SN 1987A: ULTRAVIOLET OBSERVATIONS AND MASS LOSS

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ABSTRACT

Mass loss from the B3 Ia progenitor star for SN 1987A is revealed by the recent emergence of narrow ultraviolet emission lines. The emitting gas is nitrogen-rich, has low velocity, and may be located a light-year from the supernova. This gives every sign of having been ejected from the SK -69 202 progenitor when it was a red supergiant, prior to its brief and ultimately violent life as a blue supergiant. Changes in the hydrogen line profiles during the early evolution provide a way to estimate the density distribution in the supernova atmosphere, and the mass of hydrogen it contains. A preliminary estimate is that the power-law index of density in the envelope goes as v^{-11} and the mass that lies above a velocity of 6,000 km s^{-1} is between 1 and 6 solar masses.

ULTRAVIOLET OBSERVATIONS

Promptly following the discovery of SN 1987A by Shelton at the University of Toronto's observatory at Las Campanas, a target of opportunity program to observe the supernova was put into action. The IUE was used in both its high and low resolution modes to measure the spectrum from 1200A to 3200A. Initial reports based on IUE data can be found in Kirshner et al. (1987) and Dupree et al (1987) and in European work (Panagia et al 1987, Cassatella et al 1987, Fransson et al 1987).

The ultraviolet flux was declining before the first optical maximum was reached on 27 February (day 58 of 1987), and the short wavelength bands declined much more rapidly than the long wavelength bands, due to rapid cooling of the photosphere from a high initial temperature. The decline in the shortest wavelength band is truly precipitous, descending a factor of 1000 in 3 days. The non-zero level reached is the result of two hot stars located near SK -69 202 in the aperture for the short wavelength, but is due to the supernova itself in the long wavelength bands.

These earliest UV observations can be combined with optical data to derive a bolometric light curve (Blanco et al. 1987). Although the color temperature was only of order 15,000 K at the time of our first data, it must have been far higher

https://doi.org/10.1017/S0252921100093994 Published online by Cambridge University Press

on February 23. If we take the moment of the core collapse as Feb 23.316 to agree with the Kamiokande (Koshiba 1987) and IMB (Svoboda 1987) results, then McNaught's observation at 6 mag on Feb 23.443 probably refers to an epoch when the temperature was of order 100 000 K with a photospheric radius of order 10^{13} cm. The ionizing output of the supernova cannot be reliably estimated from the ultraviolet light curves because so much of the ionizing flux that results when the shock hits the surface of the star came before the first ultraviolet observations. A reasonable estimate might be 10^{47} erg available to ionize and heat the circumstellar gas observed later.

SPECTROSCOPY

The detailed spectral evolution includes complex changes over the first few days. In the early spectra, a broad absorption and emission stretching from 2500A to 2800A is likely to be a P-Cygni line of Mg II, with the blue wing of the absorption minimum extending beyond 30,000 km s^{-1} blueshift. It seems likely that the ordinary photospheric abundance of iron peak elements is capable of producing the strong UV line blaneting observed after the first few days (Branch 1987, Lucy 1987).
The successful models for the ultraviolet spectra of previous SN II consider the emission from a substantial circumstellar layer (Fransson et al. 1984), such as might be expected around a red supergiant with a slow dense wind. The absence of these features makes it unlikely that SK -69 202 had such a wind immediately before the explosion, although it does not rule out a wind at an earlier stage of evolution. The picture in which SN 1987a has a low density circumstellar envelope is consistent with the weak, brief radio emission (Turtle et al 1987) and the absence of early X-ray flux (Makino 1987) as described by Chevalier and Fransson (1987).

The persistence of UV flux in the short wavelength range is the result of stars which are present in the aperture when the satellite is pointed at the supernova. With accurate position measurements and image synthesis of the SK -69 202 field in hand (Walborn et al 1987, West et al 1987), it is possible to conduct a careful deconvolution of the IUE data and to establish that the two stars present are stars 2 and 3. The 12 mag B3 I supergiant is not the source of the UV light. It has disappeared and it may be identified as the progenitor of SN 1987a (Sonneborn, Altner, and Kirshner 1987, Gilmozzi et al 1987).

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CIRCUMSTELLAR EMISSION

Starting in 1987 May, narrow emission lines began to appear in the short wavelength IUE spectra (Wamsteker et al 1987, Kirshner et al 1987). The lines are narrow (<1500 km s^{-1}) and near zero velocity. It is hard to see how they could emerge from the fast moving debris, especially as the opacity of that material is very high. A more likely picture is that they arise from circumstellar material surrounding the supernova. This idea is strengthened by the line identifications. Strong lines of N III, N IV, and N V are present, and the corresponding carbon and oxygen lines are weak. This suggests that the material is nitrogen-rich, as might be expected for the envelope of a star which has undergone extensive CNO hydrogen burning. While the details depend on a proper understanding of the origins of the emission, the ratio C/N implied by the observations must be down from normal values by a factor of 30 or more. A plausible picture would be that the B3 I star which exploded spent some time as a red supergiant, and that the material which we see in the short wavelength UV results from mass loss during that interlude. The investigations of mass loss in massive stars by Maeder (1987 and in this volume) are especially relevant here. The high nitrogen abundance observed requires very substantial mass loss, down to the zone where CNO cycle burning of hydrogen prevailed. It is interesting to note that a very similar UV spectrum is seen in the nitrogen-rich material ejected from Eta Carina (Davidson et al 1986), which is another star that is presumably on the path to becoming a supernova.

If we are seeing the results of a wind, the material would be at a distance that corresponds to the red giant wind velocity multiplied by the time the star spent as a blue supergiant. A reasonable estimate would be 10 km s^{-1} for 30000 years, or a distance of 1 light year. The ionizing flux from the supernova outburst would ionize and heat some of this circumstellar gas. The emission that we see would come either from the excitation of these ions, or possibly from recombination, at a temperature of order 50 000 K, as described by Lundquist and Fransson (1987). If this picture is correct, then the flux we see should grow with time as the light travel effects allow us to see more of the circumstellar shell. The available radius should grow as $t^{1/2}$; its area, and the flux should grow as t. In fact, the increasing flux of N III] 1750A matches that rate, although the data are still quite sketchy. The flux should continue to increase until the age is comparable to the light travel time across the shell.

For a reasonable guess of 1 LY scale, we can expect the flux from this shell to continue to increase for the next several months. If it grows strong enough to make a high-dispersion exposure practical, very stringent limits on the radial velocity of the emitting material will be measured. One amusing consequence of the

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circumstellar shell will be a violent interaction when the fast moving debris from the supernova collides with it. Since the debris has a velocity in excess of 0.1c, this renaissance of the supernova can be expected in 10 years. The collision will result in a high-temperature shock with copious X-ray emission as discussed by Masai et al in this meeting and possibly a new burst of radio emission. If these new sources do appear, the same light travel time effect that shapes the growth of the UV lines may dominate their temporal evolution.

The presence of a circumstellar shell is very important in establishing the evolutionary history of the SK -69 202 star. Theory alone does not provide a robust guide to understanding the travel through the H-R diagram for massive stars, including this one. In particular, this shell seems like very good evidence that the SK -69 202 star was once losing mass, presumably in a slow dense wind like that seen around red supergiants.

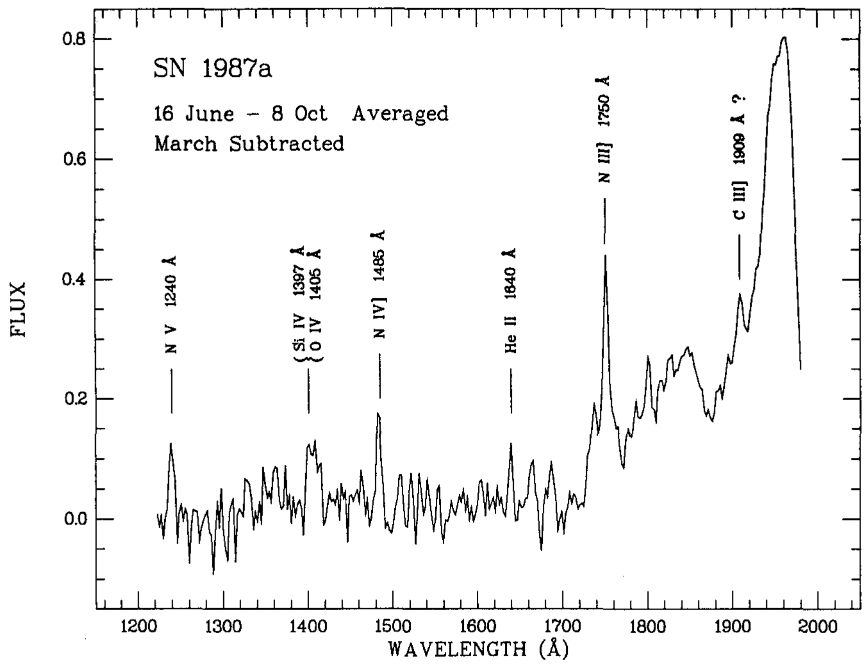

Figure 1. Averaged short wavelength spectrum, formed by subtracting the March 87 spectrum, which contains only flux from the two background stars, from the observations. Note the strong emission lines of Nitrogen.

ENVELOPE MASS

The luminosity of SK -69 202 is consistent with a helium core mass of about 6 solar masses, and this corresponds to a main sequence mass of order 15 solar masses. An important question that will affect the future behavior of the supernova is how much of the 9 solar masses not in the core was present on the surface of the star when it exploded. If mass loss was large, then the mass on the star could have been small, although we know that the surface layers were hydrogen-rich from the optical spectra.

One way to find the envelope mass would be to estimate the circumstellar mass, and subtract. This is unlikely to lead to a satisfactory estimate because the ionizing flux from the supernova is not so large that we can be sure it has ionized all the surrounding material. This approach is also vulnerable to large errors from clumping effects, and in any event requires an accurate knowledge of the density which we are unlikely to possess.

Another avenue is to look at the light curves. The large bump extending through May implies the energy deposited by radioactivity or other sources was trapped and had to diffuse out. But the details of the energy sources (which could include a neutron star or perhaps a substantial recombination energy) and of the opacity (which must depend on the composition and ionization of the stellar mantle) are not necessarily easy to model, so we may not have an accurate way to find the hydrogen mass from this approach.

A third method that has some promise is to examine the hydrogen lines and their evolution in the early weeks of the supernova. Eastman and Kirshner (1987) have carried out a preliminary analysis, based on a simple theory for the formation of the hydrogen lines. The model fits the shapes of the blue edge of the Balmer lines at various epochs. The rapid recession in velocity of the Balmer lines allows a model of the density versus velocity to be derived. Integrating that density distribution gives an envelope mass. The preliminary results are shown in the figures. The density distribution has a power law index of v^{-11} , which is in reasonable accord with expectations from hydrodynamic models, and a total mass above the velocity 6000 km s^{-1} of 1.8 solar masses. A reasonable range for the errors would admit an envelope mass from 1 to 6 solar masses. The chief uncertainty in the method is that it requires an estimate of the level populations in hydrogen. It is certainly the case that the population in n=2 is small compared to the ground state population. The population in n=2 is closely tied to the observations, but the desired quantity is the total amount of hydrogen, which depends on doing this atomic model correctly. Eastman is creating a detailed model atmosphere that will help sharpen this estimate. If we take it at face value, we would have a plausible

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picture in which the star would have had a 6 solar mass core, 1 to 6 solar masses in the envelope, and 8 to 3 solar masses in the circumstellar shell. If this picture is correct, then mass loss from a late type star is an essential part of the SN 1987A story.

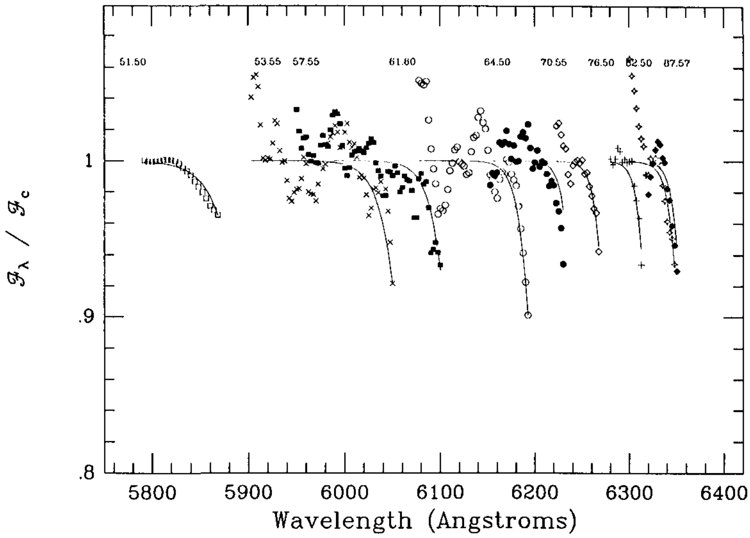

Figure 2. Observed H alpha line profiles from CTIO data fit by a simple model.

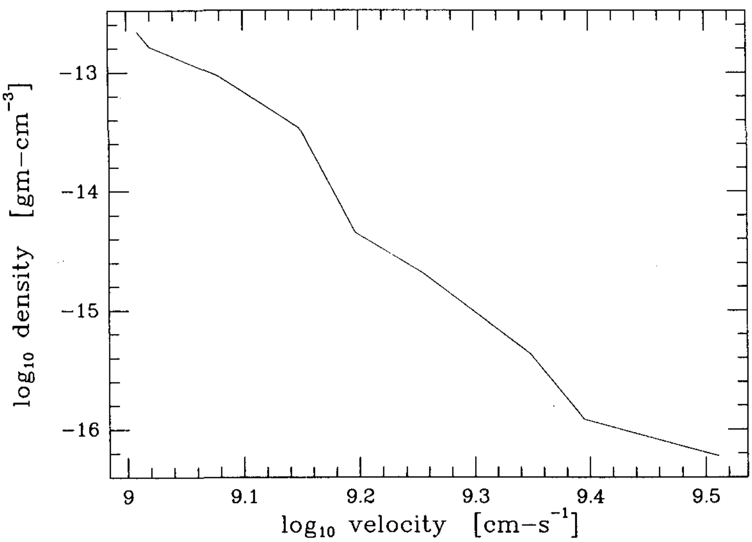

Figure 3. Density distribution required to fit the observed line profile evolution. The density falls as v^{-11}, and the integrated mass above 6000 km s^{-1} is about 2 solar masses.

I am very grateful for the outstanding cooperation of the IUE Observatroy staff, and for the tolerance of the many IUE observers whose work was dislocated by the observations of SN 1987A. The special contributions of George Sonneborn, George Nassiopoulos, Eric Schlegel, and Ronald Eastman were essential to the work reported here. Work on supernovae at the Harvard College Observatory is supported by NASA grants NAG5-841 and NAG5-645 and by NSF grant AST85-16537.

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