

On the Progenitor of Supernova 1987A

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ABSTRACT

A previously unpublished ultralow-dispersion spectrum of Sanduleak -69 202, the stellar progenitor of SN 1987A, is presented and the uncertain presupernova evolution of Sanduleak -69 202 is discussed.

Subject headings: Supernovae: individual (SN 1987A) — techniques: ultralow-dispersion spectra — Large Magellanic Cloud — supergiants — stars: Sanduleak -69 202

1. INTRODUCTION

Supernova 1987A in the Large Magellanic Cloud (LMC), the observationally brightest supernova since Kepler's supernova of 1604, was observed in all wavelength regions and its neutrino burst was detected. Its aftermath may be observed as long as there are astronomers on Earth. SN 1987A was classified as a Type II supernova (SN II) in view of the strong hydrogen lines in its optical spectrum, but because it was the explosion of a blue supergiant (BSG) rather than a red one (RSG), it was an atypical SN II: its light curve did not reach maximum until three months after core collapse and at maximum it was only about 10 percent as luminous as most SNe II. For reviews of SN 1987A see Arnett et al. (1989) and McCray (1993). Vainu Bappu Observatory, Kavalur, India also participated in the observations of SN 1987A (Ashoka et al. 1987, Anupama et al. 1988).

SN 1987A provided the first good opportunity to directly investigate a supernova progenitor star. The progenitor of SN 1987A was Sanduleak -69 202 (Sk -69 202), a twelfth magnitude star classified as OB by Sanduleak (1970) from an objective prism survey of the LMC. Unfortunately, the observational record of Sk -69 202 is limited, partly because no spectral peculiarities or variability called attention to Sk -69 202 during the decades prior to its demise.

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Only serendipitous or survey data exist for Sk -69 202. Isserstedt (1975) obtained UBV photoelectric photometry between 1971 and 1973: $V = 12.24$, $B - V = +0.04$, and $U - B = -0.65$, characteristic of spectral type B3 I. Walborn et al. (1987) analyzed eight CTIO 4-m prime-focus plates obtained between 1974 and 1983 that covered the wavelength range from blue to near-IR. Sk -69 202 appeared to be normal, and no near-IR excess (no hot dust) was detected. Also, there was little or no light variability between 1974 and 1983 (Walborn et al. 1987) and between 1970 and 1981 (Blanco et al. 1987). Plotkin & Clayton (2004) examined a large number of Harvard blue patrol plates obtained from 1896 to 1954 and found no variability at the 0.3 magnitude level.

In 1972 and 1973 Rousseau et al. (1978) obtained ESO astrograph objective-prism spectra of 110 \AA mm^{-1} dispersion at $H\gamma$ on Kodak IIa-O plates; the wavelength coverage was limited, from 3850 to 4150 \AA . They classified Sk -69 202 as B3 I. Walborn et al. (1989) analyzed and critically discussed these spectra (as well as one ESO Schmidt objective prism spectrum of 460 \AA mm^{-1} dispersion at $H\gamma$). They compared the spectrum of Sk -69 202 with the spectra of six other LMC supergiants observed in the same way. The spectral type of Sk -69 202 was constrained to be within the range B0.7 to B3, with B3 favored.

In view of the limited amount of observational data on Sk -69 202, all of it should be made available. We report on an ultralow-dispersion objective-prism spectrum of Sk -69 202 and the surrounding region that was obtained in January 1974. Formally, this spectrum extends the wavelength coverage of Sk -69 202 to 6600 \AA , although only at ultralow-dispersion.

2. ULTRALOW-DISPERSION SPECTRUM OF Sk -69 202

Morgan et al. (1954) showed that faint OB stars and very red stars could be easily detected on 103a-F plates using objective prisms that give ultralow dispersion of $30,000 \text{ \AA mm}^{-1}$. Subsequent work by Schulte (1956a,b) identified several reddened OB stars of the Cygnus OB2 (VI Cygni) association from $10,000 \text{ \AA mm}^{-1}$ objective-prism spectra. This technique requires construction of prisms of very small angle (Bidelman 1972). The ultralow-dispersion technique was developed at the Vainu Bappu Observatory (VBO), Kavalur, India and was successfully applied to detect red and blue stars (Bappu & Parthasarathy 1977; Parthasarathy 1978). Bappu, Parthasarathy, & Scaria (1977, 1978, 1985) used this method to detect very red stars in selected regions of the LMC, and Parthasarathy & Jain (1995) applied it to detect cool and reddened stars in Cyg OB2.

The instrument (Bappu & Parthasarathy 1977) used was an F/2 slitless spectrograph with a three-degree quartz prism and a Schmidt camera at the Cassegrain focus of the 1-m

Ritchey–Chretien reflector at VBO. The field of view was 40 arcminutes in diameter. Spectra covering the wavelength range 3500 to 6600 Å were obtained on Kodak 103a-E emulsion. The dispersion was 10,000 Å mm⁻¹. The spectra were unwidened and were about 250 microns in length along the dispersion (Bappu & Parthasarathy 1977; Parthasarathy & Jain 1995). With this setup ultralow–dispersion spectra of all stars within a 40 minutes of arc field could be recorded in one exposure.

Ultralow–dispersion spectra of B, A, F, G, K, and M stars are shown in Figure 1. The main criterion for classification is the shape of the image. From Figure 1 it is clear that one can easily distinguish between OB stars and very red stars. The discontinuity in the spectrum is due to the dip in the sensitivity of the 103a–E emulsion in the green, which serves as a wavelength reference to distinguish the blue part of the spectrum from the red. For example notice the difference in the spectra of the B star and the K and M stars. Observations of several selected regions of the LMC obtained between 1974 and 1976 and the detection of red stars in the LMC can be found in Bappu et al. (1977, 1978, 1985). The region of the LMC observed in 1974 in which Sk -69 202 is present is shown in Figure 2. This region also includes the nearby Sk -69 203, a B0.7 I star with $V = 12.29$, $B - V = +0.01$, $U - B = -0.85$ (Isserstedt 1975; Rousseau et al. 1978; Walborn et al. 1989), quite similar to Sk -69 202 and possibly associated with it.

The ultralow–dispersion spectrum of Sk -69 202 shows that it was a B star in 1974. Comparison of densities in different sections of the images of Sk -69 202 and Sk -69 203 indicates that the magnitude and colors of Sk -69 202 were similar to that of Sk -69 203, in agreement with the UBV photometry and spectral classification.

3. PRESUPERNOVA EVOLUTION OF Sk -69 202

All data discussed above indicate that from 1971 to 1983 Sk -69 202 showed the characteristics of a normal B3 I star, with no evidence for variability, no Balmer–line emission, and no noticeable reddening or near–IR excess. (Walborn et al. 1989). From the spectra presented by Walborn et al. we estimate that the rotational velocity may not be more than 100 km s⁻¹. Sk -69 202 was a normal B3 I supergiant shortly before exploding.

SN 1987A has three circumstellar rings that are part of a complex system of gas that appears to have been ejected by the progenitor some 20,000 years before Sk -69 202 exploded (Burrows et al. 1995; Sugerman et al. 2005 and many references therein). The inner, equatorial ring is expanding at 10 km s⁻¹; its true shape is a nearly circular ring of radius 0.67 ly, inclined at 43 degrees to our line of sight. Analysis of the emission–line spectrum of the

inner ring (Fransson et al. 2005) indicates that it is nitrogen-rich, with $N/(C+O)$ about 10 times greater than the solar ratio (or perhaps somewhat smaller than this; Zhekov et al. 2006). The enhanced N abundance is thought to be due to conversion of C and O to N by the CNO cycle in Sk -69 202 before the ring material was expelled. The outer loops have physical radii 1.5 ly and lie on planes approximately parallel to the plane of the inner ring but displaced by about 1.3 ly on either side. The outer loops have radial velocities consistent with the interpretation that they were expelled at or near the time of the inner ring material.

The presupernova evolution of Sk -69 202 and the origin of the triple ring system remain uncertain. According to the evolutionary models of massive stars the progenitors of most SNe II are expected to be RSGs. The prevailing opinion is that SN 1987A did become an RSG, during which time it may have expelled the material of the rings in the form of a slow wind, and then returned to the blue. Within the current uncertainties of stellar evolution it is possible to make assumptions that cause models of single stars to return to the blue, but it is not clear that these assumptions are natural (Woosley et al. 2002). It is supposed that the fast wind of the second BSG phase then interacted with the slow wind of the RSG phase to produce the present ring system (e.g., Lundqvist & Fransson 1996; Sugarman et al. 2005). However, to end up with a ring system rather than a more spherical shell, the RSG wind must have been for some reason equatorially enhanced, and if Sk -69 202 had been an RSG one might expect some evidence for circumstellar gas and dust, emission lines, and variability in the presupernova data obtained between 1971 and 1983.

Opposed to the single-star scenario above is that Sk -69 202 may have been the product of the merger of an RSG and a less massive companion star (Hillebrandt & Meyer 1989; Podsiadlowski & Ivanova 2003). Such a merger can result in a BSG and perhaps a complex circumstellar system. However, the scenario is complicated. Morris & Podsiadlowski (2006) find that the mass ejection would be primarily at mid-latitudes rather than in the equatorial plane. They suggest that the mid-latitude ejection provided the material of the outer rings, and that the equatorial ejection of the inner ring material occurred *after* the merger in a rotation-enforced outflow during the contraction toward the blue. Another possible difficulty with the merger model is that it requires fine tuning to get the merger to happen just 20,000 years before the supernova, which would make SN 1987A an uncommon event (Woosley et al. 2002). Also, if Sk -69 202 was a merger product, rapid rotation of a few hundred km s^{-1} is expected. As mentioned above, the spectra of Sk -69 202 showed no evidence for rapid rotation.

Is it possible that Sk -69 202 never was an RSG? Pastorello et al. (2005) presented spectroscopic and photometric observations of the peculiar Type II SN 1998A. They showed that in many respects the light curves and spectra resembled those of SN 1987A, indicating

that the progenitor of SN 1998A also was a BSG. In spite of the strong observational selection against the discovery of subluminescent events, Pastorello et al. cited the existence of several other SNe II with (fragmentary) light curves possibly similar in shape to SN 1987A and SN 1998A, which suggests that explosions of BSGs are not too uncommon. This would be inconsistent with explanations that require fine tuning. Instead, there may be some regular channel for producing SN 1987A-like events. From stellar evolution calculations Höflich et al. (2001) found that models having somewhat lower metallicity or higher main-sequence mass than SN 1987A explode as BSGs without becoming RSGs, but the quantitative results depend on various assumptions. A problem for this scenario for SN 1987A, though, is that if Sk -69 202 never was an RSG, then there may be no good explanation for the low-velocity circumstellar material, although McCray & Lin (1994) suggested that the inner ring is the inner rim of a disk of gas left over from the formation of Sk -69 202. It is interesting that Sher 25, an apparently normal B1.5 Iab supergiant in or near the Galactic open cluster NGC 3603, has a system of rings reminiscent of SN 1987A (Brandner et al. 1997). Like other B type supergiants, Sher 25 has photospheric CNO abundances that indicate strong processing via the CNO cycle (Crowther et al. 2007).

The history of Sk -69 202 continues to be a mystery. Future observations of the interaction between the high-velocity ejecta of SN 1987A and the circumstellar matter, especially in X-rays (Zhekov et al. 2006), may provide vital clues to the past.

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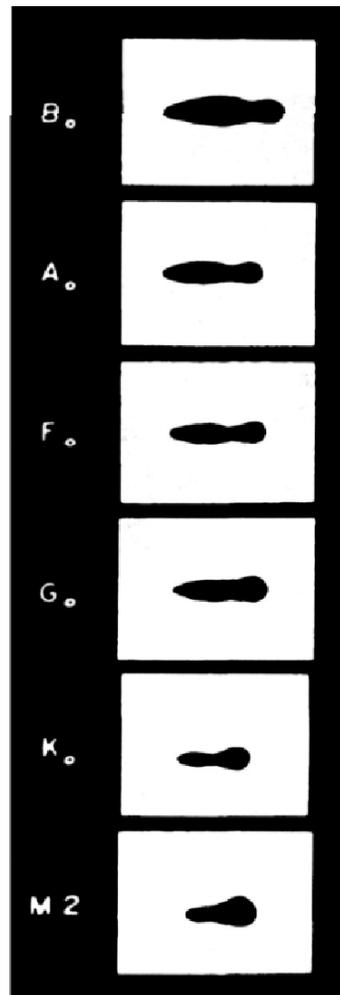


Fig. 1.— The ultralow-dispersion ($10,000 \text{ \AA mm}^{-1}$) spectra of stars of various spectral types. Wavelength increases to the right. The discontinuity in the spectrum is due to the dip in the sensitivity of the 103a-E emulsion in the green.

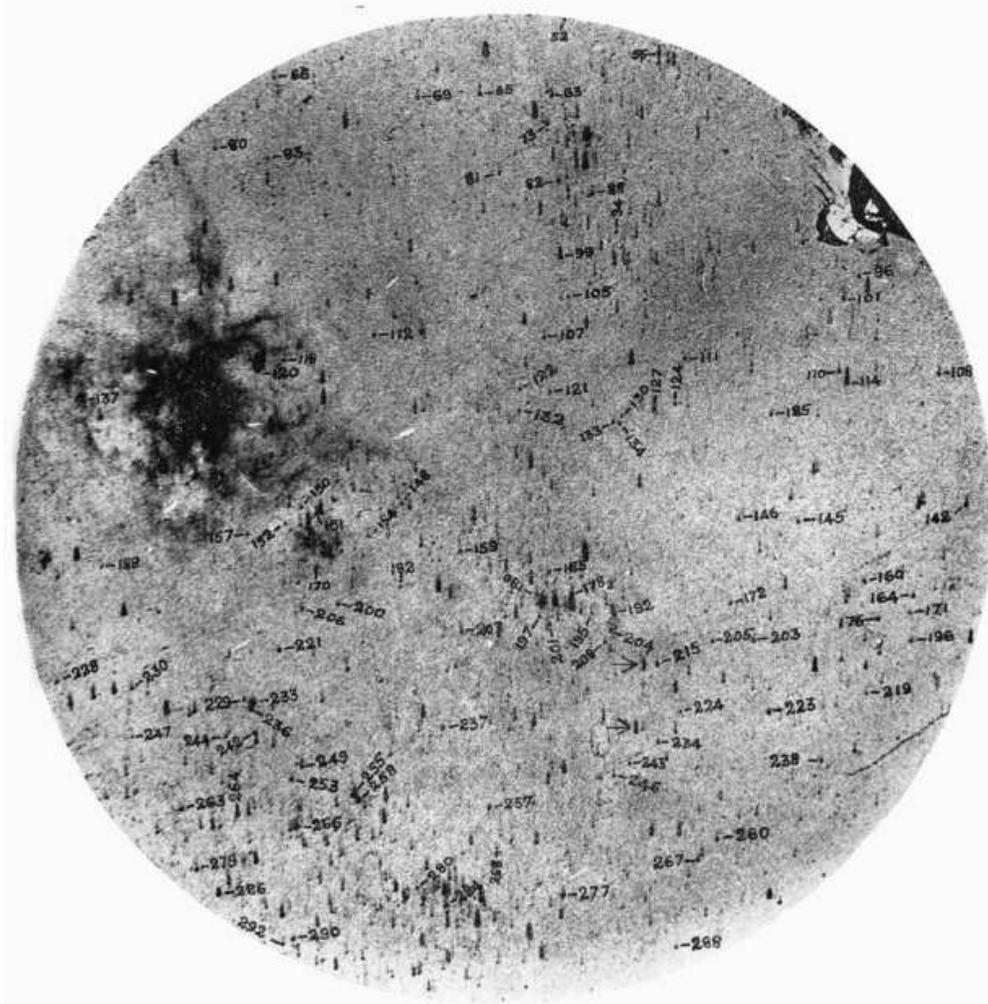


Fig. 2.— The region of the LMC that contains Sk -69 202 (lower arrow), the progenitor of SN 1987A, and Sk -69 203 (upper arrow). Numbered stars are red stars identified by Bappu et al. (1977). Spectra were recorded on 103a-E emulsion and cover the wavelength range 3500 to 6500 Å. Wavelength increases downward. The 1950 coordinates of the field center are R.A. 05 36.5 and Dec. -69 10. North is at the top and east is toward the left.