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ULTRAVIOLET OBSERVATIONS OF SN 1987A

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ABSTRACT

Ultraviolet observations of the supernova in the Large Magellanic Cloud, SN 1987A, were carried out with the *International Ultraviolet Explorer* satellite. The first observations were obtained at 1987 February 24.80, 14 hr after the discovery. The earliest data show that the UV flux from the supernova was already declining while the optical flux was still rising. The UV spectrum at these epochs consists of broad features associated with the supernova atmosphere punctuated by sharp interstellar absorptions. The long-wavelength ultraviolet resembles the spectrum of a SN I, which we attribute to the absence of a circumstellar envelope and the presence of line absorption, perhaps due to Co II and Fe II. The rapid decline of the supernova in the short-wavelength ultraviolet allows a glimpse of the stars which remain. One of these is star 2, a neighbor of Sanduleak −69°202, the other appears to be star 3, a fainter close neighbor of the Sanduleak star. If this is correct, then the star which exploded is Sanduleak −69°202.

Subject headings: galaxies: Magellanic Clouds — stars: supernovae — ultraviolet: spectra

I. THE SUPERNOVA IN THE LARGE MAGELLANIC CLOUD

This paper describes initial ultraviolet observations carried out with the *International Ultraviolet Explorer* satellite of the brightest supernova observed in 383 years. A brief sketch of other observations provides the context of the ultraviolet work.

The supernova was discovered at the 5th magnitude in the Large Magellanic Cloud by Ian Shelton at the University of Toronto station at the Las Campanas Observatory on 1987 February 24.23 UT (Madore and Kunkel 1987). Subsequent examination of films by McNaught (1987*a*) shows that the supernova had brightened to 6th magnitude by February 23.443 and had not brightened to more than 12th magnitude through February 22.4, while observations by Jones suggest that it was fainter than 7.5 as late as February 23.39 (McNaught 1987*b*). These observations place stringent constraints on the initial rise of the supernova.

Optical spectra on February 25 showed a strong continuum with well-defined P Cygni Balmer lines (Madore 1987; Phillips 1987; Dachs 1987), the defining characteristic for Type II supernovae (Oke and Searle 1975). The blueshifted absorption minima were displaced by $\sim 15{,}000$ km s^{-1}, which provides an upper limit to the expansion velocity of the photosphere (Kirshner and Kwan 1974).

Neutrinos from the supernova have been reported at February 23.124 by the Mont Blanc Neutrino Observatory (Castagnoli 1987*a*, *b*). Contrasting reports give the arrival time as February 23.316 by the Kamiokande II detector (Koshiba 1987) and by the Irvine-Michigan-Brookhaven detector (Svoboda 1987). Just as the optical spectra point to a Type II designation, the neutrino event, which is plausibly the signature of the formation of a neutron star during the collapse of a massive star, points to the interior event usually associated with SN II (Woosley and Weaver 1986). If we take the concordant results of Kamiokande and IMB, the time that elapsed from the core collapse at February 23.316 to the observed brightening at February 23.443 cannot exceed 3 hr.

Finally, we note that astrometric evidence summarized by West *et al.* (1987) shows that the supernova (R.A. = $5^h35^m49^s.992$, decl. = $-69°17'50''.08$, equinox 1950.0) is very nearly coincident with Sanduleak −69°202 (a B3 I star at 12th magnitude; Sanduleak 1969; Rousseau *et al.* 1978), which has two close neighbors. Walborn *et al.* (1987) have measured the relative positions of the three stars on several 4 m prime-focus plates from CTIO and find that star 2 is positioned 2''.12 W and 2''.12 N of star 1 (the Sanduleak star) and star 3 is placed 1''.30 E and 0''.75 S of star 1. These offsets are consistent with those measured by West *et al.*

In this paper, we describe in § II the photometric behavior of SN 1987A as observed by the *IUE* and a series of ultraviolet spectra. In § III, we consider some inferences

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about the nature of the star that exploded based on the ultraviolet data.

II. OBSERVATIONS WITH *IUE*

Observations of SN 1987A with the *IUE* began at 19 hr UT on 1987 February 24, just 14 hr after Shelton's discovery. The *IUE* has been described by Boggess *et al.* 1978. This paper deals with low-resolution ($R = 300$) measurements from 1200 to 3200 Å, while preliminary results from the high-dispersion measurements are presented by Dupree *et al.* (1987).

a) *Photometry*

The fine error sensor (FES) is an image dissector with an unfiltered S20 cathode used for target acquisition and guiding of the satellite. Despite its photometric crudity (± 0.03 mag), it is available 24 hr each day and is not vulnerable to bad weather or seeing variations. We use the FES calibration of Imhoff (1986) with colors from CTIO (Blanco *et al.* 1987) to derive V magnitudes. Figure 1 shows the photometry from February 24 (day 55) to May 13 (day 133). The supernova rose exceptionally rapidly to 5 mag, before the *IUE* observations, then more slowly to a local maximum of 4.27 mag on day 58.6 (February 27.6). This was followed by a decline to a shallow minimum at 4.37 mag on day 59.8 (March 1.8). From that date to day 120 SN 1987A increased in brightness, at a

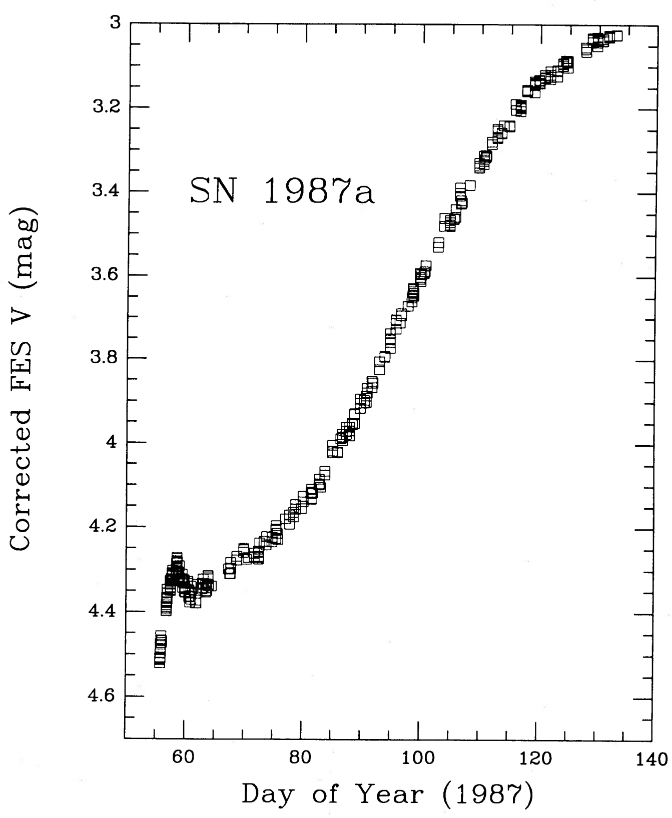

FIG. 1.—FES magnitudes derived from *IUE* measurements and colors from CTIO for SN 1987A in the interval 1987 February 24 (day 55) to May 13 (day 133).

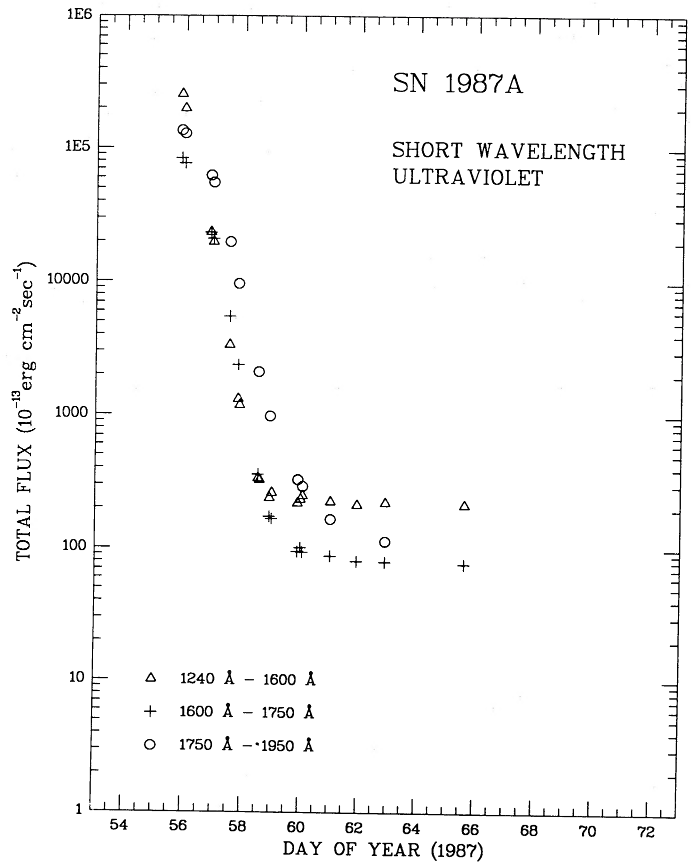

FIG. 2.—Short-wavelength ultraviolet light curves for SN 1987A. Fluxes are integrated in three rectangular bands using the UV spectra obtained through the large *IUE* aperture. After the initial decline, the flux comes principally from surviving stars in the aperture.

constant rate, and is now (day 133) reaching a second maximum. No other supernova has exhibited this behavior (see Porter 1987, in contrast to de Vaucouleurs 1987 and Murdin 1987). In models for the light curves of SN II, the rise to maximum and the fading beyond are attributed to diffusion of energy deposited by the passage of the initial shock (Arnett 1980). The flux after the initial diffusion peak, which for this event may mean after March 4, may have its origin in radioactivity (Uomoto and Kirshner 1986).

The absolute magnitude of the supernova is unusually low. For $m - M = 18.5$ and $A_V = 0.6$, the apparent magnitude of 4.3 mag corresponds to $M = -14.8$. Branch and Bettis (1978) show that typical values for SN II are $M = -16.7 + 5 \log (H_0/100 \text{ km s}^{-1})$.

We have constructed ultraviolet light curves for the supernova from the calibrated *IUE* spectra obtained through the large ($10'' \times 20''$) entrance aperture. They are presented in Figures 2 and 3. The observed flux is integrated over the indicated rectangular bands. Two features are immediately apparent: the ultraviolet flux was declining even before the optical maximum was reached, and the short-wavelength bands declined much more rapidly than the long-wavelength bands, as might be expected if the photosphere were cooling.

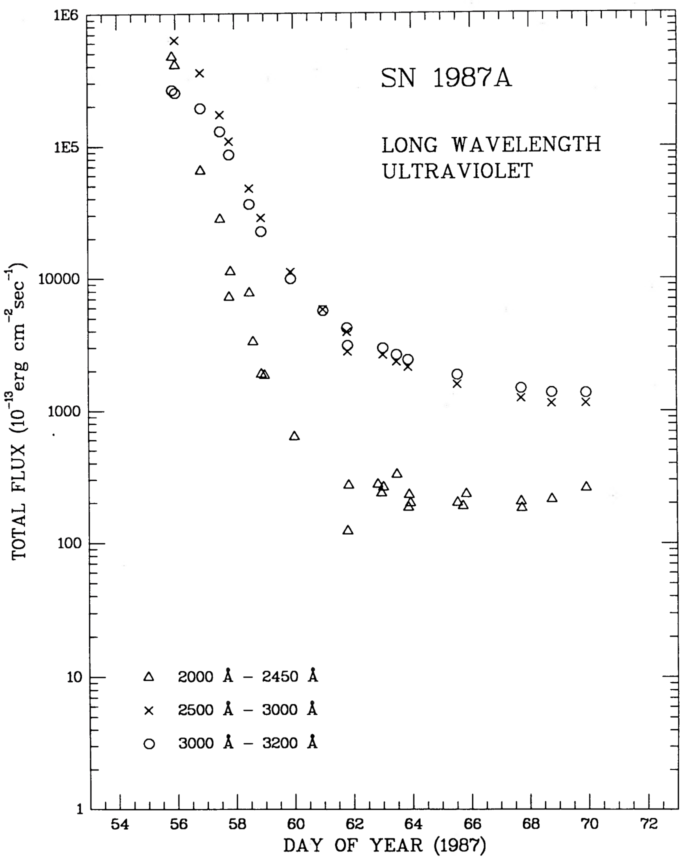

FIG. 3.—Long-wavelength ultraviolet light curves for SN 1987A. Fluxes are integrated in three rectangular bands. Even at the latest times shown, most of the flux is from the supernova.

The decline in the shortest wavelength band is truly precipitous, descending a factor of 1000 in 3 days. The nonzero level reached is the result of other stars in the aperture for the short-wavelength bands, but is due to the supernova itself in the long-wavelength bands.

The earliest UV observations offer an opportunity to estimate the radius and temperature of the supernova photosphere. Taking the ultraviolet reddening curve for the 30 Dor region from Fitzpatrick (1985) and adopting $E(B - V) = 0.2$, the observed energy distribution from the UV to the optical on February 24 yields an approximate temperature of 15,000 K and the absolute flux level corresponds to a radius of $\sim 1 \times 10^{14}$ cm. This is comparable to the product of the photospheric expansion velocity (10,000 km s^{-1}) and the time (of order 10^5 s) elapsed since the neutrino event. Evidently, the initial stellar radius cannot have been as large as 10^{14} cm (6 AU) and was probably much smaller. This exercise also makes it plausible that the supernova is actually in the LMC: in the spirit of Kirshner and Kwan (1975), we note that if it were at a distance of $m - M = 20.5$ mag required to make the absolute magnitude match other SN II, the angular size would be smaller by a factor of 2.5. The presence of interstellar absorption from gas in both our Galaxy and from the LMC in the high-dispersion *IUE* spectra assures us that it is at least as far as the LMC. Of course, the use of proper stellar atmospheres, such as those of Eastman and Kirshner (1987) or Hershkowitz and Wagoner (1987), will provide much better estimates of the stellar radius and the distance to the supernova.

The earliest observations, McNaught's 6th magnitude on February 23.443, would require a temperature of order 100,000 K if the photospheric radius were 10^{13} cm as given by the velocity times the age. The rapid decline in the UV flux we observe 1 day later is plausibly the result of a temperature declining from a higher value. The ionizing output of the supernova cannot be reliably estimated from Figures 2 and 3 because of the uncertainty in the temperature before these observations began.

b) *Spectra*

Figures 4 and 5 display a sampling of the low-dispersion spectra for SN 1987A (see Tables 1 and 2). These spectra show that the changes in ultraviolet flux exhibited in Figures 2 and 3 result from complex changes in the spectrum as well as a decline in the overall level. The features are broad, but it is not obvious from inspection which are emission and which are absorption, or whether the width derives from kinematics or blended lines. At the very shortest wavelength, in Figure 4, the sharp decline near 1200 Å may be due to Lyα absorption, which may be consistent with the presence of Balmer lines in the optical region. In the very earliest exposures, where this is the only region of the spectrum not overexposed, the flux appears to be increasing shortward of 1200 Å. In Figure 4, a feature with a peak near 1860 Å is the most conspicuous feature, gradually narrowing and shifting toward longer wavelength in the later spectra. It is tempting to identify the large absorption and emission stretching from 2500 to 2800 Å with a P Cygni profile of Mg II, with a velocity well above that of the photosphere of 20,000 km s^{-1}, although this feature does not persist for more than a few days. Interstellar absorption in both our Galaxy and in the LMC accounts for the sharp Mg II absorption line at 2800 Å, as discussed by Dupree *et al.* (1987).

To make some progress on the character of the spectrum, we compare typical spectra from SN 1979C (a SN II) (Benvenuti *et al.* 1982) and SN 1981B (a SN I) (Panagia 1982, 1984). We note that the spectrum on February 24 and 25 does not resemble either of these prototypes, but that the spectrum of SN 1987A rapidly evolves so that by February 26 the long-wavelength portion bears a strong resemblance to the long-wavelength spectrum of the SN I. The principal peaks, at ~ 2930, 3050, and 3175 Å in the spectra shown in Figure 5, agree well with those observed in SN I. In the case of SN I, the underlying mechanism is thought to be the deflagration of a white dwarf, resulting in a large observed abundance of iron peak elements (Woosley and Weaver 1986; Kirshner and Oke 1975), and models for the optical and UV spectrum have used that starting point. A reasonable fit to the long-wavelength UV spectrum for SN I comes from considering the effects of many blended Fe II and Co II lines scattering the photospheric light in an expanding atmosphere (Branch and Venkatakrishna 1986).

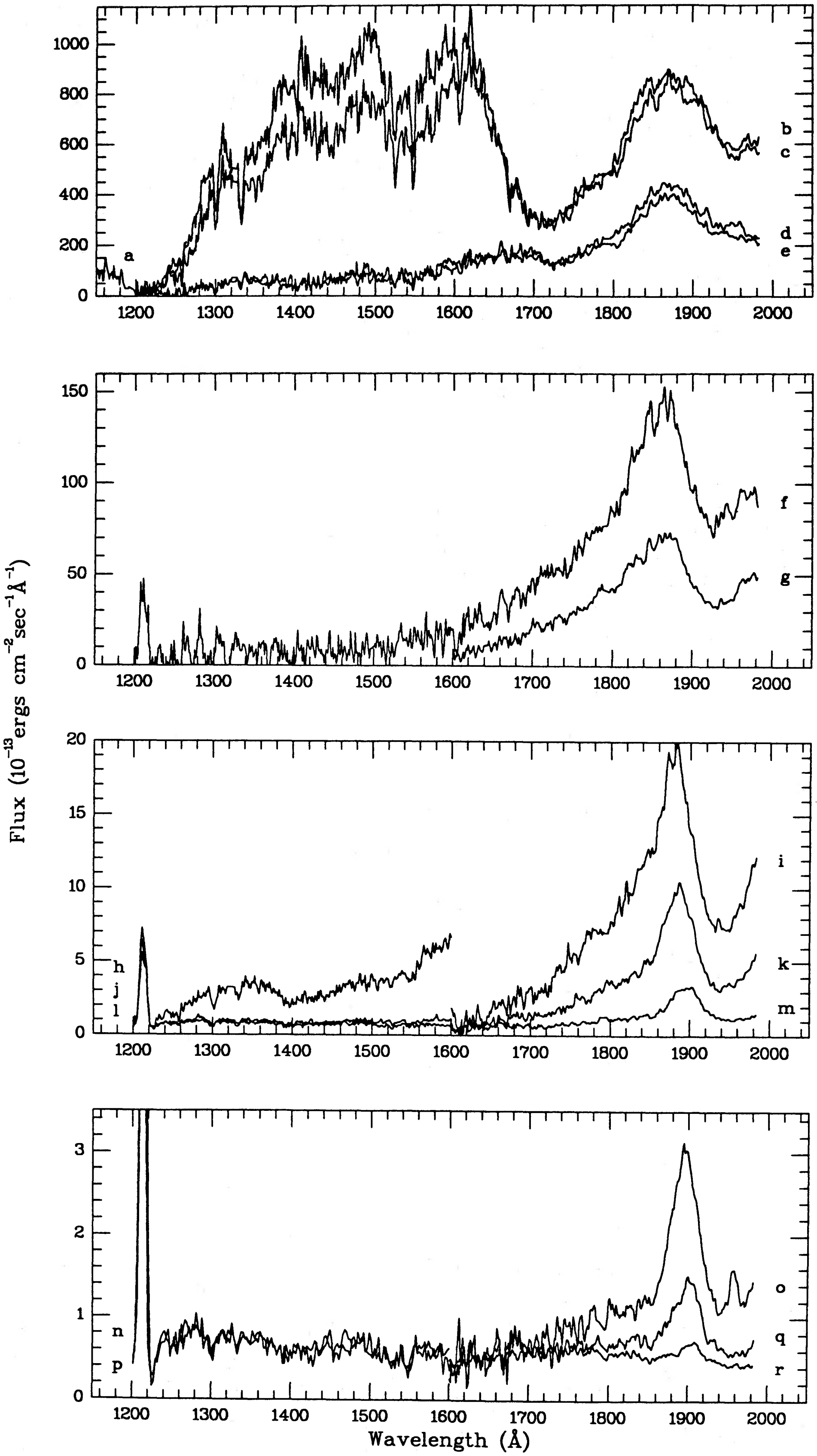

FIG. 4.—Short-wavelength ultraviolet spectra of SN 1987A. Letters labeling each spectrum refer to the dates given in Table 1.

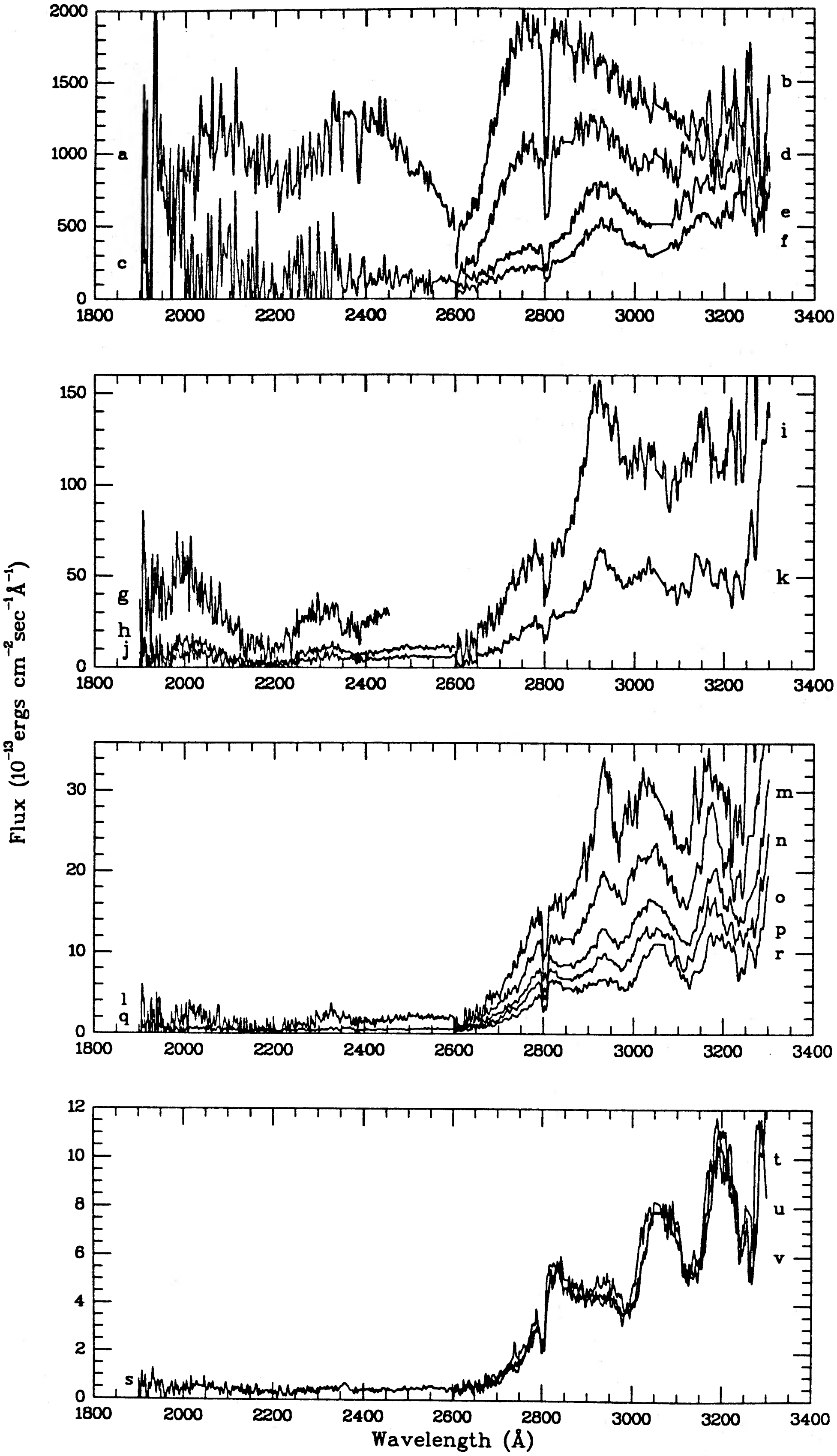

FIG. 5.—Long-wavelength ultraviolet spectra of SN 1987A. Letters labeling each spectrum refer to the dates given in Table 2.

TABLE 1

SHORT-WAVELENGTH OBSERVATIONS

Plot	Spectrum	Date	Day of Year (1987)
a	SWP 30375	Feb 24	55.836
b	SWP 30376	Feb 24	55.870
c	SWP 30378	Feb 24	55.981
d	SWP 30388	Feb 25	56.856
e	SWP 30390	Feb 25	56.947
f	SWP 30398	Feb 26	57.506
g	SWP 30401	Feb 26	57.816
h	SWP 30402	Feb 26	57.862
i	SWP 30407	Feb 27	58.506
j	SWP 30408	Feb 27	58.563
k	SWP 30410	Feb 27	58.915
l	SWP 30411	Feb 27	58.985
m ...	SWP 30413	Feb 28	59.878
n	SWP 30414[a]	Feb 28	59.976
o	SWP 30415	Feb 29	60.045
p	SWP 30421[a]	Mar 1	61.014
q	SWP 30421	Mar 1	61.014
r	SWP 30428	Mar 3	62.898

[a] Two-point bin.

TABLE 2

LONG-WAVELENGTH OBSERVATIONS

Plot	Spectrum	Date	Day of Year (1987)
a	LWP 10189[a]	Feb 24	55.878
b	LWP 10191	Feb 24	55.974
c	LWP 10199[a]	Feb 25	56.828
d	LWP 10199	Feb 25	56.828
e	LWP 10207	Feb 26	57.498
f	LWP 10210	Feb 26	57.809
g	LWP 10211	Feb 26	57.856
h	LWP 10220	Feb 27	58.618
i	LWP 10221	Feb 27	58.897
j	LWP 10222	Feb 28	59.015
k	LWP 10227	Feb 28	59.908
l	LWP 10228	Feb 29	60.010
m ...	LWP 10240	Mar 2	61.014
n	LWP 10248	Mar 2	61.819
o	LWP 10258	Mar 3–4	62.937[b]
	LWP 10260		
p	LWP 10270	Mar 4	63.875
q	LWP 10272	Mar 4	63.940
r	LWP 10287	Mar 6	65.544
s	LWP 10288	Mar 6	65.728
t	LWP 10300	Mar 8	67.717
u	LWP 10305	Mar 9	68.762
v	LWP 10312	Mar 10	69.934

[a] Two-point bin.
[b] Spectra averaged.

In contrast, the successful models for the ultraviolet spectra of SN II consider the emission from a substantial circumstellar layer (Fransson *et al.* 1984). One possible line of attack on these spectra would be to consider the effects of scattering by the same Fe II and Co II lines that dominate the SN I spectrum in the absence of a circumstellar envelope. Harkness *et al.* (1987) suggest that these lines may dominate the UV even in a hydrogen-rich atmosphere.

In general, the lines appear to maintain constant relative strengths as they drift slowly to the red. The redward drift would be a natural effect if the lines have their origin in the expanding atmosphere as it grows transparent and we see to lower, slower levels as the atmosphere expands, as illustrated in Figure 5. The exception to this drift at constant relative strength is the feature at 2930 Å which declines in strength dramatically through the spectra shown. It will be interesting to see if that change can be simply related to the declining temperature of the photosphere.

The picture in which SN 1987A has no circumstellar envelope is consistent with the low radio flux (Bunton, Turtle, and Jauncey 1987) and absent X-ray flux (Makino 1987): these effects are often attributed to the interaction of the supernova shock with the circumstellar shell (Chevalier 1984). The high-dispersion spectra discussed by Dupree *et al.* (1987) also show no strong evidence for circumstellar matter associated with the supernova.

III. SURVIVORS

One interesting feature of Figure 2 is the rapid decline to a nearly constant value in the shortest wavelength UV light curves. While in general the rapid decline makes the UV observations difficult, the silver lining in that cloud is that it allows us to inspect the vicinity of the supernova for stellar survivors in an attempt to identify the star that exploded. Inspection of the *IUE* images shows that in the supernova spectra taken through the large entrance aperture ($10'' \times 20''$), the short-wavelength flux was dominated by two unchanging stellar spectra, presumably from neighboring hot stars. The relative positions allow us to identify one of these as star 2, the hot star $3''.0$ from the 12 mag B star Sanduleak $-69°202$ (star 1). The other spectrum could belong to star 1 or perhaps to its fainter neighbor, star 3. The spatial resolution of the *IUE* is limited: the point spread function is $\sim 3''$ FWHM, and the sampling is $1''.07$ per line in the spatial dimension of the spectra. As described in detail elsewhere (Sonneborn, Altner, and Kirshner 1987), we have used a 240 minute short-wavelength exposure (SWP 30512) made on 1987 March 13 (day 72) to deconvolve these blended stars. The image is fitted with two skewed Gaussians, and the spectra extracted separately. The least-squares fit to the separation between the two spectra is $4''.13 \pm 0''.35$ when the slit was oriented at position angle 152°. We expect the projected separation between stars 2 and 1 to be $2''.8$ and between stars 2 and 3 to be $4''.0$, projected along that slit, so the positional agreement is better if the object we see is star 3. There is no evidence for a third point source in our data shortward of 1600 Å, where the spatial resolution of *IUE* is best.

Exposures made earlier, where the 1900 Å feature of the supernova was still visible at the red end of the short-wavelength spectrum but where the survivors dominate the short-wavelength end, show the supernova spectrum is separated from the star 2 spectrum by $2''.9 \pm 0''.3$, and from the other stellar spectrum by $1''.0 \pm 0''.3$. If the supernova spectrum were at the same position as star 1, we would expect those two positions to differ by no more than 0″.2.

The spectroscopic evidence based on the two spectra extracted separately shows that star 2 resembles a mid-B star, with a flux level (4.5×10^{-14} ergs cm^{-2} s^{-1} Å^{-1} at 1300 Å) that corresponds to a visual magnitude fainter than 14. This picture is consistent with West's assertion that star 2 is very blue. The second extracted spectrum, while it is surely the spectrum of a hot star, is very unlikely to be the spectrum of a 12th magnitude B3 I star such as Sanduleak $-69°202$. The extracted spectrum is noisy, but it is fainter than the spectrum of star 2 at every wavelength shortward of 2000 Å. It has a flux level (1.9×10^{-14} ergs cm^{-2} s^{-1} Å^{-1} at 1300 Å) that corresponds to a visual magnitude of ~ 15, and seems a plausible fit to star 3. When the supernova fades in the visible, astrometry will resolve any lingering doubt about the survivors of this stellar cataclysm, but on the face of it, Sanduleak $-69°202$ appears to be missing and is the likely candidate for the star that exploded.

Important clues to the nature of the progenitor can be summarized. The Sanduleak star and its neighbors are close to the supernova position, but the *IUE* images obtained after the ultraviolet flux from the supernova had faded favor the survival of the two fainter stars and the destruction of the 12th magnitude B3 I star. The neutrino signal presumably marks the moment of core collapse and requires a star massive enough to undergo such a collapse, such as a B3 I might be. The rise to maximum light was very rapid, with at least a 6 mag rise in 3 hr. This excludes very extended stars for which the diffusion time is long. The radius at the first UV measurement was roughly equal to 10^{14} cm, about what one would expect for a star that expanded from a relatively small radius at 10,000 km s^{-1}. The light curve is very unusual, with a relatively dim local maximum quickly followed by a sustained rise that may reflect the presence of radioactive energy input. Circumstellar matter did not dominate the UV spectrum which resembles that of a SN I formed by lines of Co II and Fe II. Although SN 1987A has the exterior of a SN II, and the interior collapse of a massive star, the possibility that Sanduleak $-69°202$ might have been the progenitor requires detailed consideration of the phenomena to be expected from a blue supergiant rather than the canonical extended red star (Woosley *et al.* 1987).

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