PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC
103: 958–963, September 1991

CCD PHOTOMETRY OF SN 1987A. I. DAYS 680 TO 1469

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Received 1991 May 13

ABSTRACT

We tabulate *UBVRI* CCD photometry of SN 1987A from day 680 to 1469, together with slightly revised magnitudes for the local standards.

Key words: SN 1987A–photometry–standard-star sequence

1. Introduction

By about day 680 (where day 0.0 is defined as the time of the neutrino burst at JD2446849.82 as observed by Bionta et al. 1987 and Hirata et al. 1987) SN 1987A had faded sufficiently that contamination of aperture photometry by neighboring stars amounted to a significant correction to the optical flux of the supernova. CCD photometry then became the method of choice for measuring the optical brightness of SN 1987A.

Since this time, CCD *UBVRI* photometry of the supernova has been regularly scheduled at the 0.9-m telescope at CTIO. In addition, observations at various times have been made at the 4-m telescope. The general techniques of observation and reduction have been described by Walker & Suntzeff 1990 (hereafter WS90), who established local standards near the supernova, based on CCD observations made on ten photometric nights during the period January to June 1989. These seven standards have magnitudes 12–16 and a wide range in color.

We present here the CTIO *UBVRI* optical photometry of SN 1987A for days 680 to 1469. The results have been combined with infrared photometry in a discussion of the late-time bolometric luminosity evolution of SN 1987A by Suntzeff et al. 1991. We also tabulate slightly revised magnitudes for the local standards.

2. Observations and Reductions

Several different combinations of telescopes, CCDs, and filters were used for the observations reported here. However, the majority ($\approx$ 80%) of the measurements were made on the 0.9-m telescope with a UV-flooded TI CCD (usually TI No. 3) and a single filter set, as described in WS90. The remainder of the observations were made with a variety of CCDs, two different Tektronix devices (Tektronix No. 3 and No. 4, both with 512^2 27μ pixels) and two Thomson devices (Thomson No. 1 and No. 2, 1024^2 19μ pixels, Thomson No. 2 coated with Metachrome™). Quantum efficiency measurements, made in the CTIO Detector Laboratory with respect to a calibrated photodiode, are listed in Table 1. To first order, the overall shapes of these quantum efficiency curves are similar at wavelengths longer than about 5000 Å. In the blue and ultraviolet they are very different. The uncoated Thomson No. 1 has no ultraviolet response, while both Tektronix CCDs have steep falloff below 4500 Å with little response shortward of 3500 Å. The TI CCDs and Thomson No. 2 have a reasonably flat response from 4500 Å down to the atmospheric cutoff, with the TI's having high quantum efficiency throughout the whole optical region of the spectrum. These response differences cause variations in effective wavelength and bandpass when convolved with the broad-band *UBVRI* filter responses, and large discrepancies may occur in the broad-band photometry of objects with nonstellar spectra, such as supernovae (Hamuy et al. 1990). However, we have only a small amount of *U*-band photometry of SN 1987A obtained with other than a TI CCD, and we have not been able to discern any problems of a systematic nature in the

Table 1
CCD Quantum efficiency measurements

wavelength (Å)	TI #3	Tek #3	Tek #4	Thom #1	Thom #2
3000	59	3	4	0	19
3500	53	10	15	0	20
4000	58	20	35	3	19
4500	59	30	54	12	19
5000	64	40	68	29	29
5500	64	45	76		37
6000	61	42	81		43
6500	55	38	83		41
7000	51	30	83		40
7500	47	28	77		39
8000	37	22	68		33
8500	29	18	55		23
9000	22	15	37		13
9500	15	12	21		7

[1]Operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

photometry arising from differences in the natural photometric systems of the various CCDs.

The filter set used for almost all the observations consisted of U (Hamilton No. 1), B, V, R (Harris set No. 2), and I_{10}. Early observations used I_{11}, which has almost identical response to I_{10}. Transmission measurements for these filters are given in Table 2. On a few occasions, B, V, and R filters from other CTIO sets were used; however, the responses for these filters differ little from those given in Table 2. The I-band response deserves some comment since photoelectric I-band measurements of SN 1987A made at CTIO and SAAO differ systematically, with the SAAO measurements being up to 0.4 mag brighter. Both Menzies 1989 and Hamuy et al. 1990 showed that this offset is due to the different parts of the supernova spectrum being sampled by the two (nominally) I filters. A similar comparison can be made between the CTIO photoelectric and CCD measurements during the time (near day 680) that both types of measurements were taken. Suntzeff et al. 1991 made such a test and find that the CCD and photoelectric aperture measurements, corrected for contamination, agree within a few hundredths of a magnitude, except for I where the CCD measurements are 0.27 mag brighter. The CTIO CCD I-band measurements agree almost perfectly with the SAAO photoelectric I-band measurements near day 680. The CTIO CCD I filter is an interference filter designed to give response close to the SAAO Cousins I filter and phototube combination and, indeed, does appear to match that system well. We comment that the 3-mm RG9 filter often used to reproduce the Cousins I band with phototubes is a poor choice for use with CCDs due to the significant response of the latter at wavelengths longer than 9000 Å.

On photometric nights color equations could be checked by observing bright standard stars from the lists of Graham 1982, Landolt 1983, Menzies, Banfield & Laing 1980, and Menzies et al. 1989. Small differences between the standard systems (Bessell 1990) have been disregarded. Zero points, and often color equations as well, were established from measurements of the WS90 local standards. There is no reason to believe that our local standard system differs systematically from the primary $UBVRI$ standards by more than 0.01–0.02 mag in any color, a conclusion also reached by WS90. Typical color-equation coefficients are given in Table 3. The listed coefficients are α in the equation $V = v + \alpha\,(B-V) + \tau$ and for the colors, β in equations such as $(B-V) = \beta\,(b-v) + \delta$, where standard magnitudes are uppercase and natural magnitudes are lowercase.

We do, of course, have far more observations of the local standards than were available to WS90, and we have been using slightly adjusted magnitudes for these stars. These new magnitudes were obtained by intercompari-

Table 2
Filter transmissions

λ (Å)	U	λ (Å)	B	λ (Å)	V	λ (Å)	R	λ (Å)	I
3000	0.003	3500	0.010	4500	0.003	5500	0.038	7000	0.005
3050	0.024	3600	0.068	4600	0.005	5600	0.124	7100	0.040
3100	0.062	3700	0.024	4700	0.016	5700	0.534	7200	0.115
3150	0.159	3800	0.415	4800	0.056	5800	0.786	7300	0.320
3200	0.300	3900	0.545	4900	0.330	5900	0.856	7400	0.645
3250	0.448	4000	0.638	5000	0.735	6000	0.864	7500	0.727
3300	0.575	4100	0.690	5100	0.877	6100	0.854	7600	0.755
3350	0.669	4200	0.716	5200	0.905	6200	0.835	7700	0.767
3400	0.735	4300	0.722	5300	0.897	6300	0.811	7800	0.762
3450	0.783	4400	0.716	5400	0.865	6400	0.784	7900	0.790
3500	0.811	4500	0.688	5500	0.815	6500	0.751	8000	0.779
3550	0.826	4600	0.637	5600	0.741	6600	0.717	8100	0.770
3600	0.833	4700	0.537	5700	0.643	6700	0.680	8200	0.755
3650	0.827	4800	0.403	5800	0.536	6800	0.639	8300	0.740
3700	0.808	4900	0.262	5900	0.416	6900	0.594	8400	0.730
3750	0.766	5000	0.168	6000	0.302	7000	0.549	8500	0.740
3800	0.690	5100	0.092	6100	0.203	7100	0.495	8600	0.760
3850	0.581	5200	0.041	6200	0.122	7200	0.435	8700	0.778
3900	0.426	5300	0.018	6300	0.069	7300	0.378	8800	0.700
3950	0.257	5400	0.010	6400	0.033	7400	0.332	8900	0.485
4000	0.126			6500	0.014	7500	0.292	9000	0.285
4050	0.049			6600	0.006	8000	0.126	9100	0.150
4100	0.018					8500	0.045	9200	0.095
4150	0.006					9000	0.012	9300	0.045
4200	0.003							9400	0.022
								9500	0.011

Table 3
Typical color equation coefficients

CCD	V	B-V	U-B	V-R	V-I
TI #3	-0.04	1.10	0.98	0.95	0.98
Tek #4	-0.03	1.21	0.99	0.97	1.00
Thomson #2	-0.02	1.08	0.95	0.96	1.00

Table 4
Revised photometry for the local standards

star	V	B-V	U-B	V-R	V-I
S1	14.465	-0.092	-0.755	-0.013	-0.031
S2	16.035	-0.145	-0.897	-0.052	-0.095
S4	14.002	-0.163	-0.983	-0.042	-0.088
S6	13.963	0.691	0.224	0.399	0.795
S7	15.157	0.716	0.267	0.422	0.823
S8	13.737	1.265	1.180	0.811	1.590
S10	13.773	-0.060	-0.772	0.014	0.033

sons among the local standards themselves. We give these revised magnitudes in Table 4. The median absolute change is 0.010 mag, with the largest changes being for the V magnitude of S2 (the faintest star) and the $(U-B)$ and $(B-V)$ colors of S6 (all ≈ 0.03 mag). We stress that most of these adjustments are very small and averaged over more than 2–3 stars are almost in all combinations < 0.01 mag. We find no evidence of variability for any of these stars.

3. Photometry of SN 1987A

On each frame, the local standards and any close companions, SN 1987A and its companions, and often a few additional stars, were marked. Photometry for these stars was then accomplished using DAOPHOT (Stetson 1987). Sky background was determined from the modal value within an annulus of radii typically 5 to 10 arc sec from the star being measured. For SN 1987A this annulus lies in a relatively clear area between the supernova plus stars 2 and 3 (Walborn et al. 1987) and a small "cluster" of mostly blue stars 15–25 arc sec to the NW. We fit a point-spread function (psf) determined using some of the local standards. Star S2 (WS90 nomenclature) proved to be particularly suitable for this purpose since it has no close companions within 4 arc sec while four stars between 4 and 7 arc sec distance all have $I > 21$. Other psf stars were purged of close companions using techniques as described by Stetson 1987. The resulting point-spread function was then fitted to the SN 1987A and its two companions (simultaneously) and to the local standards and any other stars chosen. The fitting radius used was almost always ≈ 1.0 arc sec; this corresponds to 2–4 pixels for the various combinations of CCDs and image scales. Experiments using different fitting radii, fitting a planar sky background explicitly, and varying the size of the sky annulus were conducted on many frames. The smallest errors in the photometry of SN 1987A and its companions were obtained when the parameters given above were adopted. Only in the 1991 March 3 V and I frames was another faint companion to SN 1987A fitted simultaneously. This star has $V = 19.1$, $V-I = 1.1$, and, with respect to the supernova, is 2.0 arc sec distant in position angle 115°. Another, even fainter, star with $I \approx 20.5$ is at distance 2.9 arc sec and position angle 160°. We will refer to these stars as "4" and "5", respectively. Both stars are visible in continuum images obtained with the NTT at La Silla by Wampler et al. 1990. Photometry and spectroscopy for stars 2 and 3 will be discussed elsewhere (Walborn et al., in preparation).

The *UBVRI* photometry for SN 1987A is listed in Table 5 and plotted in Figure 1. Suntzeff et al. 1991 estimated the internal photometric errors by fitting a running quadratic function to 12 data points around every data point and then calculating the dispersion of the observed data about the fit. The error prior to day 1000 was found to be 0.035 mag or less in *BVRI* and 0.05 mag in *U*. From days 1000 to 1368 the errors were 0.03 mag in *BVR*, 0.04 mag in *I*, and 0.07 mag in *U*. Systematic errors are difficult to quantify. However, the final data point (*BVI* only), which was obtained in excellent seeing with well-sampled data, is some 0.1 mag fainter in each color than expected from the previous few data points, which were obtained in rather poorer (≈ 1.5 arc sec) seeing, and so an error of this size (± 0.1 mag) is probably more realistic for the late-time data. The supernova is now fainter than stars 2 and 3 in all bands, and the multistar fitting is becoming increasingly difficult and subject to

Table 5
Photometry of SN 1987A

HJD	U	B	V	R	I
7530	11.59	11.70	11.48	10.92	10.50
7573	12.14	12.35	12.21	11.53	11.15
7600	12.48	12.59	12.64	11.92	11.59
7640	12.91	13.07	13.10	12.42	12.07
7643	12.97	13.19	13.13	12.38	12.09
7655	13.02	13.22	13.32	12.62	12.27
7669	13.20	13.42	13.50	12.81	12.52
7695	13.43	13.64	13.80	13.04	12.88
7790	14.35	14.69	14.72	13.85	13.84
7811	14.56	14.91	15.01	14.15	14.17
7819		14.95	15.07		
7841	14.81	15.13	15.16	14.33	14.38
7852	14.82	15.22	15.27	14.42	14.45
7873	14.98	15.38	15.40	14.47	14.52
7890	15.23	15.49	15.46	14.57	14.61
7896		15.58	15.61	14.71	14.77
7937		15.88	15.73	14.88	14.94
7961	15.45	16.01	15.88		
7974	15.45	16.04	16.01		
7997		16.09	16.06	15.13	15.23
7998	15.68	16.22	16.07	15.14	15.22
8013	15.73	16.28	16.12	15.23	15.30
8018	15.55	16.20	16.15	15.25	15.34
8045	15.75	16.46	16.33	15.41	15.52
8071	15.70	16.47	16.43	15.41	15.67
8076	15.92	16.55	16.38	15.42	15.61
8104	16.11	16.66	16.48	15.55	15.71
8115	16.10	16.70	16.52	15.53	15.71
8145			16.63	15.62	15.83
8185	16.36	16.96	16.67	15.72	15.88
8191	16.32	16.94	16.64	15.78	15.87
8219	16.40	17.04	16.73	15.82	15.94
8292	16.57	17.12	16.93	15.94	16.12
8252	16.37	17.08		15.93	16.10
8266	16.53	17.10	16.91	15.78	16.09
8270	16.48	17.11	16.89	15.83	16.12
8273	16.55	17.09	16.89	15.85	16.03
8319		17.34	17.14		16.34

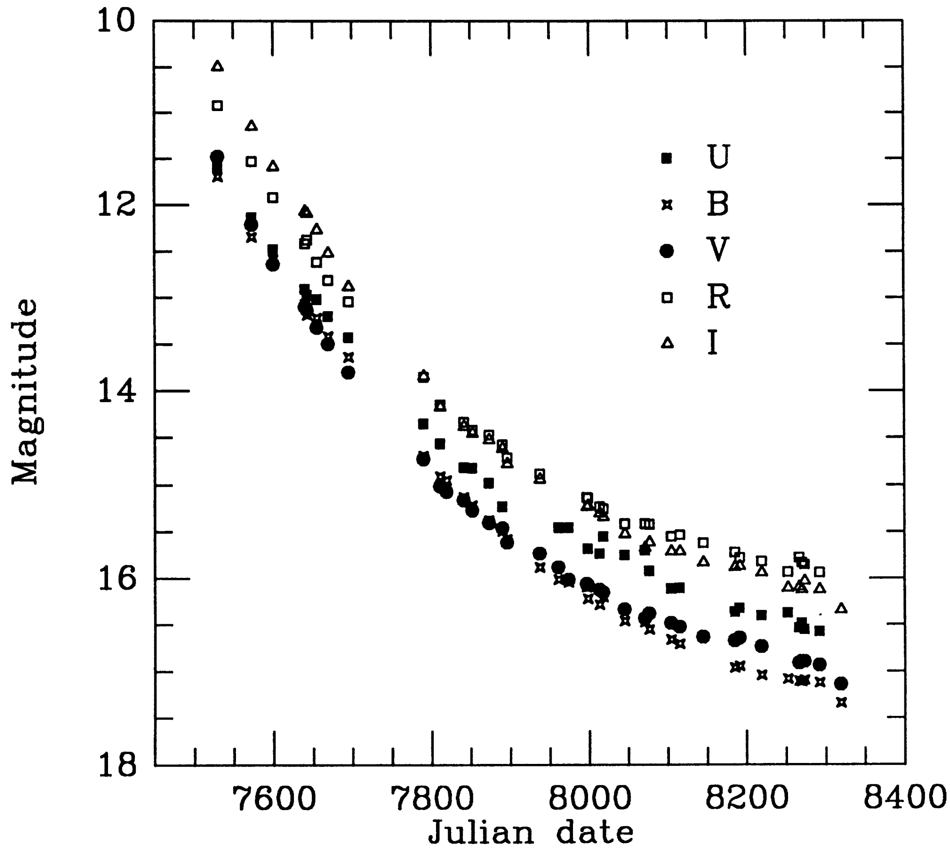

FIG. 1—*UBVRI* light curve of SN 1987A from day 680 to 1469.

systematic errors in the background as time passes. The complexity of the immediate environment of SN 1987A is illustrated in Figures 2–4. These figures are surface plots through *B* and *I* filters, from 1.0 arc sec FWHM images and 0.27 arc sec pixel size, taken at the 4-m RC focus on 1991 March 3. Figures 2 and 3 are *B* and *I* plots, respectively, viewed from the SE direction, while Figure 4 is an *I*-band plot, viewed from the SW direction, and has increased vertical scale compared to Figures 2 and 3 in order to more clearly show faint stars. Both stars 4 and 5 are visible in Figure 4, star 4 on the left-hand side of SN 1987A and star 5 in front of star 4. It seems certain that, in the future, seeing as good or better than ≈ 1 arc sec will be a prerequisite for accurate photometry, and additionally, more sophisticated methods of evaluating the background (e.g., Parker 1991) will be mandatory.

We would like to thank Howard Bond, Luis Gonzalez, Karen Meech, Mauricio Navarrete, and Lisa Wells for obtaining some of these observations. Thanks are also due to Jorge Bravo, who measured quantum efficiencies for the CCDs, and Ricardo Gonzalez, who provided the filter transmission measurements.

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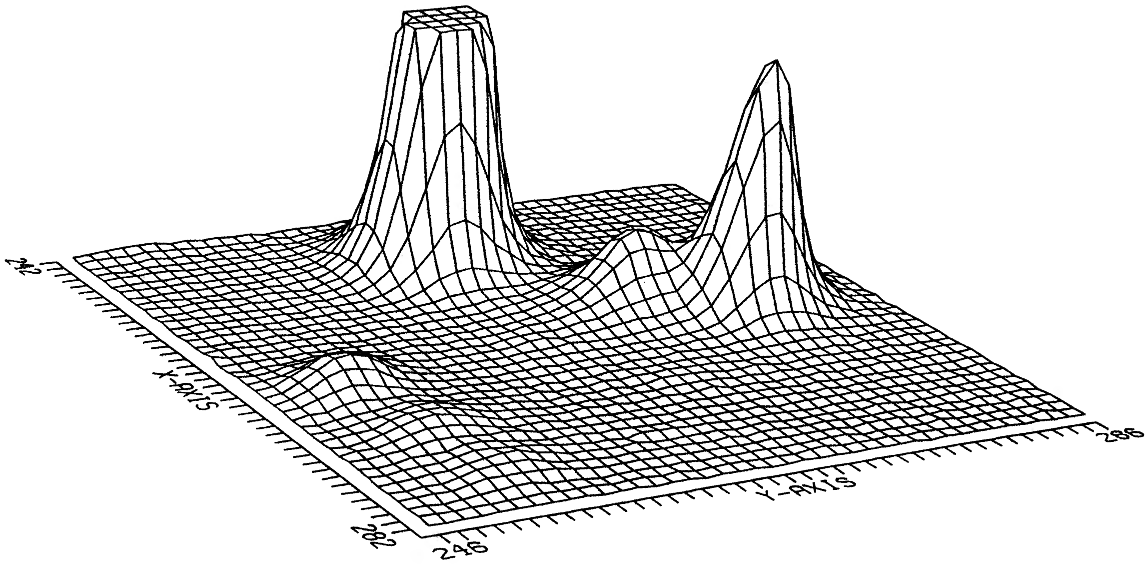

FIG. 2–B-band surface plot of the environment of SN 1987A, viewed from the SE direction. The plot is 11 arc sec along each side, and the plot has been truncated in the z-direction (intensity). SN 1987A is bracketed by the much brighter stars 2 (left) and 3 (right).

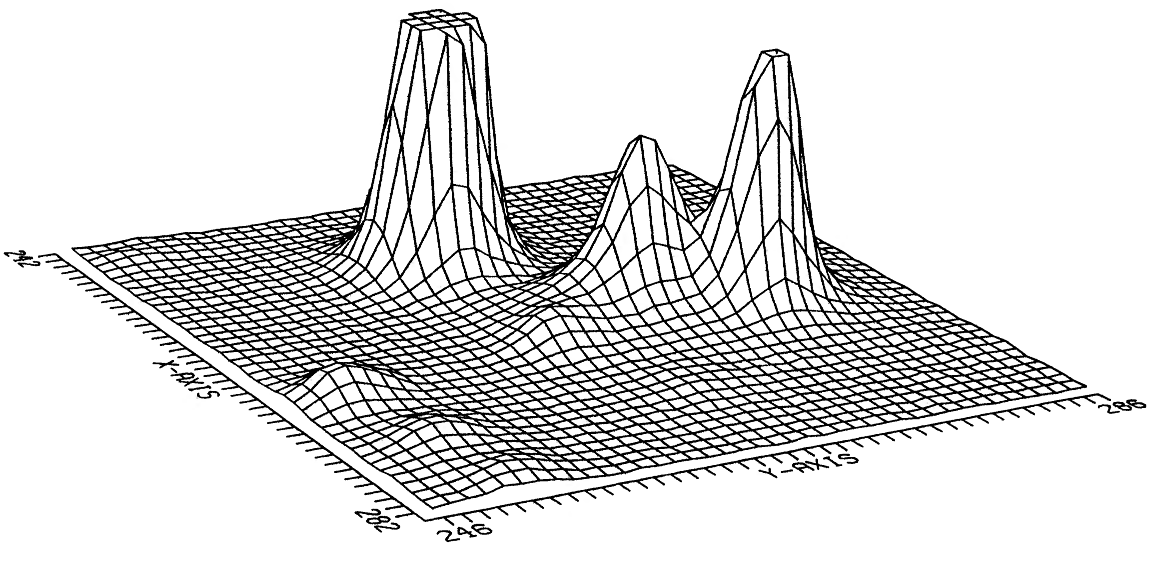

FIG. 3–As for Figure 2, except for the I band. SN 1987A is more prominent with respect to the relatively blue stars 2 and 3 than in Figure 1. Star 4 is the weak bump just to the SE of the supernova.

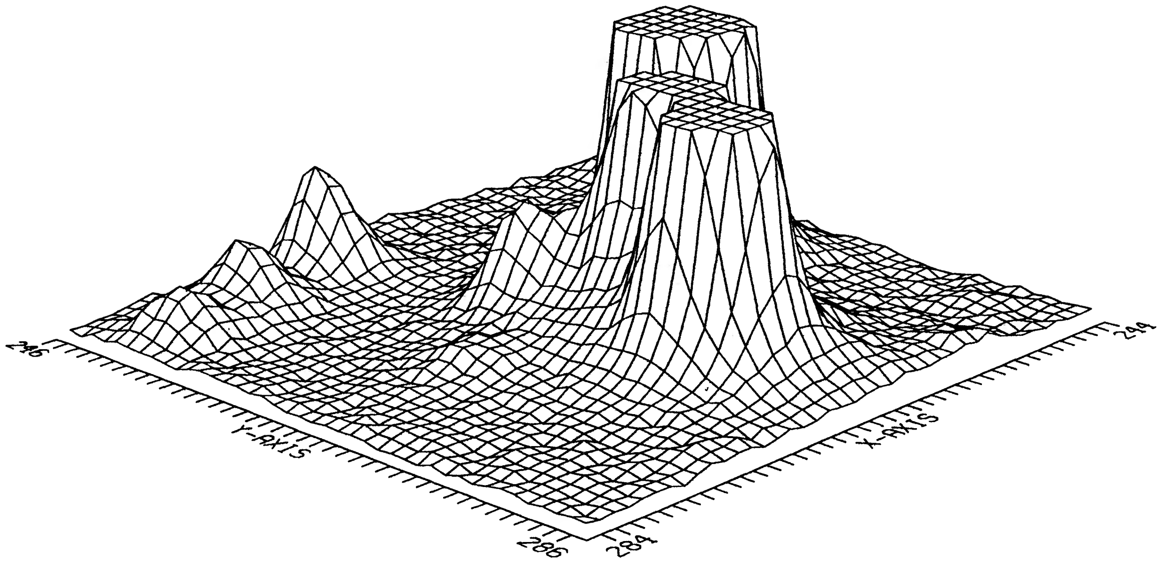

FIG. 4–I-band surface plot viewed from the SW. The z-direction (intensity) scale has been magnified compared to Figure 3. Star 4 can now be easily seen to the SE (left) of the supernova, with star 5 the weak bump just in front of star 4.