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SEMI-ANNUAL REPORT

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The purpose of this grant is to support IUE investigations of SN 1987A, the brightest supernova observed in 383 years. A detailed summary of the extensive scientific results from the IUE observations has been prepared for inclusion in the revised version of "Exploring the Universe with the IUE Satellite" which is edited by Yoji Kondo. Since that book chapter provides a comprehensive summary of the work to date, it is being submitted as the semi-annual report for this period.

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OBSERVING SN 1987A WITH IUE

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1. Introduction

The IUE satellite has played a leading role in elucidating the nature of SN 1987A, providing a unique ultraviolet perspective on the brightest supernova since 1604. One fundamental property of the IUE project proved essential: it is a satellite whose program can be rapidly changed to take advantage of scientific opportunities. On both sides of the Atlantic, there was a target-of-opportunity proposal in place, so that an orderly, though very exciting, series of observations was carried out starting within 4 hours of the first report, on February 24, 1987, as recounted by de Vorken (1988) and by Kirshner (1988).

IUE observations of SN 1987A began promptly after the discovery and have been frequent through 1988 and 1989, using the FES for photometry, low dispersion spectra for the supernova spectrum as described in section 2, and high dispersion observations for the interstellar medium when the supernova was bright (section 3) and for circumstellar gas surrounding the supernova as the initial event faded (section 5). The UV data have been especially useful in determining which star exploded (section 4), assessing the ionizing pulse produced as the shock hit the surface of the star, and in constraining the stellar evolution that preceded the explosion through observations of a circumstellar shell. These discoveries are placed in a broader context by the review of Arnett, Bahcall, Kirshner and Woosley (1989) and earlier reports on the ultraviolet data are summarized by Kirshner (1988). The ultraviolet spectrum of the supernova itself is produced by the superposition of many lines of Fe, Co, and other elements in the stellar photosphere, and it has

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remained opaque long after the infrared and optical have changed to emission-line spectra. High-dispersion IUE observations provide a detailed look at the ionization structure of the line-of-sight to the supernova, both in our Galaxy and in the LMC. Future observations will include a UV observation of the light echo, monitoring the decay of the circumstellar emission, and perhaps a glimpse into the enriched material that was formerly the interior of Sanduleak -69 202.

Supernova 1987A in the Large Magellanic Cloud has moved the subject of supernovae from plausible argument to observational demonstration in a number of areas and the IUE observations have helped in essential ways. 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. The Large Magellanic Cloud is ideally placed for observation: circumpolar for the outstanding observatories of the Southern hemisphere, it is also near the ecliptic pole, facilitating observations with the IUE at almost any time of the year. The observations gathered over the entire spectrum from radio to gamma rays and the direct detection of neutrinos from SN 1987A have helped sketch the most complete picture of the life and death of a massive star.

A combination of stellar evolution theory and astronomical observation supports the picture 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 (Woosley and Weaver 1986). In a remarkable leap of scientific intuition, the essence of this picture was sketched by Baade and Zwicky (1933), shortly after the discovery of the neutron. Testing this picture for SN 1987A required 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 (Bahcall 1989). The neutrino observations provide a fiducial point: the moment of core collapse at 1987 February 23.316. On interesting sidelight (section 6) is that UV observations of a light echo may provide a way to observe the flux emitted from the surface of the star in the hours between the arrival of the shock and the discovery of the supernova by Ian Shelton on February 24.23 (Madore and Kunkel 1987). A key part of this picture was the identification of the star which exploded. As described in section 4, IUE provided essential data to identify directly the massive progenitor. This is the first time that a pre-supernova star has been observed, and the star is Sanduleak -69 202, a B3 I star of about 20 solar masses. Many of the unique features of SN 1987A as observed in the ultraviolet trace their origin to the explosion of a blue supergiant, rather than the red supergiants favored for most extragalactic SN II's. IUE observations of a nitrogen-rich circumstellar shell help trace the stellar evolution of SK -69 202 into the recent past, as described in Section 5.

Supernovae are essential players 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, such as the radioactive isotopes of the iron peak. The chemistry of the stellar interior can now be probed by infrared observations (Rank et al. 1988), and the gamma ray detections (Matz et al. 1988) provide strong proof that radioactive ^{56}Ni is produced in the explosion. The indirect effects of the energy release are seen in the light curve, measured with the Fine Error Sensor on IUE, as presented in section 2, but the direct measurement of the interior composition through ultraviolet lines will occur only after the opaque atmosphere turns transparent, as suggested in section 7. Clues to a possible neutron star remnant may also be embedded in the light curve for SN 1987A, but the resolution of these tantalizing questions lies in the future.

2. Observations

The first IUE spectra of SN1987A were taken from Goddard on the afternoon of Tuesday, February 24, about 4 hours after the report from the Central Bureau for Astronomical Telegrams. The first frame of 15 seconds duration was heavily overexposed, and good low dispersion spectra were eventually obtained with 1.5 second exposures. The initial spectra were unlike the other IUE spectra of supernovae (Blair and Panagia 1987, Benvenuti et al. 1982), and changed very rapidly in the first few days of observation as shown in Figure 1. Interestingly, by February 26 the UV spectrum of SN 1987A resembled the spectrum of a Type I supernova (SN I) as seen in the ultraviolet, while the combined optical and UV spectrum in Figure 2 shows that the supernova had distinct hydrogen Balmer lines: the identifying criterion for SN II. The solution to this paradox is straightforward: in SN I, as shown by Branch and Venkatakrishna (1986) and in the atmosphere of the blue supergiant SK -69 202, as shown by Lucy (1987) the strong blended lines of Fe II and Co II dominate the opacity in the ultraviolet region of interest. In SN II, like SN

1979C, the analysis of Fransson et al. (1984) shows that the slow, dense wind of a red supergiant plays a key role in determining the UV spectrum.

The conspicuous P-Cygni lines in the UV and optical indicated an initial expansion velocity near 30 000 km/sec in the first hours of observation and a temperature near 14 000 K. Model atmospheres for SN 1987A have been calculated by Eastman and Kirshner (1989) which provide a good understanding of the effects of scattering and spherical geometry in the expanding atmosphere, as Figure 2 indicates. These models allow the distance to the LMC to be determined by the Expanding Photosphere Method (Kirshner and Kwan 1974): the result of 50+/- 6 kpc is in good accord with the distances found from Cepheids and from RR Lyrae stars (Walker 1987, Walker and Mack 1988), and raises the prospect of using SN II as an important tool in establishing the extragalactic distance scale.

The apparent velocity declined rapidly as the fastest-moving layers turned transparent, and the temperature declined rapidly as the supernova atmosphere expanded and cooled adiabatically. The effect on the ultraviolet flux was profound: both the cooling and the onset of powerful line blanketing combined to reduce the UV flux in the SWP range by a factor of 1000 in the first three days, as shown in Figure 3. The level flux at later times is due to the presence of the two B stars near SK -69 202 which are in the IUE aperture, as described in section 4.

The plummeting UV seen on Feb 24 is presumably the cooling tail of a much hotter photosphere which must have been present on Feb 23, when the shock from the stellar interior first reached the surface of Sk -69 202 about 2 hours after core collapse. Theoretical calculations show that the temperature might have reached the range of 2-5 x 10^6 K for a brief time on Feb 23. This ultraviolet flash is the source of photoionization of the circumstellar matter, as described in section 5, where ionization up to N V is observed. Another way to detect the ultraviolet flash emitted before the supernova was discovered is through its UV echo from interstellar dust, as described in section 6. Empirical evidence that the surface of the Sanduleak star was very hot comes from the photograph of the LMC taken by McNaught (1987) on February 23.443, which showed that SN 1987A was already at about mag 6. The product of velocity and age requires a temperature of order 100,000 K to produce the observed flux. To press the UV observations back to the earliest possible moment, we have begun to examine the badly over-exposed images taken in the first attempts to get IUE spectra of SN 1987A. In the depths of the absorption lines, and in the regions of the spectrum where IUE has the least sensitivity, some reliable measurements may be recovered which will help trace the arrival of the shock at the surface of the Sanduleak star.

Following the dramatic changes of the first days, the IUE spectrum of SN 1987A has remained remarkably constant. This is illustrated in Figure 4, which shows the LWP spectrum, like the stable dog in the Sherlock Holmes story, is remarkable for what it does <u>not</u> do from February of 1987 through 1988. There are changes in the UV flux through this period, but the spectrum, set by the atomic physics of photospheric iron and cobalt shows only subtle variations. Although the optical spectrum is now dominated by strong emission lines which arise from material that was originally far below the photosphere of the star, the UV photosphere has remained opaque. Although there have been predictions of a "UV Renaissance" when the ultraviolet finally turns transparent (McCray, Shull and Sutherland 1987), Figure 5 indicates that we must first endure the ultraviolet Dark Ages of 1989. To obtain Figure 5, the LWP spectra have been integrated over broad wavelength intervals. Ultraviolet observations of the material from the stellar interior should eventually prove very helpful in determining the mass of carbon, magnesium, and silicon produced by SN 1987A, but that time has not yet arrived. These elements are important in comparing the observed composition for SN 1987A with the theoretical results for massive star evolution, and they are difficult to observe at optical wavelengths.

Measurements from the Fine Error Sensor have proved surprisingly accurate and useful in monitoring the flux from SN 1987A. Even though the FES was never intended as an accurate photometer, we have found that careful attention to calibration by a standard star during the same observing session produces a marked decrease in the random errors of FES measurements. While the carefully integrated bolometric measures of the Cerro Tololo workers (Suntzeff et al. 1988) and of the South African group (Whitelock 1988) are the primary data for comparing the radiative output of SN 1987A with models, the FES data are instructive, illustrating every major feature of the bolometric light curve, as shown in Figure 6. The familiar features of the rise to maximum in late May 1987, the long exponential tail from age 110 days to 300 days, and the subsequent drop below the extrapolated output of ^{56}Co are all illustrated in the FES light curve. In Figure 7, the most recent data show that the steepening decline in the FES light curve has abated. One possible interpretation is that a constant source at a luminosity of 5 x 10^{37} erg/sec is now contributing to the SN 1987A light curve. Whether this is related to the putative pulsar (Kristian et al 1989) or possible accretion on to the neutron star (Chevalier 1989) remains to be seen. The FES measurements will continue, unaffected by weather or seeing and never vulnerable to the errors that accrue at large hour angles! Ultimately, contamination from the neighboring stars will become a serious problem, and only the superb images of HST will permit a light curve for SN 1987A into the 1990's.

The UV light curves of Figure 5 show a distinctly different behavior. While they share the rise to maximum seen in the FES data, they did not experience the long exponential decline. Evidently, the small fraction of the energy coming out in the UV rose during that period, presumably as a result of decreasing line blanketing. The future of the UV light curve is hard to predict, but it may show a dramatic change when the spectrum changes to emission lines.

3. The Interstellar Medium Towards SN 1987A

Although SN 1987A reached its maximum bolometric luminosity in late May 1987, the rapid decline in the UV flux made the fruitful time for high resolutions observations very brief. During February 24 and 25, IUE high resolution spectra were obtained which provided the best signal-to-noise for study of the interstellar gas from Earth to the Sanduleak star. The brightness of the supernova as a background source allowed much shorter exposures than previous studies of the ISM toward the LMC were compelled to use, and the resulting particle background in the data was much lower. Because the time span for obtaining these exquisite data was short, there was little opportunity to study the time-dependent effects of the ionizing flash from SN 1987A, but the very high quality of the data that were obtained not only allowed them to confirm kinematic results obtained at higher resolution from the ground, but to extend them by providing the chemical composition of the intervening absorbers.

Several velocity components were detected in a wide range of ionization stages ranging from neutral gas to triply ionized carbon (de Boer et al. 1987, Dupree et al. 1987, Blades et al. 1988a,b, Savage et al. 1989). The observed UV absorption components to SN 1987A have a velocity distribution which is similar to that observed on the lines of sight to other stars in the LMC (eg. Savage and de Boer 1979, Savage 1986) and which agrees with the main optical absorption systems found by Andreani et al. (1987) in the spectrum of SN 1987A.

Table 1, adapted from Blades et al. (1988b) shows the velocity structure of the interstellar species detected with IUE, and Table 2 summarizes the same information for various Fe II lines. Figure 8 shows an example of the IUE data for some of the higher ionization stages. Note that the high velocity component is highly saturated.

The absorption features over the velocity range from 0 to +300 km/sec arise in the disk and halo of our Galaxy and in the LMC. While it is not controversial to assign the absorptions with v >/= 200 km/sec to gas in the LMC and those with v </= 70 km/sec to our Galaxy, intermediate velocities require more discussion. An abundance analysis of the intermediate velocity components at 129 and 171 km/sec by Blades et al. (1988a) shows that they are not intergalactic clouds, but belong to the LMC. These clouds may have their origins in gas that is stripped by tidal interactions or may arise from wind-driven shells or supernova remnants in the LMC.

Although there are some weak and unidentified features in the spectra, there is no evidence for narrow lines in the absorbing material at high velocity associated with the supernova explosion itself. Similarly, over the limited time span of the high resolution observations, no variations in the spectra have been found which could be attributed to time dependent effects in the neighborhood of the supernova. However, one absorption component, at 206 km/sec, is unusual with only high ionization species (C IV, Si IV, and possibly Al III) and is not typical of absorption spectra seen toward other LMC stars. It is tempting to speculate that this unique component might be related to the supernova or the effects of its progenitor. One way to tell will be to study the absorption spectra of the Sanduleak star's close neighbors, star 2 and star 3, with HST. By examining these neighboring lines of sight, the extent of the peculiar absorbing region can be pinned down.

Another special feature is the cloud observed at 281 km/sec in which the highly ionized species of C IV and Si IV have equivalent widths which are significantly larger than found in other LMC stars (see Figure 8). One possible origin for this increased strength is that the UV flash increased the ionization of the region out to 1 pc. If this region has an average density greater than 10 cm^{-3}, it could account for the observed line strengths. As detailed in section 5, circumstellar <u>emission</u> lines have been observed with IUE (Fransson et al. 1989), and high dispersion observations of these lines show they have a velocity near 281 km/sec. It is tempting to identify the absorption component seen in the first days with the gas that produced the emission seen many months later: circumstellar gas at the interface between the slow, dense red supergiant wind, and the fast, low density wind of the blue supergiant. However, the analysis by Savage et al. (1989) places limits on the density of material very near the supernova by examining the 1264Å line from Si II in an excited fine-structure level. They conclude that it is unlikely that the ultraviolet flash from the shock breakout could explain the strong Si IV and C IV features seen at LMC velocities.

The absence of N V absorption in the spectrum of SN 1987A has been used by Fransson et al (1987) to constrain the luminosity of the UV flash. From the observed upper limit to N V absorption, they derived an upper limit to the N V column density of 3 x 10^{14} cm^{-2} and inferred a limit to the number of ionizing photons $S < 1.6 \times 10^{57}/n^2$ (where n is the ambient density) for a temperature $T_{eff} = 5 \times 10^5$ K. Comparison with models for the shock arriving at the surface of a star (Klein and Chevalier 1978) shows that a red supergiant would produce too much ionization, but a blue supergiant, such as SK -69 202 would be a good match to the observational constraint.

4. Ultraviolet Clues to the Progenitor of SN 1987A

The ultraviolet data from IUE played an interesting role in determining that the B3 I supergiant Sanduleak -69 202 (Sanduleak 1974) was the progenitor of SN 1987A. Initial position measures (McNaught 1987) indicated that this star was coincident with the supernova, and indicated the presence of a companion about 3" away. As the supernova plummeted in the ultraviolet (see Figure 5), IUE observers found the surprising result that five days after the explosion the spectrum resembled an early B star. This suggested the possibility that SK -69 202 had survived the explosion, and was not itself the supernova progenitor (Gry et al. 1987).

The situation began to become clearer when careful astrometry of plates in the region of the supernova was carried out by West et al (1987) and by Walborn et al (1987). They showed that there were actually three stars within three arc sec of the supernova position. The excellent positional agreement between the SN and the Sanduleak star (B3I, V=12.36) made this the best candidate for the progenitor, while the position of star 2 (3" at PA=315°, V=15.3) made it clear that this star could be excluded. A third star (1.5" at PA= 120°, V=15.7) was also detected. The possibility of two stars not connected with the supernova explosion prompted a re-analysis of the IUE spectra which showed two objects were present in the IUE aperture (Sonneborn and Kirshner 1987). Both Panagia et al (1987) and

Kirshner et al (1987) concluded that the two spectra seen by IUE were the spectra of stars 2 and 3. Both of these stars are hot enough to be important in the IUE SWP spectral range, especially as the supernova faded so rapidly at those wavelengths.

Even though the IUE is not an imaging instrument, there is some information on the spatial distribution of light in the aperture which can be extracted from the line-by-line files. A quantitative reanalysis of the two-dimensional spectra (see Figure 9) was performed in the 1300Å to 1500Å region where the Point spread function of the instrument is good and the supernova flux was negligible to examine which two stars were contributing the UV flux (Gilmozzi et al 1987, Sonneborn, Altner, and Kirshner 1987). The spatial profile was fit using the skewed point spread function of the SWP camera (Cassatella et al. 1985). This deconvolution showed that the two stars were separated by 4.5" +/-0.2", and the intensity ratio was 1.75 +/- 0.12. These values are in good accord with the projected separation of stars 2 and 3 (4.4") and demonstrably different from the 3" separation between the Sanduleak -69 202 star and star 2. Further tests of the flux from the stars and changes in the projected separation as the satellite changed orientation confirmed these findings. The stars seen by IUE were stars 2 and 3, and the 12 mag B3 I star Sanduleak -69 202 had disappeared because it was the progenitor of SN 1987A.

The spectra of the two stars could be extracted separately. Gilmozzi et al (1987) measured the flux from star 3 and provided a classification of B0 V for star 2 and B1.5V for star 3, based on a comparison with UV standard stars. To examine this more closely, Gilmozzi and Panagia (1989) and Gilmozzi (1988) have constructed a useful color-magnitude diagram [M(V), m(lambda)-V] with the loci of luminosity classes V to III for the spectral classes B0 to B5, as shown for two wavelengths in Figure 10. A consistent result for stars 2 and 3 is reached only for luminosity class V, with a reddening of E(B-V) of 0.18. The galactic contribution, assumed to be 0.05 (Panagia et al 1987) can be seen in the figure as the steeper portion of the reddening line. While the intrinsic ultraviolet colors for stars come from a galactic sample and the metallicity of the LMC is lower, which may introduce some uncertainty, it appears that star 2 is a genuine B0V star, while star 3 may be slightly earlier than the B1.5V type derived by Gilmozzi et al (1987).

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 as modelled by Woosley et al. (1987). It is to the everlasting credit of the theorists that even when the IUE results appeared to show that the Sanduleak star might have survived, they adhered to their conviction that the progenitor of SN 1987A must have been just like that star! It is a satisfying outcome of the observational work that the star which disappeared in the star which exploded!

5. Circumstellar Matters

Blue supergiants like SK -69 202 often have low density, high velocity stellar winds, but IUE observations of SN 1987A show that this star had a dense circumstellar shell that resulted from an interesting stellar history. The weak radio emission from SN 1987A (Turtle et al 1987) was interpreted (Chevalier and Fransson 1987) as arising from a shock in the low density blue supergiant wind of SK -69 202. After 1987 May 24, the short wavelength IUE spectra began to show evidence for narrow emission lines, as shown in Figure 11. Here the flux from the two neighboring stars as observed in March 1987 has been subtracted from the subsequent spectra.

The observed lines include He II, C III, N III, N IV, N V and O III, and they increased in strength with time. 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 CNO-enriched composition of material that results from a massive star's mass loss (Chevalier 1987, Fransson et al 1989) and constrains the history of SK -69 202.

The excitation of this circumstellar shell results from 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 ($T > 10^5$ 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 was just the tail of this violent UV flash.

The observed UV flux from the circumstellar shell increasing with time until 400 days after the explosion, then began a symmetric decline, at least in some lines, as shown in Figure 12. A plausible geometrical picture for the fluorescent material is a shell at a distance of 200 light days from the supernova site. Light travel times are important in determining the observed flux, and this dimension of order 5 x 10^{17} cm is indicated by the duration of the increase. The spatial extent of this shell would be about one arc second, not measurable with IUE, but well within the reach of HST.

Because the flux increased, high dispersion IUE measurements of the circumstellar lines were possible. They remain unresolved at 30 km/sec resolution. 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 (Wampler and Richichi 1988). With the physical conditions reasonably well determined, the chemical abundances result from a nebular analysis. Fransson et al. find N/C = 7.8 +/- 4 and N/O = 1.6 +/- 0.8. These are respectively factors of 37 and 12 higher than the solar values, implying that the gas has undergone substantial CNO processing. To reveal CNO-processed material at the surface, the progenitor of SN 1987A is likely to have lost much of its hydrogen envelope before the explosion. This, and the existence of the shell, are consistent with models where a red supergiant evolves to the blue supergiant stage before exploding.

High nitrogen abundance was also found in the circumstellar matter of an earlier SN II with IUE (Fransson et al 1984). 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 for the 20 000 years before it exploded.

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, for example, by Saio, Kato, and Nomoto (1988). Key ingredients seem to be the lower heavy element abundance in the LMC, thorough mixing of hydrogen-burning products, and substantial mass loss as a red supergiant.

One prediction based on the presence of a circumstellar shell is that the rapidly expanding debris, moving at 1/10 c, will strike the shell, at 1/2 light year, in the next several 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 renewed nonthermal radio emission.

6. The Ultraviolet Echo?

The discovery of two echo rings in the optical (Crotts 1988, Rosa 1988, Heathcote et al 1988, and a third echo ring reported by Bond et al 1989) attributed to dust scattering of light from the supernova by matter in the LMC, has provided the opportunity for an interesting IUE investigation. In the optical, the rings reflect light from the optical maximum observed in May 1987. This is demonstrated by spectra of the rings taken in 1988, in which the light from the rings has the spectrum of the supernova in May, 1987. The expected UV ring would be the result of the UV maximum, the brief flash of UV emitted in the first hours of the event. This means that, if detected, the UV echo could provide direct information on the supernova spectrum at the time of shock breakout: the observations would show the properties of the supernova before discovery!

From an inspection of the optical images of the echo rings and a comparison with pre-SN images, the brightest patch of the inner ring was selected for the IUE observation (Gilmozzi 1989), since a simple calculation following Chevalier and Emmering (1988) shows that the UV echo should be just a few arcsec external to the optical ring. The ring was observed on 1 May 1988 with the long axis of the IUE aperture perpendicular to the ring, to obtain spatial information on the distribution of UV light. A second, longer exposure on May 25 confirms the presence of a weak UV signal, as illustrated in Figure 13. Although the feature near 1550 Å may be spurious, the rise around 1250Å is real.

No background star contamination is expected, since the slit location includes no stars brighter than 18 mag. The coincidence of the emission and the calculated position for the echo are consistent with the flux observed arising from a UV echo. However, there is still the possibility that the emission is due to diffuse matter scattering the light from nearby hot stars. They key test is to observe the same location in 1989: if the flux is still present, it is not due to the echo ring, which will have expanded to a larger diameter.

If the detected signal is the UV echo, the spatial extent of the emission (about 5 arc minutes) is a good measure of the thickness of the scattering cloud, since the UV emission is the echo of a very brief event (Chevalier and Emmering 1988). The derived cloud thickness is about 40 pc, which agrees well with the upper limit of 50 pc derived from the optical observations .

The flux from the UV echo, if confirmed, will also be instructive. If it is of the same order as the optical echo, this implies that the energy emitted in the UV represents about 10% of the total energy radiated by the supernova. Since the optical maximum lasted at least 100 times as long as the UV peak (two months compared to less than a day), and the scattering efficiency in the UV is about 10 times better (Chevalier and Emmering 1988), then equal observed fluxes would imply that the integrated UV luminosity was about 10% of the bolometric luminosity radiated near the SN peak. If this observation is confirmed, it provide a useful constraint on theoretical models of the outburst.

While the case is not yet proven, the IUE results provide the tantalizing possibility of detecting a signal which was emitted two days before the IUE first pointed at SN 1987A, and which may proved useful in understanding the physics of supernova explosions.

7. Future Observations of SN 1987A

IUE observations of SN 1987A in 1989 and beyond will depend on the behavior of the supernova, but will surely include a diligent monitoring of the UV spectrum, with the hope that the opaque atmosphere will begin to turn transparent and reveal the internal composition of the now-vanished Sanduleak -69 202. The changes in ionization of the circumstellar shell should provide a time-lapse view of the recombination of that gas, and an improved understanding of the physical setting for the emission. A carefully planned observation of the UV echo position should provide the decisive test for that possible observation.

Continued ultraviolet investigation of the supernova should continue with HST. Its powerful UV spectrometers will allow the interstellar medium near SN 1987A to be studied by looking in absorption at the nearby stars 2 and 3. The UV flux from the supernova itself will be safely resolved from those neighbors so it can be followed down to much fainter levels both in spectroscopic and photometric observations. The circumstellar shell that IUE detects spectroscopically should be a good target for HST imaging. While IUE observations of the debris from the supernova hitting the circumstellar shell would be interesting, it is reasonable to hope that when this event occurs in 1999 we will have another instrument to use! Finally, HST should be an effective tool for studying the expanding debris itself, and perhaps the pulsar within SN 1987A. Even though we can anticipate these desirable observations, the most intriguing possibilities may be the observations that we have not yet conceived. The ability to change the observing program, sometimes on short notice, in response to events in the LMC rather than constraints imposed from Earth, is an essential part of studying an evolving object.

The fact the target-of-opportunity proposals were in place, and that interested observers were ready to carry out a planned program of observation is only half the story of the UV observations of SN 1987A. The target-of-opportunity proposals focussed on the aspects of supernovae which had been important in previous investigations: the explosion physics and the chemical analysis of the debris. But astronomy is an observational science and the observed objects have rarely read the proposals. In the case of SN 1987A, the contributions of IUE turned out to be especially important in areas that were not anticipated, using the satellite in ways which were not customary. For example, the identification of the progenitor by using the astrometry and the imaging properties of IUE was a useful contribution that required novel use of IUE. Employing the FES as an accurate photometer was not anticipated, but new calibration methods make those measurements quite helpful. No one predicted that IUE short-wavelength observations of narrow emission lines from a fluorescent circumstellar shell would be a major constraint on the late stages of stellar evolution for the LMC supernova, but a careful background subtraction technique has made this a reality. While the jury is still out on the UV echo, there is a chance that the IUE observations may provide a glimpse of the supernova explosion's flux before it was discovered.

The key ingredient in the success of the IUE observations of SN 1987A has been the ability to modify the observing program in response to the behavior of the supernova. On the first day, this meant a rapid change in schedule and real-time adjustment of exposure times. Later, it implied changing the balance of long and short wavelength exposures, and combining shifts for very long exposures. For the echo observations, it required precise choice of dates of observation. In every case, the IUE Observatory has had the flexibility to accommodate these requirements, and a deeper understanding of this unique event has been the result.

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. We are especially grateful to the dedicated crews at Goddard and at VILSPA for their diligent cooperation in gathering the data, and to our many colleagues who cheerful changed their schedules so that we could make these once-in-a-lifetime observations. 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. Collaborators on these observations and their interpretation include Angelo Cassatella, Nino Panagia, George Sonneborn, and Willem Wamsteker. RPK's research on supernovae is supported by NASA grants NAG5-645 and NAG5-841, and by NSF grant AST85-16537.

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TABLE 1

VELOCITY STRUCTURE OF INTERSTELLAR SPECIES TOWARD SN 1987A

ION	MEAN HELIOCENTRIC VELOCITIES OF THE 10 INTERSTELLAR FEATURES (km s^{-1})[b]									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
C I	...	18	...	...	...	...	...	...	...	280
O I	nr	nr	nr	63	127	166	...	233	...	286
Mg I	−15	...	27	79	131	174	...	226	...	281
Cl I	...	11	...	...	...	...	...	...	...	276
Mg II	nr	nr	nr	nr	139	185	...	nr	nr	nr
Al II	...	11	...	67	123	166	...	221	...	270
Si II	...	16	...	67	126	168	...	228	...	285
S II	...	16	...	78	...	...	...	...	...	270
Cr II	...	...	25	...	...	...	...	231	...	292
Mn II	...	...	21	72	...	...	...	223	258	288
Ni II	...	15	...	72	...	167	...	228	...	288
Zn II	...	13	...	...	...	...	...	223	...	281
Fe II[a]	−19	18	...	72	126	170	...	219	261	288
Al III	...	16	...	69	...	...	213	...	...	279
Si IV	...	...	29	72	135:	...	196	...	...	281
C IV	...	14	...	63	...	...	209	...	...	280
C I*	...	...	27	...	...	...	...	...	273	...
C I**	...	16:	...	...	...	...	...	...	268	...
C II*	...	...	...	...	...	...	...	...	261	...
Si II*	...	...	...	...	...	...	...	...	262	...

[a] Details are given in Table 4.

[b] An "nr" means the line is present but not resolved.

TABLE 2

A SUMMARY OF THE Fe II INTERSTELLAR LINES TOWARD SN 1987A

ION	λ	HELIOCENTRIC VELOCITY (km s^{-1})[a]							
		(1)	(2)	(4)	(5)	(6)	(8)	(9)	(10)
Fe II	2599	−18	18	74	130	175	nr	nr	286
	2585	−17	19	73	127	172	221	257	294
	2382	nr	nr	71	126	171	nr	nr	nr
	2373	−4:	18	75	126	173	217	258	289
	2366	...	...	...	...	...	...	...	283
	2343	−18	21	72	127	167	220	267	295
	2260	...	23	...	...	...	...	...	288
	1611	...	15	...	...	...	...	...	283
	1608	−22	12	68	120	159	219	nr	282

NOTE.—The numbers in parentheses refer to nine of the 10 velocity features given in Table 1 (feature 3 is not included in this table). An "nr" means the line is present but not resolved.

Figure Legends

Figure 1: The rapidly changing LWP IUE spectrum of SN 1987A as observed in the first weeks after discovery.

Figure 2: Combined UV and optical spectrum for SN 1987A on 24 February 1987. Also shown are model spectra by Eastman and Kirshner (1989).

Figure 3: The short wavelength IUE light curve for SN 1987A. The precipitous decline observed in the first few days halted at the level contributed by stars 2 and 3, then increased slightly due to flux from the fluorescent echo of circumstellar matter.

Figure 4: The spectral history of SN 1987A in the IUE long wavelength region. Except for rapid evolution in the first week, the spectrum remained almost unchanged in the following year.

Figure 5: The long wavelength light curve of SN 1987A as observed with IUE.

Figure 6: An optical light curve for SN 1987A as observed with the Fine Error Sensor on IUE.

Figure 7: Detail of the late light curve for SN 1987A as observed with the Fine Error Sensor on IUE. The solid line indicates the decay energy of 0.07 solar masses of ^{56}Co. Note the recent levelling out which may indicate the onset of a new energy source.

Figure 8: Velocity profiles of the high ionization components for interstellar lines towards SN 1987A.

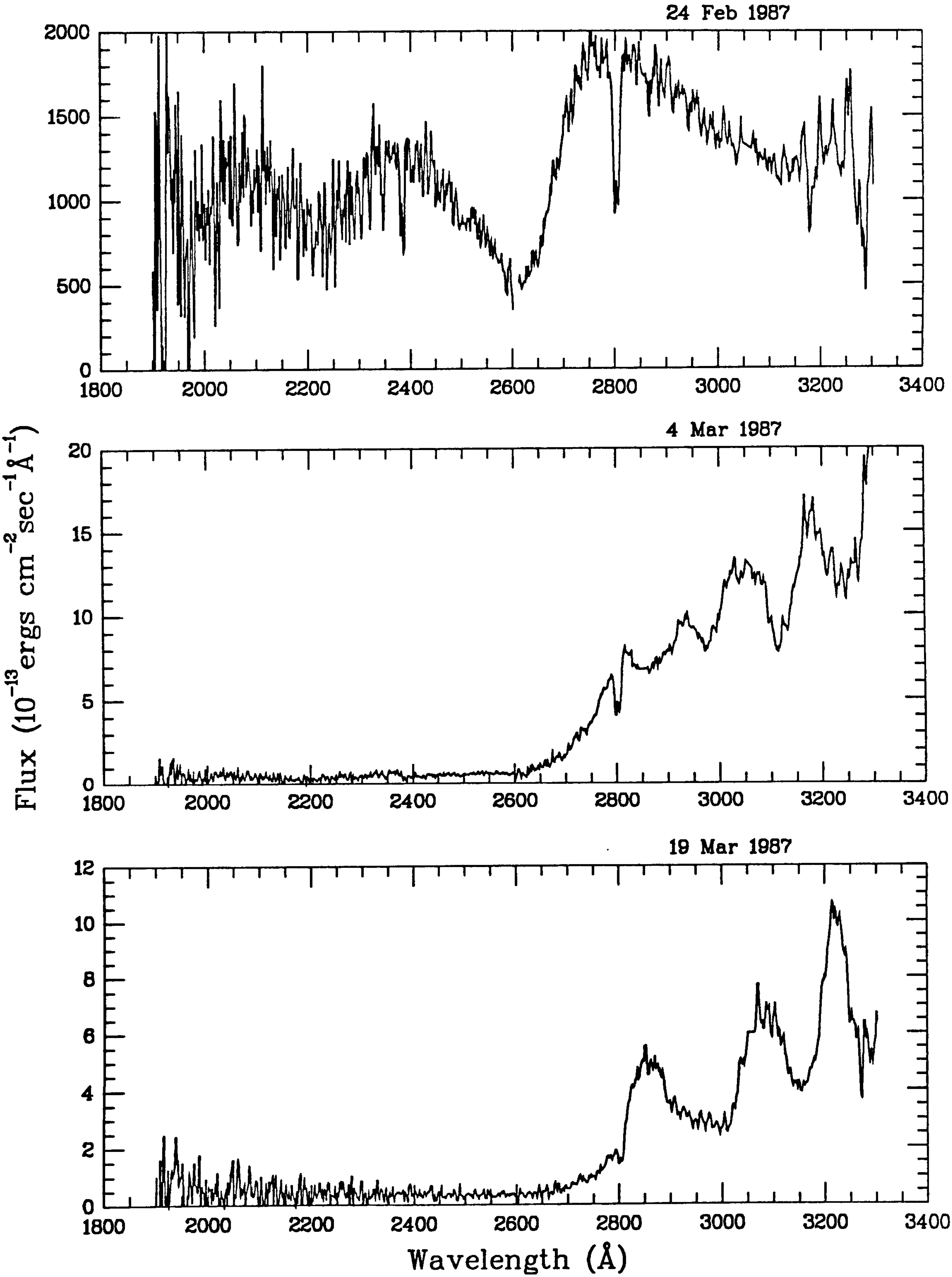
Figure 9: Composite line-by-line spectrum between 1210Å and 1510Å, obtained after the supernova had faded in this band. Two objects are present in the aperture (bottom). For comparison, the spectrum of a single point source is shown (top).

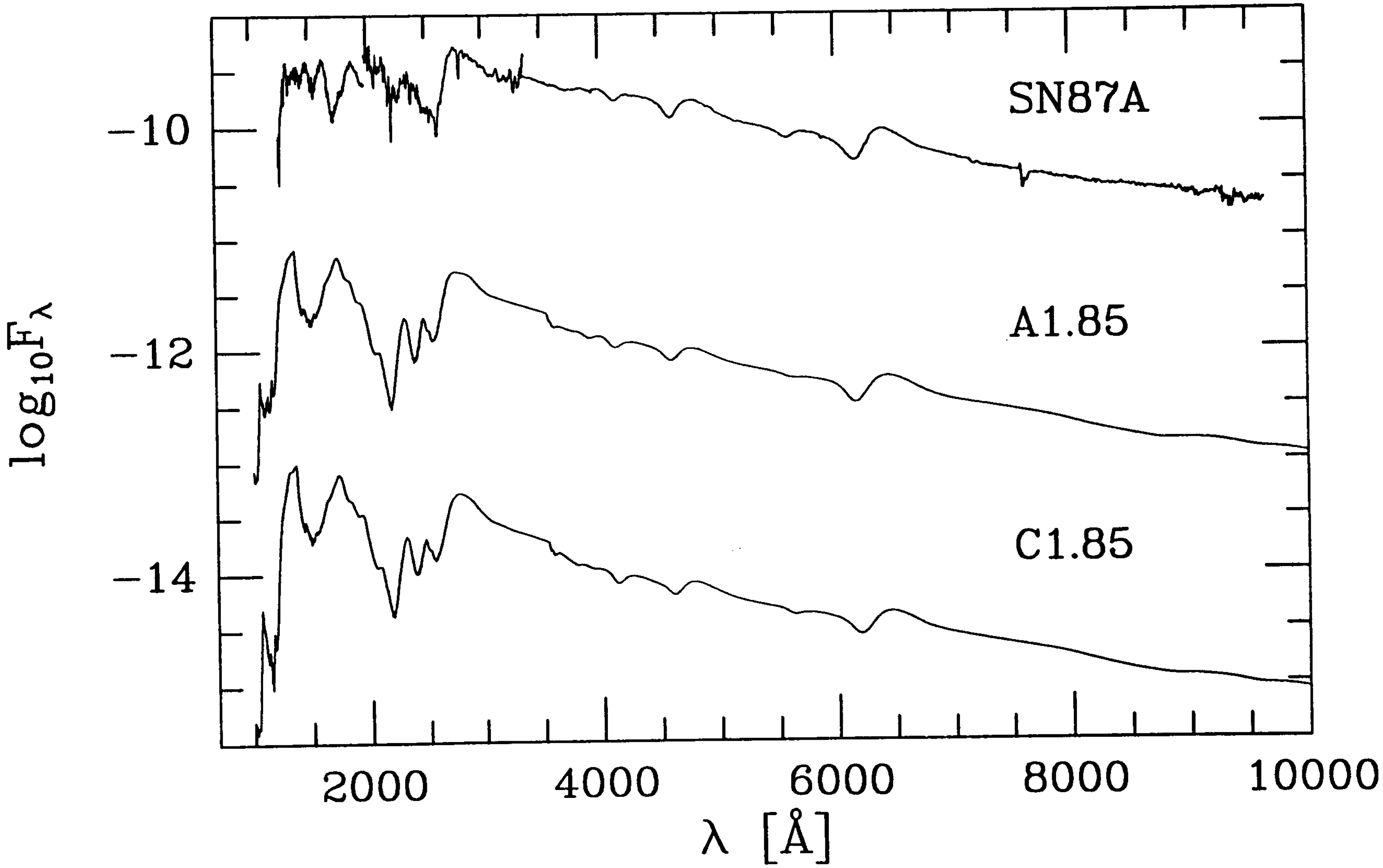
Figure 10: Ultraviolet color-magnitude diagram for stars 2 and 3..The rightmost dot for each star represents the observed values, while each successive dot represents a correction of 0.05 in E(B-V). The steeper correction corresponds to the galactic extinction law. A value E(B-V)= 0.18 is indicated as the simultaneous solution for both stars and both wavelengths.

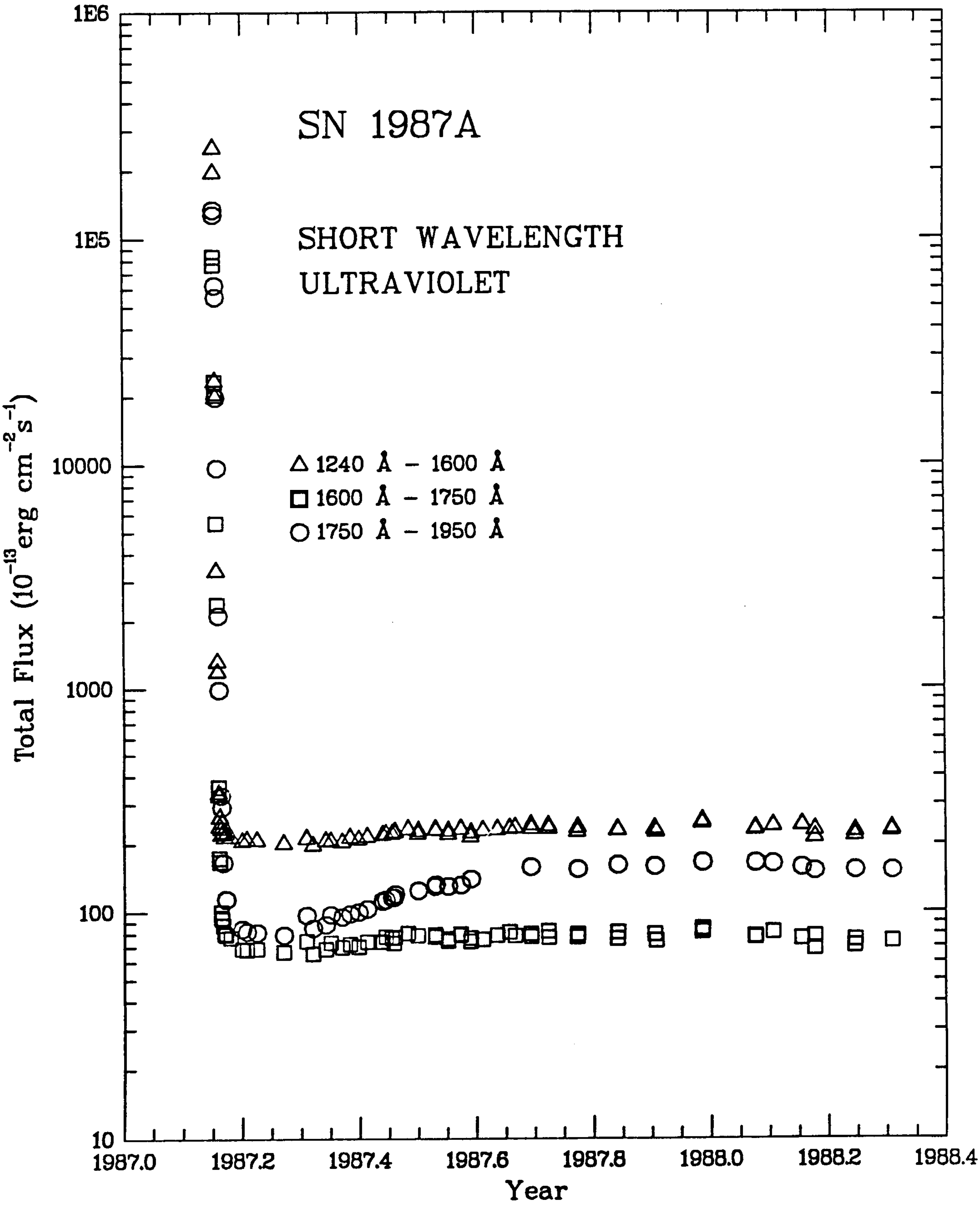
Figure 11: Averaged spectrum of the narrow emission lines from the circumstellar shell of SN 1987A. The spectrum of stars 2 and 3, as observed in March 1987 is subtracted from the subsequent spectra.

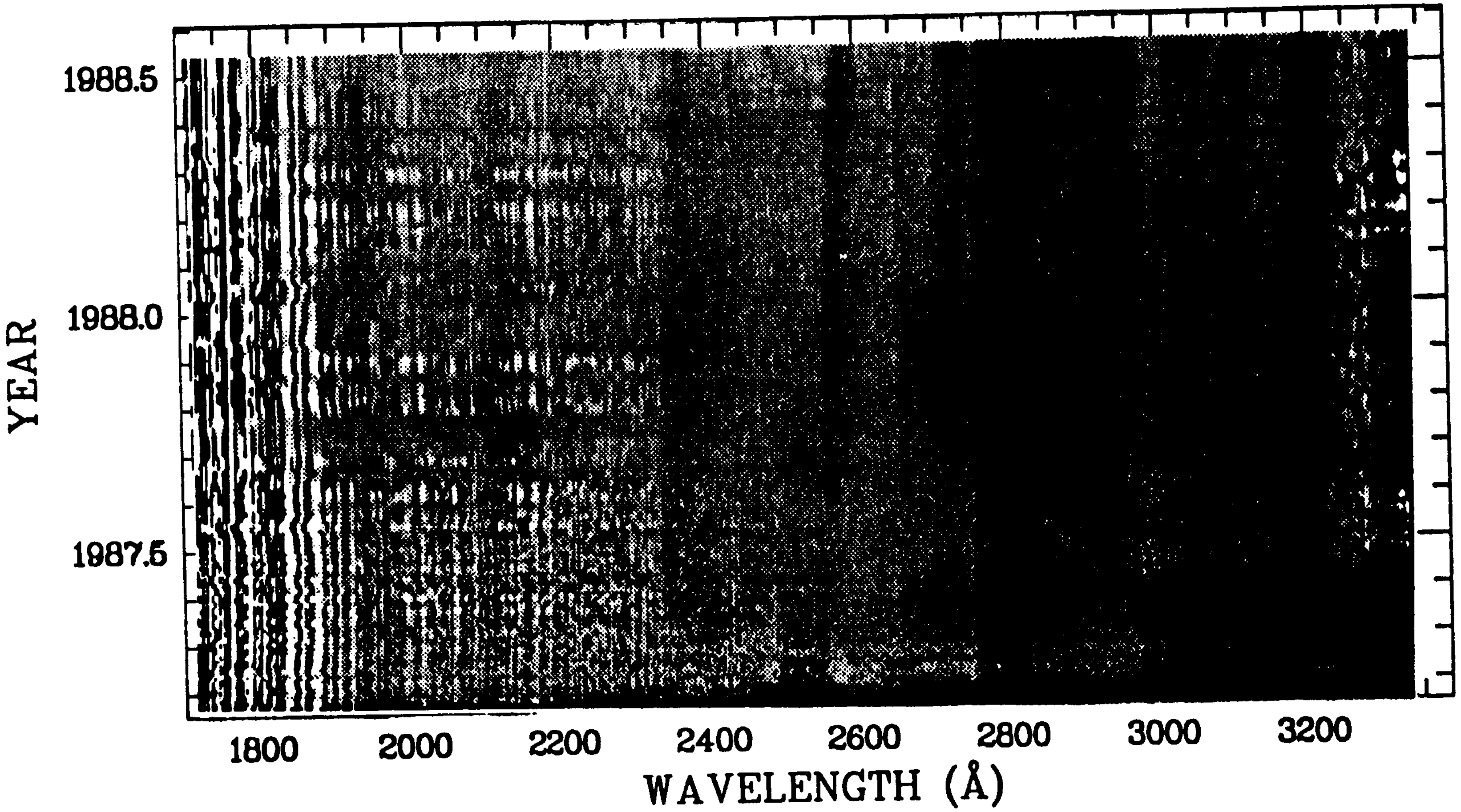
Figure 12: Flux measured in the N V emission line of the circumstellar shell. The increase to age 400 days is attributed to light travel time effects in a shell of dimension 200 light days.

Figure 13: A 12 hour SWP spectrum obtained at the predicted position of the UV echo on May 25, 1988.

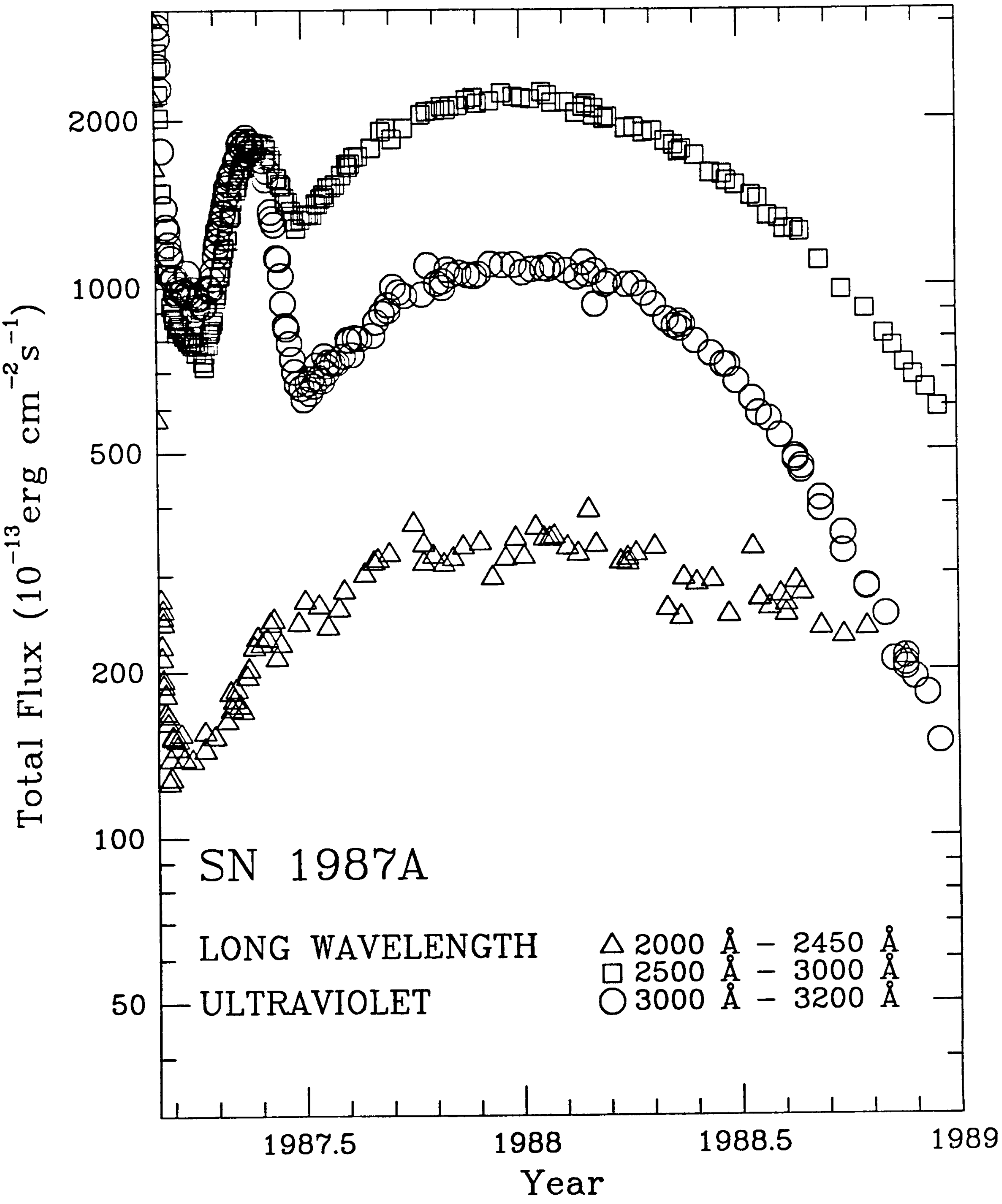

24 Feb 1987
2000
1500
1000
500
0
1800
2000
2200
2400
2600
2800
3000
3200
3400
4 Mar 1987
20
15
10
5
0
1800
2000
2200
2400
2600
2800
3000
3200
3400
19 Mar 1987
12
10
8
6
4
2
0
1800
2000
2200
2400
2600
2800
3000
3200
3400
Flux (10^{-13} ergs cm^{-2}sec^{-1}Å^{-1})
Wavelength (Å)


SN87A
A1.85
C1.85
−10
−12
−14
$\log_{10}F_\lambda$
2000
4000
6000
8000
10000
λ [Å]

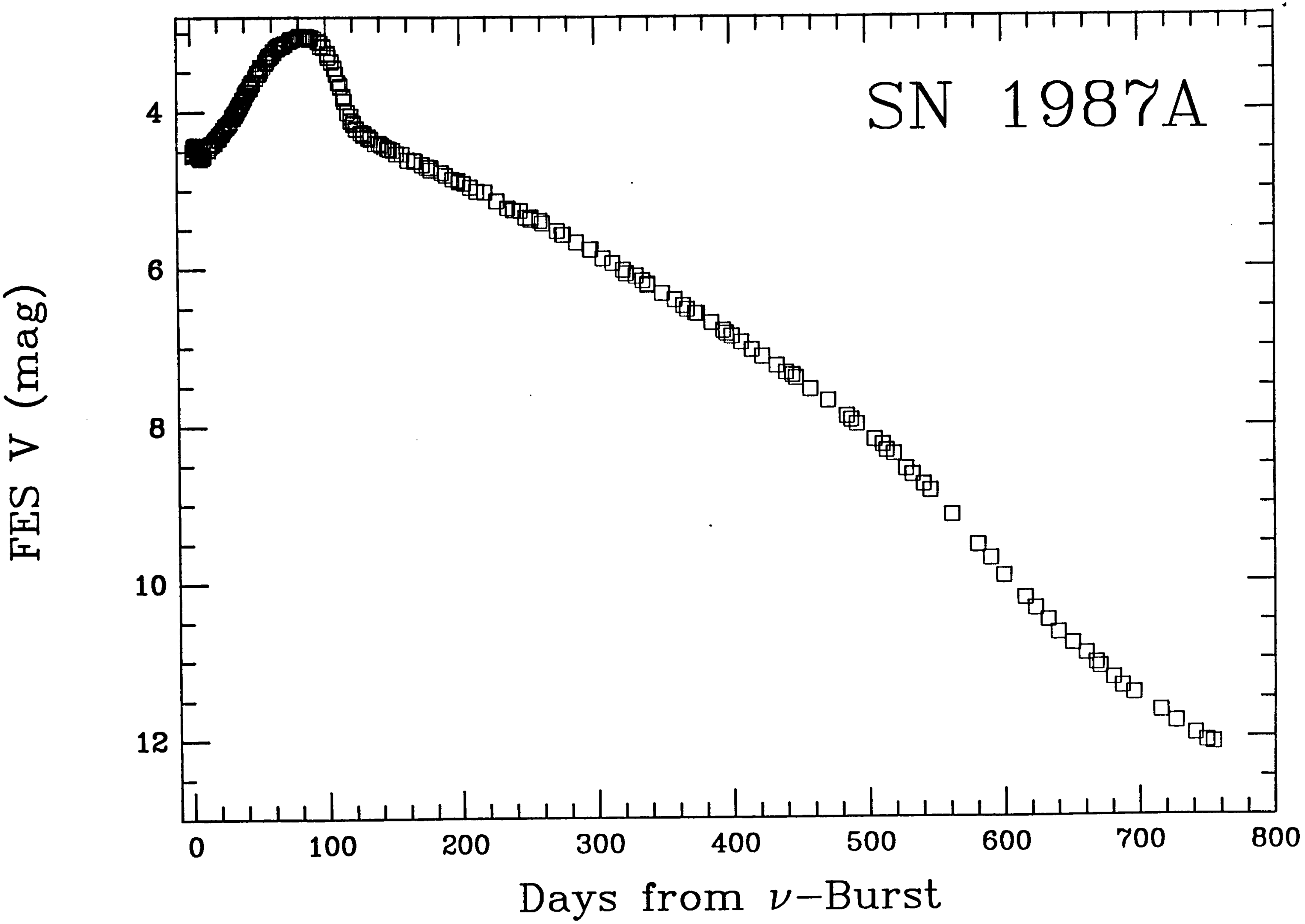
SN 1987A
SHORT WAVELENGTH
ULTRAVIOLET
△ 1240 Å – 1600 Å
□ 1600 Å – 1750 Å
○ 1750 Å – 1950 Å
Total Flux (10^{-13}erg cm^{-2}s^{-1})
Year
1E6
1E5
10000
1000
100
10
1987.0
1987.2
1987.4
1987.6
1987.8
1988.0
1988.2
1988.4

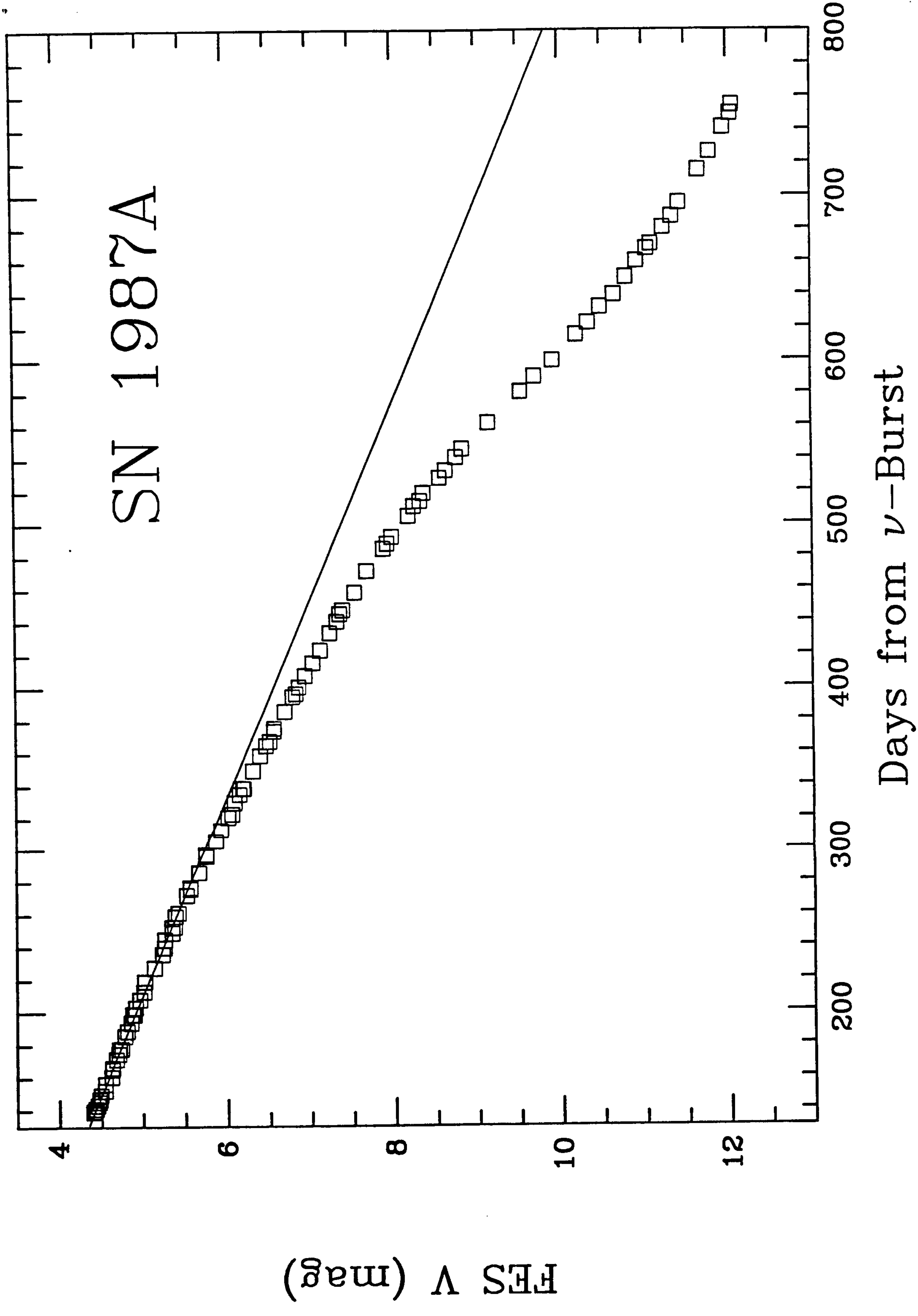

SN 1987A LONG WAVELENGTH

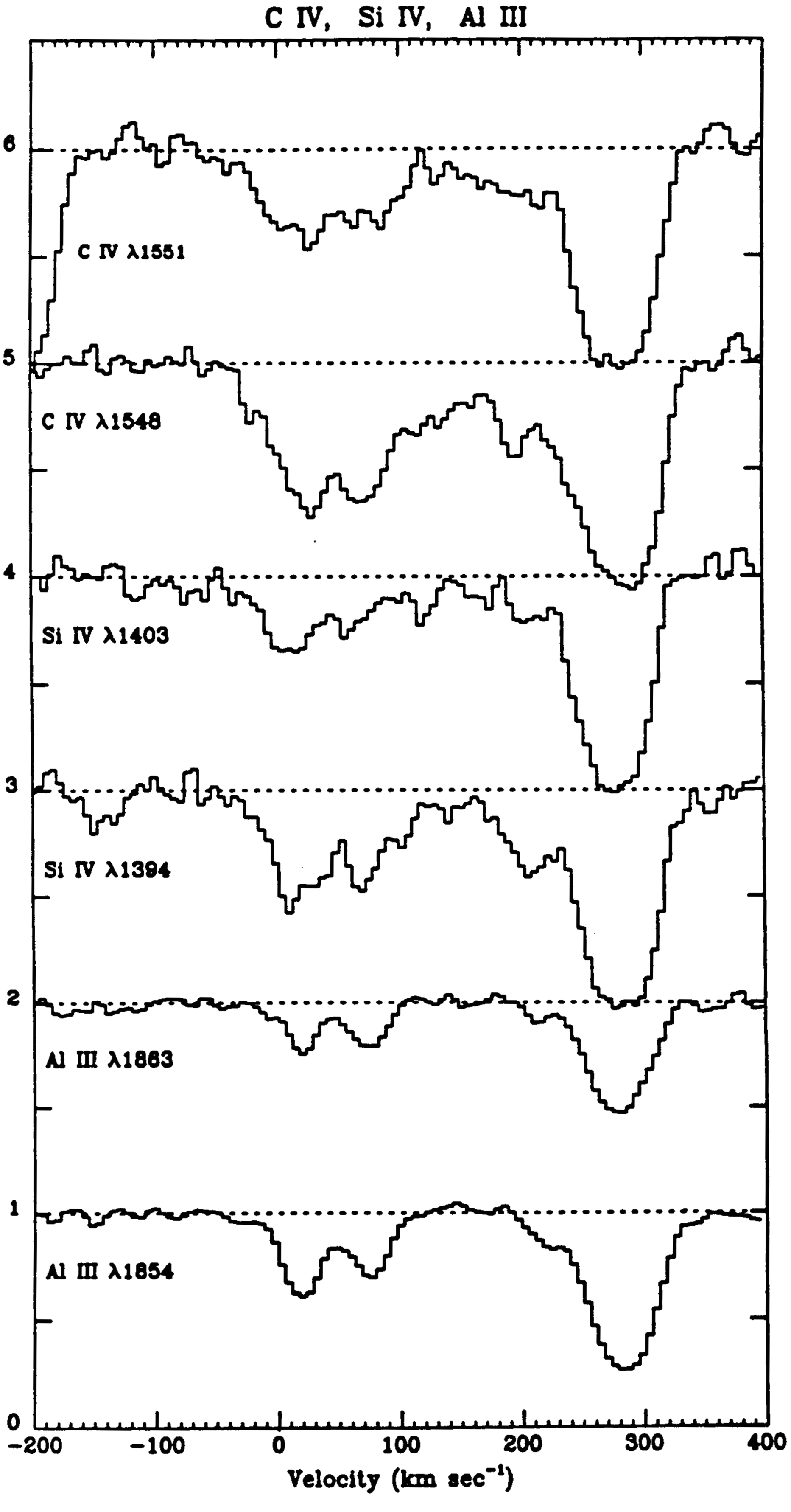
[redacted]



SN 1987A
LONG WAVELENGTH
ULTRAVIOLET
△ 2000 Å – 2450 Å
□ 2500 Å – 3000 Å
○ 3000 Å – 3200 Å
Total Flux (10^{-13} erg cm^{-2} s^{-1})
2000
1000
500
200
100
50
1987.5
1988
1988.5
1989
Year


SN 1987A
FES V (mag)
4
6
8
10
12
0
100
200
300
400
500
600
700
800
Days from ν–Burst


SN 1987A
FES V (mag)
4
6
8
10
12
Days from ν–Burst
200
300
400
500
600
700
800


C IV, Si IV, Al III
C IV λ1551
C IV λ1548
Si IV λ1403
Si IV λ1394
Al III λ1863
Al III λ1854
0
1
2
3
4
5
6
−200
−100
0
100
200
300
400
Velocity (km sec^{-1})

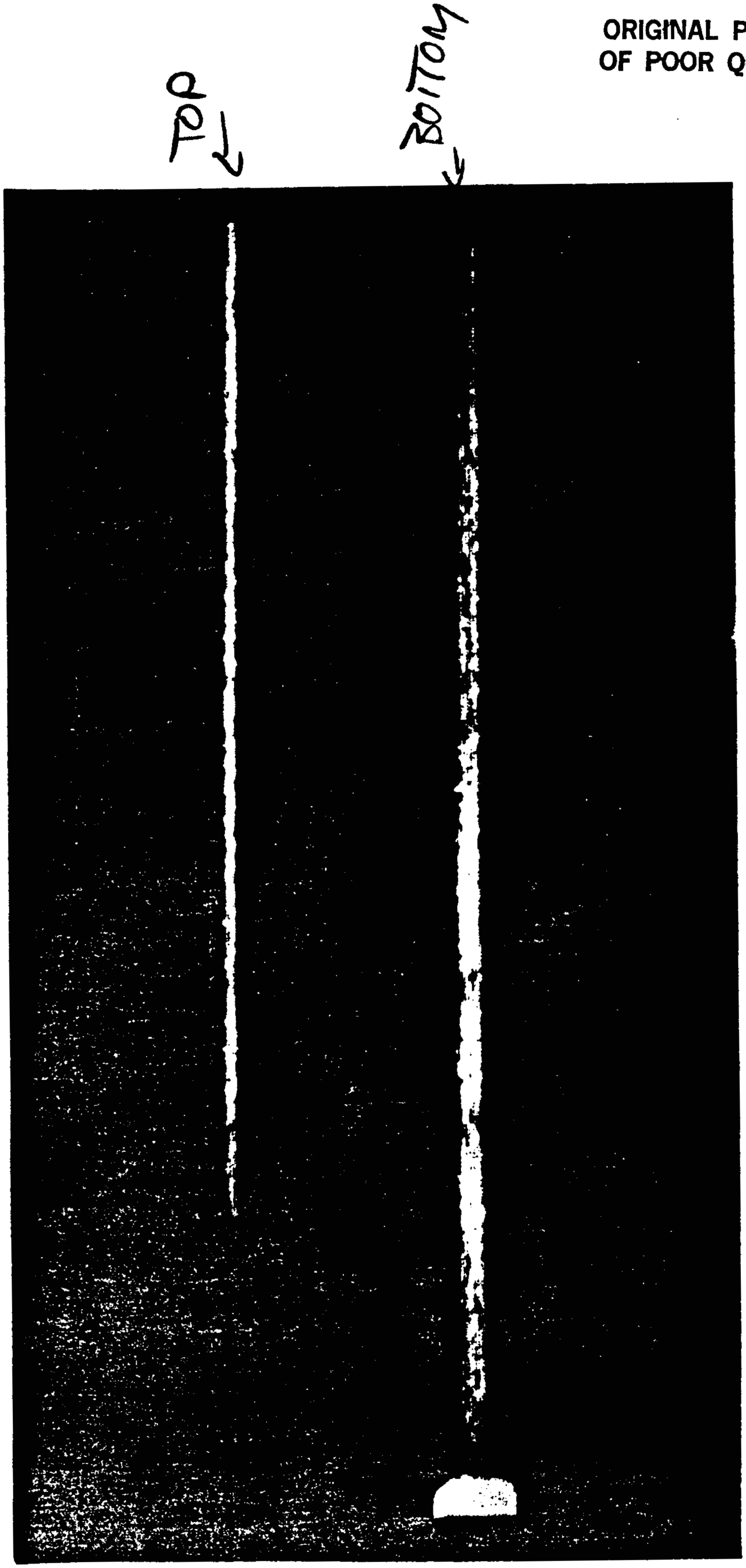
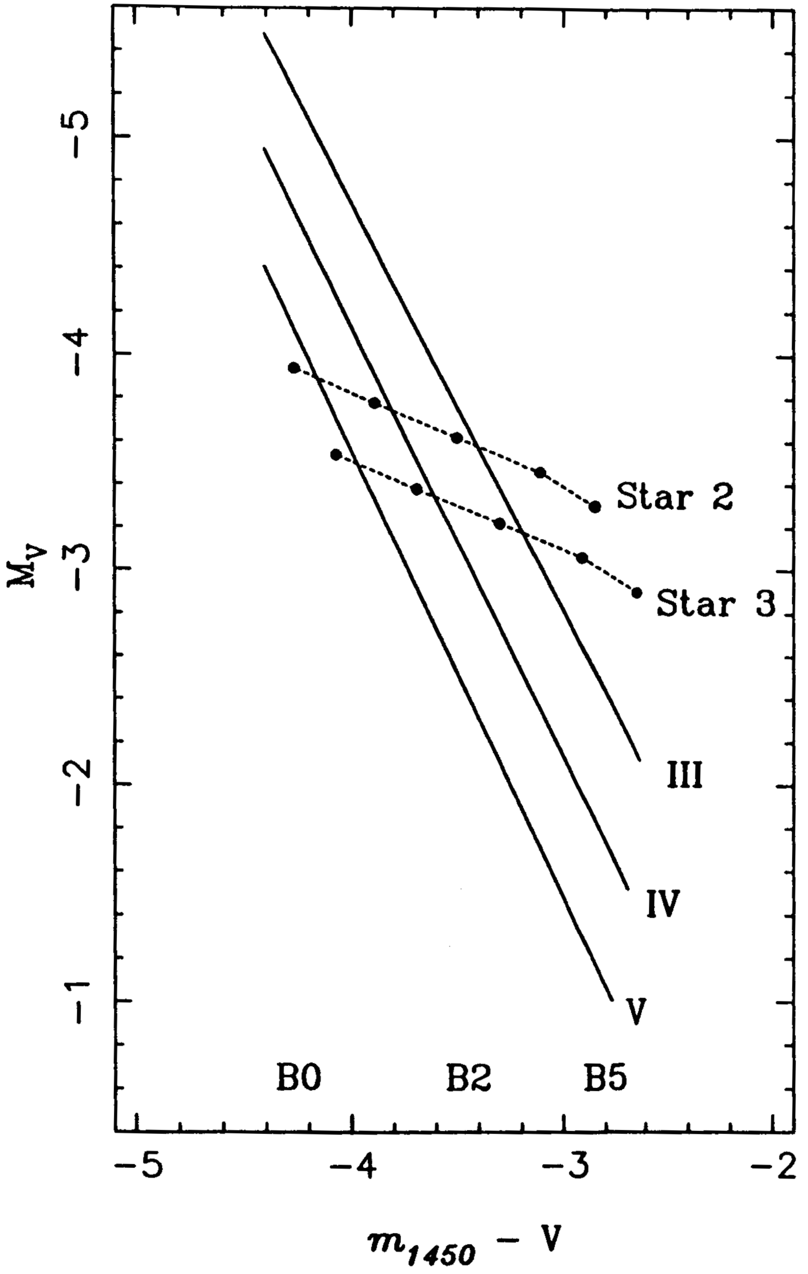
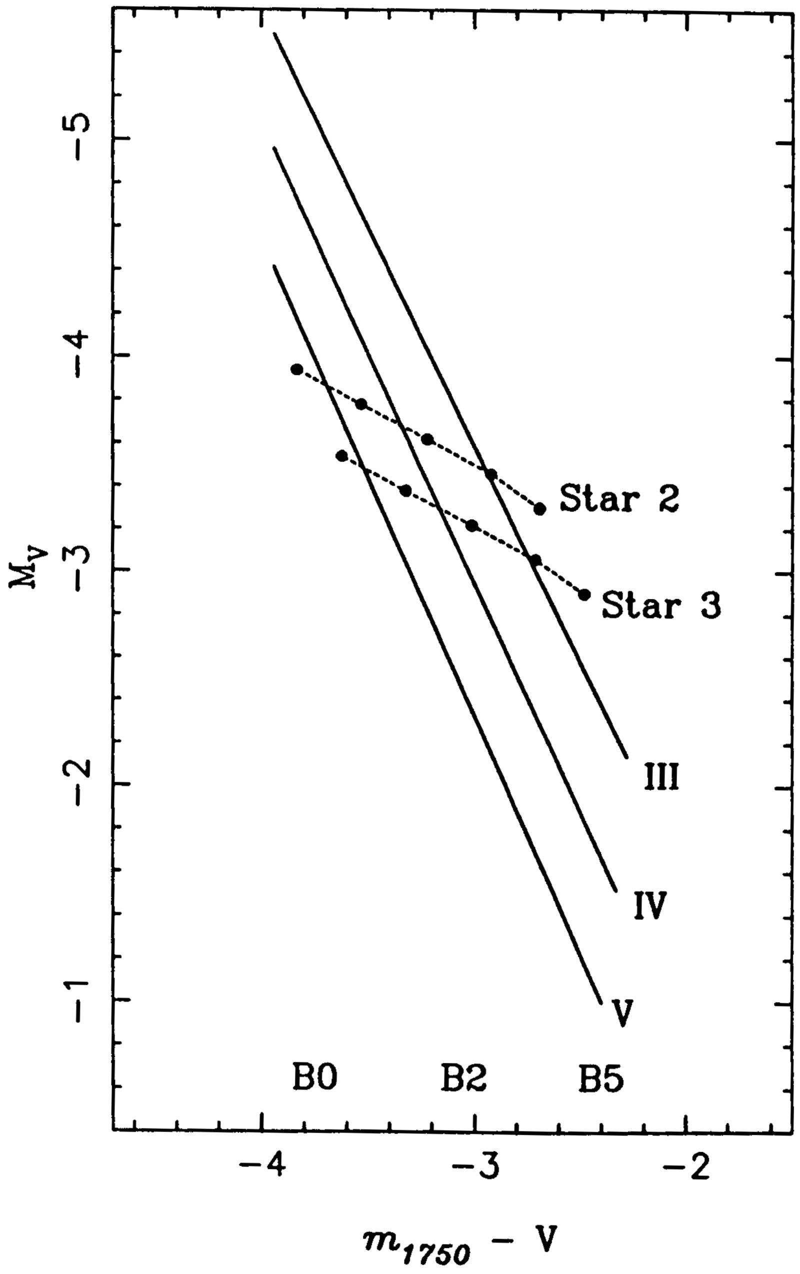
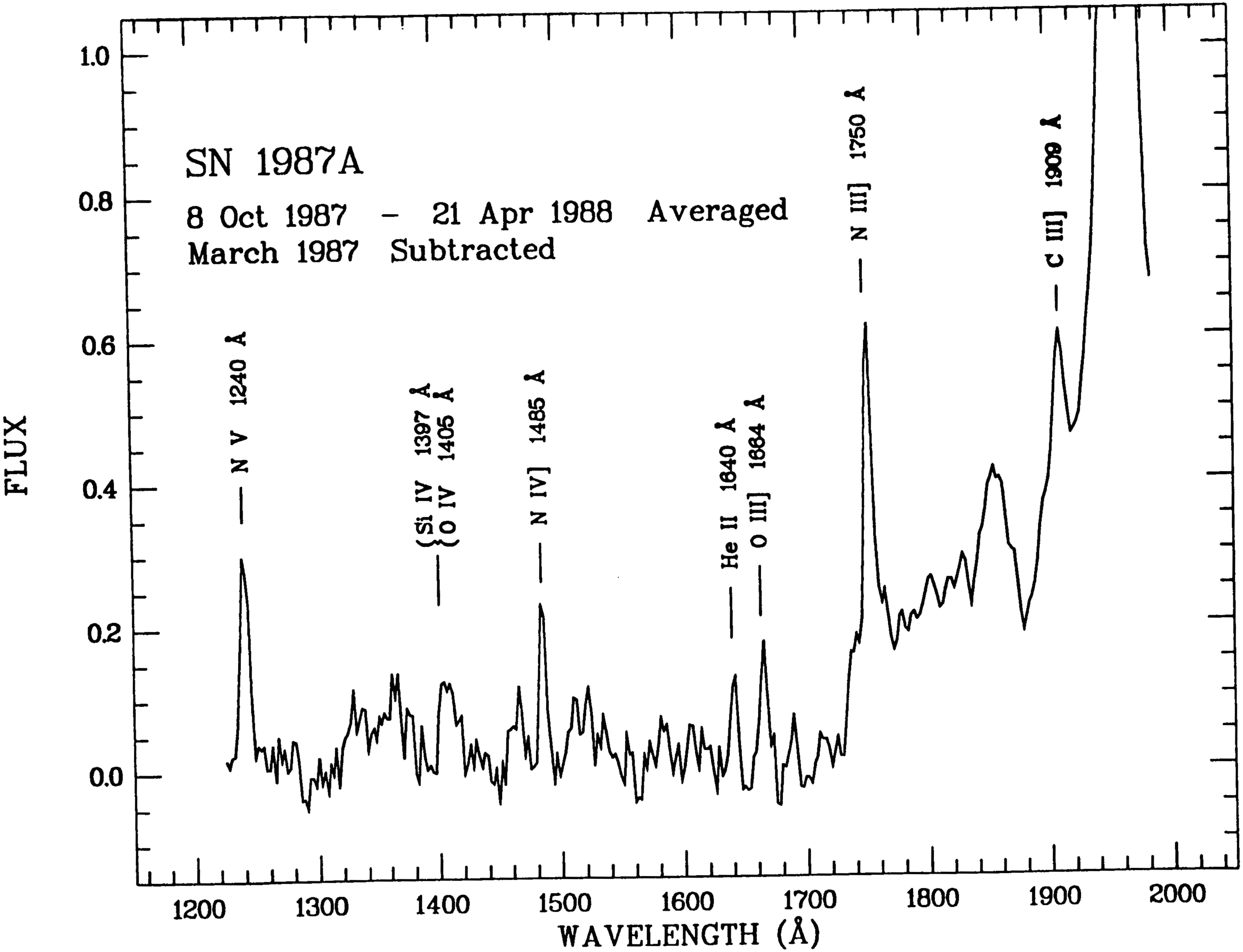
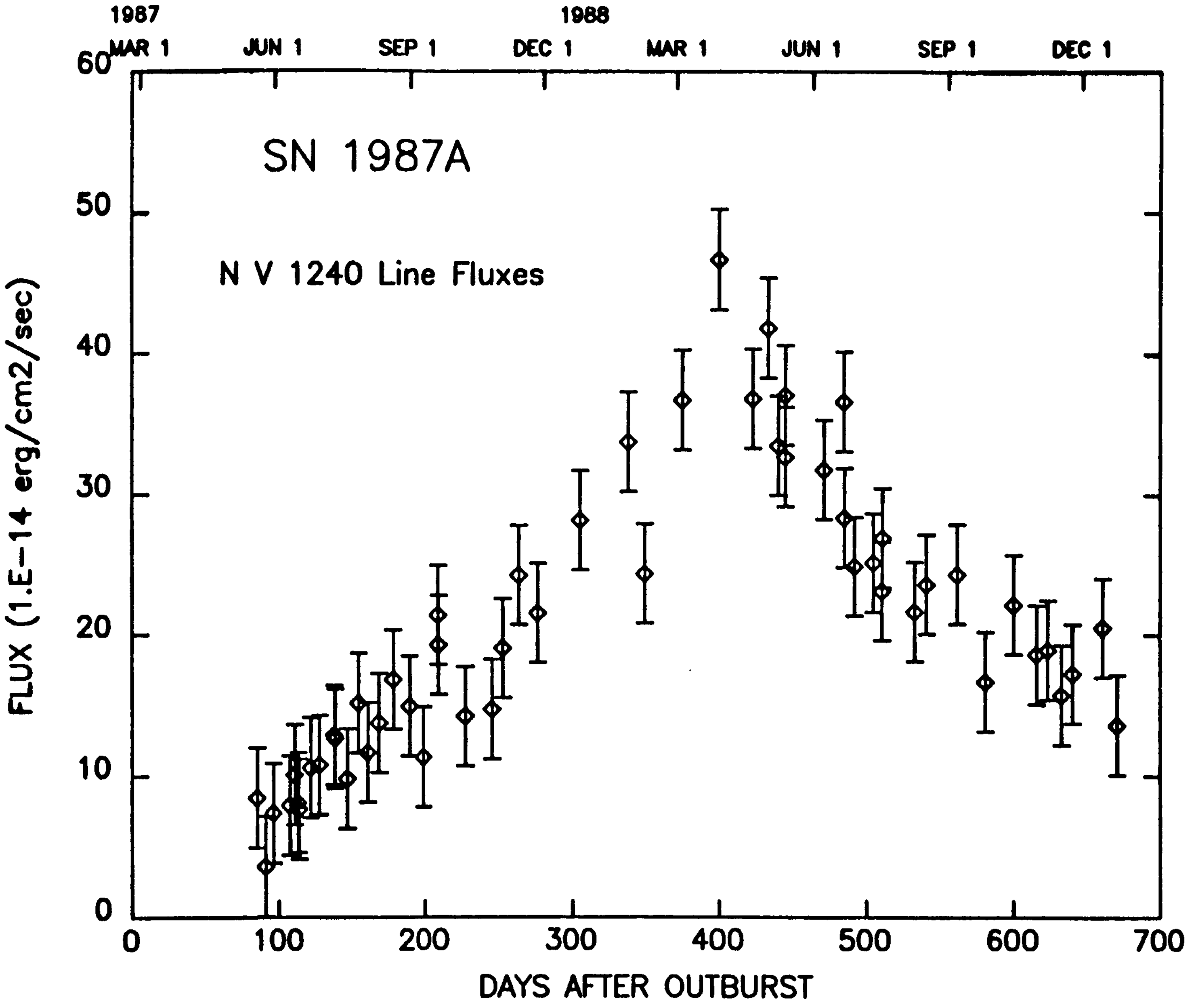


FIG 9


M_V
−5
−4
−3
−2
−1
Star 2
Star 3
III
IV
V
B0
B2
B5
−5
−4
−3
−2
m_1450 − V


M_V
−5
−4
−3
−2
−1
Star 2
Star 3
III
IV
V
B0
B2
B5
−4
−3
−2
m_1750 − V

SN 1987A
8 Oct 1987 – 21 Apr 1988 Averaged
March 1987 Subtracted
N V 1240 Å
Si IV 1397 Å
O IV 1405 Å
N IV] 1485 Å
He II 1640 Å
O III] 1664 Å
N III] 1750 Å
C III] 1909 Å
FLUX
1.0
0.8
0.6
0.4
0.2
0.0
1200
1300
1400
1500
1600
1700
1800
1900
2000
WAVELENGTH (Å)


SN 1987A
N V 1240 Line Fluxes
1987
1988
MAR 1
JUN 1
SEP 1
DEC 1
MAR 1
JUN 1
SEP 1
DEC 1
FLUX (1.E-14 erg/cm2/sec)
0
10
20
30
40
50
60
DAYS AFTER OUTBURST
0
100
200
300
400
500
600
700

swp 33643, sn1987a light echo, lo disp, lg aper, 870 min, 26 may '88
swp 33643 wave = sw ical = 3 exposure = 52200.0000 factor = 0.000
disp = lo aper = lg nspec = 0 rip = 0 bin = 2 smooth = 0
linad parameters : 37- 39/ 45: 67/ 73- 75