The Ten-Year Photometric Evolution of SN 1987A

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Abstract.

Ten years of photometric observations of SN 1987A are reviewed. The optical and near-infrared colors are now declining at $\lesssim 1$ magnitude per 1000 days, which is consistent with both the infrared "freeze-out" and the possible energy sources powering the nebula. The "uvoir" bolometric luminosity at ten years is estimated to be $\log_{10}(L) \sim 36.1-36.4$ ergs s⁻¹. The most recent photometric measurements are given in Table 1. A deep color-magnitude diagram shows that the young stars are concentrated within a projected distance of $\sim 25''$ (6pc) in a field out to $\sim 3'$ from the supernova. It is likely that Stars 2 and 3 which project to within 0.7pc of the supernova are associated with Sk $-69^{\circ}202$.

1. Introduction

With the announcement of a supernova in the Large Magellanic Cloud (Shelton 1987), many astronomers in the southern hemisphere stopped the projects they were working on, and began programs of the long-term monitoring of this unique object. A tremendous literature has developed on the observation and theory of the supernova. At the time of this conference, there are more than 1000 refereed papers listed under "SN 1987A" by the Astrophysics Data System of NASA. In this short contribution, I would like to summarize the observational work on the photometry and spectrophotometry of SN 1987A, and discuss the stellar population surrounding the supernova.

2. Photometry of SN 1987A

In the years following the explosion of Sanduleak $-69^{\circ}202$ on UT 7:36 23 Feb 1987 or JD 2446849.8165 (Bratton *et al.* 1988, Hirata *et al.* 1988), all major southern hemisphere observatories followed the photometric evolution SN 1987A in optical and infrared colors. In addition, IUE and later HST measured photometric indices. For ground-based observatories, it was not always easy finding a telescope *small* enough to follow the supernova. The ground-based observations

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were also complicated by the fact that the only detector generally available was a single channel device such as a photoelectric photometer. A measurement therefore required photometric weather (not a problem today with CCD detectors and fainter SNe) or at least scattered clouds so that quick differential photometry could be done relative to a nearby standard like δ Doradus. At maximum light on day 84.5, the supernova was V=2.975 (Hamuy & Suntzeff 1990). At this brightness, we had to reduce the aperture of the 0.4m telescope at CTIO by using the Hartmann mask, and masking off all but 5 holes, leaving a collecting area of only 26 cm²! Future bright events may leave observatories unprepared as small telescopes are closed in the face of financial pressures.

2.1. Atlases of Photometry

Each observatory published the photometric data in a number of different papers. Generally the last paper in the series contains references to the earlier papers. Here I will list only the latest paper from the series of publications of a particular observatory group. The number is parenthesis gives the date (since explosion) of the last observation. In some cases the data are only presented in graphical form.

- AAO/MSSSO: near-infrared spectrophotometry (day 1114), Meikle et al. (1993)
- CTIO: UBVRI photoelectric photometry (day 813), Hamuy & Suntzeff (1990); CCD optical photometry (day 1469), Walker & Suntzeff (1991); UBVRIJHK[10][20] and "uvoir" bolometric luminosities (day 1594), Suntzeff et al. (1992); optical spectrophotometry (day 805) Phillips et al. (1990); near-infrared spectrophotometry (day 1445), Bautista et al. (1995)
- **ESO:** Near and mid-infrared photometry and spectrophotometry (day 1493), Bouchet & Danziger (1993), Bouchet et al. (1996); Stromgren photometry(day 330), Helt et al. (1991); spectrophotometry (day 314), Hanuschik et al. (1994); Walraven photometry (day 120, some data quoted up to day 393 in Pun et al. 1995), Pel et al. (1987); Geneva photometry (day 917), Burki et al. (1991)
- **KAO:** Near and mid-infrared spectrophotometry (day 775), Wooden *et al.* (1993)
- IUE: Spectrophotometry and ultraviolet magnitudes (day 1567), Pun et al. (1995); FES (V_{IUE}) light curve (day 760) Kirshner & Gilmozzi (1989) (see also Sonneborn 1988)
- LCO: UBVRI photoelectric photometry and early photographic photometry (day 156), Shelton(1993a,b), Shelton & Lapasset (1993)
- HST: Ultraviolet magnitudes (day 2431), Pun et al. (1995)
- **SAAO:** *UBVRIJHKLM* single-channel and CCD photometry (day 1770), Caldwell *et al.* (1993). Also uvoir bolometric magnitudes.

• Astron station: ultraviolet spectrophotometry (day 394), Lyubimkov (199)

I also list a number of papers which are relevant to the photometric data: finding chart and star names, Walborn et al. 1987 and Walker & Suntzeff (1990); detailed photometry and spectroscopy of Stars 2 and 3, Walborn et al. (1993); "uvoir" bolometric luminosities from optical and infrared spectrophotometry, Suntzeff & Bouchet (1990), Hamuy et al. (1990), and Bouchet et al. (1991); summary of polarization measurements through day 600, Wang & Wheeler (1996); HST spectrophotometry of Star 2 (and a discussion of age and reddening of this star), Scuderi et al. (1996).

Although there is a good local photometric sequence near SN 1987A in the optical (Walker & Suntzeff 1991, Walborn et al. 1993), the photometric observations are by no means easy. The supernova, which is now at $m \sim 17-20$, is within 3" of Stars 2 and 3 which have magnitudes of 15 < V < 16. Walborn et al. (1993) show that Star 3 is a variable Be star with $\delta(V) \sim 0$."6 and star 2 shows signs of also being a star Be star. Even with excellent local standards and image quality, there can be systematic differences as large as $\delta(m) \sim 0$."4 in the photometric data published by different observatories due to the non-stellar flux distribution of the supernova in the nebular phase coupled with the different CCD quantum efficiency/filter combinations (Menzies 1989, Hamuy et al. 1990). The near-infrared photometry is more accurate since the crowding hot stars are fainter and the image quality is generally better, but the local standards are only accurate to about 0."1 (Suntzeff et al. 1991, Walborn et al. 1993).

2.2. The Light Curve of SN 1987A

In Table 1 I list the most recent photometric data for SN 1987A. The HST WFPC2 optical photometry was measured by P. Challis, The near-infrared photometry was measured from CTIO 4m telescope IR imager data.

| Table 1. Optical and Near-Infrared Photometry of SN 1987A | | | | | | | |
|---|-------|----------|----------|----------|----------|--|--|
| Date | U | B | V | R | I | | |
| 2927 (3 Mar 95) | | 19.68 | 19.72 | 18.63 | 19.07 | | |
| 3267 (6 Feb 96) | 19.85 | 19.93 | 19.96 | 18.88 | 19.37 | | |
| $decline rate^a$ | 0.89: | 1.03(13) | 0.63(05) | 0.82(03) | 0.96(02) | | |

| Date | J | H | K | |
|---------------------------|----------|----------|----------|--|
| 3274 (10 Feb 96) | 17.71 | 17.28 | 17.14 | |
| 3558 (20 Nov 96) | 18.24 | 17.63 | 17.46 | |
| 3616 (17 Jan 97) | 18.01 | 17.41 | 17.34 | |
| 3621 (22 Jan 97) | 18.11 | 17.54 | 17.22 | |
| decline rate ^a | 0.75(13) | 0.78(10) | 0.45(11) | |

^aDecline rate calculated over days 2500-3600 in units of magnitude $(1000 \text{ days})^{-1}$. The error is the standard deviation of a single observation, in units of 0.0^{10} 01.

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The ground-based JHK magnitudes were measured with DAOPHOT (Stetson 1987) psf fitting techniques and do not include flux from the inner ring. The inner ring adds about $0^{\text{m}}3$ on day 3274. The psf errors are $0^{\text{m}}05$ ($0^{\text{m}}1$ on 3616) and the photometric zero point error is about $0^{\text{m}}07$. The (preliminary) HST magnitudes were measured through a digital aperture of diameter 0.6'', with an estimated error of $0^{\text{m}}15$. I also list the decline rate for the data starting around day 2500. In Figure 1 I plot the UBVRI data from CTIO and HST the JHK data from CTIO and ESO.

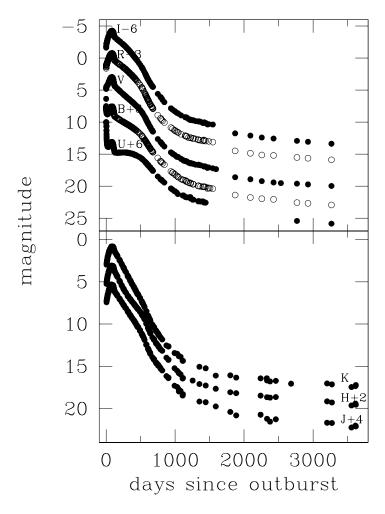


Figure 1. UBVRI and JHK photometry of SN 1987A through February 1997. The photometric data have been shifted by (+6,+3,0,-3,-6) for UBVRI and (+4,+2,0) for JHK

The supernova light curve is declining at 1 magnitude per 1000 days or less, consistent with the possible sources of energy powering the nebula (44 Ti, 22 Na, and a pulsar) and the effects of the infrared "freeze out" (Woosley *et al.* 1989, Kumagai *et al.* 1991, Fransson & Kozma 1993).

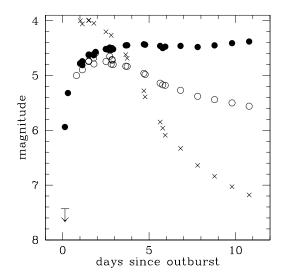


Figure 2. UBV photometry of SN 1987A through the first 11 days. The symbols are: U exes, B open circles, and V filled circles.

We cannot directly measure the "uvoir" bolometric luminosity at these late times because we do not have 10-30 micron fluxes. However, we can use the bolometric corrections to the optical colors VK to estimate a bolometric magnitude on the assumption that the flux distribution is indeed frozen. Under this assumption, the uvoir luminosity on day 3600 is $\log_{10}(L) \sim 36.1 - 36.4$ in units of ergs s⁻¹.

From the re-analysis of the early photographic and photoelectric data, the early-time light curve has been improved (West & McNaught 1992, Shelton 1993a, Shelton & Lapasset 1993). In Figure 2 I plot the data from these papers along with the early CTIO, SAAO, and LCO photoelectric photometry. I also include the photoelectric data published by Matthews (1987), Moreno & Walker (1987), and the visual lower limit of Jones (1987). The Jones limit happened 1.8 hours after the neutrino detections. The first optical detection was made by McNaught at 3.1 hours after outburst.

2.3. The Stellar Population Near SN 1987A

As summarized by Melnick in this conference, Sk $-69^{\circ}202$ was located about 4' from the center of the loose cluster NGC 2044 (LH90) near NGC 2070 (30 Doradus). The whole region is enveloped in emission associated with the star formation in the 30 Dor complex. At the position of Sk $-69^{\circ}202$ there is no large-scale star formation activity as in NGC 2044 or NGC 2050 to the south. Walker & Suntzeff (1990) however noted a small young association within 30" of the supernova, which is called KMK80 in the catalog of Kontizas et al. (1988). Efrevmov (1991) and Walborn et al. (1993) have estimated the age of this association at 12 ± 4 Myrs using the CTIO photometry. Scuderi et al. (1996) have estimated an upper limit (dependent on mass loss) to the age of Star 2 at

13Myrs. This, of course, is similar to the age estimate for Sk $-69^{\circ}202$ of 11Myrs by Arnett *et al.* (1989).

The field population near SN 1987A can be seen in more detail in Figure 3. Here I plot the BV color-magnitude diagram along with the (Y,Z)=(0.25,0.008) isochrones from Bertelli et~al.~(1994) and the photometry of Sk $-69^{\circ}202$ from Walborn et~al.~(1987). I have used a reddening of E(B-V)=0.16 and a true distance modulus of 18.50. These data were taken in January and March 1996 at the CTIO 4m telescope CFCCD system by Mark Phillips. A total of seven frames in each color were used to calculate the magnitudes. The large scatter about the main sequence down to V=20 is not due to photometric errors, but due to variable reddening (Walborn et~al.~1993).

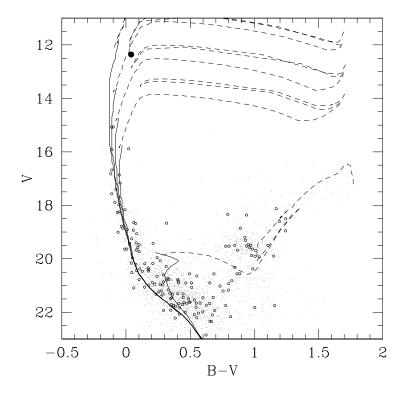


Figure 3. BV color-magnitude diagram of the stellar field surrounding SN 1987A. The stars within 25" of the supernova are marked as open circles and the stars outside this circle are marked as points. The whole field extends roughly 2.7' from the supernova. The position of Sk $-69^{\circ}202$ is marked as a closed circle. Isochrones from Bertelli et al. (1994) for ages 5, 10, 20, 40Myr, and 1Gyr are plotted. The more rapid evolution on the giant branch is indicated by dashed lines. The star at V=16 which lies well off the main sequence is Star 3, a known Be variable.

Figure 3 shows that the young field population within 25" of the supernova is consistent with a population of $\sim 15 \mathrm{Myr}$, although this value critically depends

on the accuracy of the theoretical T_{eff} to (B-V) conversion, the reddening, and the small number of hot stars. There is also a dominant older field population with a prominent turnoff at V = 20.4 which corresponds to a 1.5Gyr population.

These two populations are not well mixed however. Figure 3 shows that the young field population is strongly concentrated towards the position of SN 1987A. This can be shown with simple statistics. Divide the field by a circle with radius of 25" (projected distance of \sim 6pc) around SN 1987A and count the number of hot stars, defined here simply as any star with (B-V)<0.5. Form the ratio of the number of stars with V<18 and 18< V<20. The ratios for inside and outside the circle are 14/23 and 20/178 or 61% versus 17%. Furthermore, of the eight brightest hot stars in this region (V<16), four are inside the circle (stars 2,3,10,30), and two are inside 3"! Given such statistics, it is extremely likely that Sk $-69^{\circ}202$ was part of a loose association including KHK80 with an age of ~ 15 Myr, and that Stars 2 and 3, which are less than 3"away, are physically associated with progenitor of the supernova. However, because there is no obvious interaction of the outer rings of the supernova with Stars 2 and 3, it is unlikely that the supernova lies in precisely the same plane on the sky as the two crowding stars.

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References

Arnett, W. D., Bahcall, J. N., Kirshner, R. P., & Woosley, S. E. 1989, ARA&A, 27, 629

Bautista, M. A., et al. 1995, AJ, 109, 729

Bratton, C. B., et al. 1988, Phys. Rev. D., 37, 3361

Bouchet, P. et al. 1991, A&A, 245, 490

Bouchet, P., & Danziger, I. J. 1993, A&A, 273, 451

Bouchet, P. et al. 1996, in Supernovae and Supernova Remnants: Proceedings IAU Colloq. 145, eds. R. McCray and Z. Wang (New York, Cambridge Univ. Press), p. 201

Bertelli, G., Bressan A., Chiosi C., Fagotto F., & Nasi E. 1994, A&AS, 106, 275

Burki, G., Cramer, N., & Nicolet, B. 1991, A&AS, 87, 163

Caldwell, J. A. R. 1993, MNRAS, 262, 313

Efremov, Y. N. 1991, Sov. Astron. Lett., 17, 173

Fransson, C., & Kozma, C. 1993, ApJ, 408, L25

Hamuy, M., & Suntzeff, N. B. 1990, AJ, 99, 1146

Hamuy, M., Suntzeff, N. B., Bravo, J., Phillips, M. M. 1990, PASP, 102, 888

Hanuschik, R. W. et al. 1994, A&A, 281, 737

Helt, B. E., et al. 1991, A&AS, 89, 399

Hirata, K. S. et al. 1988, Phys. Rev. D, 38, 448

Lyubimkov, L. S. 1990, Sov. Astron., 34, 239

Jones, A. 1987, IAU Circ. 4340

Kirshner, R. P., & Gilmozzi, R. 1989, in Exploring the Universe with the IUE Satellite, ed. Y. Kondo (2nd ed.; Dordrecht: Reidel), 771

Kontizas, E., Metaxa, M., & Kontizas, M. 1988, AJ, 96, 1625.

Kumagai, S., Shigeyama, T., Nomoto, K., & Hashimoto, M. 1991, A&A, 243, L13

Matthews, J. 1987, IAU Circ. 4328

Meikle, W. P. S. et al. 1993, MNRAS, 261, 535

Menzies, J. W. 1989, MNRAS, 237, 21p

Moreno, B., & Walker, S. 1987, IAU Circ. 4316

Pel, J. W. et al. 1987, in Proc. ESO Workshop on SN 1987A, ed. I.J. Danziger (ESO:Garching), 97

Phillips, M. M. et al. 1990, AJ, 99, 1133

Pun, C. S. J, et al. 1995, ApJS, 99, 223

Scuderi, S. et al. 1996, ApJ, 465, 956

Shelton, I. K. 1987, IAU Circ., 4316

Shelton, I. K. 1993a, AJ, 105, 1886

Shelton, I. K., & Lapesset, E. 1993, AJ, 105, 1892

Shelton, I. K. 1993b, AJ, 105, 1895

Sonneborn, G. 1988, in A Decade of UV Astronomy with IUE, ed. E. Rolfe, ESA SP-281, 111

Stetson, P. B. 1987, PASP, 99, 191

Suntzeff, N. B., & Bouchet, P. 1990, AJ, 99, 650

Suntzeff, N. B., Phillips, M. M., DePoy, D. L., Elias, J. H., & Walker, A. R. 1991, AJ, 102, 1118

Suntzeff, N. B., Phillips, M. M., Elias, J. H., DePoy, D. L., & Walker, A. R., 1992, ApJ, 384, L33

Walborn, N. R., et al. 1993, PASP, 105, 1240.

Walborn, N. R., Lasker, B. M., Laidler, V. G., & Chu, Y.-H. 1987, ApJ, 321, L41

Walker, A. R., & Suntzeff, N. B. 1990, PASP, 102, 131

Walker, A. R., & Suntzeff, N. B. 1991, PASP, 103, 958

Wang, L., & Wheeler, J. C. 1996, ApJ, 462, L27

West, R. M., & McNaught, R. H., 1992, A&A, 256, 447

Wooden, D. H., et al. 1993, ApJS, 88, 477

Woosley, S. E., Pinto, P. A., & Hartmann, D. 1989, ApJ, 346, 395