EFOSC instrument at the 3.6-m telescope, see the figure. A team of nine astronomers have now submitted a Letter to the Editor of *Astronomy and Astrophysics*, with expected publication in the June(I) 1988 issue. This paper is also available as ESO Preprint no. 591.

For these exposures, the bright light from the supernova itself was dimmed by the insertion of a small, obscuring disk into EFOSC. Two almost concentric rings are clearly visible. On February 13, the radii were 32 and 52 arcseconds. The rings are brighter towards North, because there is more interstellar matter in this direction. The integrated intensity of the light echo is about 2,000 times fainter than the current brightness of the supernova and is in agreement with the predicted intensity.

EFOSC spectra of the rings were also obtained, proving that they are the reflected supernova light from the time of the maximum, in May 1987. From the time delay and the angular dimensions of these rings, it can be inferred that the reflecting clouds are at distances of approximately 120 and 315 pc in front of the supernova, respectively.

Continued observations of these light echoes will allow to determine the three-dimensional structure of the interstellar clouds near the line-of-sight to the supernova (like a movie). The rings currently expand by about 3 arcsec per month and variations in the brightness along the periphery will indicate variations in the density of the reflecting material.

Among the other observations of SN 1987A during the past three months, there is a notable activity around the infrared spectra being obtained with the Kuiper Airborne Observatory; they show important and rapid changes, while the total infrared intensity decreases as the supernova fades. In early May 1988, the visual magnitude was around 7.5, or almost 100 times fainter than at maximum last year.

Several successful observations of SN 1987A during balloon flights with γ-ray detectors have been reported. One of these instruments, the Caltech Imaging Gamma-Ray Spectrometer, was flown from Alice Springs in Australia and yielded some of the first γ-ray pictures ever taken of any celestial object. *R. M. WEST (ESO)*

Observations of the Antique Wind of SN 1987A

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In the last days of 1987, green spectra of SN 1987A obtained with the ESO Cassegrain Echelle Spectrograph (CASPEC) and the 3.6-m telescope, show strong, narrow lines of forbidden [O III]. These [O III] lines are very narrow, in marked contrast to the wide emission lines emitted by the expanding supernova shell. In fact, their observed width is largely determined by the resolution of CASPEC (about 12.5 km/sec). For comparison, the strongest lines in the expanding supernova envelope, such as Hα, show velocity widths of several thousand km/sec. And the narrowest features that can be associated with the envelope itself, such as the substructure seen in the [O I] $\lambda\lambda$ 6300, 6364 lines, have velocity widths of several hundred km/sec. Thus the [O III] lines point to an ionized region associated with the supernova but distinct from the expanding envelope.

We describe here our observations and give the arguments for believing that we are seeing fluorescence radiation caused when the ultraviolet flash of SN 1987A ionized a shock front that had previously been generated in the progenitor wind when the star switched from a red to a blue supergiant. From the diameter of the nebula we can estimate the duration of the blue supergiant phase that culminated in the explosion of SN 1987A. This age is less than 10,000 years. We have, therefore, decided to call the red supergiant wind an "antique" wind to emphasize that it stopped blowing on a time scale comparable to the age of human civilization.

Using CASPEC with the 31.6 ℓ/mm grating, SN 1987A was observed at the end of October and again at the end of December. The wavelength interval 3700 Å–9500 Å was covered. Following the discovery of [O III] λ 5007, the supernova spectrum was searched for other identifiable narrow features. In addition to [O III] λ 5007, we have found [O III] λ 4959 and λ 4363, together with Hβ, Hγ and, possibly, Hδ and He II λ 4686. None of these features, which are present in the December spectra, are seen in the October spectra of the supernova. Of course, the supernova was much brighter in October than it was in December. Also, the spectra we obtained in October have a lower S/N ratio than those obtained in December. Thus it is not surprising that we did not see the weaker lines which are near the limit of detection even in the December data. But we also failed to detect [O III] λ 5007 in October, a line that is very strong in December. We estimate that we would have clearly seen a feature if it had been $\frac{1}{2}$ as strong in October as in December. While it is difficult to set a precise upper limit to the October line strength, it does appear that [O III] λ 5007 increased substantially in strength between October and December.

Figure 1 shows the lines that we found in the December spectra of SN 1987A. The peak intensities of the individual lines are given in fractions of the continuum intensities. Note that many of the lines have peak intensities only a few per cent above the local continuum. The equivalent widths ranged from about 5 to about 50 milli-

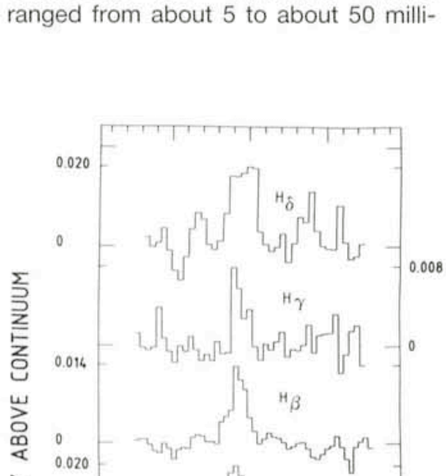

Figure 1: *CASPEC observations of narrow emission lines in SN 1987A. The intensity of the peak of each line, in units of the fractional intensity above the continuum, is given.*

angstroms. The velocity widths (~ 15 km/sec) of the observed lines are appropriate for galactic H II regions or the velocities of outflowing winds from red supergiant stars. Other types of stellar winds, such as found for blue supergiants, WR stars, etc. have wind velocities one to two orders of magnitude greater than the velocities seen here. The possibility that the nebula is a normal galactic H II region can be ruled out as it is very highly ionized. The ratio of the O^{++} lines to Hβ is much higher than is seen in H II regions or even planetary nebulae. Also, the ratio of [O III] λ 4363 / [O III] λ 5007, which is temperature sensitive, gives a gas temperature of about 55,000°K instead of the 9,000–10,000°K expected for H II regions.

As the CASPEC data did not have sufficient resolution to determine the velocity structure of the [O III] λ 5007 line and also because the CASPEC spectra were trailed in order to improve the signal-to-noise ratio, we decided to obtain untrailed spectra of SN 1987 A using the ESO 1.4-m CAT together with the CES. The peak intensity of [O III] λ 5007 was quite strong relative to the local continuum so that observations with CES at a spectral resolution of about 60,000 were relatively easy. H. Schwarz, D. Gillet, P. Molaro, S. D'Odorico and U. Munari very generously shared some of their CES time so that we could obtain a series of high resolution spectra of the λ 5007 region during the January-March 1988 interval. Figure 2 shows the results obtained from a spectrum taken on March 25, 1988. The line is clearly resolved. The full-width-half-maximum is about 14.5 km/sec and the heliocentric velocity is 286.3 ± 0.8 km/sec. This is in agreement with the idea that the line comes from a shell within the red giant wind.

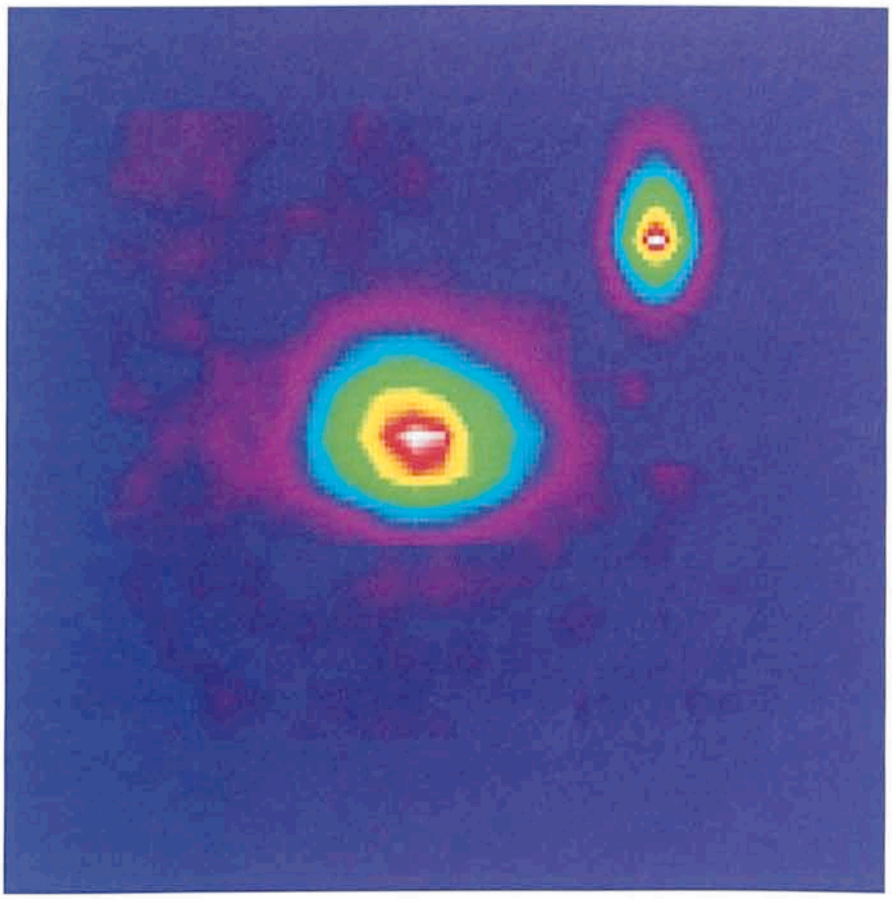

Figure 2: *The smoothed structure of [O III] λ 5007 from a March 26, 1988 CES spectrum (centre). The image in the upper right is the instrumental profile for this observation. The position along the slit (ordinate) is given as a function of wavelength (abscissa). The outer, deep blue, contour of the instrumental profile image measures 10.4 km/sec by 3.2 arcsec. The asymmetry of the instrumental profile in the slit direction was caused by imperfect telescope tracking.*

Starting in late May 1987, IUE spectra of SN 1987 A showed lines of He II, C III, N III, N IV, and O III which increased in strength with time (Fransson et al. 1988). These line widths were narrower than the IUE instrumental profile (ca. 30 km/sec). Their mean velocity, 284 ± 6 km/sec, agrees with the velocity of the optical emission lines seen in the CES spectra as well as a 284.8 km/sec component of the interstellar absorption lines (Vidal-Madjar et al. 1987). Thus it would appear that all of these features come from the same ionized cloud. While the IUE data do not provide an accurate estimate of the gas temperature, the ratio of C III] λ 1906.7 to C III] λ 1908.7 does give the density. Using the temperature determined from the optical [O III] lines and the λ 1906.7/ λ 1908.7 ratio given by Fransson et al. (1988), we find that $N_e \approx 3 \times 10^4$ cm^3. In addition it is possible to use the IUE data to study the abundances in the nebula. A preliminary estimate (Fransson et al. 1988) indicates that nitrogen is very much over-abundant relative to carbon and oxygen.

Taken together, all the available data suggest that the narrow lines originate from a slow moving, heavy element enriched, remnant stellar wind that is near the supernova. The most plausible origin for this wind is that it came from the supernova's progenitor during an earlier, red giant phase in its evolution. Enough material was removed from the progenitor during this phase that a substantial amount of the end products of nuclear burning were ejected along with the hydrogen rich portion of the envelope. Then, when the supernova progenitor switched to a blue supergiant, the high velocity blue supergiant wind expanded into the older antique red supergiant wind and compressed the gas to the observed density of about 3×10^4 cm^{-3} behind the expanding shock front. The shock interface between the red and blue supergiant winds is expected to expand with a velocity of 50–100 km/sec, depending on the relative strengths of the two stellar winds. When SN 1987 A exploded, the initial ultraviolet flash from the explosion ionized this compact nebula and drove the temperature to at least 55,000°K. We are now seeing it as it cools down. The diameter of the nebula gives the position of the shock front and therefore an estimate to the amount of time that has passed since the blue supergiant wind started blowing. By deconvolving the two-dimensional line profile of Figure 2 with the measured instrumental profile shown in the upper right corner of the figure, we find that the nebula extends about 2 arcseconds along the spectrograph slit. This is surprisingly small. At the distance of the LMC one arcsecond corresponds to 1 light-year. A shock front travelling at 50 km/sec can cover that distance in less than 7,000 years. Thus the progenitor could only have remained in the penultimate, blue supergiant, phase for a similar time. This suggests that the supernova exploded only a short time after it became a blue supergiant.

If it had been a blue supergiant for a

longer time, the shock front should have progressed much further into the antique red supergiant wind and the nebula would have been much larger. It is not likely that we are seeing only part of a much larger nebula: first, it has been over a year since the supernova exploded. But the angular radius of the nebula is only about one light-year. Thus, we are not seeing the apparent superluminal expansion that would be expected if the actual size of the nebula was much larger. And second, the detected flux of [O III] λ 5007 has remained approximately constant since February 1, 1988. Therefore we are not seeing the rapid increase in flux that would signal an expanding linear radius of the nebula.

It is also not likely that we are witnessing the interaction of the fast moving outer parts of the supernova envelope with the surrounding medium. In this case the nebula that we see is rather large to be produced by particle interaction from the expanding outer shell of the supernova and, in addition, the X-rays that would be expected to accompany the collisions should be rapidly increasing in strength as the density of particles increases. This is not happening.

Model calculations (Woosley, 1988) show that the final blue supergiant lifetime implied by the diameter of the nebula is the same as the time for the outer stellar envelope to reach equilibrium. But, to explode, the progenitor must form a massive iron core. If, as the Woosley models suggest, the star returns to the blue part of the H-R diagram after helium exhaustion, the mass of the helium core determines the length of time for carbon, neon, oxygen and silicon burning before the final collapse of the iron core to produce the supernova event. This time is dominated by the helium core collapse and the carbon burning lifetime. Woosley finds that stellar models that have about 19 solar masses of material when they are on the main sequence end up with helium cores in about the right mass range to power the SN 1987A explosion. An 18 $M_\odot$ star ends up with a helium core near 5 $M_\odot$. This star would explode 70,000 years after it switches to the blue supergiant phase. A 20 $M_\odot$ star produces a 6 $M_\odot$ helium core and explodes after 20,000 years.

These calculations suggest that it will be possible to construct a model that will be a good fit to all the observational data. Rotation, the $^{12}C\,(\alpha,\delta)\,^{16}O$ reaction rate, convection, etc. can all affect the lifetime of the last stages of stellar evolution. And, observationally, the radius of the nebula is still somewhat uncertain. The important point to make is that observations of this nebula together with theoretical calculations are likely to provide important additional constraints on SN 1987A models. It is probably fortuitous that the first estimate of the duration of the blue supergiant wind is comparable to the Kelvin Helmholtz contraction time for the progenitor envelope. We observers, therefore, don't have to worry too much about the details of the helium core. The contraction of the outer envelope is decoupled from the details of the inner core physics. We need only to model the outer envelope contraction to obtain the time dependence of the progenitor radiation field that drives the shock wave into the red supergiant wind. This, in turn, will lead to a more accurate velocity for the shock and, hence, a better estimate for the time interval between the time of helium core collapse and the supernova explosion.

Finally, of course, the very existence of the nebula shows that there *was* a red giant phase for the progenitor of SN 1987A. This by itself eliminates all those models that explode before they reach a red giant phase.

This small nebula from the antique red giant wind has proven to be an important new clue for understanding SN 1987A. As the supernova fades, the contrast of the nebula will increase and the spatial information will be easier to obtain. Then the observational constraints can be greatly improved.

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Deep Photometry of Supernovae

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1. Introduction

Supernovae are among the more exciting transient astronomical phenomena. Unfortunately the interest for them appears to fade faster than their luminosity. Only for one fifth of the 637 confirmed supernovae discovered up to the end of 1987, there are sufficient data to describe the photometric evolution; moreover, the majority of the published light curves are limited to the first two or three months after the maximum. On the other hand, the knowledge of the faintest tail of supernova light curves can give useful constraints in the discrimination among different theoretical models (Sutherland et al., 1984). The analysis of data available in literature, allowed Barbon et al. (1984) to investigate the behaviour of the late decline of supernovae. They showed that the late light curves can be described by a single exponential decay with different rates of decline, $<\gamma^{B}_{200^d}> \simeq 1.52$ mag/100^d for type Ia SNe (half-life 49^d.5) and $<\gamma^{B}_{200^d}>$ $\simeq 0.81$ mag/100^d for type II SNe (half-life 93^d), favouring therefore the possibility that the $Ni^{56}-Co^{56}-Fe^{56}$ radioactive decay is the main energy source up to these stages. More recently the bibliographical material of type II SNe has been used by Schaefer (1987a) to test the effect of light echoes in the B-band light curves, but the shortage of observations compelled him to include objects not observed at very late stage. He claimed to find different decline rates and argued that scattered light echo in the circumstellar dust can dominate the shape of the light curves of supernovae. To progress on this subject we decided to start photometric observations of supernovae at intermediate and late stages, extending to much fainter limits the extensive SN survey carried out at Asiago Observatory in the last thirty years by Rosino and collaborators.

2. Observations

The first observing session was performed at the 1.5-m Danish telescope equipped with RCA 320 × 512 #3 CCD on 17–19 January 1988. The sample of