/ / /) S / /
5 - 5 7

N89-10683

OBSERVING SN 1987A WITH IUE

Robert P. Kirshner

Harvard-Smithsonian Center for Astrophysics
60 Garden Street
Cambridge, MA 02138 USA

ABSTRACT

IUE observations of SN 1987A began promptly after the discovery. They have been especially useful in determining which star exploded, and its stellar evolution before the explosion. When the supernova turns transparent in the ultraviolet, probably in 1988, the ultraviolet spectra will provide important chemical information about the interior of the massive star.

Keywords: SN 1987A, supernovae, spectroscopy

1 INTRODUCTION

The presence of the IUE satellite, and the prescience of its management, have helped provide a unique set of data on the most important event in the study of supernovae since the day Fritz Zwicky was born. Because the IUE was operating, and a target-of-opportunity proposal in place, an orderly, though very exciting, series of observations was carried out starting on the day of discovery, February 24, 1987, and has been sustained through the past year The effectiveness of this work is due in no small part to the encouragement of Project Scientist Yoji Kondo, and the hard work by the entire IUE Observatory staff at Goddard Space Flight Center, especially George Sonneborn, and the productive cooperation with our European colleagues, including Panagia, Gilmozzi, Cassatella, Wamsteker, and Fransson. Another source of help and inspiration was the high-minded cooperation of many IUE users who gracefully stepped aside so that these data could be collected in a timely way. This was often inconvenient for them, and I am especially grateful for their understanding and good will.

Supernova 1987A in the Large Magellanic Cloud has moved the subject of supernovae from plausible argument (hand waving) to observational demonstration (science) in a number of areas and the IUE observations have helped in key areas While the supernova was the first visible to the unaided eye since Kepler's 1604 supernova, retinal observations have not proved the most novel. Instead, the advances in technology, including geosynchronous satellites, have provided the data for real insight.

We have long believed, without powerful evidence, that one class of supernova explosions (Type II) results from massive stars, which release 10^{53} ergs of neutrinos as their iron cores collapse to become neutron stars. The essence of this picture was sketched by Baade and Zwicky in 1933 (ref. 1), shortly after the discovery of the neutron. Testing this part of the picture has involved the underground neutrino detectors, which caught enough of the neutrinos to make a convincing case that we understand the binding energy of a neutron star, as well as the temperature and duration of the neutrino emission (ref. 2). It has also involved the IUE, which helped in identifying the massive star that exploded, both directly through astrometry and indirectly through the behavior of the UV output. This is the first time that a pre-supernova star has been observed, and the first time we have known the name of the victim: Sanduleak -69 202.

Supernovae are also widely believed to play a central role in the chemical enrichment of the universe When the star destroys itself, the accumulated products of stellar energy generation such as helium, nitrogen, carbon, oxygen, calcium and silicon are dispersed into the interstellar gas along with the elements synthesized in the explosion. The chemistry of the stellar interior can now be probed by infrared observations (ref.3), and the gamma ray detections (ref 4) provide strong proof that radioactive ^{56}Ni is produced in the explosion. The IUE observations of SN 1987A helped establish the history of for Sanduleak -69 202, and it has turned out to be a challenging and surprising test of stellar evolution theory.

2. OBSERVATIONS

The first IUE spectra of SN1987A were taken from Goddard on the afternoon of Tuesday, February 24 The first frame of 15 seconds duration was heavily overexposed, and good low dispersion spectra were eventually obtained in about 1 5 second. The initial spectra were unlike the other IUE spectra of supernovae (ref 5,6), and changed very rapidly in the first few days of observation as shown in Figure 1

PRECEDING PAGE BLANK NOT FILMED

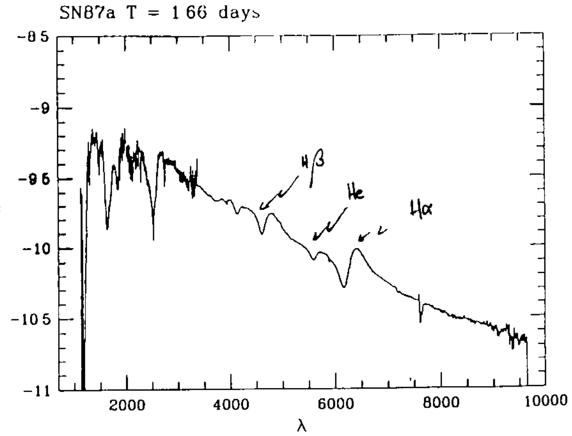

Figure 1. Early IUE spectra.

The combined optical and UV spectrum for the first day of observations is shown in Figure 2.

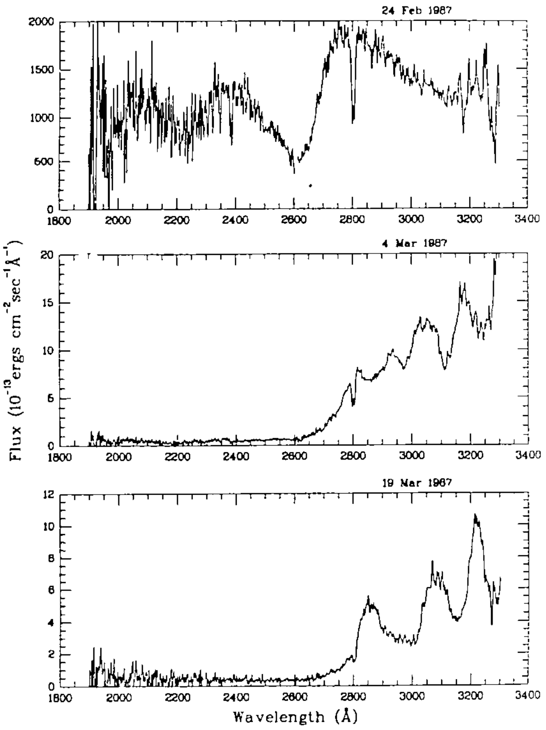

Figure 2 A combined optical and UV spectrum for 24 February 1987

This spectrum shows that the supernova had distinct hydrogen Balmer lines: the identifying criterion for SN II. The P-Cygni lines in the UV and optical indicated an initial expansion velocity near 30 000 km/sec and a temperature near 14 000 K, but this declined very rapidly as the supernova atmosphere expanded and cooled adiabatically. The effect on the ultraviolet flux was profound, as the cooling and the onset of powerful line blanketing combined to reduce the UV flux from the supernova by a factor of 1000 in the first three days, as shown in Figure 3.

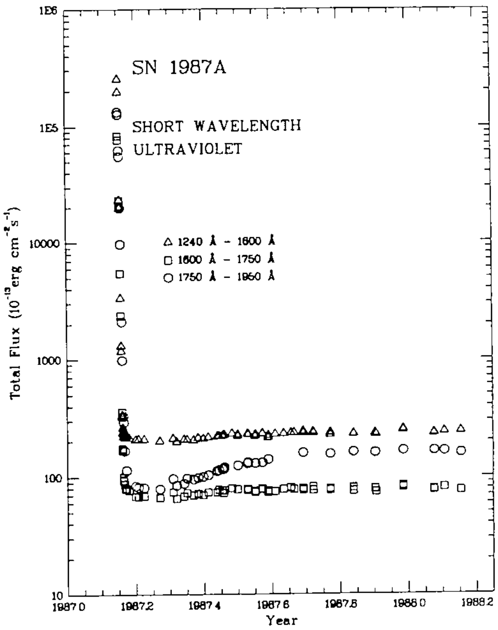

Figure 3. Decline in the short wavelength UV flux.

Although high-dispersion IUE observations of the interstellar medium were obtained in the first days, the rapid decline of UV flux made this fruitful probe of the interstellar gas a brief one (ref. 7,8).

2.1 Clues to the Progenitor

Several features of this supernova were remarkable, as emphasized in the early reports (ref. 9,10,11). Not only were the velocities higher and the color evolution rapid, but the luminosity of the supernova was lower than for other SN II, and did not reach its peak for nearly 3 months, on May 20. All of these properties can be understood as effects of the deposit of the usual 10^{51} ergs in the envelope of a blue supergiant, rather than the red supergiant which matches the properties of most SN II progenitors (ref. 12). In this case, the adiabatic losses in expansion are more severe, and radioactivity plays a larger role in providing energy during the rise to maximum and dominates the energy balance on the exponential tail shown in Figure 4.

Despite the differences between SN 1987A and the Type II supernovae that come from red giant stars, hydrogen in the atmosphere make both amenable to modelling. This is of special interest because SN II might be useful as distance indicators, even if they are not standard candles, by comparing the expansion velocity with an angular size inferred from the flux and temperature (ref. 13). Models for the optical and UV should help establish the run of density with velocity in the atmosphere, the helium abundance at maximum light, and the luminosity of the star for determining distances. While the distance to the LMC is not the goal,

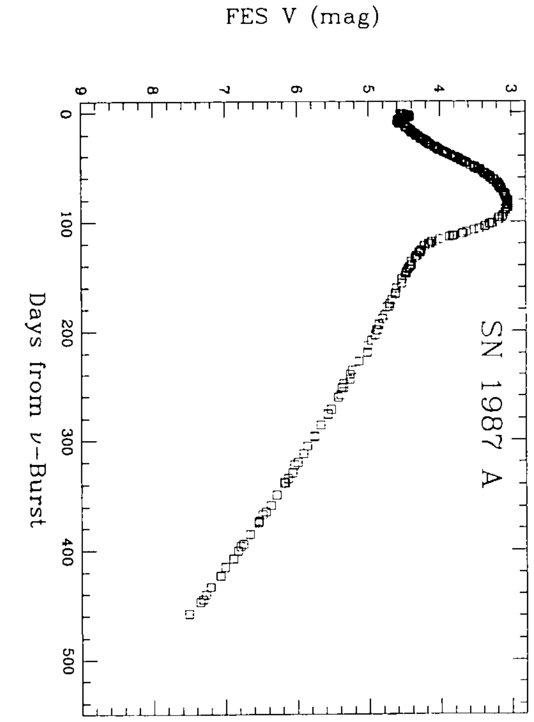

Figure 4 Light curve as observed by the FES on IUE

success in modeling the atmosphere of SN 1987A would be a good sign for the application of this technique to more distant objects. An early attempt by my graduate student, Ronald Eastman, is shown in Figure 5 The resemblance is encouraging, but more work needs to be done.

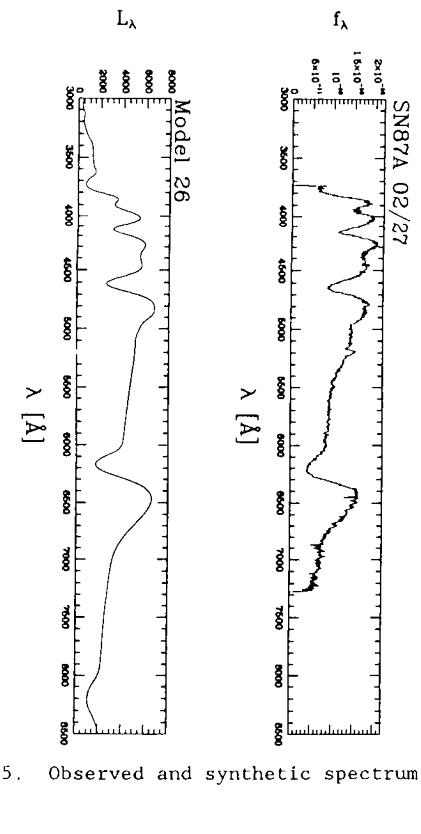

Figure 5. Observed and synthetic spectrum for SN 1987A

2 2 <u>A Massive Star</u>

A central view in the supernova story is that SN II come from massive stars. The first identification of a pre-supernova star has come for SN 1987A, based on archival photographs from the ground and the IUE observations. Early measurements of the supernova position showed that the supernova was very nearly coincident with a completely undistinguished blue star: one of over a thousand on the long roster compiled by Sanduleak (ref. 14) Sanduleak -69 202, whose core was furiously fusing the last available scraps of nuclear binding energy to stave off collapse, showed no special properties on its surface, and no comment or other designation is offered in Sanduleak's catalog. The thermal relaxation time for a blue supergiant atmosphere is long compared to the time for nuclear changes in the core: other stars on his list may also be sliding toward disaster with a serene exterior.

The identification of SK -69 202 as the progenitor was surprising, since conventional wisdom holds that SN II come from red supergiants. But the destruction of this star, a B3 Ia supergiant, radiating 10^5 solar luminosities with surface temperature near 15 000 K, and an extent of only 40 solar radii, would produce the observed unusual velocities, color changes, and luminosity.

Available images showed that SK -69 202 had a close neighbor, about 3" to the northwest. As the supernova faded in the UV, the story took an amusing twist as the line-by-line files from IUE clearly showed that after the supernova faded, there were spectra of two hot stars in the center of the aperture. It seemed likely that these two were the Sanduleak star and its neighbor, so that neither was the supernova progenitor. However, careful analysis of better optical data showed (ref 15, 16) that there were actually three stars at the site of the explosion, all within the point spread function of the IUE.

To unravel this puzzle, Sonneborn, Altner, and I (ref. 17) and independently Gilmozzi et al. (ref. 18) dissected the IUE spectrum in the spatial direction and made careful measurements of the separation of its two components. The astrometry showed that the separation was just that of the two other stars· that SK -69 202 had in fact disappeared, and was the best identification for the supernova progenitor.

2.3 <u>Circumstellar Matters</u>

The weak radio emission from SN 1987A (ref. 19) was interpreted (ref. 20) as arising from a shock in the low density blue supergiant wind of SK -69 202. An interesting aspect of the evolution of this star has recently been revealed by the IUE observations. After a few months, the short wavelength IUE spectra began to show evidence for narrow emission lines, as shown in Figure 6.

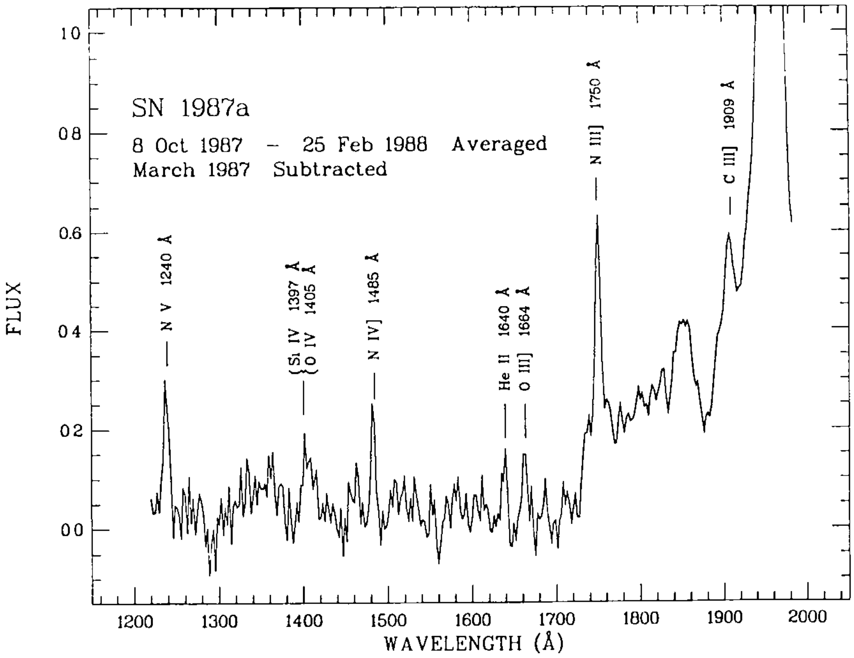

Figure 6. Narrow UV lines from circumstellar shell

Here the flux from the two neighboring stars as observed in March 1987 has been subtracted from the subsequent observed spectra

The observed lines are principally those of nitrogen, ranging from N V to N III. The observed velocities are low, and the velocity widths of the lines are unresolved at the low dispersion, implying velocities less than 1000 km/sec. All of these clues point toward a circumstellar origin for the emission lines. First, the fact that we can see the emission, while the supernova photosphere is opaque to the UV implies that the source of the emission is outside the expanding star. Second, the low velocities do not correspond to the debris, where the characteristic velocities are a few thousand km/sec. The great strength of the nitrogen lines is consistent with the chemical composition of material that might result from mass loss for a massive star (ref. 21, 22).

The excitation of this circumstellar shell would be the result of the UV flash that took place when the shock traversing the Sanduleak star hit the surface This initial pulse of energy would have been very hot (10^5 K) and brief (1 hour). Since the supernova was not discovered on the day of the neutrino burst, but the day after, the declining UV seen on 24 February must have been just the tail of this violent UV flash.

The observed UV flux from the circumstellar shell has been increasing with time from the first detection in the summer of 1987 to the current epoch, 400 days after the explosion. A plausible picture for the shell would be that it is far enough from the supernova site that light travel times are important in determining the observed flux. In that case, a dimension of order 10^{18} cm (1 light year) is indicated by the duration of the increase, since we are seeing the effects of the initial UV flash echoed to us from the circumstellar shell The spatial extent of this shell would be of order 2", not yet measurable with IUE

Because of the increasing flux, we have been able to make high dispersion IUE measurements of the circumstellar lines. They remain unresolved at 30 km/sec resolution as shown in Figure 7.

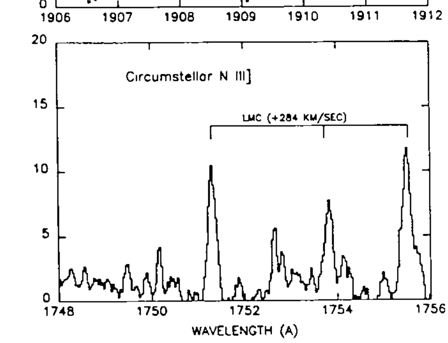

Figure 7 High dispersion spectra of the circumstellar emission

The observed line ratios are consistent with a density of order 10^4 in the emitting gas, and ground based observations of narrow [O III] help determine the temperature at about 45 000 K (ref 23). With the physical conditions reasonably well determined, we can determine the chemical abundances. We find N/C is about 10, a factor of 40 above the solar value.

High nitrogen abundance was also found in the circumstellar matter of an earlier SN II with IUE (ref 24). There, the explosion took place while the star was a red supergiant: here, the circumstellar matter was evidently ejected from the star as a red supergiant, but the star evolved to the blue before exploding. Thus the IUE observations help establish the history of SK -69 202, 20 000 years before it became famous.

Matching the path in the H-R diagram and the chemical composition of the circumstellar matter has proved a challenging task for theorists, who were already struggling with the question of why the star exploded as a blue supergiant. The evolution from blue (on the main sequence) to red (as a mass-losing red supergiant) back to the blue (to explode as a B3 Ia star) has been examined by Saio, Kato, and Nomoto (ref 25). Key ingredients seem to be the lower heavy element abundance in the LMC and substantial mass loss as a red supergiant. The possible abundance peculiarities at the supernova's surface suggested by Williams (ref. 26) might be related to structural changes in the star at the time of extensive mass loss.

While the details remain to be worked out, it is clear that the IUE observations have been exceptionally helpful in tracing the evolution of Sk -69 202 in the millennia before the explosion.

One prediction of this picture is that the rapidly expanding debris, moving at 1/10 c, will strike the circumstellar shell, out at 1 light year, in about 10 years. So for the end of the century, we may expect a recrudescence of SN 1987A, with a hot shock interaction producing copious X-rays and perhaps another blast of UV emission. While I hope that all of us are able to observe this event, I also hope that we will do it with a successor to IUE, rather than with a satellite which will be 20 years old!

3 ACKNOWLEDGEMENTS

One of the great pleasures of studying SN 1987A has been the lively and stimulating discussion among the participants, and the cooperation of so many who supported the observations by adapting to a revised schedule. This generous spirit places a special obligation on those of us who are working on the data to do the best job we can, and to leave a unique set of data for future astronomers. RPK's research on supernovae is supported by NASA grants NAG5-645 and NAG5-841, and by NSF grant AST85-16537.

4. REFERENCES

1. Baade,W. and Zwicky,F. 1933, Phys. Rev **45**, 138.

2. Spergel, D.N., et al. 1987, Science **237**, 1471.

3. Rank, D.M. et al. 1988, Nature **331**, 505.

4. Matz, S.M. et al. 1988, Nature **331**, 416.

5 Blair, W.P. and Panagia, N. 1987, in "Exploring the Universe with IUE" (Y. Kondo, editor), Reidel.

6. Benvenuti, P., et al. 1982, ESA SP-1046.

7. Dupree, A. et al. 1987, Ap.J. **320**, 597.

8. Blades, J.C., et al. 1988, Ap.J. in press.

9 Kirshner, R.P. et al. 1987, Ap.J. **320**, 602.

10. Wamsteker, W. et al. 1987, A&A **177**, L21.

11. Blanco, V.M. et al. 1987, Ap.J. **320**, 589.

12. Woosley, S.E. and Phillips, M.M. 1988, Science **240**, 750.

13. Kirshner, R.P. and Kwan, J. 1974, Ap.J. **193**, 27.

14. Sanduleak, N. 1969, CTIO Publications #89.

15 Walborn, N. et al. 1987, Ap.J.(Lett.) **320**, L41.

16. West, R.M. 1987 A. & A. **177**, L1.

17. Sonneborn, G., Altner, B., and Kirshner, R.P. 1987, Ap. J. (Lett) **232**, L35.

18 Gilmozzi, R. et al. 1987, Nature **328**, 318.

19. Turtle, A.J. et al. 1987, Nature **327**, 38.

20. Chevalier, R.A. and Fransson, C. 1987, Nature, **328**, 44.

21. Fransson, C. et al. 1988, Ap.J. in press.

22 Chevalier, R. 1987, Nature **328**, 44.

23. Wampler, E. J. private communication

24. Fransson, C. et al. 1984, A.& A. **132**, 1.

25 Saio, H., Kato, M., and Nomoto, K. 1988, Ap.J.(Lett.) in press.

26. Williams. R.E. 1987 Ap.J.(Lett.) **320**, L121.