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THE COMPOSITE IMAGE OF SANDULEAK −69°202, CANDIDATE PRECURSOR TO SUPERNOVA 1987A IN THE LARGE MAGELLANIC CLOUD

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ABSTRACT

The image of Sk −69°202 has been analyzed on the basis of eight (of 32 available) CTIO 4 m prime-focus plates obtained in 1974–1983, covering wavelengths from blue through near-infrared. Density differences and intensity syntheses based upon reference stars from the same plates are presented. The 12th mag blue supergiant (star 1) has two companions with V magnitudes, position angles, and separations 15.3, 315°, 3″ (star 2) and 15.7, 115°, 1″.5 (star 3), respectively. Both companions appear to be early-type stars; there is no evidence for a very red star in the system. The two companions are capable in principle of producing the current *IUE* spatial and spectral results, consistent with the interpretation that star 1 has disappeared.

Subject heading: stars: supernovae

I. INTRODUCTION AND DATA

From the first reports of supernova 1987A in the Large Magellanic Cloud (Shelton, Duhalde, and Jones 1987), the close positional coincidence with the cataloged OB star Sk −69°202 (Sanduleak 1970) was apparent. For this star, Rousseau *et al.* (1978) provide an objective-prism (110 Å mm^{-1} at Hγ) spectral classification of B3 I, while Isserstedt (1975) gives photoelectric determinations through an 18″ diaphragm of $V = 12.24$, $B - V = +0.04$, $U - B = -0.65$. Inspection of several photographic plates of the 30 Doradus region obtained by three of the authors at the prime focus of the Cerro Tololo Inter-American Observatory 4 m telescope (scale 18″.6 mm^{-1}) showed the image of Sk −69°202 near the field edge, and revealed a fainter companion to the northwest (Lasker 1987). Subsequently, an additional, closer companion to the southeast was detected (Walborn *et al.* 1987; Chu 1987). A listing of all our pertinent 4 m plate material is given in Table 1.

Initially, the two companions to Sk −69°202 discovered on these plates were of interest as potential alternative progenitors of SN 1987A. However, astrometric measurements have now shown the SN position to be coincident with that of the bright supergiant, with an accuracy that excludes the companions (West 1987; White and Malin 1987*a*, *b*; West, Lauberts, and Schuster 1987; Girard and van Altena 1987*a*, *b*; West *et al.* 1987). The companions are now significant for the interpretation of preoutburst observations of Sk −69°202, as well as the ultraviolet geometrical and spectroscopic information from the *International Ultraviolet Explorer* since the UV fading of the SN, and in particular with regard to the question of which stars are still present, as discussed below.

II. ANALYSIS

a) *Scanning*

Eight of the plates in Table 1, covering wavelengths from 4765 Å through 9000 Å, were scanned with a PDS microdensitometer of the Space Telescope Guide Star Selection System. The area scanned is shown in Figure 1 (Plate L7), which also identifies Sk −69°202 and several nearby reference stars used in the analysis. Each plate is calibrated by means of a wedge sensitometer grid, which was also scanned. The scanning was performed with an 8 μm round aperture and a 3.8 μm sampling interval, at a speed of 4 mm s^{-1} and a low-pass filter setting of 3.15 kHz. The area digitized comprises 4500 × 4500 pixels, corresponding to a 5′.3 square.

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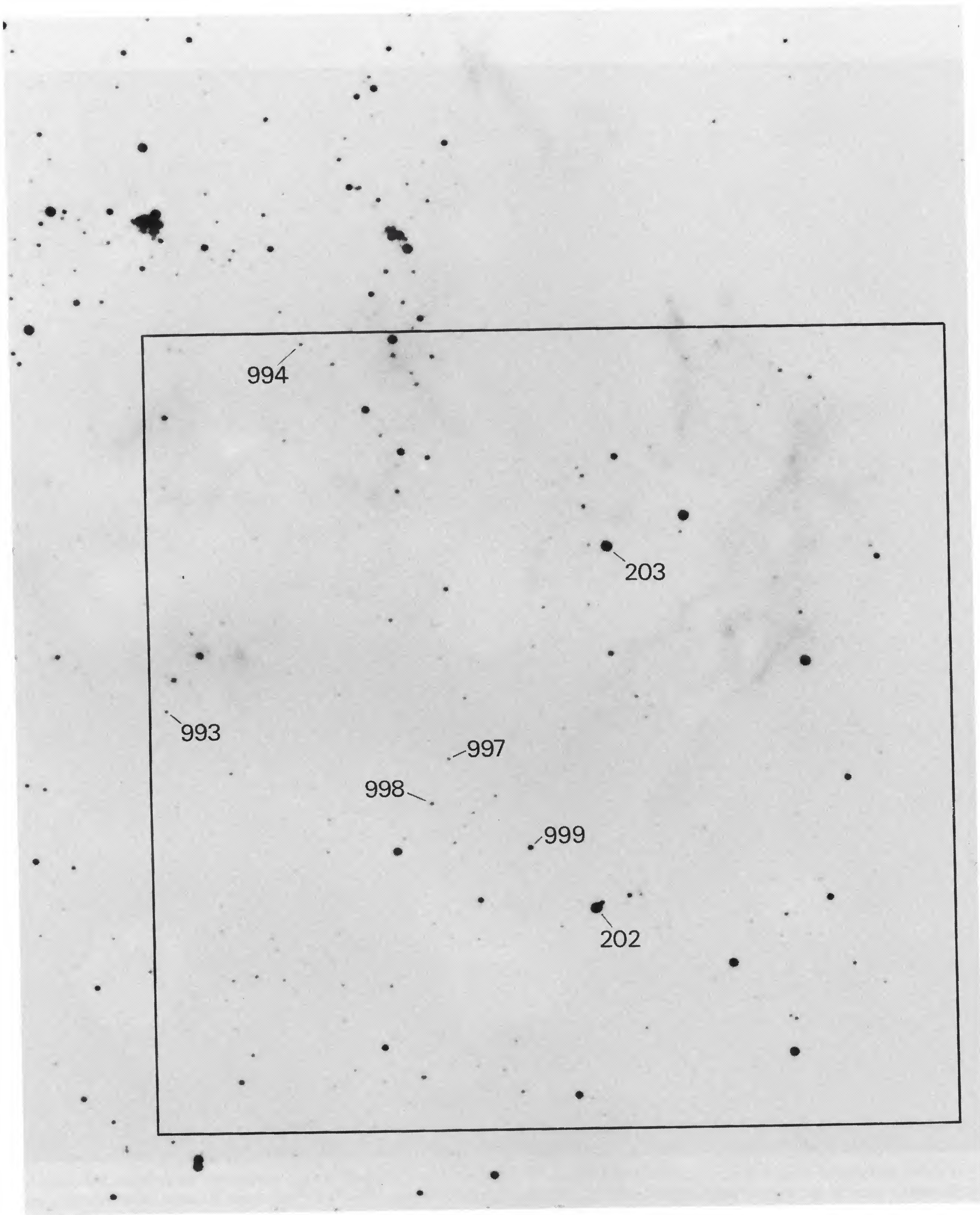

FIG. 1.—The field of Sk −69°202, from plate 720 (Hα, 5 minutes). North is at top and east to the left; part of NGC 2044 is visible at the northeast corner. The square indicates the area of the PDS scans and is 5′.3 on a side (note that it includes the edge of the exposure to the right). Several reference stars used in the image analysis are also identified. (The centering of the raster varied slightly among the different plates.)

TABLE 1

CTIO 4 Meter Plate Material

Number	Date (UT)	Observer	Filter[a]	Emulsion	Exposure (minutes)	Seeing
25......	1974 Nov 6	MGS[b]	6565	098–04	45	2″
145[c]	1974 Nov 27	NRW	4765	IIIa–J	30	2.5
146......	1974 Nov 27	NRW	4765	IIIa–J	5	6
152[c]	1974 Nov 28	NRW	5000	IIIa–J	15	2.5
153......	1974 Nov 30	NRW	4680	IIIa–J	5	1.5
335......	1974 Dec 27	NRW	5000	IIIa–J	3	3.5
344......	1974 Dec 28	NRW	4680	IIIa–J	2	2.5
345[c]	1974 Dec 28	NRW	4765	IIIa–J	2	2.5
346......	1974 Dec 28	NRW	5000	IIa–O	2	2.5
347......	1974 Dec 28	NRW	5000	IIa–O	4	2.5
719[c]	1975 Mar 2	NRW	6725	098–04	30	2.5
720[c]	1975 Mar 2	NRW	6565	098–04	5	2.5
721......	1975 Mar 2	NRW	4765	IIIa–J	1	2.5
722......	1975 Mar 2	NRW	4680	IIIa–J	1	2.5
4858[c]	1980 Nov 12	BML	RG665	IV–N	90	2
4859......	1980 Nov 12	BML	*V*	IIIa–F	60	2
4925......	1980 Dec 9	BML	*B*	IIIa–J	85	1.5
5973[c]	1983 Jan 26	YHC	4765	IIIa–J	10	1
5974......	1983 Jan 26	YHC	4765	IIIa–J	4	1
5975......	1983 Jan 26	YHC	4765	IIIa–J	1	1
5976[c]	1983 Jan 26	YHC	5000	IIIa–J	10	1
5978......	1983 Jan 27	YHC	4680	IIIa–J	4	1
5979......	1983 Jan 27	YHC	4680	IIIa–J	1	1
5999......	1983 Feb 25	YHC	4680	IIIa–J	1	1
6000......	1983 Feb 25	YHC	4765	IIIa–J	1	1
6006......	1983 Feb 26	YHC	6565	IIIa–F	0.5	1
6007......	1983 Feb 26	YHC	6565	IIIa–F	0.5	1
6008......	1983 Feb 26	YHC	6485	IIIa–F	4	1
6009......	1983 Feb 26	YHC	4680	IIIa–J	0.5	1
6010......	1983 Feb 26	YHC	4680	IIIa–J	3	1
6011......	1983 Feb 26	YHC	4765	IIIa–J	0.5	1
6012......	1983 Feb 26	YHC	4765	IIIa–J	3	1

[a] Four-digit numbers are central wavelengths in Å of ~ 100 Å wide interference filters.

[b] Malcolm G. Smith.

[c] Plate scanned with PDS.

b) *Density Differences*

In order to enhance the visibility of the companions and facilitate measurements of their position angles and separations, image subtractions were undertaken using the nearby OB star Sk −69°203 (B0.5, Rousseau *et al.* 1978; $V = 12.29$, $B - V = +0.01$, $U - B = -0.85$, Isserstedt 1975) as a reference on each plate. Density differences were judged preferable to intensities because the images of the 12th mag stars are saturated on most of the plates. While no quantitative magnitude information is provided by this approach, it does demonstrate the reality of the blended companions from a direct comparison with an apparently unblended image of the same magnitude and color. The final image centering was performed manually by trial and error; this procedure was found to be quite sensitive, and for the fine-grain plates an offset of 1 pixel (0″.07) from the optimum produced a noticeable misregistration in the difference.

Figure 2 (Plates L8–L9) displays the original images and the differences from five plates ranging from 4765 Å to the IV-N. The shortest exposure, which does not detect the companions, shows complete cancellation in the difference, indicating that the two 12th mag images are very similar. Position angles and separations of the companions were measured from the other plates at the image-display terminal, with the following results: for the northwest companion (hereafter star 2) 315° ± 3°, 2″.8 − 3″.0; and for the southeast companion (star 3) 120° ± 5°, 1″.5 − 1″.7. The most saturated plates tended to yield larger separations, which were disregarded. The same results were obtained for star 2 with a density-weighted centroiding routine. The sequence in Figure 2 indicates qualitatively that the colors of stars 2 and 3 are fairly similar, and the consistency of the IV-N image structure with the others shows that there is no bright red star in the system.

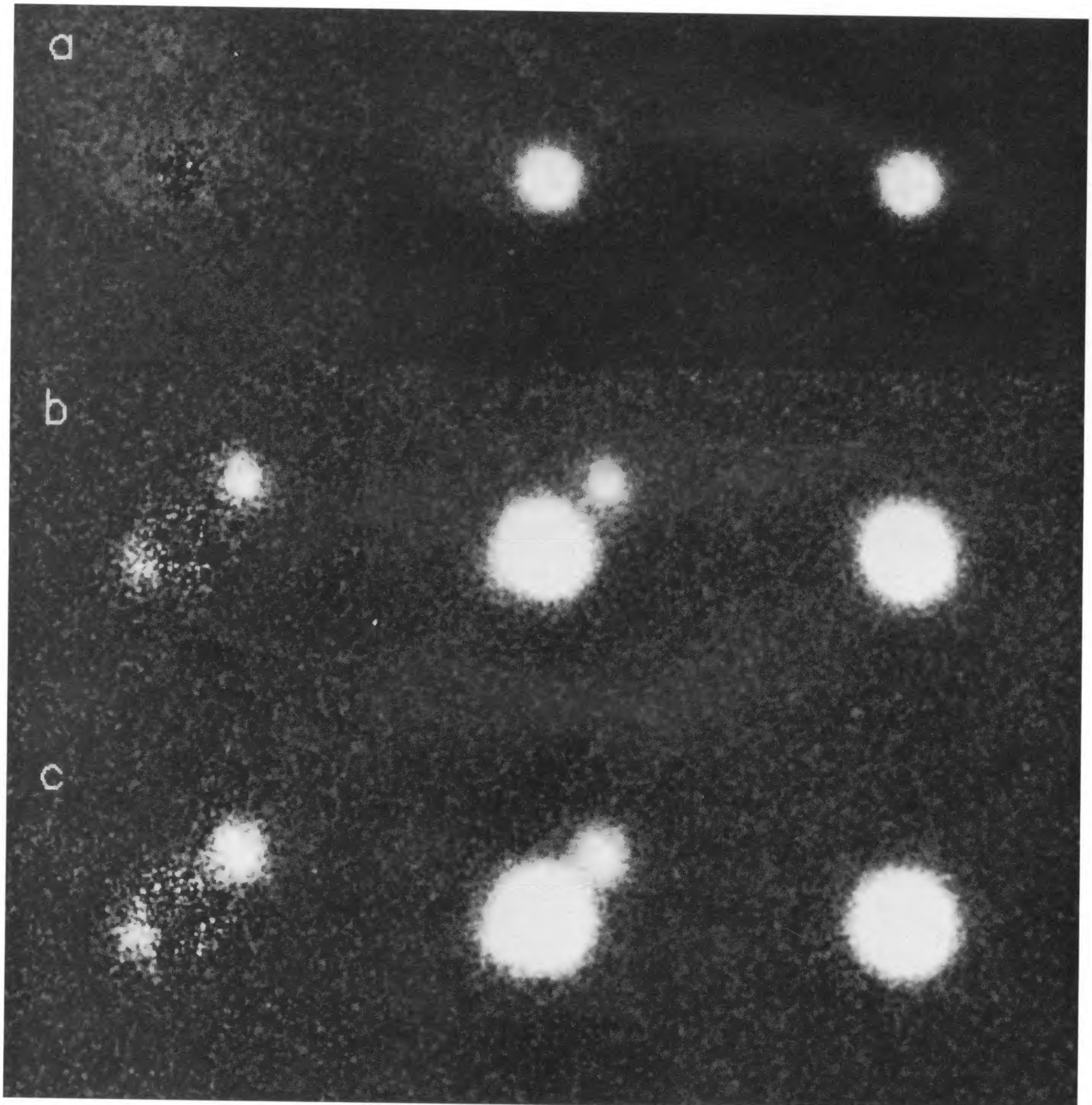

FIG. 2.—Density differences from five plates, Sk −69°202 minus Sk −69°203. The left panel of each row shows the image subtraction from a given plate, while the center panel is the original image of Sk −69°202 and the right panel is that of Sk −69°203, from the same plate. North is up and east to the left in each case. Star 2 is at 3″ in PA 315°, and star 3 is at 1″.5 in PA 115°. (*a*) Plate 345 (4765 Å, 2 minutes—the apparent "nebulosity" is spurious); (*b*) plate 5973 (4765 Å, 10 minutes); (*c*) plate 5976 (5000 Å, 10 minutes); (*d*) plate 719 (6725 Å, 30 minutes); (*e*) plate 4858 (IV-N, 90 minutes).

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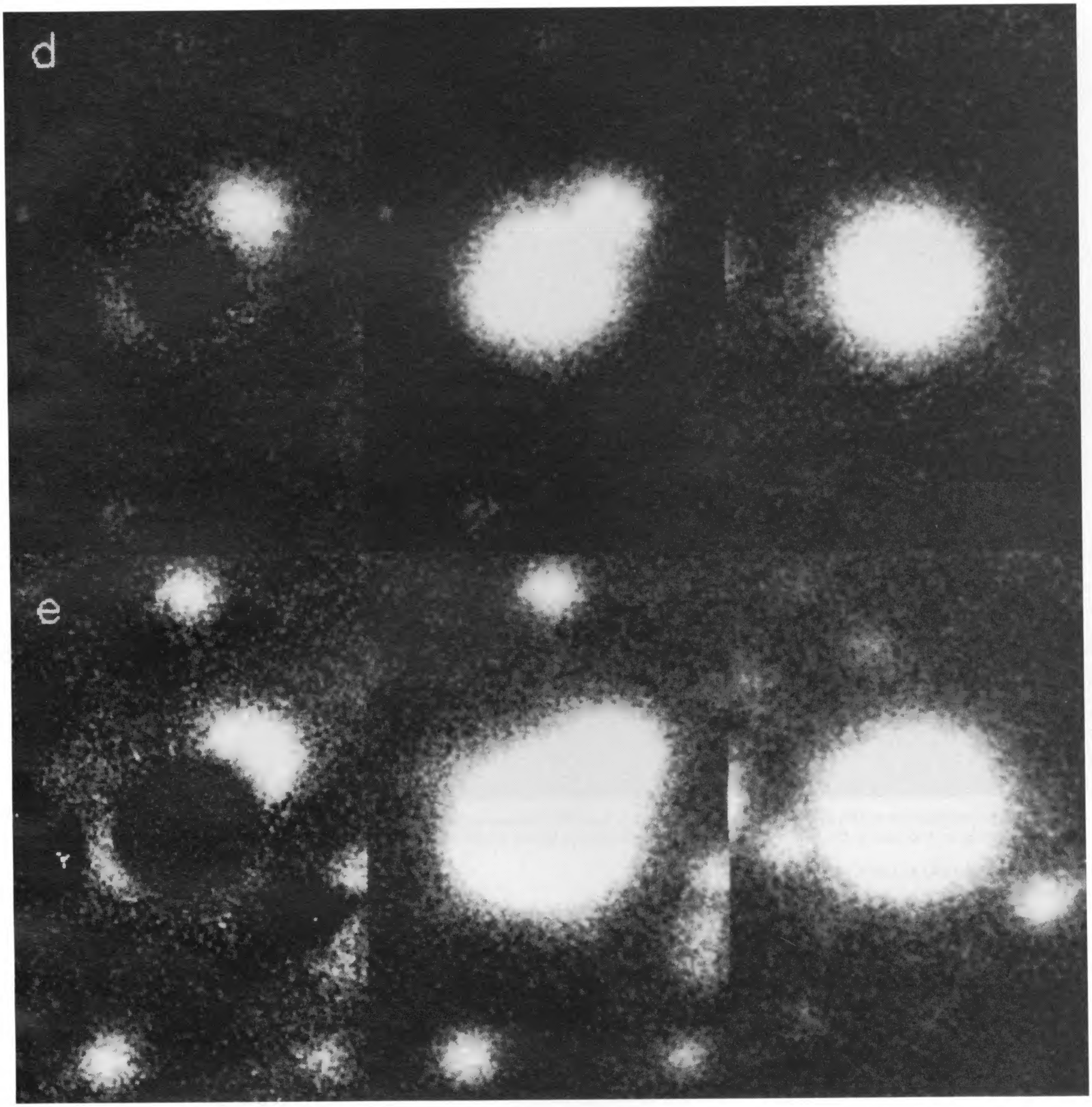

FIG. 2.—*Continued*

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Djorgovski (1987) reported a companion to SN 1987A at 235°, 1″.8 in postoutburst images at [O II] λ3727. None of the present plates is sensitive to that wavelength, but several include [O III] λ5007 or Hα, and none of them shows an obvious object at that position. Testor and Lortet (1987*a*, *b*) have suggested that star 1 was a 0″.4 north-south double prior to the outburst. Such an observation is near the limit of their material as well as ours, and we do not find evidence to either support or strongly exclude their suggestion. If star 1 was such a double, it should be noted that neither component could have been very red (see above); and that neither component is visible now in the ultraviolet (see § III below), even though the SN ejecta could not yet have engulfed a companion at that distance. However, from a more detailed analysis of one of our images (plate 5976), Heap and Lindler (1987) have found possible evidence for features which may be related to both the Djorgovski and the Testor-Lortet structures.

c) *Image Synthesis*

Following the above demonstration of the reality and separability of star 3, despite saturation of the blended image, we proceeded to obtain a quantitative albeit approximate estimate of the photometric properties of the individual components by using apparently unblended images (identified in Fig. 1) to synthesize a blend that simulates the appearance of Sk −69°202. As our goal was to define a simple algorithm and to be relatively insensitive to saturation effects, we adopted the following procedure: (1) select a set of components with appropriate magnitudes from other images on the plate; (2) convert these images to intensities, making some reasonable but necessarily uncertain assumption about the density-intensity relation near saturation; (3) add the three components at appropriate separations, taking care to subtract off all but one of the sky background levels; (4) use the inverse density-intensity transform to convert the synthesized blend back to density space; and finally, (5) perform a visual comparison (on the image-display screen) of the Sk −69°202 blend and the synthesized blend. Note that this procedure is relatively insensitive to errors due to saturation because additions near saturation yield a result near saturation.

We performed this analysis for plates 720 (6565 Å) and 5973 (4765 Å), subject to the additional constraint that the geometrical parameters, position angle and separation, be the same in both syntheses. The best results were obtained with 315°, 3″.0 for star 2 and 110°, 1″.4 for star 3. In both cases, Sk −69°203 was the reference for star 1. On plate 5973, the average of stars 993 and 994 with intensity multipliers of 1.4 and 1.0 was used for stars 2 and 3, respectively. On plate 720, star 999 with a multiplier of 0.9 was used for star 2, and the average of stars 997 and 998 with a multiplier of 1.8 for star 3. (The use of a multiplier less than unity in intensity space is certainly undesirable in view of the error discussion given above; however, no stars only slightly fainter than 999 are located sufficiently close to Sk −69°202 to be appropriate.) These results are displayed in Figure 3 (Plate L10).

The passband of plate 720 was approximated by $R \approx V - (B - V)$ and that of plate 5973 by $m_{4700} \approx 0.68 \times (B - V) + V$; these relations were straightforwardly inverted to obtain V and $B - V$. Using these approximations and the nearby NGC 2044 stars for which photometry is given by Lucke (1972), we calibrated the synthesis reference stars (Table 2) and then derived $V = 15.29 \pm 0.2$, $B - V = +0.20 \pm 0.4$ for star 2, and $V = 15.68 \pm 0.2$, $B - V = +0.15 \pm 0.4$ for star 3. The cited error estimates are based on the standard deviations from different calibrations of the reference stars against NGC 2044 (0.18 mag), an estimate of the sensitivity of the visual test of the synthesized images against the Sk −69°202 system (0.24 mag), and the use of two measures for magnitude and one for color. These $B - V$ values are uncertain, but they are consistent with neutral or blue colors for the companions and inconsistent with a very red color, in agreement with the density difference results from the previous section.

TABLE 2

MAGNITUDES OF ANONYMOUS REFERENCE STARS FOR THE IMAGE SYNTHESIS

Star	Plate 5973(m_{4700})	Plate 720(R)
993	15.90	...
994	15.68	...
997	...	16.17
998	16.42	15.94
999	15.49	14.98

Subtracting these results from Isserstedt's (1975) photometry of the blend, we obtain $V = 12.36$, $B - V = +0.02$ for the parameters of star 1 alone. This corrected color is insensitive to our colors for stars 2 and 3; it remains +0.04 if we adopt $B - V = 0$ for them.

III. DISCUSSION

Astrometric measurements have shown that the position of SN 1987A coincides with that of the bright supergiant in Sk −69°202 (star 1) to within 0″.1, excluding the companions (stars 2 and 3) as possible progenitors (see references in § I above). Following the rapid decline of the SN in the far ultraviolet (Panagia *et al.* 1987), the *International Ultraviolet Explorer* revealed through its 10″ × 20″ entrance aperture two spatially resolved spectra with early B-type absorption features, which initially were interpreted as arising from stars 1 and 2 (Sonneborn and Kirshner 1987*a*). The implication would then be that the SN precursor was a fourth, unobserved star positionally coincident with star 1. However, realization of the existence of star 3 led to more accurate determinations of the *IUE* image separation and fluxes (Panagia *et al.* 1987; Sonneborn and Kirshner 1987*b*; Kirshner *et al.* 1987; Gilmozzi *et al.* 1987; Sonneborn, Altner, and Kirshner 1987), which turn out to be consistent with stars 2 and 3, and inconsistent with either 1 and 2 or 1 and 3. If stars 2 and 3 are early B giants, they will have absolute visual magnitudes about 3 mag fainter than supergiants (Walborn 1972), and UV spectral features similar to, albeit somewhat weaker than, the supergiants (Wu *et al.* 1983). These characteristics are consistent with both the optical and *IUE* observations. Therefore it now appears that star 1 has indeed

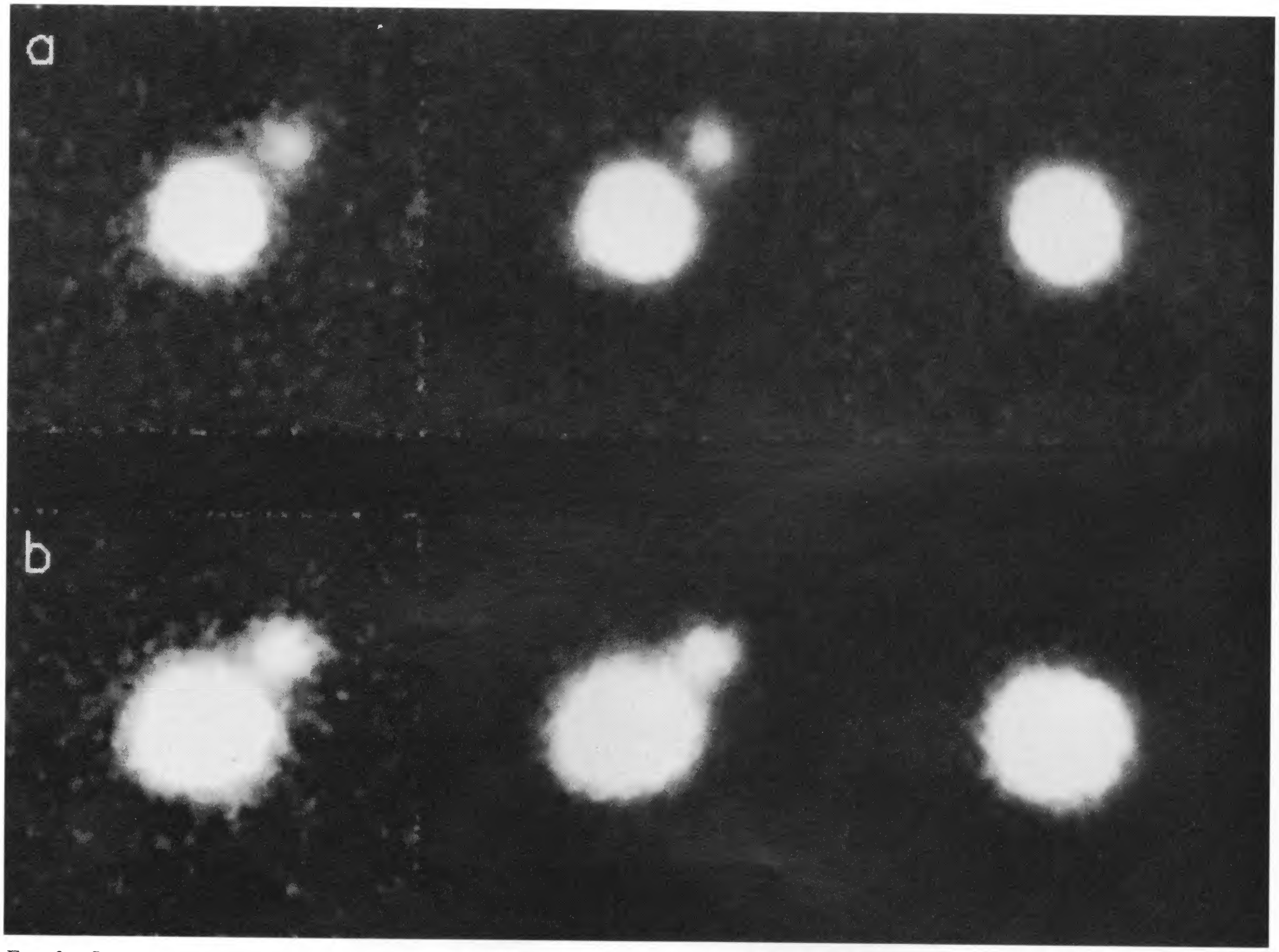

FIG. 3.—Image syntheses from two plates (*left panel of each row*), with the original images of Sk −69°202 (*center*) and Sk −69°203 (*right*) from the same plates. North is up and east to the left in each panel. (*a*) Plate 5973 (4765 Å, 10 minutes); (*b*) plate 720 (6565 Å, 5 minutes).

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disappeared, and that this apparently normal B3 I object was likely the SN 1987A progenitor.

This circumstance is unexpected, if not disconcerting. Hillebrandt *et al.* (1987) have proposed a model in which stars of 15–20 $M_\odot$ become supernovae before reaching a red supergiant stage, for a metallicity corresponding to that of the LMC. However, this suggestion conflicts with the observation that the red supergiant regions in the H-R diagrams of the Magellanic Clouds are well populated up to masses of about 50 $M_\odot$ (Humphreys 1986, 1987); moreover, the observed ratios of red to blue supergiants *increase* with decreasing metallicity (Humphreys and McElroy 1984). More likely Sk −69°202 was a post–red supergiant evolving blueward in the H-R diagram (Stothers 1975; Maeder 1987; Woosley, Pinto, and Ensman 1987); or alternatively, its apparent spectral type might have been due to a shell as in the luminous blue variables (Wolf 1986; Lamers 1986; Davidson 1987). However, it should be noted that a low-dispersion, objective-prism plate obtained with the Curtis Schmidt at CTIO by B. M. L. excludes any Hα emission with an equivalent width greater than ~ 7 Å, and no evidence for prior large light variations has been found (McNaught 1987; McNaught and Morel 1987; Blanco, Walker, and McCarthy 1987; West *et al.* 1987; Blanco *et al.* 1987), although Hazen (1987) allows the possibility of variability at the 0.3–0.5 mag level. Perhaps some further information can be extracted from the spectrogram of Rousseau *et al.* (1978), which appears to offer the highest spectral resolution available prior to the explosion; on either of the above hypotheses one might expect to see some chemical anomalies and/or weak emission lines. A third, somewhat unappealing possibility should be mentioned, namely that star 1 has not exploded, but is merely obscured by the debris from a fourth, positionally coincident object, about which we have little or no preoutburst information; in this case the spectrum of star 1 really will reappear when the ejecta become optically thin in the UV. However, while this hypothesis cannot yet be strictly excluded, it is neither necessary nor likely, because the characteristics of the explosion itself have been shown to be consistent with a blue supergiant progenitor (e.g., Woosley, Pinto, and Ensman 1987), and it is just such an object which has disappeared. In any event, it will be of some interest to analyze direct images comparable to those discussed here, after SN 1987A has faded in the optical.

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