Photometry of SK –69°202, the Progenitor of SN 1987A from 1896 to 1954

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Received November 18, 2003; revised July 8, 2004

Abstract We investigated possible variability of the B3Ia-type progenitor of SN 1987A on a large sample of blue-sensitive photographic plates at the Harvard College Observatory. The observed plates covered the time period 1896–1954. No variability of the star was found at the 0.3-magnitude level, which is consistent with the results of previous studies on its variability. How these results fit into the context of the present understanding of the evolution of this progenitor is discussed.

1. Introduction

The progenitor star of SN 1987A was a blue supergiant of spectral type B3Ia, a type that was not expected to become a supernova at the time (Arnett *et al.* 1989; Hillebrandt and Höflich 1989; Saio, Kato, and Nomoto 1988; Weiss 1989). Therefore it is important to acquire knowledge about its pre-supernova behavior to gain a better understanding of the supernova event.

SN 1987A was discovered in the Large Magellanic Cloud (LMC) on February 24, 1987, independently by Ian Shelton in Chile, Oscar Duhalde in Las Campanas, and Albert Jones in New Zealand (Kunkel 1987). Due to the close proximity (and well-determined distance) of the LMC, SN 1987A provided unprecedented observations of a supernova. For example, SN 1987A tested the reliability of using Type II supernovae as standard candles. It also provided the first observed bolometric light curve of a supernova (Hillebrandt and Höflich 1989), and it marked the birth of extra-solar neutrino astrophysics (Bionta *et al.* 1987; Hirata *et al.* 1987).

Perhaps the most exciting property of SN 1987A is that it allowed astronomers for the first time to identify a supernova with a known, albeit little-studied, progenitor star. The supernova's position coincides with the brightest component of the three-star complex Sanduleak −69°202 (Girard, van Altena, and Lopez 1988; West *et al.* 1987; Kirshner *et al.* 1987). The brightest component (star 1) was not seen in observations taken after the supernova, further evidence that star 1 was indeed the progenitor star (Walborn *et al.* 1987). SK −69°202 was catalogued as a B3 I blue supergiant with photoelectric magnitude and colors, $V = 12.24$, $B{-}V = 0.04$, and $U{-}B = -0.65$ (Isserstedt 1975; Rousseau *et al.* 1978).

The big surprise to most astronomers was the peculiar nature of the progenitor. Judging from its spectral type, the progenitor was probably born 10^7 years ago and had a main sequence mass around 20 $M_{\odot}$. It left the main sequence about 10^6 years ago and entered a red supergiant phase around the time of the onset of helium burning in the core. It is unclear what the progenitor's evolutionary path was from this point; the star may have stayed red for a while, or it may have undergone one or more blue-red-blue excursions on the HR diagram. Regardless, it is certain that the progenitor exploded as a blue supergiant and fairly certain that the star made its final blue transition 20,000–35,000 years before explosion. Carbon ignition most likely occurred a few thousand years before explosion, and subsequent burnings in the core took place quickly until the production of an iron core.

The existence of a blue progenitor that once underwent a red supergiant phase was the most surprising and the most difficult aspect of the evolution to explain (Arnett *et al.* 1989; Hillebrandt and Höflich 1989; Saio *et al.* 1988). Thus, several evolution models of SK −69°202 emerged that produced a broad spectrum of results using different yet realistic input physics. For example, some models failed to produce a blue progenitor, some models failed to make a red excursion in the HR diagram, and some models made multiple blue-red-blue loops (see Weiss 1989). Ten years after explosion, Woosley *et al.* (1997) still found it difficult to explain a blue progenitor.

The curious circumstances surrounding SN 1987A motivated us to conduct a detailed study focusing on the progenitor. Post-supernova models of SK −69°202 predict it would not have undergone any detectable motion in the HR diagram during its final ~50 years (Wood and Faulkner 1987). We were interested in determining if the available observations of the progenitor agreed with the theory, and were curious if SK −69°202 gave any signal of its impending violent death during its final hundred years. It is important to acquire as much knowledge as possible about SN 1987A's pre-supernova behavior not only to understand the physics of the supernova event, but also to learn what similar stars might be doing immediately prior to a supernova event. This information could be useful in identifying probable Type II supernova progenitor candidates and maybe even predict the next nearby supernova.

The photographic plate archives at Harvard College Observatory (HCO) house a substantial number of plates of the LMC containing SK −69°202 which span several decades. These plates provide us the opportunity to monitor SK −69°202 before it went supernova. We performed differential photometry on a sample of HCO plates and looked for possible variability of the progenitor. Section 2 describes our methods and presents our results. Section 3 discusses the results and compares them to previous studies. A summary and conclusion are given in section 4.

2. Monitoring the progenitor star

We compiled a data set of 182 A series and 9 circular ADI I series blue-sensitive photographic plates from HCO that sporadically covered the time period 1896–1954, with the majority falling between 1923 and 1954. The time between successive plates was from days to years, allowing the investigation of short-term and long-term variability. The plates had a photographic magnitude limit of 15 so SK –69°202 is clearly visible. An additional 147 plates were rejected from our sample due to poor seeing, trailed images, coma effects, cracks, or poor focus. Most of the plates in our sample were cracked or broken, but the majority of these plates were still usable since the cracks tended to be far away from SK –69°202. Figure 1 shows a histogram of the number of plates per year in our final sample.

We created a photometric sequence from CCD frames taken in 2002 by Arlo Landolt at Cerro Tololo Inter-American Observatory (CTIO). The stars in the sequence are not known to be variable, nor do they exhibit any signs of variability on the photographic plates. *B* and *V* magnitudes of the comparison stars were converted to photographic magnitudes using the algorithm in Arp (1961). A digital image of an A series plate with our comparison stars labeled is shown in Figure 2, and their magnitudes are listed in Table 1. For the 191 usable plates, photometry was done by eye estimates on the actual plates and also on digital images of the plates. Photometry performed on the actual plates and on the digital images were consistent with each other. SK –69°202 was found not to vary at the 0.3-magnitude level.

3. Discussion

Our result agrees with other studies (Blanco *et al.* 1987; Fuhrmann 1987; West *et al.* 1987; Hazen 1987). The SK –69°202 complex was monitored on eight red and ten near- infrared plates covering 1970–1981, on 162 blue plates covering 1934–1938, 1952–1953, and 1959, and on 40 European Southern Observatory (ESO) *UBVRI* plates covering 1972–1980 by Blanco *et al.* (1987), Fuhrmann (1987), and West *et al.* (1987), respectively. All three studies found no variability of SK –69°202 at the 0.5-mag level. Hazen (1987) found “no major change in the brightness of SK –69°202” on 502 Harvard blue patrol plates covering 1899–1953 and 59 Damon blue patrol series plates covering 1971, 1978–1979, and 1981–1986. However, she allows for the possibility that the progenitor “may have been varying by ±0.3–0.5 mag over that interval.” The average number of plates per year observed by these groups is shown in Figure 1.

It is well known that SK –69°202 can be deconvolved into three separate stars including the SN 1987A progenitor (e.g., Walborn *et al.* 1987). These stars are hopelessly blended on the HCO plates. The three stars have *V* magnitudes of approximately 12.4, 15.3, and 16.7 (Walborn *et al.* 1987). Girard *et al.* (1988) suggest that the second star varies from 13.9 to 15.3. If this were the case then the blended image would vary by ~0.4 mag, which we did not observe. However, none of the HCO plates cover the time period of the Girard *et al.* measurement. Similarly, we saw no variations of 0.3–0.5 mag suggested by Hazen (1987). Other independent measurements of plates show no significant variation in the brightness of the blended star or the progenitor (Blanco *et al.* 1987; Isserstedt 1975; Rousseau *et al.* 1978; Testor 1988; Heap and Lindler 1987; Shelton 1993; West *et al.* 1987; Walborn *et al.* 1993). It has been suggested that the progenitor star itself had a binary companion (Barkat and Wheeler 1989). We saw no photometric evidence that it is an eclipsing binary system.

Stellar evolution models predict that the progenitor should not be variable in the last century before the explosion (Wood and Faulkner 1987; Weiss 1989). The nuclear time scale of events in the progenitor's core after the onset of carbon burning is expected to be ~50 years, while the thermal time scale of the star is 1000–3000 years. Therefore, although the core may have changed relatively quickly, changes would not be reflected at the surface (Weiss 1989). The progenitor should not have undergone any detectable motion in the HR diagram towards the end of its life (Wood and Faulkner 1987).

4. Conclusion

There is still little known about the progenitor of SN 1987A fifteen years after its discovery, motivating us to go back in time and monitor SK –69°202's final 100 years on photographic plates. We do not detect any variability of the star greater than 0.3 magnitude. This agrees with previous studies and stellar evolution models of massive stars, which do not predict that a massive star like the progenitor changes in luminosity during its final hundred years because the nuclear time scale of events in the core (~50 yr) is much less than the thermal time scale of the star (1000–3000 yr).

Although models (such as Weiss 1989; Wood and Faulkner 1987; Woosley *et al.* 1997) can now explain the existence of a post-red supergiant progenitor, it is still difficult to replicate the progenitor's exact evolution and the supernova event. It is important to acquire knowledge about the progenitor to help constrain current supernova theory.

This project was supported by the NSF/REU grant AST-0097694 and the Nantucket Maria Mitchell Association. We thank Vladimir Strelnitski (Maria Mitchell Observatory) and Alison Doane (HCO) for their assistance in this project.

References

Arnett, W. D., Bahcall, I. N., Kirshner, R. P., and Woosley, S. E. 1989, *Ann. Rev. Astron. Astrophys.*, **27**, 629.
Arp, H. 1961, *Astrophys. J.*, **133**, 869.
Barkat, A., and Wheeler, J. C. 1989, *Astrophys. J.*, **342**, 940.
Bionta, R. M., *et al.* 1987, *Phys. Rev. Lett.*, **58**, 1494.
Blanco, V. M., *et al.* 1987, *Astrophys. J.*, **320**, 589.
Fuhrmann, B. 1987, *IAU Circular*, No. 3027, ed. D. W. E. Green.
Girard, T., van Altena, W. F., and Lopez, C. E. 1988, *Astron. J.*, **95**, 58.
Hazen, M. L. 1987, *IAU Circular*, No. 4367, ed. D. W. E. Green.
Heap, S. R., and Lindler, D. J. 1987, *Astron. Astrophys.*, **185**, L10.
Hillebrandt, W., and Höflich, P. 1989, *Rep. Prog. Phys.*, **52**, 1421.
Hirata, K., *et al.* 1987, *Phys. Rev. Lett.*, **58**, 1490.
Isserstedt, J. 1975, *Astron. Astrophys. Suppl.*, **19**, 259.
Kirshner, R. P., Sonneborn, G., Crenshaw, D. M., and Nassiopoulos, G. E. 1987, *Astrophys. J.*, **320**, 602.
Kunkel, W. 1987, *IAU Circular*, No. 4316, ed. D. W. E. Green.
Rousseau, J., Martin, N., Prevot, L., Rebeirot, E., Robin, A., and Brunet, J. P. 1978, *Astron. Astrophys. Suppl.*, **31**, 243.
Saio, H., Kato, M., and Nomoto, K. 1988, *Astrophys. J.*, **331**, 388.
Shelton, I. K. 1993, *Astron. J.*, **105**, 1886.
Testor, G. 1988, *Astron. Astrophys.*, **190**, L1.
Walborn, N. R., Lasker, B. M., Laidler, V. G., and Chu, Y. -H. 1987, *Astrophys J.*, **321**, L41.
Walborn, N. R., Phillips, M. M., Walker, A. R., and Elias, J. H. 1993, *Pub. Astron. Soc. Pacific*, **105**, 1240.
Weiss, A. 1989, *Astrophys. J.*, **339**, 365.
West, R. M., Lauberts, A., Jorgensen, H. E., and Schuster, H.-E. 1987, *Astron. Astrophys.*, **177**, L1.
Wood, P. R., and Faulkner, D. J. 1987, *Proc. Astron. Soc. Australia*, **7**, 75.
Woosley, S. C., Heger, A., Weaver, T. A., and Langer, N. 1997, astro-ph/9705146.

Table 1. CCD magnitudes of our four comparison stars.

Star	*V*	*B-V*	m_{pg}
I	12.14	–0.01	11.96 ± –0.1
II	12.29	0.00	12.13 ± –0.1
III	13.28	–0.12	12.97 ± –0.1
IV	12.17	0.55	12.60 ± –0.1

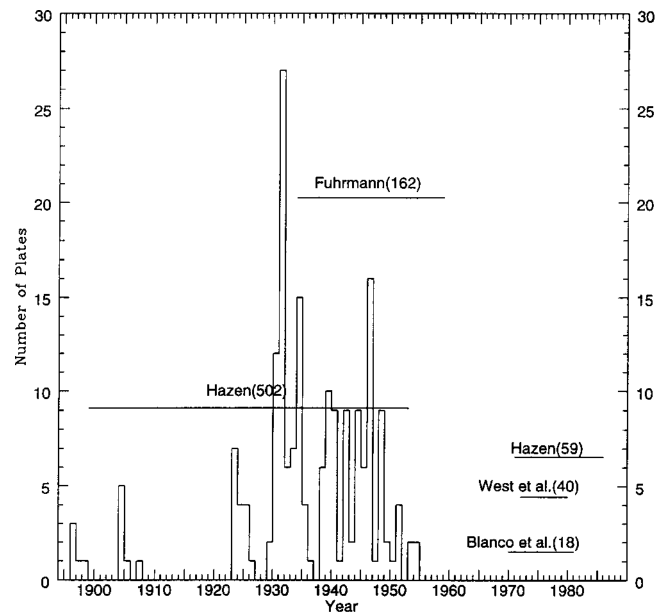

Figure 1. Histogram of the number of plates per year in our final 191-plate sample. Also shown are the range in time, average number of plates per year in other authors' samples, and the total number of plates in each author's sample (number in parenthesis.)

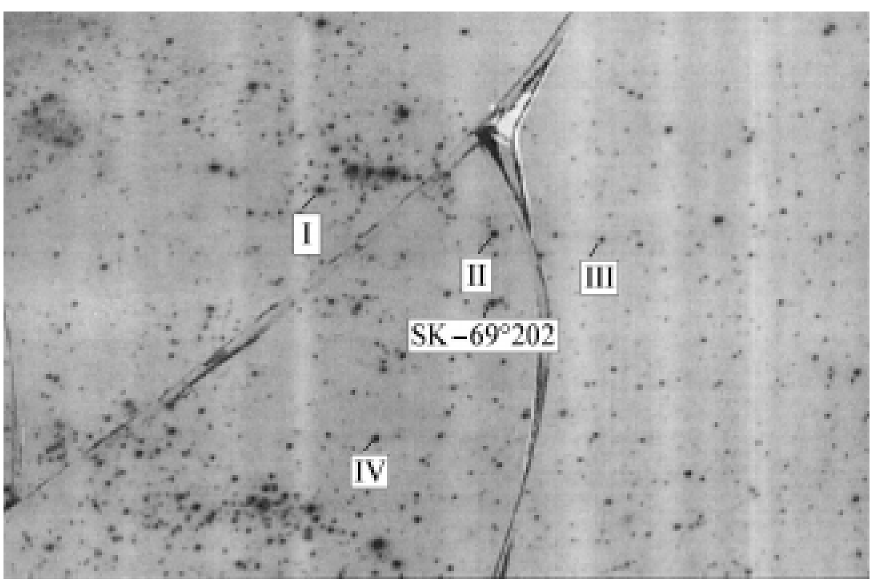

Figure 2. A sample digital image of a (cracked) plate from our sample, with the SK –69°202 complex and our four comparison stars labeled. Comparison star magnitudes are shown in Table 1.