THE NONVARIABILITY OF THE PROGENITOR OF SUPERNOVA 1993J IN M81

JUDITH G. COHEN, JEREMY DARLING, AND ALAIN PORTER[1]

Palomar Observatory, California Institute of Technology, Mail Code 105-24, Pasadena, California 91125
Electronic mail: jlc@astro.caltech.edu, darling@ugsc.caltech.edu

ABSTRACT

An archive of images taken in the early 1980s exists for a field which includes the progenitor of supernova 1993J in M81. Fifty-four CCD frames in V, and several in other colors from this set taken in 1984 are analyzed to demonstrate that the progenitor of supernova 1993J was not variable to within a limit of 0.2 mag. The frames analyzed cover a time span of 150 days. The colors of the M81 SN progenitor are consistent with those of a late G supergiant. © *1995 American Astronomical Society.*

1. INTRODUCTION

Supernova 1993J is extremely unusual in several respects. It was discovered on 1993 March 18.906 by Fransicso Garcia (Ripero 1993) in M81, a galaxy which is sufficiently nearby that Cepheids have been observed, both from the ground (Freedman & Madore 1988) and with HST (Freedman *et al.* 1994). This of course makes the supernova bright and easy to study in detail at many wavelengths. The supernova itself was peculiar. Its lightcurve at optical wavelengths shows a double peak (Benson *et al.* 1994; Richmond *et al.* 1994), and its spectrum evolved from a Type II at early times to a type Ib at late times (Filippenko *et al.* 1993; Swartz *et al.* 1993). This has led to much speculation that SN 1993J occurred in a massive star which had lost nearly all of its hydrogen-rich envelope prior to the explosion, either via mass loss associated with the normal course of stellar evolution or through mass transfer in a binary system (Hoflich *et al.* 1993; Schmidt *et al.* 1993; Podsiadlowsky *et al.* 1993).

Because M81 is so nearby, there exist some observations of the progenitor of this supernova, and it is on this aspect of the event that we focus our attention here. With the exception of SN 1987A in the LMCV (see review by Arnett *et al.* 1989, and especially Hazen 1987), this is the only case where the progenitor was bright enough to have been observed. Those observations of the progenitor star of SN 1993J available in early 1993 were summarized by Benson *et al.* (1994). They consisted of a collection of CCD images through random filters taken by random people at random times with various telescopes and instruments covering the period from 1982 to 3 Feb. 1993. In their compilation there are four B detections, four V detections, six R detections, and two I detections of the progenitor star. Detections, as distinct from upper limits, were contributed by their group and by Perelmutter (1993), Humphreys *et al.* (1993), Magnier *et al.* (1993), Cohen (1993), Prugniel (1993), Blakeslee & Tonry (1993), Salzer *et al.* (1993), and Tomaney & Crotts (1993).

Benson *et al.* commented that based on their compilation the progenitor star appeared to be variable. However, Aldering *et al.* (1994) reviewed these observations, redid the analysis from the original data in several cases, and attempted to use common photometric calibrations for all the data. They revised Perelmutter's and Magnier *et al.*'s magnitudes substantially, producing much better agreement among this heterogeneous sample. They also suggest that several stars (plus perhaps nebular emission) may be contributing to the observed flux of the supernova progenitor at the bluest wavelengths, where the image appears to be slightly extended, but there was no evidence for an extended image at red wavelengths.

As part of a program to detect novae in M81, J. C. routinely monitored several fields in M81 in the early 1980's. The data for 1984 have been analyzed here. We find no evidence for variability of the progenitor of supernova 1993J during the period of observation.

2. ANALYSIS OF THE 1984 DATA

M81 was observed repeatedly in the early 1980s with the 1.5 m telescope on Palomar Mountain in an attempt to detect novae in that galaxy. The observations in 1984 used an RCA 320×512 CCD detector with a Johnson V filter. Occasionally frames through the Thuan & Gunn (1976) g and r filters were obtained. Exposures were obtained on every assigned night that was not so cloudy that it was hopeless, irrespective of the seeing or of the transparency. All V exposures were 360 s long.

While the quantum efficiency of this detector is reasonably good, especially in the blue, its readout noise is fairly high (30 electrons RMS) compared to the current state of the art devices and it had a very high apparent "cosmic ray" rate, which was probably due to a poor choice of materials by RCA somewhere in the CCD packaging. It is this high "cosmic ray" rate which led in part to the failure of the nova search program.

The scale of the detector at the 1.5 m telescope using reimaging optics is 1.2 arcsec/pixel. Thus the field is 6×10 arcmin, and M81 was covered using six separate fields, which had some overlap among them. The location of SN 1993J appears in two of these fields.

The frames of those two sectors of M81 from 1984 were recovered from the old backup tapes and were analyzed. The best 54 frames taken through the V filter were used. (There were a total of about 80 V frames taken during 1984, but the ones with the worst seeing and/or poor transparency were

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[1]Deceased.

TABLE 1. Derived magnitudes of local standard stars

Star ID	V	δ(East)	δ(North)
	(mag)	(arc-sec from SN)	
Star 2	17.63	2	24
Star 4	17.90	−22	−55
Star 1	18.92	−25	41
Star 3	20.09	1	11

rejected.) There are also two *r* frames and one *g* frame. Photometric standards from Thuan and Gunn were observed in 1984 on the same nights as M81 when the weather was suitable.

To analyze the data, the standard aperture photometry code of Figaro was used with a radius of 2 pixels (2.4 arc-sec). Photometry of four local standard stars selected to be near the progenitor of the supernova, as well as that of the progenitor itself, was obtained from each of the good frames. Three of these local standard stars are quite bright, while the fourth is only slightly brighter than the M81 supernova progenitor. Although de Vaucouleurs *et al.* (1994) have redone the photometric calibration for 36 comparison stars around SN 1993J, this was intended as an aid to those observing the supernova during its decline. All of their objects are too bright to avoid saturating the CCD images and most are lo-

cated outside the rather small field of our CCD images. However, they quote (as a private communication from Humphreys and Prugniel) magnitudes for a star (star A) located 25 arcsec NNE of the SN, $V=17.78$ mag, $B-V\approx1.24$ mag, $V-R_C\approx0.85$ mag. This star was one of the three bright local standard stars we adopted.

Using observations of M81 carried out on eight photometric nights during early 1984 and magnitudes measured for large apertures around the images of the Thuan–Gunn standard BD26-2606, we derive the magnitudes for the three local bright standard stars we use that are listed in Table 1.

In the Thuan–Gunn system, we only have data on two photometric nights, and we find for Star 2, $r=17.26\pm0.04$ mag and $g=17.91\pm0.04$ mag. Although the published value for V (Star 2=Star A) is 0.15 mag fainter than we obtained, we use our values, fearing contamination from the much brighter supernova in the recent determinations, and hesitating to trust the poorly calibrated and anecdotal published magnitudes; the reader should be aware of this discrepancy.

For the observations through the V filter of the relevant sectors of M81, Table 2 lists the date of the observation, the magnitude of the faintest local standard star, and the magnitude we obtain for the progenitor of SN 1993J in M81 for 54 epochs in 1984. The mean V magnitude of this object is 20.58 ± 0.17 mag from 51 frames. $\langle V \rangle$ for the faint local standard is 20.09 ± 0.15 mag from 54 frames. The errors are the 1σ deviation about the mean of the data. The formal errors computed by the aperture photometry program are based on the photon statistics of the object and of the sky. They are

TABLE 2. V magnitudes of the progenitor of the M81 supernova.

| Julian Date (−2445000)	V(Star 3) (mag)	V(SN prog.) (mag)	Julian Date (−2445000)	V(Star 3) (mag)	V(SN Prog.) (mag)
708.949	20.023	20.398	798.797	20.307	20.567
710.847	20.035	20.325	811.652	19.843	20.600
753.683	19.896	20.587	811.672	20.012	20.488
754.722	20.023	20.605	811.774	20.305	20.597
755.700	19.991	20.892	812.651	20.212	20.499
755.721	20.326	20.351	812.779	20.062	20.531
755.801	19.929	20.322	813.679	20.241	20.366
765.640	20.069	20.814	824.661	20.268	20.575
766.646	20.212	20.624	824.749	19.880	20.460
766.866	20.014	20.523	824.768	20.253	20.653
767.763	20.441	20.810	825.662	20.178	20.502
768.656	20.131	20.538	825.756	20.063	20.779
769.686	20.234	20.809	825.775	20.191	20.721
770.839	19.934	20.309	827.757	20.272	20.401
770.888	20.111	20.775	827.776	20.074	20.559
770.902	20.108	20.522	828.754	20.404	20.659
779.640	20.017	20.372	828.773	19.989	20.383
780.708	20.108	20.999	839.667	20.023	20.745
782.656	20.007	20.858	840.688	19.910	20.460
782.691	20.057	20.840	841.667	19.931	20.503
783.642	20.130	20.482	841.686	19.855	20.523
797.926	20.067	20.546	842.669	20.231	20.429
798.649	19.980	20.905	842.688	20.331	20.560
798.669	20.311	20.460	844.676	20.004	20.633
798.699	20.147	20.606	844.699	19.946	20.351
798.704	19.972	20.562			
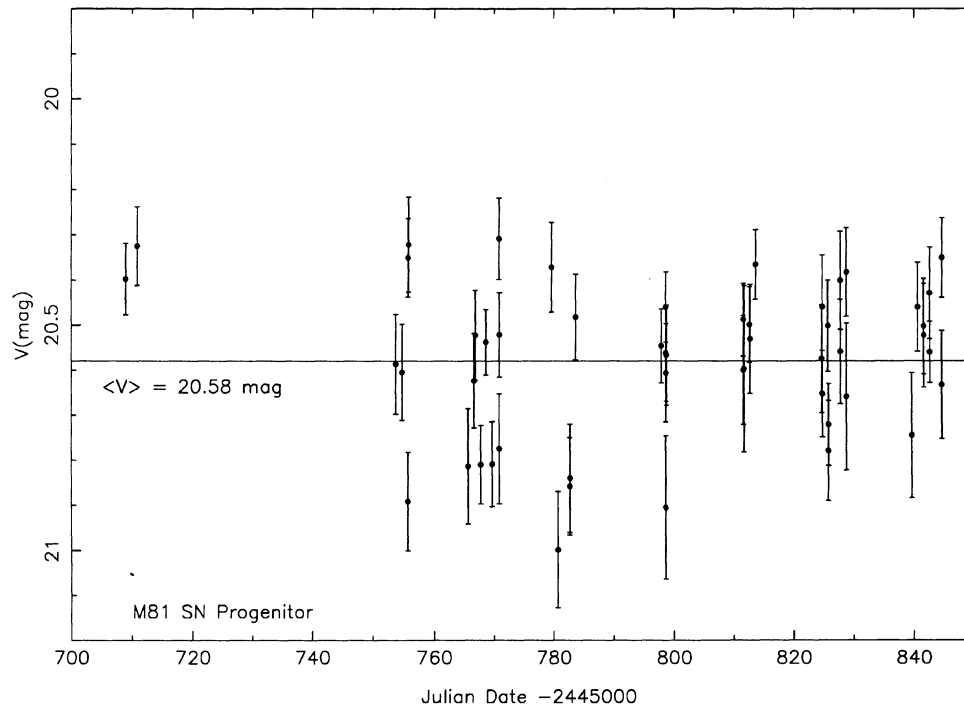
FIG. 1. The *V* magnitudes for the progenitor of SN 1993J in M81 are plotted as a function of Julian Date for a period spanning 150 days in 1984.

typically 0.01 mag for the brightest local standards and 0.10 mag for the progenitor of the M81 SN. However, the predominant source of uncertainty is the spatial variations in the bright mottled background of the M81 arms and bulge, which in the vicinity of the M81 SN progenitor reaches $\approx$21.2 mag/arcsec^2. Several different prescriptions for defining the appropriate local sky were tried during the course of reducing the data. Use of a small annulus 4 to 8 pixels in radius around the object seemed to give the most consistent results.

We find no evidence that the M81 SN progenitor is variable with an amplitude exceeding 0.2 mag, either from the size of the RMS deviations about the mean or from the light-curve itself, which spans 150 days and is plotted in Fig. 1.

3. COLORS OF THE PROGENITOR OF SN 1993J

We use the results of Kent (1985) to transform our Thuann–Gunn *r* magnitude into a Johnson *R*. This must then be transformed into a Kron–Cousins *R* using the relationship of Landolt (1983). We obtain for Star A (the comparison object) $V-R$=0.96±0.04 mag, while de Vaucouleurs *et al.* quote $V-R$=0.86 mag, a comforting agreement. For the SN progenitor we obtain $\langle (V-R) \rangle$=0.59±0.05 mag, where *R* is the mean from two frames. (The difference between *R* in the Kron–Cousins and in the Johnson system is insignificant.)

This is an excellent agreement with the values determined by Aldering *et al.* (1994) from the heterogeneous set of old CCD data, namely, $\langle V \rangle$=20.60±0.16 mag and $\langle (V-R) \rangle$=0.73±0.19 mag.

There is also good agreement with the mean $B-V$ color, where we obtain (from transforming $g-\langle V \rangle$) 1.20±0.05,

and Aldering *et al.* (1994) give as the mean of their heterogeneous data set $B-V$=1.13±0.16 mag.

4. COMMENTS ON VARIABILITY

Our observations confirm and extend the earlier suggestion that the progenitor of SN 1993J in M81 is not variable at optical wavelengths, at least not with an amplitude of 0.2 mag or larger. This is also true of the progenitor of SN 1987A in the LMC (Hazen 1987).

With regard to stellar evolution, the last stages of stellar burning in the center of a massive star are so fast that the evolution of the envelope and of the core are decoupled. By the time carbon burning has begun in the core of a massive star, the outer layers have assumed their final configuration (Woosley & Weaver 1986). Thus it is no surprise from this point of view that the luminosity emitted by the envelope of the supernova progenitor is observed to be constant $\approx$10 yr prior to the explosion.

Although it is hard to predict what kind of binary system the progenitor star might have been in, the total light does not appear to have been dominated by the accretion disk itself, but rather by the supergiant SN progenitor star. Any binary system with a nondegenerate primary whose initial mass is at least 15 solar masses would have a large separation and a long period, at least a year. The light from the less massive and less evolved secondary could easily comprise less than 5% of the total emitted luminosity from the system, and hence be undetectable in our old and somewhat imprecise photometry.

5. COMMENTS ON THE PROGENITOR ITSELF

We adopt from Freedman *et al.* (1994) a distance to M81 of 3.63 Mpc (corresponding to a distance modulus of 27.80 mag) and a mean reddening of about $E(B-V)=0.05$ mag. Thus M_V for the M81 supernova progenitor is ≈ -7.4 mag, certainly typical of a supergiant. The V, I (Kron–Cousins) color–magnitude diagram of the field of M81 from *HST* WFPC2 images is given in Hughes *et al.* (1994) while the older ground-based data for the brightest stars in M81 is given for several colors in Zickgraf & Humphreys (1991). It is apparent that the progenitor star, with $V=20.58\pm0.17$ mag and $V-R=0.59\pm0.05$ mag, is not a red supergiant in M81. Typical bright red supergiants in M81 have $V\approx 22$, with $V-I\approx 2$ mag and redder. For $(V-R)\approx(R-I)$, typical of most stars of that color (see Landolt 1983), we expect $(V-R)\approx1.0$ mag for a typical red (M type) supergiant in M81.

The color temperature corresponding to $V-R=0.59$ ±0.05 mag is 6000 ± 300 K. The color temperature corresponding to the measured $B-R$ color is slightly lower, 4800 K. We disregard the color temperature corresponding to $B-V$ since the wavelength leverage is so short and the errors in the magnitudes are relatively large. The consistency of these colors does not support the suggestion of Aldering *et al.* (1994) that substantial contamination of the light of the progenitor of SN 1993J occurs in the blue due to neighboring hotter stars. Thus the progenitor of the M81 supernova corresponds to a late G supergiant, rather than an M supergiant.

6. SUMMARY

We have presented the 1984 data on the progenitor of SN 1993J in M81. These images are part of a longer series obtained as part of search for novae in nearby galaxies. By chance, two of the fields monitored in M81 include the location of SN 1993J. Based on 51 CCD frames taken in the V filter, and several other taken through other filters, we find that the progenitor star is a late G supergiant and it is not variable at the level of 0.2 mag and over a time interval of 0.4 yr. Consistency with the compilation of previously published photometric observations of the progenitor star of SN 1993J by Aldering *et al.* (1994) extends the time scale over which variations were not detected, with very spotty coverage, to ≈ 10 yr.

REFERENCES

Aldering, G., Humphreys, R. M., & Richmond, M. 1994, AJ, 107, 662
Arnett, W. D., Bahcall, J. N., Kirshner, R. P., & Woosley, S. E. 1989, ARA&A, 27, 629
Benson, P. J., *et al.* 1994, AJ, 107, 1453
Blakeslee, J., & Tonry, J. 1993, IAUC, 5758
Cohen, J. G. 1993, IAUC, 5742
de Vaucouleurs, G., Corwin, Jr., H. G., & Skiff, B. 1994, PASP, 106, 156
Filippenko, A. V., Matheson, T., & Ho, L. C. 1993, ApJ, 415, L103
Freedman, W. L., & Madore, B. F. 1988, ApJ, 332, L63
Freedman, W. L., *et al.* 1994, ApJ, 427, 628
Hazen, M. 1987, IAU Circ. No., 4365, 4367
Hoflich, P., Langer, N., & Duschinger, M. 1993, A&A, 275, L29
Hughes, S. M. G., *et al.* 1994, ApJ, 428, 143
Humphreys, R. M., Aldering, G. S., Bryja, C. O., & Thurmes, P. M. 1993, IAUC, 5739
Kent, S. M. 1985, PASP, 97, 165
Landolt, A. 1983, AJ, 88, 439

Magnier, E., Lewin, W., Lubin, L., Zimmerman, U., & Gabbiano, G. 1993, IAUC, 5741
Perelmutter, J. M. 1993, IAUC, 5736
Podsiadlowski, P., Hsu, J. J. L., Joss, P. C., & Ross, R. R. 1993, Nature, 364, 509
Prugniel, P. 1993, IAUC, 5742
Richmond, M. W., Treffers, R. R., Filippenko, A. V., Paik, Y., Leibundgut, B., Schulman, E., & Cox, C. V. 1994, AJ, 107, 1022
Ripero, J. 1993, IAUC, 5731
Salzer, J. J., Herbst, W. E., & Vinton, G. 1993, IAUC, 5741
Schmidt, B. P., *et al.* 1993, Nature, 364, 600
Swartz, D. A., Clocchiatti, A., Benjamin, R., Lester, D. F., & Wheeler, J. C. 1993, Nature, 365, 232
Thuan, T. X., & Gunn, J. E. 1976, PASP, 88, 543
Tomaney, A., & Crotts, A. 1993, IAUC, 5737
Woosley, S. E., & Weaver, T. A. 1986, ARA&A, 24, 205
Zickgraf, F.-J., & Humphreys, R. M. 1991, AJ, 102, 113