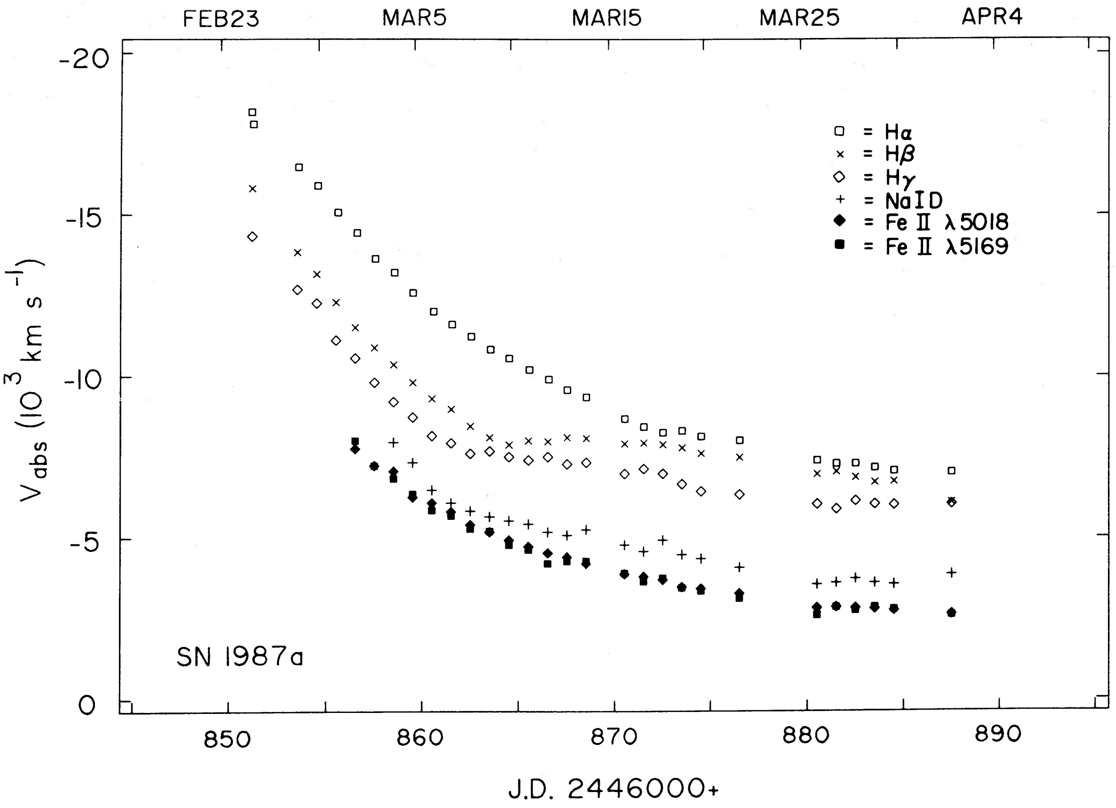

FIG. 2.—Velocities deduced from the stronger, unblended absorption lines. The velocities all decreased with time, as one saw deeper into the envelope. Note that the metals and higher Balmer lines showed systematically lower velocities. After the first week in March, the Hβ and Hγ velocities were affected by blending with Fe II lines.

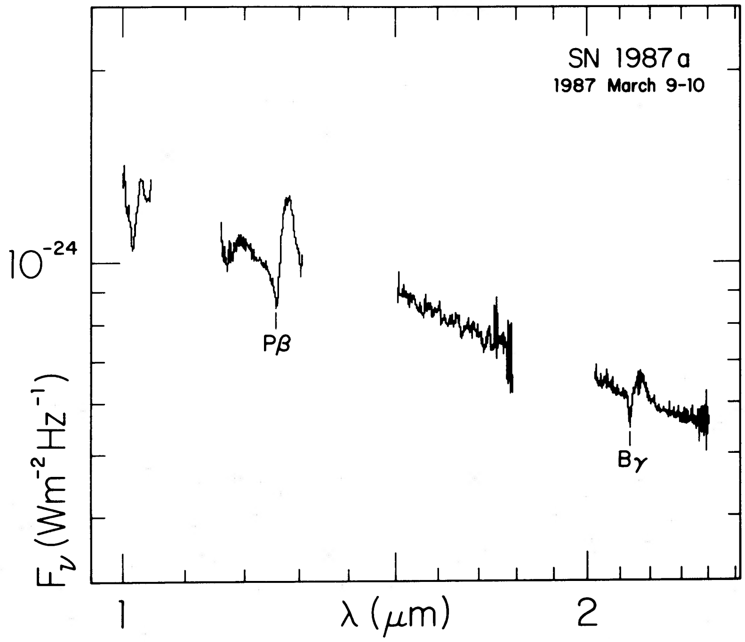

FIG. 3.—The infrared spectrum of SN 1987A on March 9–10 in the 1–3 μm wavelength region. The complexity of the optical spectrum is not evident in the IR, where only the lowest transitions of the Paschen and Brackett series were observed.

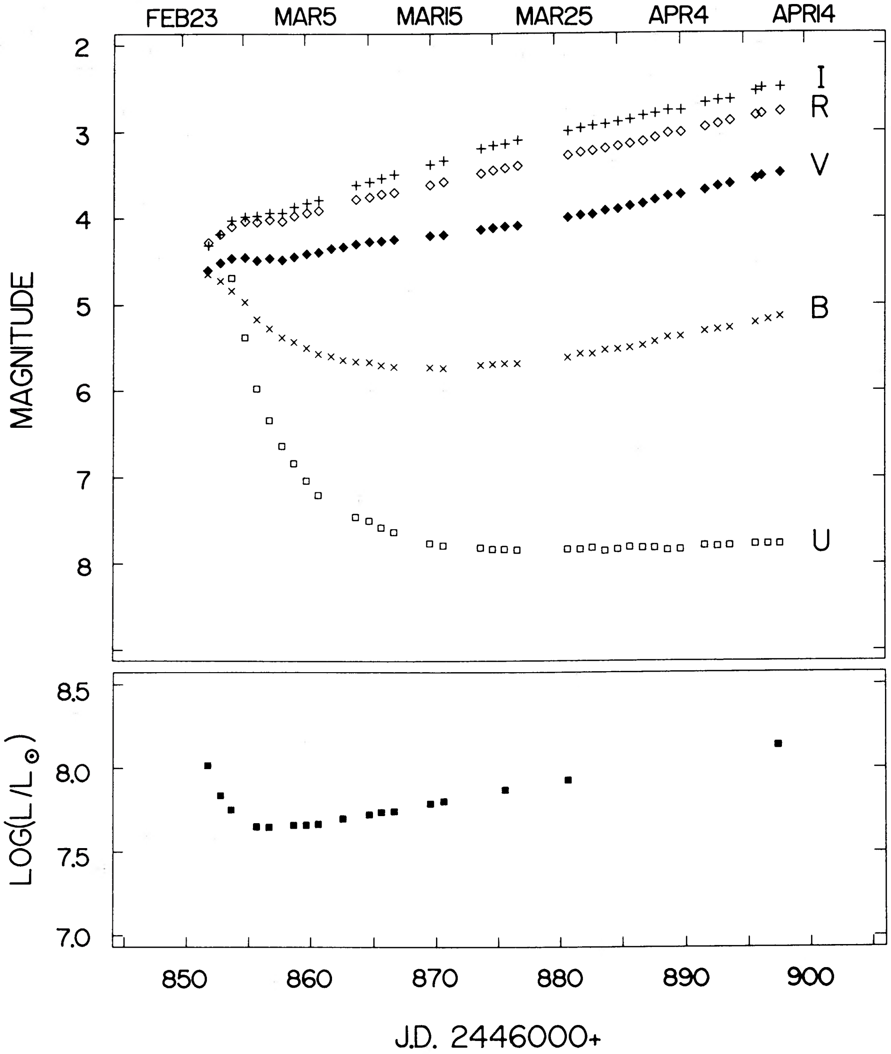

FIG. 4.—(*Upper*) photometric light curves of SN 1987A in the Cousins *UBVRI* system. The steady increase in brightness in all wavelengths longer than *B* is evident. (*Lower*) the bolometric luminosity of the supernova, obtained by integrating all dereddened photometric fluxes from the UV to the IR. The UV data are from the *IUE* results of Kirshner *et al.* (1987), and the *UBVRI* photometry from this paper. The *JHKLMN* data were taken from Bouchet *et al.* (1987), Winkler *et al.* (1987), Cropper *et al.* (1987), Catchpole (1987), Catchpole and Winkler (1987), Ashley and Straw (1987), Meikle, Graham and Gregory (1987), Bailey, Ogura, and Sato (1987), Gregory and Elias (1987), and Malkan and Sun (1987). Of the total reddening $E(B-V) = 0.20$ adopted for the supernova, the foreground was assumed to contribute 0.06 mag and the dust in the LMC the remaining 0.14 mag. For the Galactic foreground, we used the reddening law given by Seaton (1979), and for the LMC, we assumed the average 30 Dor reddening law derived by Fitzpatrick (1985).

III. *UBVRI* PHOTOMETRY

Photoelectric *UBVRI* photometry of SN 1987A in the Cousins system (Cousins 1976) has been obtained nightly at CTIO with the 0.4 m telescope. Light curves in each color are displayed in Figure 4. The initial rise of SN 1987A at visual wavelengths was apparently quite rapid, with the supernova brightening by greater than 5 mag in the 6 hr period between February 23.056–23.443 (McNaught 1987; Madsen 1987). If the neutrino burst detected by the Kamiokande II (Koshiba 1987) and IMB (Svoboda 1987) groups signaled the moment of core bounce, then the rise time in the visual took place in ≤ 3 hr. By the time that observations commenced at CTIO on February 25.1, the supernova was brightening only very slowly in V, R, and I, and had peaked or was already decreasing in U and B. The U brightness declined over 3 mag over the next 2 weeks, but then slowly leveled off to a nearly constant magnitude of ~ 7.8. The blue light curve fell from a peak at $B \approx 4.6$ to a shallow minimum in mid-March at $B \approx 5.7$, but since that time has shown a surprisingly steady increase in brightness of ~ 0.02 mag day^{-1}. The visual light curve rose to a temporary maximum on February 27 at $V \approx 4.45$, declined very slightly for a few days, and then began a fairly steady climb at 0.025 mag day^{-1} which has continued uninterrupted until the present time. The R and I light curves displayed a similar behavior, with the most distinctive features being the small inflections observed around March 2.

Over the first 2 weeks of observation, the UBV light curves (and, hence, the $U-B$ and $B-V$ color evolution) of SN 1987A superficially resembled that of the plateau Type II

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supernova SN 1969L (Ciatti, Rosino, and Bertola 1971). However, we note the following important differences: (1) as in the case of the spectral evolution, the time scale for the color changes in SN 1987A was many times more rapid. (2) The blue light curve implies a reddening-corrected, peak absolute magnitude of $M_B \approx -14.7$, which is 3 mag fainter than the average value for plateau Type II supernovae (Barbon, Ciatti, and Rosino 1979).[3] (3) The steadily increasing V light curve and the slow brightening at B observed since mid-March is entirely without precedent among previously observed supernovae of either Type I or II.

The bolometric luminosity of SN 1987A as calculated from the dereddened *UBVRIJHKLMN* and *IUE* data is plotted as a function of time at the bottom of Figure 4. The flux for the first 3 days after discovery included a substantial contribution in the ultraviolet, and hence the calculated luminosities for these dates are sensitive to the reddening law adopted. However, these uncertainties do not change the general light curve morphology of a steep initial decline followed by a slower, nearly constant brightening at a rate of 0.012 dex day^{-1}. In the 7 weeks since outburst, the supernova has emitted $\sim 1.5 \times 10^{48}$ ergs.

IV. PHOTOGRAPHIC *R* AND *I* PHOTOMETRY OF SANDULEAK −69°202

The position of SN 1987A is coincident to within ~ 0".1 with that of the blue supergiant Sanduleak −69°202 (West *et al.* 1987; White and Malin 1987). In order to measure preoutburst integrated R and I magnitudes of this star and its close neighbors—namely stars 2 and 3 found by Walborn *et al.* (1987) (see also West *et al.* 1987) and possible further component(s)—IRIS photometry was carried out on eight red sensitive and 10 near-infrared sensitive plates taken at CTIO with the Curtis Schmidt telescope during the period 1970–1981. Calibration was made via a photometric sequence obtained recently with a TI CCD detector on the CTIO 1.5 m telescope. Care was taken to establish the sequence as close as possible to the supernova, to include stars that closely matched the brightness of the Sanduleak −69°202 group, and to avoid background emission regions. The preoutburst plates give mean values of $R = 12.02 \pm 0.01$ and $I = 12.06 \pm 0.03$ in the Cousins system, with no evidence for variability.

Combining the mean R and I measurements with Isserstedt's (1975) *UBV* photometry of the Sanduleak −69°202 group, we obtain the total magnitudes and colors listed in column (2) of Table 1. Rousseau *et al.* (1978) list a B3 I class for the brightest component (star 1), but enough is now known about possible companions and about the integrated brightness of the group that we can safely assume luminosity class Ia. Assuming an LMC distance modulus of 18.5 and $E(B-V) = 0.20$ as indicated by the color excesses of nearby OB stars, we infer for star 1 alone the magnitudes listed in column (3) of Table 1. Here we have used the absolute magnitudes and colors listed by Schmidt-Kaler (1965) and Johnson (1966), and conversions to the Cousins system by Bessell (1979).

CTIO 4 m plates taken through narrow-band interference filters centered at 4765 and 6485 Å show star 2 as being relatively faint and bluer than star 1 (Chu 1987, and private communication). In one of our Curtis Schmidt plates taken in excellent seeing, this star has $R = 14.5 \pm 0.5$. It follows that star 2 is most likely a main-sequence star earlier than class B3. The available data suggest type B0 V, and this is assumed in the following discussion. The contribution of this star to the integrated magnitude of the group is small as shown in the fourth column of Table 1, and it is not necessary to know its type with precision. Comparison of columns (2) and (4) of Table 1 shows that these two stars alone suffice to explain the observed *UBV* magnitudes, but that one is left with a relatively small excess flux in R and I.

West *et al.* (1987) estimate that star 3 in the group is not very blue and has $R \approx 16.5 \pm 1.0$. Kirshner *et al.* (1987) have concluded that star 3 is of early type on the basis of its UV spectrum. In either case, the contribution that such a star, if it is on the main sequence, can make to the integrated magnitudes is negligible in all colors. Hence, the observed red excess suggests the presence of yet a fourth star.

According to conventional wisdom, the progenitors of Type II supernovae are massive red supergiants. Column (5) of Table 1 shows the integrated brightness of the group if a K0 Ia star is added to stars 1 and 2. Obviously, this possibility can be eliminated. On similar grounds, we can discard the existence of any red supergiant of luminosity class Iab. In particular, bright late-M supergiants can be rejected because they would show TiO bands that are not observed in CTIO preoutburst near-infrared objective prism plates taken with the Curtis Schmidt telescope. As shown in the last column of Table 1, a less luminous star of K2 or earlier spectral type, e.g. a K2 Ib supergiant, could have existed in the group. However, the possibility that the progenitor was a luminous red supergiant is clearly excluded.

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[3] In this paper, we assume a true distance modulus of 18.5 and a reddening $E(B-V) = 0.20$ (see § IV) for SN 1987A.

TABLE 1

OBSERVED AND ESTIMATED MAGNITUDES FOR THE SANDULEAK −69°202 GROUP

Color	Observed	Star 1[a]	Star 1 + 2[a]	Star 1 + 2[a] +KO Ia	Star 1 + 2[a] +K2 Ib
U	11.63	11.7	11.6	11.4	11.6
B	12.28	12.4	12.3	11.7	12.3
V	12.24	12.3	12.2	10.8	12.1
R	12.02	12.3	12.2	10.3	12.0
I	12.06	12.3	12.2	9.3	11.9

[a] Inferred values.

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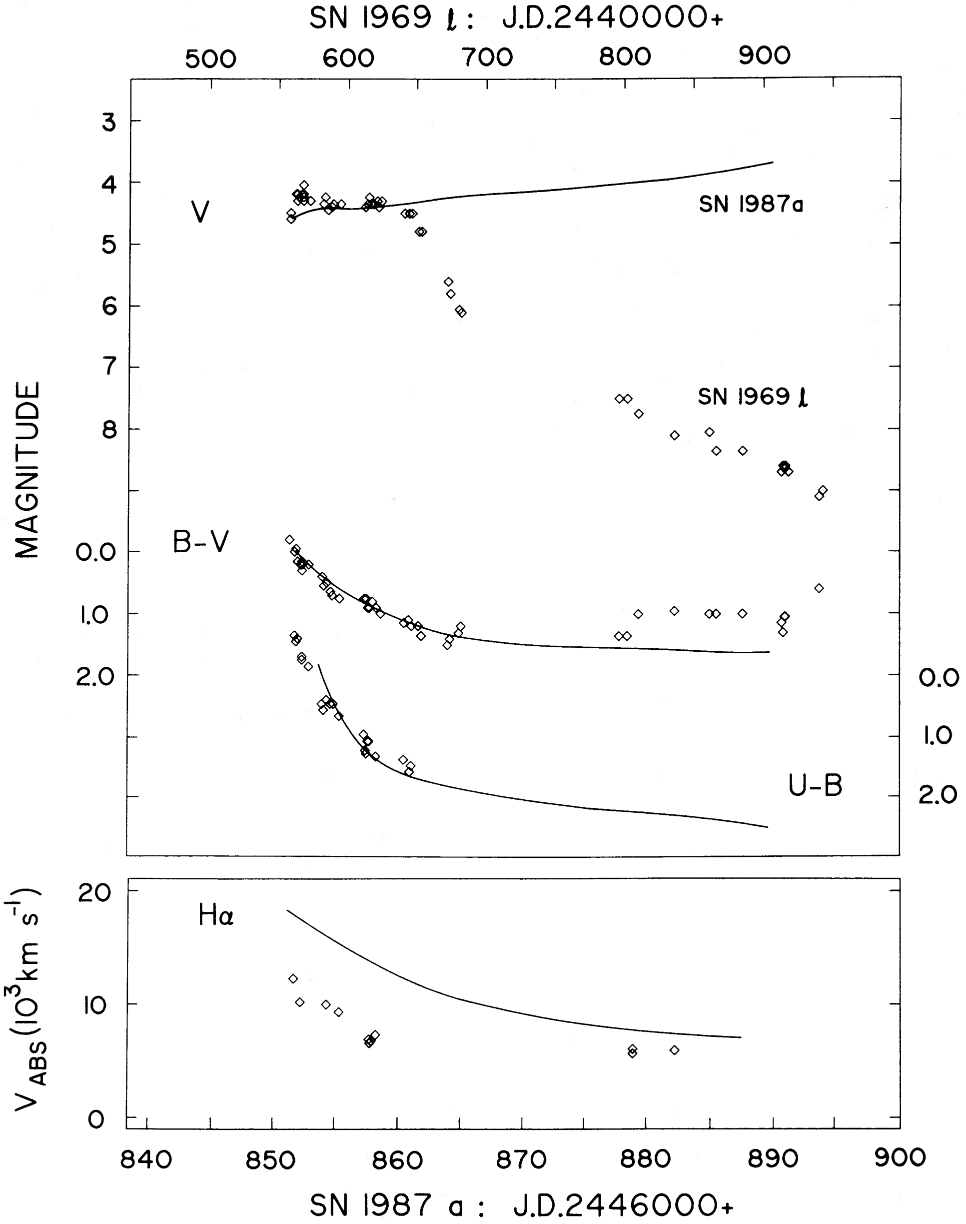

FIG. 5.—Comparison of the relative time evolution of the visual brightness, $U - B$ and $B - V$ colors, and Hα expansion velocities of SN 1987A and the prototype "plateau" Type II supernova 1969L. The data for SN 1969L have been taken from Ciatti, Rosino, and Bertola (1971) and Kirshner and Kwan (1974), and are plotted on a time scale which has been compressed by a factor of 9 with respect that of SN 1987A.

V. DISCUSSION AND CONCLUSIONS

In many respects, SN 1987A has resembled a "fast" version of a normal plateau Type II supernova. This is illustrated in the upper panel of Figure 5, where it may be seen that the $U - B$ and $B - V$ color evolution of SN 1987A (corrected for a reddening of $E[B - V] = 0.2$) agrees quite well with that of the plateau Type II supernova 1969L, if the data for the latter is compressed in time scale by roughly a factor of 10.[4] As emphasized in § II, the spectral evolution of SN 1987A was nearly identical to that of SN 1969L, but was faster by a similar factor. These properties imply that the photospheric temperature of SN 1987A dropped much more quickly than normal. A related phenomenon is the unusually rapid decrease in the expansion velocities measured from the Balmer lines of SN 1987A. As illustrated in the lower panel of Figure 5, if we compress the Hα velocity measurements of SN 1969L by the same factor utilized in comparing the color evolution, a good match is achieved to the initial decline in velocities observed for SN 1987A, although the absolute values of the velocities for SN 1987A are ~ 6000 km s^{-1} higher.

The one departure of SN 1987A from a very rapid development of a plateau Type II supernova is the continued bright-

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[4] In making this comparison, we have assumed that B_{max} occurred on February 24 UT for SN 1987A, and December 3 UT for SN 1969L.

ening (see Fig. 4). To illustrate the situation, we have compared in Figure 5 the *V* light curve of SN 1987A with a compressed version of the same curve for SN 1969L. We see that a rapid dimming might have been expected to take place in early March. This phase in plateau Type II supernovae has been interpreted in terms of a sudden drop in the opacity (and, hence, the photon diffusion time) due to recombination effects as the envelope cools (Falk and Arnett 1973). In fact, SN 1987A did show the beginnings of a very slight decline from February 28 to March 2, but then began slowly to brighten again. This behavior could indicate that an additional source of energy is now powering the light curve. One obvious possibility is the radioactive decay of ^{56}Co, which is probably an important source of energy in the late-time evolution of other Type II supernovae (e.g., see Weaver and Woosley 1980; Uomoto and Kirshner 1986).

The nature of the progenitor of SN 1987A is obviously of great interest. We have shown that the progenitor could not have been a luminous red supergiant. Since the spectrum of the B3 Ia supergiant component of the Sanduleak $-69°202$ group was not detected in the ultraviolet after the supernova had dimmed (Kirshner *et al.* 1987), this star must be considered the prime candidate! However, the evidence from presupernova plates of a slight red excess for Sanduleak $-69°202$ leaves open the possibility that this star had a close binary companion. Mass transfer might then account for the compact, low-mass envelope implied by the photometry and spectra. Alternatively, it is interesting to speculate that the progenitor was not the B3 Ia supergiant, but rather a close companion (Livio 1987; Harkness *et al.* 1987). In this case, to explain its apparent absence, the B3 supergiant must be hidden within the expanding envelope, or it was disrupted by the shock wave from the outburst.

The optical spectrum of SN 1987A, although containing hydrogen absorption, does not preclude the possibility that the supernova was more closely related to a Type I (either Ia or Ib) event. As has been noted by Kirshner *et al.* (1973), except for the present of Balmer absorption in Type II supernovae, the principal absorption features in the spectra of Type I and II objects a few months after maximum appear to be the same. Thus, an outer layer of accreted hydrogen overlying a white dwarf could cause a Type Ia event to mimic a Type II outburst spectroscopically (Livio 1987). Likewise, a small skin of hydrogen surronding the core of a massive star might cause a Type Ib supernova to be similarly misclassified (Woosley *et al.* 1987). In order to determine the amount of hydrogen-rich gas necessary to produce the observed Balmer absorption in SN 1987A, we have applied the same procedure used to calculate the masses of ejected nova shells (Williams *et al.* 1981), in which the envelope mass can be directly related to either the line or continuum optical depths independent of the unknown density or filling factor. In the case of the Balmer lines in SN 1987A, the population of the excited levels is a source of some uncertainty. However, the results of Hershkowitz, Linder, and Wagoner (1986) for the level populations can be used to compute the Balmer opacities. The Balmer line absorption strengths in the weeks following the outburst leads to a mass for a putative hydrogen-rich layer of $M_{\rm H} > 10^{-2}\ M_{\odot}$, adopting temperatures derived from the extinction-corrected red and infrared colors. Thus, it would be possible to produce the line spectrum in SN 1987A with very little hydrogen, and so one must be cautious about rejecting the possibility of either a Type Ia or Ib event solely on the basis of the optical spectrum.

Finally, we briefly consider why other supernovae like SN 1987A have not been previously detected. One obvious explanation is the unusually low peak luminosity. The largest and most homogeneous data base available on supernova discoveries is the visual search that has been carried out since 1980 by R. Evans. For information included in a recent analysis by van den Bergh, McClure, and Evans (1987), we conclude that more than 90% of the galaxies searched by Evans are too distant for a low-luminosity supernova like SN 1987A to have been detected.[5] Evans found (or would have found) 15 supernovae in the 5 year period 1980–1985, all of which were normal Type Ia, Ib, or II events. If we consider only his sample, then the relative frequency of supernovae like SN 1987A could be comparable to that of the normal Type I or II events.

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[5] This estimate was made assuming that SN 1987A gets no brighter than $V \sim 3$.

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