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THE PROGENITOR OF SN 1987A: SPATIALLY RESOLVED ULTRAVIOLET SPECTROSCOPY OF THE SUPERNOVA FIELD

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ABSTRACT

Careful deconvolution of spatially resolved *IUE* ultraviolet spectra shows that only two of the three stars detected in plate material before 1987 are now present near the site of SN 1987A. The separation, magnitudes, and spectra of these two are consistent with their identification as star 2 and star 3 of the Sanduleak −69°202 trio. The clear implication is that star 1, the 12th mag B3 I star, has disappeared, and it may be identified as the progenitor of SN 1987A.

Subject headings: astrometry — stars:supernovae — ultraviolet:spectra

I. INTRODUCTION

Ultraviolet spectra of SN 1987A obtained with the *International Ultraviolet Explorer* (*IUE*) satellite within 15 hr of its discovery showed that the supernova's far-ultraviolet flux ($\lambda < 2000$ Å) was rapidly fading (Sonneborn and Kirshner 1987*a*; Kirshner *et al.* 1987). By 1987 February 28 the far-ultraviolet flux had dropped by three orders of magnitude, a level where a constant, stellar background was detected shortward of 1500 Å.

Examination of preoutburst plates revealed an excellent positional coincidence (< 0".1) between the supernova and the 12th mag B3 I star Sk −69°202 (McNaught 1987*a*, *b*; White and Malin 1987*a*, *b*; West *et al.* 1987*a*; West *et al.* 1987*b*), the presence of a second star 3" to the northwest (Lasker 1987), and some evidence for a third star about 1" southeast of Sk −69°202 (Walborn *et al.* 1987*a*; Chu 1987). Similarities between the *IUE* spectrum of the ultraviolet source at the position of the supernova and that of a luminous early-type star led to a suggestion that Sk −69°202 might have survived the explosion (Cassatella *et al.* 1987; Sonneborn and Kirshner 1987*b*). In addition, the *IUE* spectra were broadened perpendicular to the dispersion direction shortward of 1500 Å, indicating the presence of more than one point source in the 10" × 20" aperture during the supernova exposures (Sonneborn and Kirshner 1987*b*).

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The detection of two early-type ultraviolet stellar spectra at the site of the fading supernova and the identification of two early-type stars in the Sk −69°202 system on preoutburst plates led to a suggestion that the spectra came from the two stars: Sk −69°202 (star 1) and star 2 (Sonneborn and Kirshner 1987*b*). Because Chu (1987) estimated the visual magnitude of star 3 to be near 17.5, this did not seem a plausible source for the light detected in our *IUE* exposures. The confused situation about the presence or absence of Sk −69°202 was summarized in late March by Panagia *et al.* (1987), who said "we feel that drawing firm conclusions ... is still premature." The purpose of this *Letter* is to resolve this confusion.

Subsequently, high-precision measurements and image syntheses of the Sk −69°202 field (Walborn *et al.* 1987*b*; West *et al.* 1987*a*; West *et al.* 1987*b*) provided more accurate relative positions and magnitudes for the three stars. These investigations showed that star 3 was about 2 mag brighter than previously thought, at $m = 15.5$, about 1".5 southeast of star 1, and blue in color, prompting further analysis of the available *IUE* spectra of SN 1987A, as reported here.

Our preliminary results (Sonneborn and Kirshner 1987*c*; Kirshner *et al.* 1987) showed that the objects detected near the supernova were stars 2 and 3 and that Sk −69°202 was not present in our ultraviolet spectra of SN 1987A. In this *Letter* we present the evidence which shows that Sk −69°202 is absent from the field of SN 1987A and was plausibly the supernova's progenitor. An independent investigation which also confirms this result has been carried out by Gilmozzi *et al.* (1987).

II. OBSERVATIONAL MATERIAL

a) IUE Spectra

The ultraviolet observations reported in this *Letter* are part of a much larger body of *IUE* spectra of SN 1987A (see Kirshner *et al.* 1987). Starting in 1987 March the far-UV flux level of the supernova was below that of the other stars in the aperture and, as discussed below, the projected separation between the stars was sufficiently large to allow deconvolution of their spectra. The relevant SWP (1150–2000 Å) exposures are listed in Table 1.

The position angle of the direction perpendicular to the dispersion was computed for the midpoint of the exposures using the expressions given by Sonneborn *et al.* (1987). This position angle is the standard large-aperture position angle minus 9° (see Turnrose and Thompson 1984, § 7.2.2).

The observations were made from the *IUE* Science Operations Center at Goddard Space Flight Center. All exposures were taken in the low-dispersion mode (resolution ~ 6–7 Å) under conditions of optimum telescope focus. The supernova's optical center of light, as measured by the *IUE* fine error sensor, was centered in the large aperture for each exposure.

The *IUE* SIPS spectral extraction procedures which preserve the spatial information in low-dispersion *IUE* images are described by Turnrose and Thompson (1984) and updated by Munoz Piero (1985) for the so-called extended line-by-line (ELBL) enhancement. The ELBL spectral file is a two-dimensional array of *IUE* flux numbers with about 800 wavelength points (1150–2000 Å) and 110 lines in the spatial direction at each wavelength. The spatial separation between adjacent lines is $\sqrt{2}/2$ diagonal pixels. Adopting the spatial scale of 1″51 ± 0″05 per diagonal pixel (Panek 1982), this corresponds to 1″07 ± 0″04 per line. The separation between the spectra of two point sources in the ELBL data is the projection (perpendicular to the dispersion) of their true angular separation on the plane of the sky.

b) The Sk −69°202 System

The relative positions of Sk −69°202 and its neighbors have been measured independently by West *et al.* (1987*b*) and Walborn *et al.* (1987*b*, hereafter WLLC). West *et al.* measured the positions of the Sk −69°202 stars on ESO plates obtained from 1976 to 1982. WLLC measured the positions of stars 2 and 3 relative to star 1 (Sk −69°202) from digitized 5.3 arcmin² portions of eight CTIO 4 m prime-focus plates obtained from 1974 to 1983. Relative to star 1, they find separations and position angles of 2″9 ± 0″1 at p.a. 315° ± 3° and 1″6 ± 0″2 at p.a. 120° ± 5° for stars 2 and 3, respectively. The relative equatorial positions derived from these separations are given in Table 2.

We adopt the measurements of WLLC for comparison with our data due to their large-scale plate material and smaller estimated errors. The orientation of the three stars and the *IUE* large aperture for SWP 30408, 30512, and 30592 are shown to scale in Figure 1.

TABLE 1

IUE EXPOSURES OF SN 1987A

SWP Image Number	Exposure start (1987 UT)	Duration (minutes)	p.a.[a]	Measured Separation
30426........	Mar 2.8303	180	320.9	4″51 ± 0″41
30428........	Mar 3.8882	180	322.0	4.54 ± 0.25
30440........	Mar 6.4956	300	324.6	4.48 ± 0.27
30512........	Mar 13.5990	240	331.5	4.36 ± 0.15
30547........	Mar 16.5271	240	334.6	4.22 ± 0.20
30592........	Mar 22.5858	300	340.7	3.97 ± 0.16
30743........	Apr 8.5374	225	357.5	3.19 ± 0.29
31273........	Jul 1.2013	240	78.0	2.52 ± 0.37
31371........	Jul 20.1875	240	96.3	3.36 ± 0.14
31462........	Aug 3.0983	240	109.4	3.93 ± 0.17

[a] Position angle for the direction perpendicular to the dispersion, calculated for midpoint of exposure.

TABLE 2

RELATIVE ASTROMETRY OF SK −69°202

Stars	Distance	p.a.	Δ R.A.	Δ Decl.
2–1	2″90 ± 0″10[a]	315°0 ± 3°0[a]	2″05 ± 0″11 W	2″05 ± 0″11 N
3–1	1.60 ± 0.20[a]	120.0 ± 5.0[a]	1.38 ± 0.20 E	0.80 ± 0.20 S
2–3	4.46 ± 0.20	129.7 ± 4.0	3.43 ± 0.20 W	2.85 ± 0.20 N

[a] Walborn *et al.* (1987*b*) and private communication.

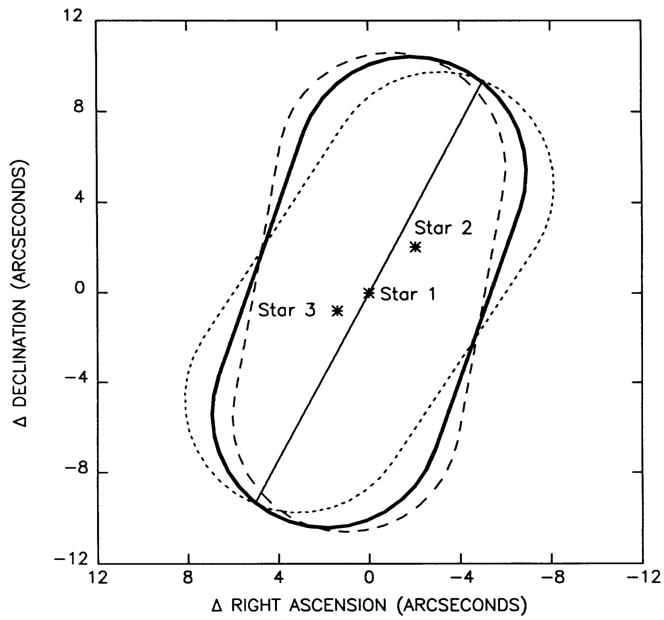

FIG. 1.—Changing *IUE* aperture orientation with respect to the SN 1987A field. The outline of the aperture is shown for three images, SWP 30408 (*small-dashed line*), 30512 (*solid line*), and 30592 (*large-dashed line*), taken over a three week period (see Table 1). The straight line is the direction perpendicular to the dispersion for SWP 30512. The aperture orientation rotates about 1° per day due to *IUE* spacecraft-Sun orientation constraints and the LMC's position near the south ecliptic pole.

III. DATA ANALYSIS

The 1250–1600 Å ELBL data for one of our images (SWP 30512) are compared in Figure 2 with similar data for a single point source. The spectral data have been averaged in 50 Å intervals. No binning or smoothing has been applied in the

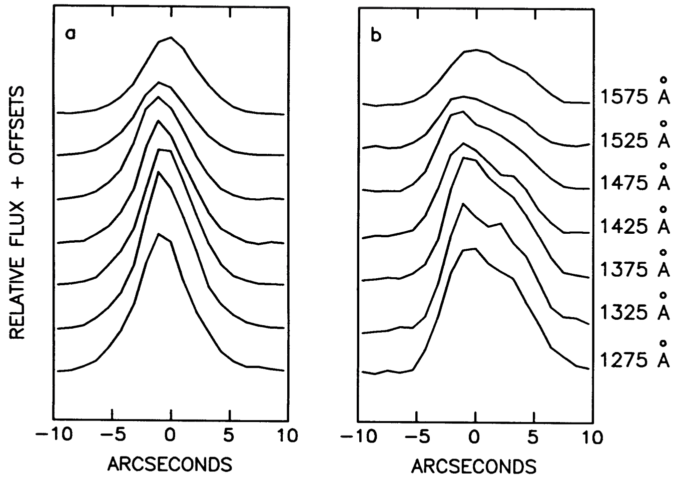

FIG. 2.—Low-dispersion SWP spatially resolved spectra. (*a*) The ELBL data for a single point source, Sk −70°50 (SWP 28765), is shown at 50 Å intervals from 1275 to 1575 Å. (*b*) SWP 30512 shows the presence of two sources close to the position of SN 1987A.

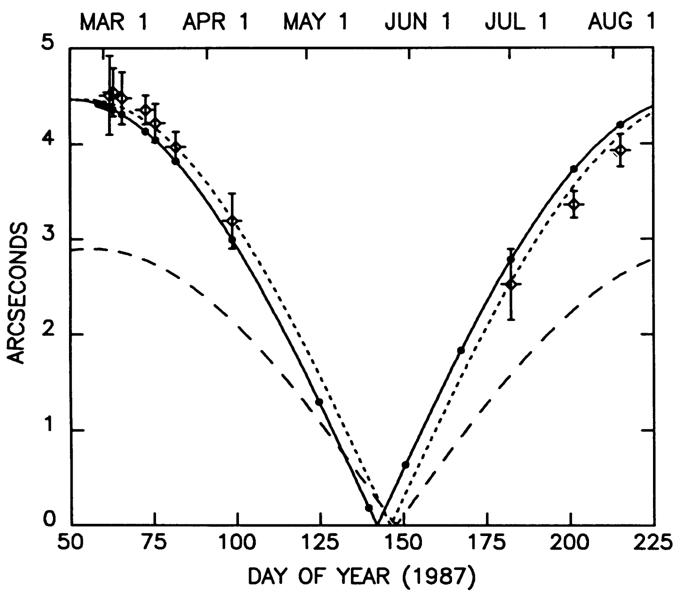

FIG. 3.—Measured (*diamonds*) and predicted (*solid line and dots*) separation between stars 2 and 3 in the *IUE* ELBL spectra as a function of time. The expected separation between stars 1 and 2 is also shown (*large-dashed line*). The small-dashed line represents a 4° change in the star 2–star 3 position angle to 133.°7, within the stated errors of WLLC.

spatial direction. The presence of two sources in the aperture during the supernova exposure is apparent. In this section, we describe the method used to determine the number of objects present in the ultraviolet spectra taken at the position of SN 1987A, their projected separations, and their relative brightnesses.

We have used a procedure developed by Altner (1987) to separate overlapping spectra in *IUE* low-dispersion images of the cores of globular clusters. Multiple point-spread functions (PSF) are fitted to the spatial profile of the ELBL data with a multivariable least-squares fitting technique based on the CURFIT algorithm of Bevington (1969). This procedure adopts the wavelength-dependent analytic (skewed Gaussian) form of the *IUE* low-dispersion PSF determined by Cassatella, Barbero, and Benvenuti (1985). The FWHM in SWP spectra varies between 4.″6 at 1350 Å and 6.″0 at 1900 Å. After fixing the Gaussian width and skewness, the two other parameters which describe each stellar component, the position along the spatial axis and the peak flux, are determined by the least-squares analysis.

This procedure was used to fit two point sources in the 1250–1550 Å region of ten well-exposed line-by-line spectra taken at the position of SN 1987A. The mean separation for each image, listed in Table 1, is the average of the separations measured in 25 Å bandpasses. Figure 3 compares the measured separations as a function of time with that expected for the WLLC positions of stars 2 and 3.

IV. RESULTS

The Gaussian separations, shown in Figure 3, are in very good agreement with those predicted by the WLLC astrometry only if the observed stars are star 2 and star 3. The results are not consistent with the expected separation between star 1 and star 2. The error in the component separations is small, generally less than 5% of the Gaussian FWHM. We do not know the relative contributions to the small systematic differences between measured and predicted separations from measurement error in the WLLC positions and in the *IUE* analysis and spatial scale. However, this difference could be accounted for by a 4° rotation of the star 2–star 3 position angle to 133.°7, as shown in Figure 3.

Figure 4*a* shows the two-component fit to the ELBL data for 1350–1375 Å interval of SWP 30512, which is representative of our images taken after 1987 March 4. The excellent fit of two point sources to this short-wavelength region of the data and the general agreement with the astrometry of preoutburst plates of the Sk −69°202 system makes it unlikely that a third point source contributes significantly to the *IUE* spectra. At this wavelength the flux expected from a B3 I star in the LMC is about 10^{-12} ergs cm^{-2} s^{-1} $Å^{-1}$. We estimate that 10^{-15} ergs cm^{-2} s^{-1} $Å^{-1}$ is a conservative upper limit to the flux from a third point source, be it the supernova or its "mystery spot" (Nisenson *et al.* 1987), contributing to the observed 1250–1550 Å spectrum in 1987 March.

A section of SWP 30408, taken on 1987 Feb 27.6 when star 2, star 3, and SN 1987A had comparable ultraviolet flux levels, was also analyzed. Figure 4*b* shows the unsatisfactory result when two point-spread functions (PSFs) are fitted to the spatial profile, adopting a projected separation consistent with our previously determined values. When a three-component fit is computed, an excellent fit is obtained (Fig. 4*c*). In the latter case, we used the same projected separation as in Figure 4*b* and set the flux ratio of two of the Gaussians to that found in later spectra when only stars 2 and 3 were present. The third point source is located between stars 2 and 3, 2.″89 ± 0.″30 from star 2 (the leftmost component in Fig. 4*c*), in excellent agreement with the position of Sk −69°202/SN 1987A.

The Gaussian fitting procedure also allows us to determine the relative contribution of stars 2 and 3 (e.g., Fig. 4*a*) to the

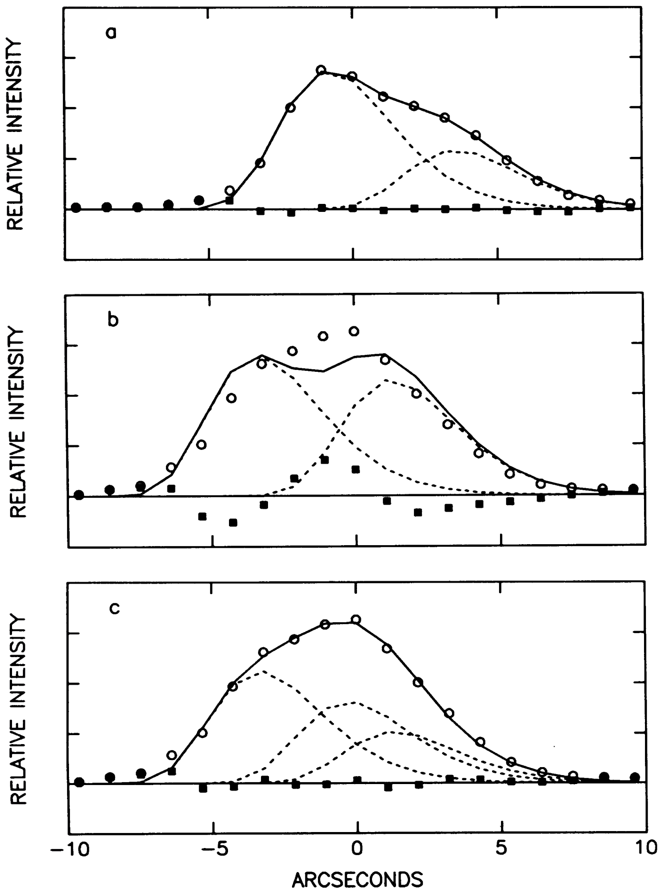

FIG. 4.—Least-square fits of *IUE* PSFs to spatial profiles of the 1350–1375 Å region of ELBL data. (*a*) Two components are fitted to SWP 30512. The computed fit (*solid line*) is in excellent agreement with the observations (*open circles*). The individual PSFs (*dashed lines*) and the residuals (observed–computed, *solid squares*) are also shown. The leftmost and rightmost components correspond to stars 2 and 3, respectively. (*b*) A two-component fit to SWP 30408 does not adequately reproduce the observations. The component separation was fixed at 4″.50. (*c*) A three-component fit to the same data as in (*b*) (see text).

total flux for the entire SWP spectral range. The wavelength dependence of the flux ratio was taken to be its mean value from the two-component fits for SWP 30440, 30512, 30547, and 30592. Their spectra have the appearance of early-B spectral types. The strength of the numerous interstellar lines in both spectra is consistent with *IUE* low-dispersion spectra of other LMC early-type stars. Both star 2 and star 3 must be located in the LMC and are not foreground objects.

We have attempted to place some constraints on the characteristics of stars 2 and 3 by comparing their dereddened fluxes with the Kurucz (1979 and unpublished) model atmosphere grid. The reddening was estimated from the colors of Sk −69°202 (Isserstedt 1975) and recent work on intrinsic colors of LMC supergiants by Fitzpatrick (1987). We assumed a two-component extinction: $E(B-V) = 0.08$ from the Galaxy (Savage and Mathis 1979) and 0.1 from the LMC (30 Doradus curve from Fitzpatrick 1985). The one-third solar abundance Kurucz models which give the best continuum fits are: $T_{\rm eff} = 20{,}000$ K and 25,000 K (± 2000 K) and $\log g = 3.0$ and 4.5 (± 0.5) for stars 2 and 3, respectively. Assuming a LMC distance of 50 kpc, we calculate $V = 14.4$ and 16.0 (± 0.4) for stars 2 and 3, respectively, in agreement with the estimates of West *et al.* (1987*b*) and WLLC.

In summary, only two of the original three stars comprising the Sk −69°202 system are detected in spatially resolved ultraviolet spectra taken at the position of SN 1987A. The temporal variation of the projected separation of the spectra is in good agreement with the positions of stars 2 and 3 measured on preoutburst plates. Furthermore, in late 1987 February the position of the supernova spectrum shortward of 1500 Å, relative to stars 2 and 3, was in excellent agreement with the expected position of star 1. We identify the stellar spectra with stars 2 and 3. Sk −69°202 is absent from the field and is plausibly identified as the star which exploded. The known characteristics of Sk −69°202 are consistent with the interpretation that the progenitor of SN 1987A was a relatively compact star (Woosley *et al.* 1987), having a high-velocity, low-density stellar wind prior to the outburst (Chevalier and Fransson 1987). Our recent SWP spectra of SN 1987A (1987 August) show no evidence that Sk −69°202 still exists inside the expanding shell. The results reported here are consistent with an independent analysis by Gilmozzi *et al.* (1987).

We thank our colleagues on the *IUE* observatory staff for their continued assistance in acquiring the *IUE* data. We are especially grateful for the cooperation of many *IUE* Guest Observers who relinquished telescope time for some of these observations. We benefited from discussions about *IUE* spatially resolved spectra and image processing with Cathy Imhoff and Randy Thompson. This work was supported in part by NASA contracts NAS5-28749 to Computer Sciences Corporation and NAS5-29301 to Applied Research Corporation and NASA grant NAG5-841 to the Harvard College Observatory.

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