SUPERNOVA 1987A: PHOTOMETRY OF THE DISCOVERY AND PRE-DISCOVERY PLATES

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ABSTRACT

The discovery and pre-discovery plates for Supernova 1987A have been analyzed. SN 1987A was found to have $B=5.00$ (±0.15) on Feb 24.12 UT 1987; and Sanduleak $-69°$ 202 was $B=12.12$ (±0.15) on Feb 23.08 UT 1987. These represent, respectively, the second earliest reliable photometric measure for the Supernova and the last known observation of its precursor.

1. INTRODUCTION

In the early morning of 1987 February 24th, the brightest supernova since the invention of the telescope was discovered independently by the author at the University of Toronto Southern Observatory (UTSO) in Chile, by Oscar Duhalde at the Las Campanas Observatory, and by Albert Jones from Nelson, New Zealand (IAU Circular 4316). The author's discovery was made in the darkroom of the UTSO while examining a photographic plate taken earlier that same night. This discovery plate was preceded by a nearly identical prediscovery plate taken twenty-five hours earlier (before the precursor star underwent core-collapse). Herein are reported the B magnitudes for Sk $-69°$ 202 and Supernova 1987A derived from the prediscovery and discovery plates.

2. OBSERVATIONS

Both the prediscovery and discovery plates were taken with a 10-Inch Astrograph belonging to the Carnegie Institute of Washington at Las Campanas Observatory. This instrument was equipped with a blue-corrected (unfiltered) lens stopped down to a 5 and 3 in aperture on February 23rd and 24th, respectively (to improve off-axis image quality). The prediscovery exposure was 1 h long and the discovery plate was exposed for 3 h. $8''\times10''$ glass photographic plates were used (Kodak 103a-O, baked 3 h in 4% forming gas at 65 °C) and developed for 7 min at 20 °C in MWP-2. The limiting magnitude for both plates was approximately $B\approx15$ at a plate scale of ~181 arcsec/mm. From the DAOPHOT stellar fitting procedure described in the next section, stars with a magnitude of $B\approx12$ (similar to that of Sk $-69°$ 202) had a FWHM (in density) of about 16 arcsec. The finest details discernable on the plates were a bit smaller, but still several times larger than the theoretical resolution of the emulsion itself. The prediscovery and discovery plates are reproduced in Figs. 1 and 2 (Plates 89 and 90).

3. REDUCTIONS AND RESULTS

3.1. The Prediscovery Plate

A section of the prediscovery plate was scanned using the David Dunlap Observatory PDS microdensitometer. A single 9 mm$\times$12 mm box immediately surrounding Sk $-69°$ 202 was measured using a 12.5 μm square aperture stepped at a scanning pitch of 12 μm. The original pixels were then "rebinned" 2-by-2 to better match the pixel scale to the actual plate resolution. All further references to "pixels" will be to these rebinned 24 μm square cells ($\sim$4.3 arcsec square). No attempt was made to convert image density into image intensity, as the photographic plate was not spot calibrated. Figure 3 shows a reproduction of the area scanned. (See Fig. 1 for the location of the scan box on the prediscovery plate.)

The determination of stellar magnitudes from photographic data is often done by measuring *integrated* densities within a fixed aperture, and then reading off the magnitudes from a plot of [log(D) vs magnitude] calibrated against a sequence of standard stars. Because Sk $-69°$ 202 was surrounded by many close companions, a somewhat modified approach was used in order to minimize the contribution due to these nearby stars. Using the software package DAOPHOT (Stetson 1987), a representative "point spread function" (PSF) was determined using six uncrowded stars within the 9 mm$\times$12 mm scan box approximately equal in brightness to Sk $-69°$ 202. The model PSF was then fit to Sk $-69°$ 202 and a sequence of 27 standard stars selected from the catalogs of Walker & Blanco (1988) and Walker & Suntzeff (1990). The PSF fitting returned estimates of *peak* density for each object, which were substituted for the usual integrated ones in the reduction procedure described above.

It should be noted that DAOPHOT assumes you are working with data from a *linear* detector. A photographic plate is not a linear detector. Linearity is essential if you intend to accurately determine magnitudes for substantially overlapped stellar profiles. But here, we're simply trying to "pluck out" magnitudes for stellar profiles that are crowded but mostly nonoverlapping. As we will still be

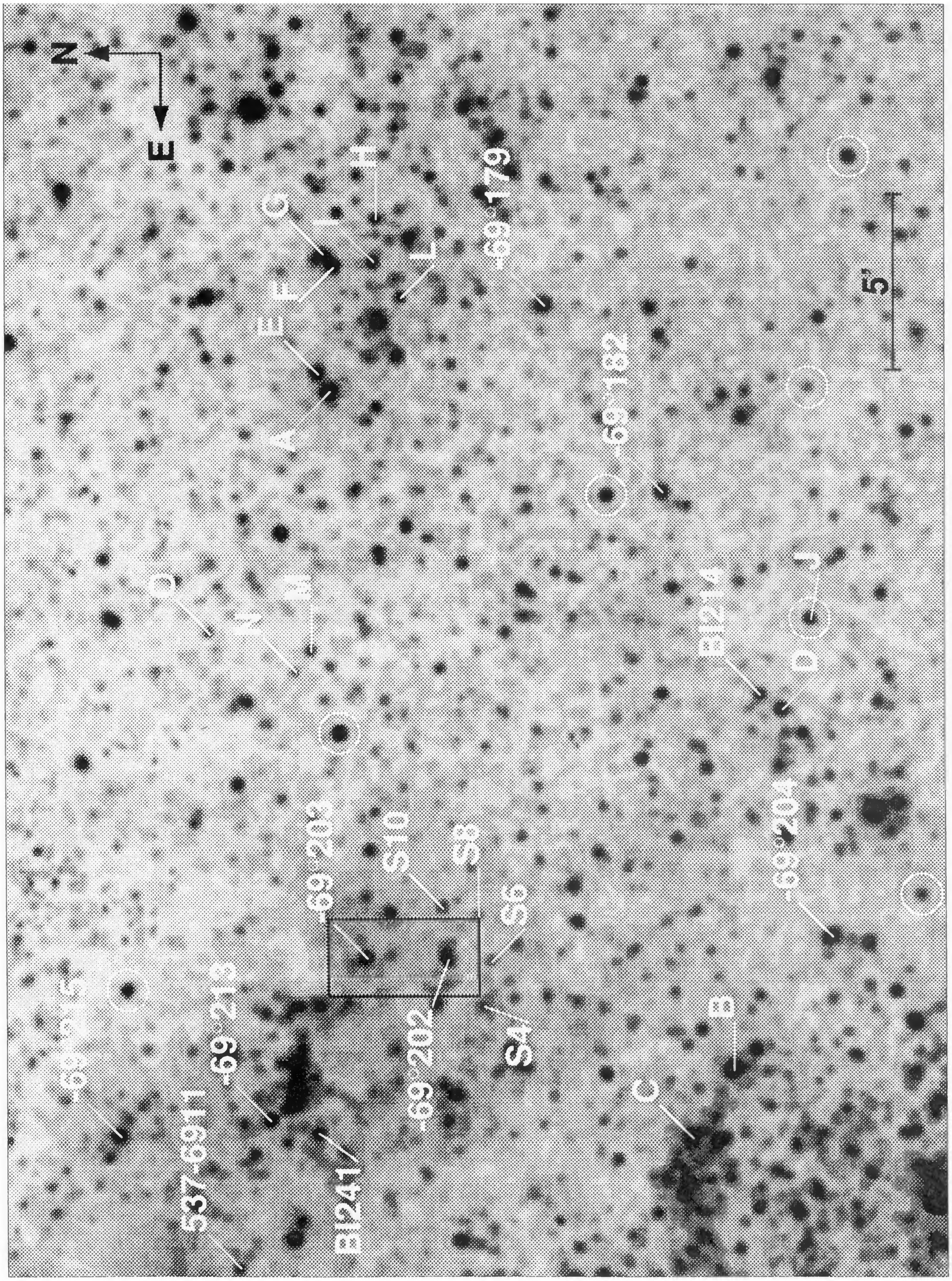

FIG. 3. The 27′×36′ region surrounding Sanduleak −69° 202 scanned off the pre-discovery plate. Stars labeled with a single capital letter correspond to calibration stars given in Walker & Blanco (1988); alpha-numeric labels starting with an "S" correspond to calibration stars given in Walker & Suntzeff (1990); remaining designations refer to OB supergiants given in Isserstedt (1975). Circled stars are those used in defining the PSF for the prediscovery plate analysis.

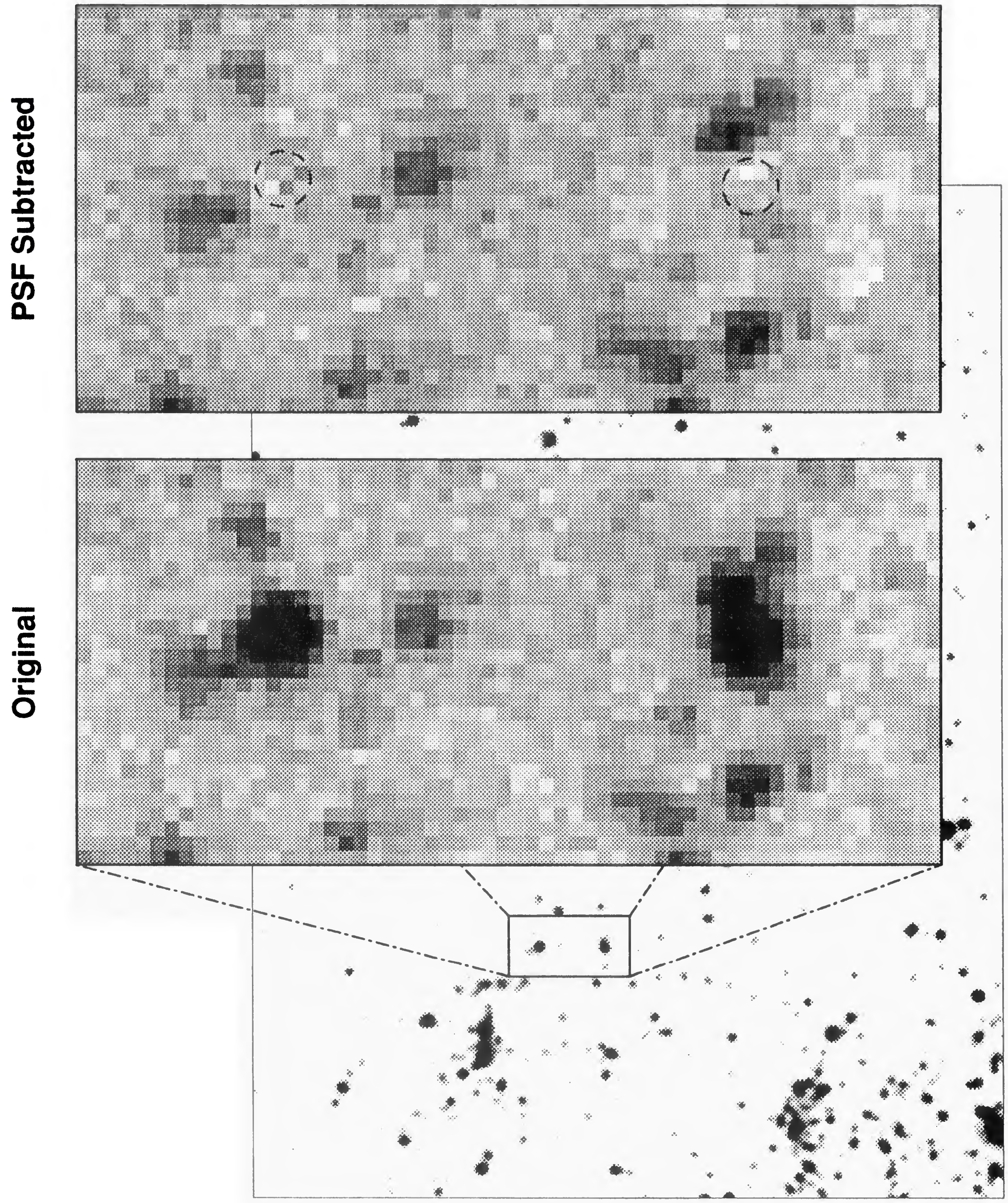

FIG. 4. Magnified subsection of Fig. 3, showing the area immediately surrounding Sk $-69°$ 203 (upper) and Sk $-69°$ 202 (lower). It measures $2.0' \times 4.3'$. The left-hand representation is how the area appeared originally; the right-hand representation is after subtracting the model PSF from the two stars. The black circles mark the former location of the stars and correspond to the 16 arcsec diameter (3.7 pixel) FWHM of the PSF model. Proof of the PSF-fitting technique's effectiveness is shown by the "residual" less than 3 pixels to the left of where Sk $-69°$ 202 formerly resided: this is, in fact, a 16th magnitude star, "S2" in Walker & Suntzeff (1990).

making use of a density-to-magnitude calibration plot, we don't care if this is linear, just as long as it can be adequately fit by some continuous and monotonic function.

The nonlinearity of photographic plates means that stellar PSFs change as a function of magnitude; it's therefore best to construct model PSFs using stars similar in magnitude to the program objects. DAOPHOT works best when the stellar profiles are "nonsaturated," but will continue to return nondegenerate peak densities once saturation sets in. Note that if the data are strongly afflicted by positionally variable optical aberrations, it's unlikely that either integrated or peak density calibrations will return reliable magnitudes without taking this additional complication into account. The analysis of the prediscovery plate was restricted to a small region immediately surrounding the

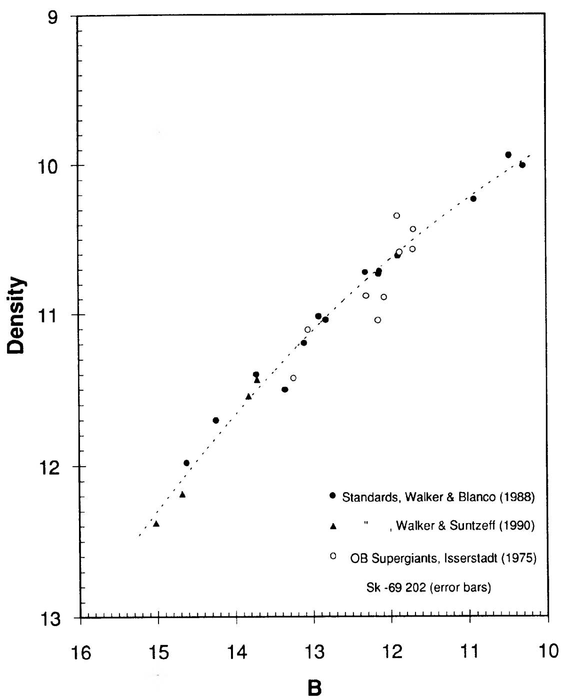

FIG. 5. Profile-fitted peak densities (expressed in magnitudes) vs catalog B magnitudes for calibration stars and Sk $-69°$ 202 on the prediscovery plate. The dashed line is the second-order polynomial fit that best described the data. The open symbols (not used in the fit) are for OB supergiants similar to Sk $-69°$ 202, taken from Isserstedt (1975). The vertical error bar shown on the Sk $-69°$ 202 data point is the standard deviation from the standard star fitting. The horizontal error bar indicates how this density error maps into uncertainty in the B magnitude.

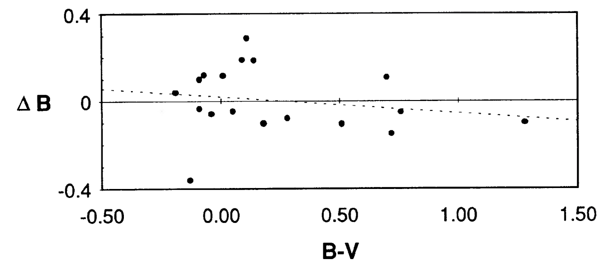

FIG. 6. $B-V$ color dependence of B magnitudes for calibration stars on the prediscovery plate (in the sense: delta $B = B_{\text{catalog}} - B_{\text{calculated}}$).

program star, close to the plate center, rendering this latter effect inconsequential.

Figure 4 illustrates the effectiveness of the PSF-fitting technique with respect to the prediscovery plate reductions.

Peak densities (expressed in magnitudes) versus B magnitudes are plotted in Fig. 5, along with the second-order polynomial fit that best described the data. From this, a magnitude of **B=12.12 (±0.15)** was determined for Sk $-69°$ 202 at the mid-exposure epoch of **Feb 23.08 UT 1987**. The stated error is based solely upon the scatter seen in the standard star magnitudes. Figure 6 shows a search for $B-V$ color dependence, revealing only a subtle trend that would add $\leqslant 0.02$ mag to the above magnitude using the $B-V$ color of 0.04 reported by Isserstadt (1975).

3.2. The Discovery Plate

With less than a half-dozen stars of comparable brightness scattered about the entire discovery plate, care was needed to arrive at a reliable value for the supernova B magnitude. The calibration stars were nonhomogeneously afflicted by lens aberrations but their profiles were felt sufficiently "condensed" to yield meaningful results using aperture photometry. In total, thirteen 1.2 mm square boxes were scanned on the discovery plate using the David Dunlap Observatory PDS microdensitometer; twelve of the scan boxes were centered upon single, bright reference stars and one was centered upon SN 1987A. A 12.5 μm square aperture was used, stepped at a scanning pitch of 12 μm, and the individual images "rebinned" 2-by-2 to better match the pixel scale to the actual plate resolution. ("Pixels" will refer to the rebinned cells for the rest of this discussion.) No attempt was made to convert image density into image intensity, as the photographic plate was not spot-calibrated. The thirteen individual scan regions are shown in Fig. 7, and their positions on the discovery plate are shown in Fig. 2.

The software package DAOPHOT (Stetson 1987) was used to analyze the scan data using its "PHOTOMETRY" routine to perform "synthetic aperture photometry" upon the star within each scan box. The routine numerically integrates the density contained within a fixed number of pixels of each star's peak central density, automatically correcting for the plate background contribution. In order to ascertain the effect of aperture size on the final results, four separate passes were made, integrating densities over all pixels within 5, 7, 10, and 14 pixels of each star's central peak. The background levels were in all cases the average density determined within annuli extending from 20 to 25 pixels about each star. Figure 8 shows the plots of [log(D) vs B magnitude[1]] for the four separate aperture sequences, along with the second-order polynomial fits that best characterized each aperture sequence. Using a weighted mean of the four solutions determined for the different aperture sequences, SN 1987A was found to have a magnitude of **B=5.00 (±0.15)** at the midexposure epoch of **Feb 24.12 UT 1987**. The stated error is the average of the mean errors determined for the three largest aperture sequences as indicated by residuals in the reference star magnitudes with respect to the fitting functions. A search for color trends revealed only a small dependence on $B-V$ and $U-B$, as shown in Fig. 9. Making the uncertain extrapolation in supernova colors to $U-B=-0.9$ and $B-V=-0.05$ for

[1]Magnitudes and colors are taken from Nicolet 1978.

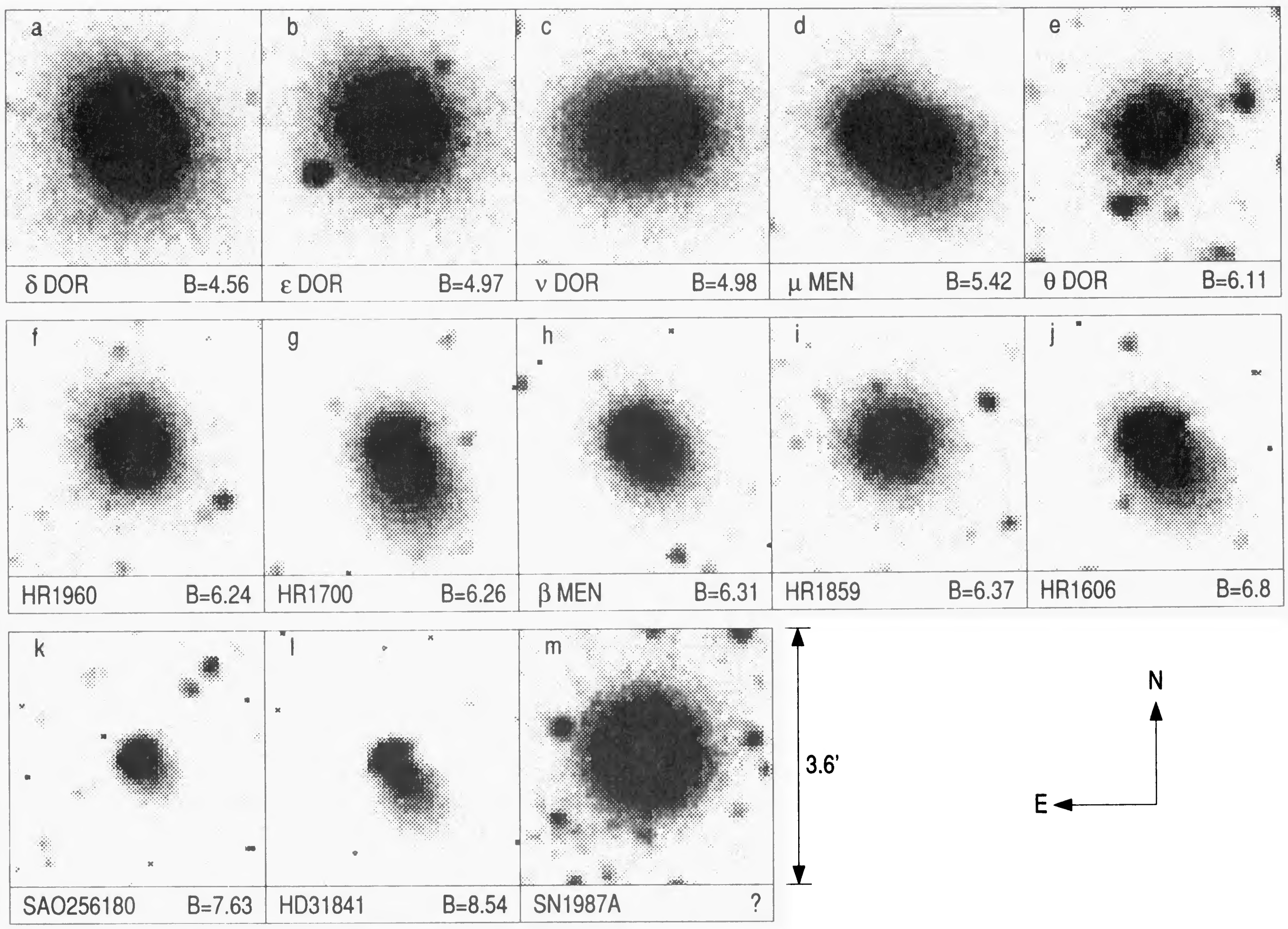

FIG. 7. PDS scans of the twelve calibration stars and SN 1987A off the discovery plate. Each scan corresponds to an area 1.2 mm (50 pixels) square. The lower-case letter in the top left corner of each box identifies the star in Fig. 2. Magnitudes are from Nicolet (1978).

this epoch, the trends indicate a correction of $\leqslant +0.05$ may be needed in the reported magnitude.

The important issue of how plate aberrations affected the results cannot be exactly quantified as there were simply too few suitable stars to work with. Still, some level of assessment can be made by examining the data presented in Figs. 2, 7, and 8. The two stars most closely resembling the supernova in integrated density are ϵ and ν Doradus. These two stars have nearly identical B magnitudes and very similar $B-V$ colors (-0.14 and -0.08, respectively); these colors probably were not very much different from that of the supernova at this epoch. Noting that ν Doradus lies 50% further from the plate-center than ϵ Doradus (74 mm vs 51 mm), and noting that ϵ Doradus always appears somewhat brighter than ν Doradus in the reductions: if we were to attribute this wholly to the effects of the optical aberrations, we might claim a resultant error of about 0.12 mag. Given that the supernova lies about as far away from the plate center (21 mm) as ν Doradus is beyond ϵ Doradus, it is reasonable to infer that the reported magnitude is in need of no greater than ~ -0.12 mag correction.

4. DISCUSSION

The B magnitude reported here for SN 1987A is about 0.2 mag fainter than that found by Shelton & Lapasset (1993) 5 h later using a photoelectric photometer. Although this is only a 1σ difference, it may indicate that the supernova was still rising to "first maximum light" in the B bandpass 19 h after the IMB/Kamiokande-II neutrino detection;[2] data obtained subsequent to this observation through to the third day indicates a nearly constant B magnitude.

The B magnitude reported for Sk $-69°$ 202 from the prediscovery plate stands as the last known observation for

[2]Feb 23.3165 UT 1987 (JD 2,446,849.8165); see Bionte *et al.* (1987) and Hirata *et al.* (1987).

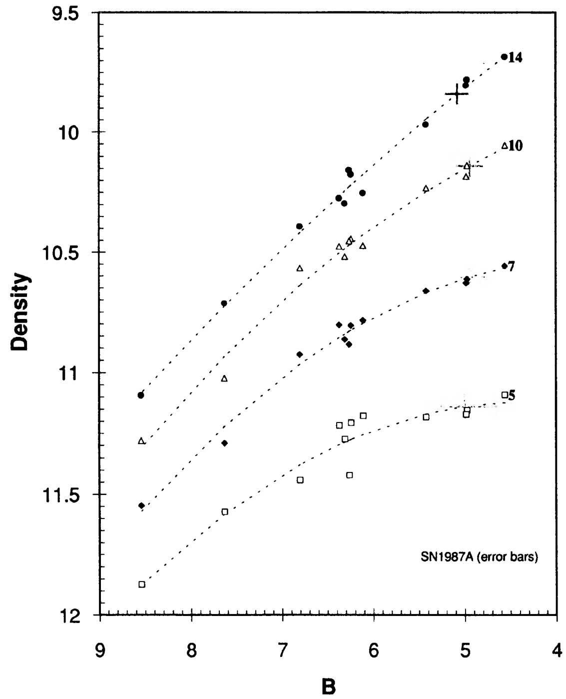

FIG. 8. Aperture-photometry integrated densities (expressed in magnitudes) vs catalog B magnitudes for calibration stars and SN 1987A on the discovery plate. The four sequences correspond to measurements made with 5, 7, 10, and 14 pixel radius synthetic apertures. The dashed lines are second-order polynomial fits that best describe the individual sequences. The vertical error bars shown on the SN 1987A data points are the standard deviations from the standard star fits. The horizontal error bars indicate how these density errors map into uncertainties in the B magnitude.

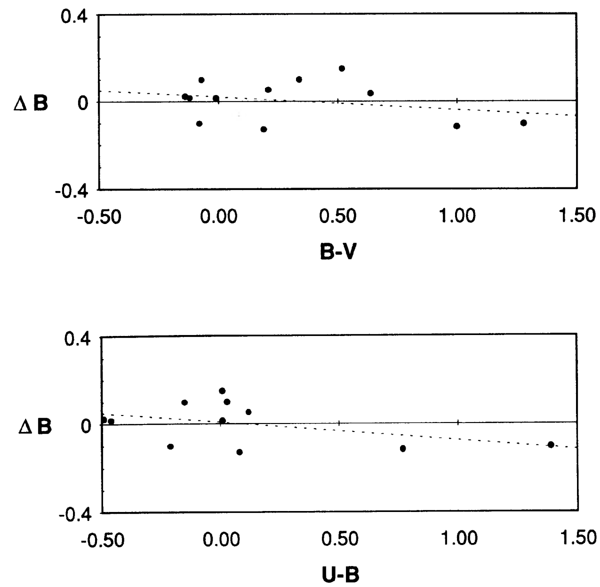

FIG. 9. $B-V$ and $U-B$ color dependence of B magnitudes for calibration stars on the discovery plate (in the sense: delta $B=B_{\mathrm{catalog}}-B_{\mathrm{calculated}}$). $B_{\mathrm{calculated}}$ is the weighted mean of results from the four different aperture sequences.

the progenitor to SN 1987A. It comes just 6 h prior to core collapse. The value found here is 0.16 mag brighter than that reported by Isserstadt (1975), a 1σ difference that is not inconsistent with the conclusion of Blanco *et al.* (1987) that Sk $-69°$ 202 was nonvariable during the last years of its life. But according to Hazen (1987), a study of Harvard plates dating from 1899 through 1986 indicates that Sk $-69°$ 202 may indeed have been varying by up to ± 0.5 mag. In Fig. 5, presented along with the standard star data, are identical measurements made for nine early-type supergiants within the vicinity of Sk $-69°$ 202 taken from the catalog of Isserstadt. Three of these objects display magnitudes discordant by $>3\sigma$ (0.45 mag), indicating that variability may be a common feature of the LMC OB supergiants.

I am very grateful to the administrative and support staff of the Las Campanas Observatory for their help and encouragement throughout my stay at the Observatory. They assisted with numerous personal requests when clearly they need not have, as when granting permission to refurbish and use the 10″ Astrograph, and later in supplying the photographic plates that would eventually lead to the Supernova's discovery. I must share with them fully any accolades earned in that fortuitous find. And on the night of discovery, I would like to thank Angel Guerra and Dr. William Kunkel for their help in getting the word out, and Dr. Barry Madore for helping me prepare for what was to follow. I would also like to thank Dr. R. F. Garrison, director of the University of Toronto Southern Observatory for making my presence on the mountaintop possible. His enthusiasm and support for the UTSO has proven invaluable. The observations reported herein were gathered while the author was serving as Resident Astronomer at the UTSO, which is supported by an infrastructure grant from the Natural Science and Engineering Research Council of Canada. This paper is dedicated to the memory of Michael Stewart Fieldus, a good friend who cared passionately about life and about astronomy in particular.

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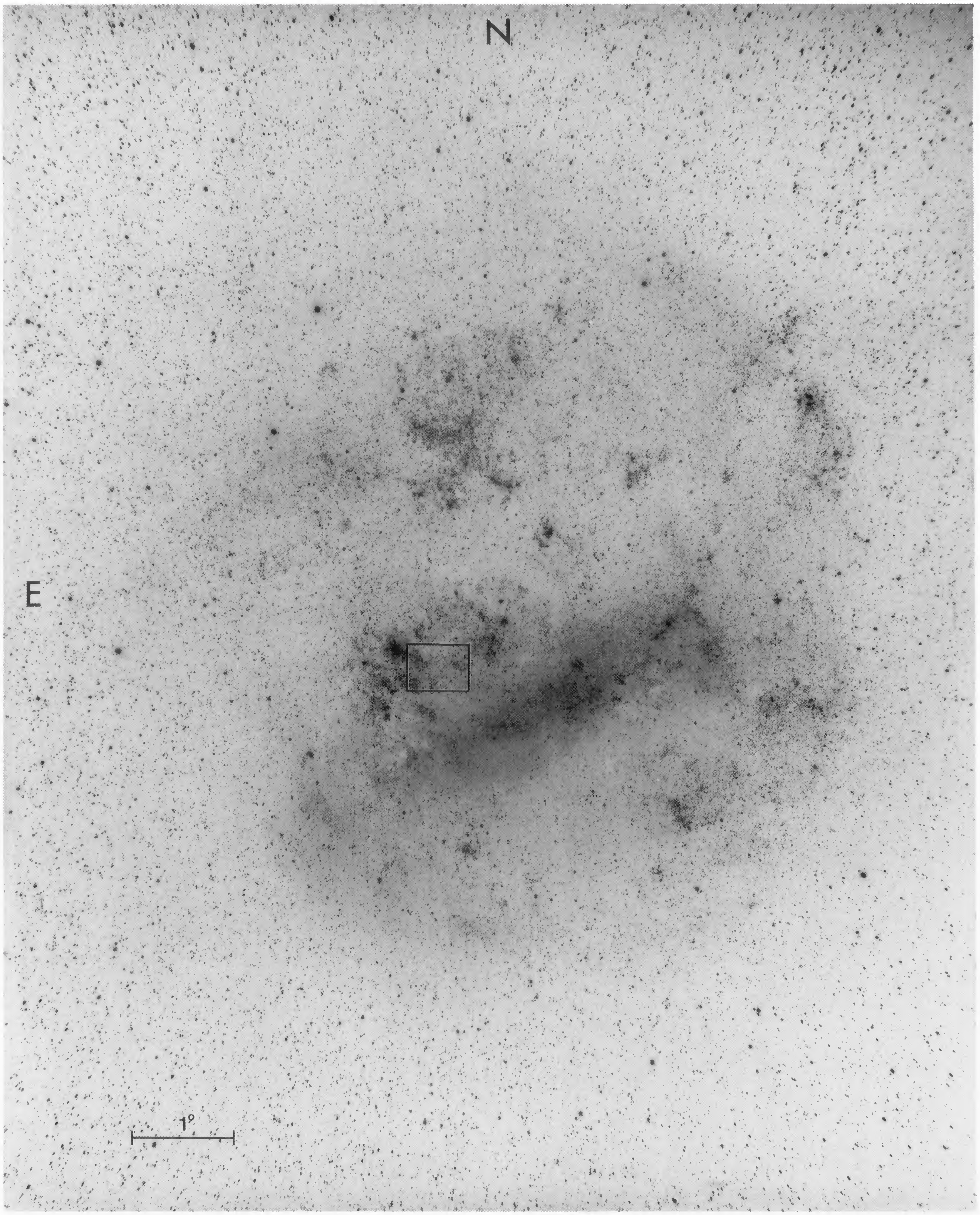

FIG. 1. Prediscovery plate for SN 1987A, reproduced at 90% lifesize. The 1 h blue-light exposure covers 10°×12° at an original plate scale of ~181 arcsec/mm. It was obtained February 23.08 UT 1987 (midexposure) using the Carnegie Institute of Washington 10″ Astrograph at Las Campanas Observatory in Chile. The precursor to SN 1987A, Sanduleak −69° 202, is located within the black box delineating the area scanned for the plate analysis; a close-up view of this scan region is shown in Fig. 3.

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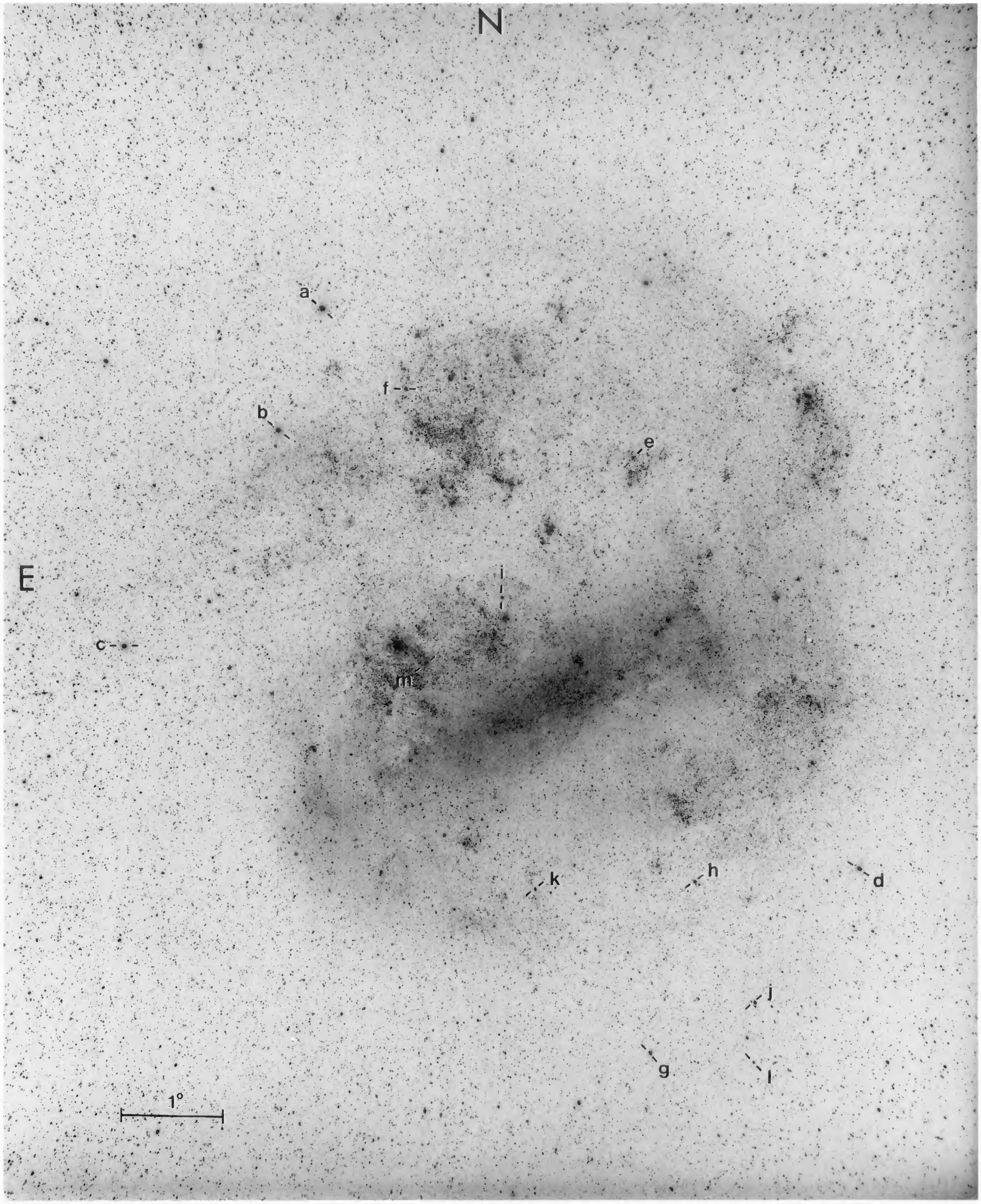

FIG. 2. Discovery plate for SN 1987A, reproduced at 90% of lifesize. The 3 h blue-light exposure covers 10°×12° at an original plate scale of ∼181 arcsec/mm. It was obtained February 24.12 UT 1987 (midexposure) using the Carnegie Institute of Washington 10″ Astrograph at Las Campanas Observatory in Chile. SN 1987A and the twelve stars used in its brightness determination are marked with lower-case letters; refer to Fig. 7 for the identities and close-up views of these objects.

Shelton (see page 1886)

