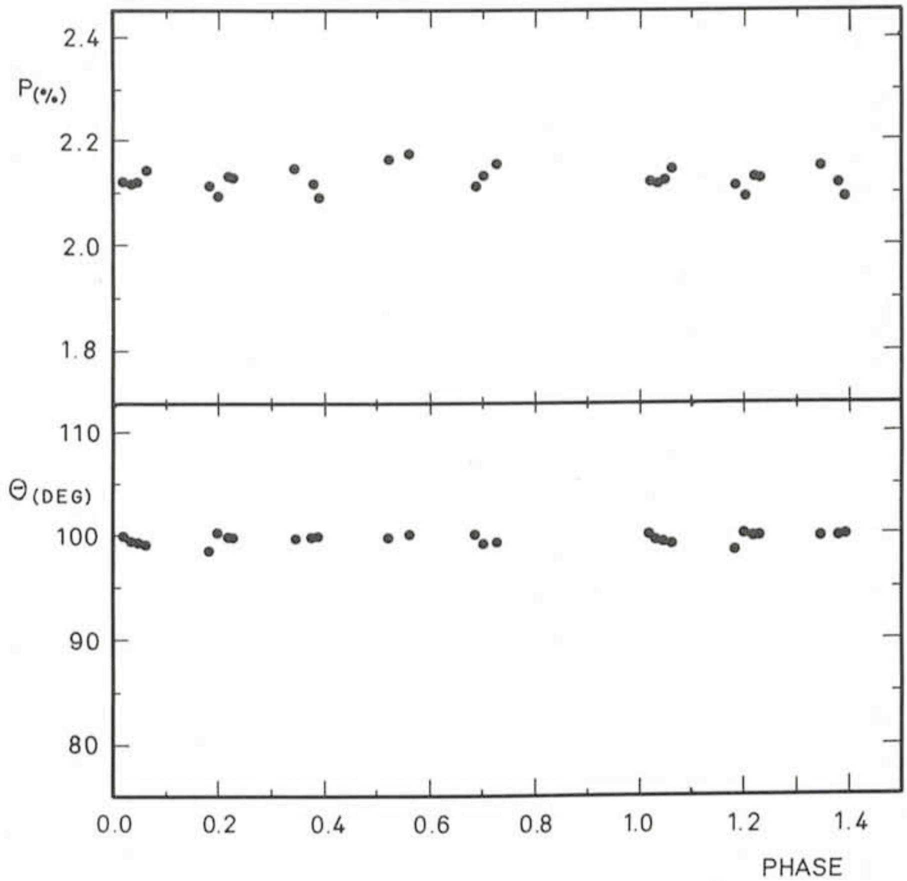

Figure 4: *P and θ versus orbital phase for the O3 V +O8 V binary HD 93205 (period 6.0810 d). Periastron passage occurs at phase 0.0 ± 0.1.*

system. These masses are in line with previous suspicions that the hotter WN stars tend to be less massive on the average than the cooler ones. In fact, HDE 311884 is the most massive known WR star. We will save deriving mass loss rates $\dot{M}$ for these stars until we have a more substantial data base with more stars.

For the sake of comparison, we show similar observations for a double O-type binary, HD 93205, in the central part of the bright Carina Nebula (cf. Conti and Walborn 1976). This system, of type O3 V + O8 V, with a period of 6.0810 d in an eccentric orbit (e = 0.49), contains the earliest main-sequence star known in a binary. It is of great importance to estimate its mass. Our results, shown as plots of P and θ versus spectroscopic orbital phase in Figure 4, were somewhat disappointing to say the least, since they failed to reveal a significant modulation. Contrast this with the WR binary HDE 311884 in Figure 3, of similar period and thus similar orbital separation! In retrospect however, it may not be too surprising that the amplitude of HD 93205 is so small, since O-type stars (even the hottest ones) especially near the main sequence, are known to have mass loss rates that are generally a factor $\gtrsim 10$ less than the mass loss rates of WR stars. Our polarization data here confirm this. Hence, the mass of the O3 V star must remain as a lower limit on the basis of the spectroscopic orbit: $M_{O3V}^{\times} \sin^3 i = 39\ M_{\odot}$.

Acknowledgements

We wish to congratulate K. Metz and his team for the fine work in constructing such a superb instrument. We are very grateful to ESO for observing time, and to the ESO mountain staff, especially our introducing astronomer Hugo Schwarz, for able assistance at the telescope and the reduction terminal. AFJM acknowledges financial support from the Natural Sciences and Engineering Research Council of Canada, WS from the Deutsche Forschungsgemeinschaft.

References

Brown, J.C., McLean, I.S. and Emslie, A.G.: 1978, *Astron. Astrophys.* **68,** 415.
Conti, P.S. and Walborn, N.R.: 1976, *Astrophys. J.* **207,** 502.
Drissen, L., Moffat, A.F.J., Bastien, P., Lamontagne, R. and Tapia, S.: 1986, *Astrophys. J.* **306,** 215.
Drissen, L., St-Louis, N., Moffat, A.F.J. and Bastien, P.: 1987, *Astrophys. J.* (in press).
Luna, H.C.: 1982, *Publ. Astron. Soc. Pacific* **94,** 695.
Luna, H.C.: 1985, *Revista Mexicana Astron. Astrofis.* **10,** 267.
Niemela, V.S.: 1987, priv. comm.
Niemela, V.S.: Conti, P.S. and Massey, P.: 1980, *Astrophys. J.* **241,** 1050.
Niemela, V.S. and Moffat, A.F.J.: 1982, *Astrophys. J.* **259,** 213.
Robert, C., Moffat, A.F.J., Bastien, P., St-Louis, N. and Drissen, L.: 1987 (in prep.).
Rudy, R.J. and Kemp, J.C.: 1978, *Astrophys. J.* **221,** 200.
Stahl, O., Buzzoni, B., Kraus, G., Schwarz, H., Metz, K. and Roth, M.: 1986, *The Messenger* **46,** 23.
St-Louis, N., Drissen, L., Moffat, A.F.J., Bastien, P. and Tapia, S.: 1987a, *Astrophys. J.* (in press).
St-Louis, N., Moffat, A.F.J., Drissen, L., Bastien, P. and Robert, C.: 1987b (in prep.).

HR 4049: an Old Low-Mass Star Disguised as a Young Massive Supergiant

C. WAELKENS, Astronomisch Instituut, Leuven, Belgium
H. LAMERS and R. WATERS, Space Research Laboratory, Utrecht, the Netherlands

Preface

Scientific collaborations can be triggered by fortuitous circumstances. The common project we report on here started in a bizarre way. Two of the authors (HL and CW) first met during a third-cycle course in Han-sur-Lesse in the south of Belgium, where HL was lecturing on mass loss in massive stars. During a conversation it turned out that we were both puzzled by results we had obtained on a southern late-B super-

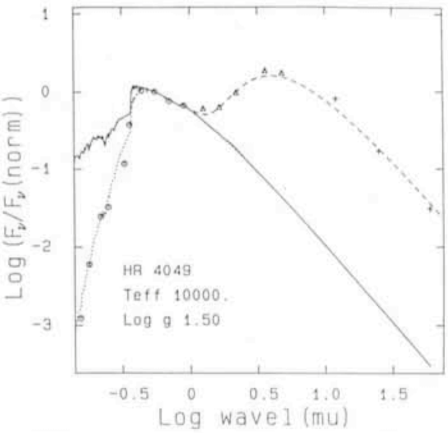

Figure 1: *Observed energy distribution of HR 4049 and model fit as described in the text.*

giant. HL was involved in a study of the most unusual UV deficit and IR excess of the object HR 4049 while CW had been monitoring for several years the large-amplitude and long-time-scale photometric variability of HD 89353. Knowing that there are approximately 9,000 stars in the Bright Star catalogue and 225,000 in the HD catalogue, and realizing that

$$4049/9120 \approx 89353/225000 \qquad (1)$$

we considered it probable that we were actually discussing the same object, but we had no Bright Star Catalogue at our disposal to check this conjecture. So, CW decided to drive back to his home institute in Leuven the same evening and could verify that the conjecture was true. That exciting moment was the beginning of a collaboration on HR 4049 and possibly similar stars, in which several colleagues have joined now. Eventually, we must confess that, two years later, equation (1) still led to about the only confirmed prediction we could make concerning our star: indeed, the star has yielded continuous surprises. But we always have our Bright Star Catalogue with us when we travel!

Energy Distribution of HR 4049

The fifth-magnitude star HR 4049 has been classified as B9.5 Ib–II. One may wonder how the peculiarity of such a bright object was noticed only now, after about one century of monitoring of the southern sky. The answer is that the exotic nature of some objects only becomes apparent from observations in space, at wavelengths outside the visual range. HR 4049 is in that respect a typical case. Although we shall see below that the visual behaviour is by no means normal, it is at shorter and longer wavelengths that HR 4049 most markedly revealed its peculiar nature. With respect to normal stars with the same spectral type, it is severely underluminous in the ultraviolet, and it presents an impressive excess in the infrared. It partly was the detection of this excess with the IRAS experiment that started interest in this star. Accordingly, UBV and near-IR observations were obtained at ESO, by Mario Perez. UV data were also available, as the star had been measured by both the S2/68 space experiment and the ANS Orbiting Ultraviolet Telescope.

The observed energy distribution of HR 4049 is plotted in Figure 1. The star is located at intermediate galactic latitude, so that interstellar reddening is small. Various determinations led to a most likely value for the reddening E (B–V) of 0.10 mag. This value is somewhat uncertain because of the colour variability (see below). However, the uncertainty does not affect the main conclusion, which is that the energy distribution of HR 4049 is characterized by three components:

(1) A model atmosphere flux with low gravity and a temperature of about 10^4 K (the continuous line on the figure). The visual energy distribution thus agrees well with the spectral type, so that it is not so surprising that the peculiarity of the object was not noted earlier.

(2) A circumstellar absorption component, which is very pronounced in the UV and which causes additional reddening of B–V by about 0.15 mag. Shortwards of 5000 Å the absorption scales as $1/\lambda$. The energy deficit with respect to the model atmosphere amounts to 5 mag at 1550 Å. Of course, adopting a lower temperature would lessen the deficiency. It is not possible, however, to account for the whole UV spectrum of HR 4049 by merely changing the effective temperature of the model. The $1/\lambda$ absorption law indicates that the size of the absorbers is smaller than about 500 Å.

(3) A circumstellar dust component which manifests itself through emission in the infrared. The excess flux can be represented accurately by a black-body spectrum with a temperature of 1250 K. From the flux at maximum of the excess it is found that the effective area of the IR source is 800 times as large as the stellar disk. A black-body is not the only possible model for the excess IR flux, but the order of magnitude of the temperature and size given here is realistic.

The Spectrum

The energy distribution of our star in the visual may be not markedly peculiar, but the spectrum surely is. The main criterion for classifying HR 4049 as B9.5 Ib–II was the appearance of the Balmer lines. However, H. Abt (see Morgan, 1984) found that the other spectral features do not fit the MK classification: while the narrow Balmer lines suggest an AOI-type, the Ca II lines are very weak for this type, the He I line at 4021 Å is absent, as are the expected lines of Fe II and Mg II.

We have obtained several coudé spectra of HR 4049 at ESO, using the 1.52-m and 1.4-m CAT telescopes. A 12 Å/mm spectrum in the range 3622–3900 Å is shown in Figure 2. The spectrum is remarkably regular and shows nothing but the Balmer lines from H9 to the Balmer limit. In fact, we had problems to convince some colleagues that we were showing them a stellar spectrum and not a hydrogen spectrum made in the laboratory! The last line of the series that can be identified is H30. Such a large number of Balmer lines is typical for low-density atmospheres and is the main reason for the classification of HR 4049 as a supergiant.

Describing the other characteristics of the visual spectrum is easy: it is essentially cataloguing lines that are absent.

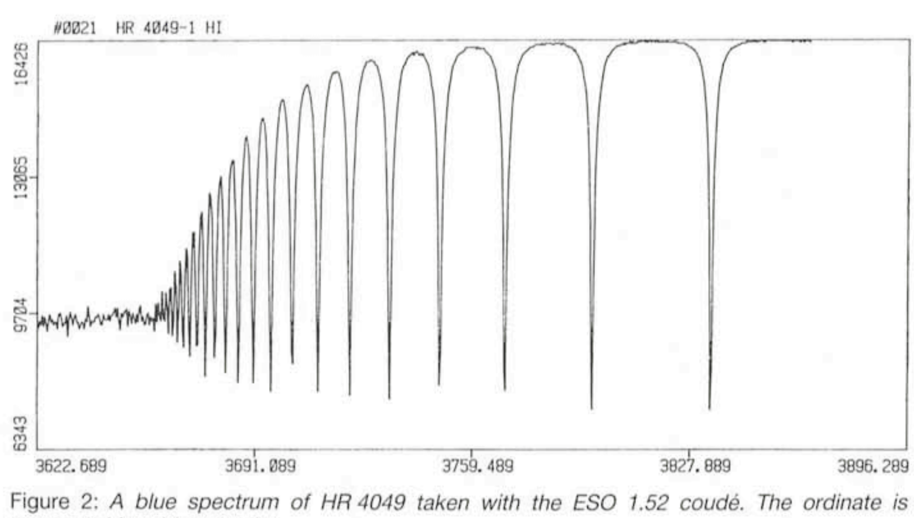

Figure 2: *A blue spectrum of HR 4049 taken with the ESO 1.52 coudé. The ordinate is expressed in arbitrary units.*

None of the stronger helium lines are seen, even at the high resolution of the CES. On our 12 Å/mm spectra there is no trace of lines of Mg II, Fe II, or Cr II, lines that tend to be prominent in early-A supergiants. Some weak features are present, however. The Ca II H and K lines and Na D lines show a weak stellar component, besides several interstellar ones. The most prominent lines besides the Balmer lines belong to neutral carbon. These lines, which arise from metastable levels with rather high excitation potential, imply a very strong overabundance of carbon. The only other lines we have identified are two weak lines of O I.

The difference between HR 4049 and normal early supergiants is still more prominent in the UV. An IUE low-resolution spectrum was kindly obtained for us by Dr. A. Cassatella from Vilspa in Madrid. Many spectral features are seen, but nothing in common with spectra of typical late-B or early-A-supergiants. Had we not seen the visual spectrum, where line identification is not so difficult, first, we would never have been able to interpret the IUE spectrum. But now it appears that almost all lines in the UV spectrum can be identified with C I or C II. So both the UV and the visual spectrum indicate that HR 4049 is a very metal-deficient star with a high C-abundance.

HR 4049 as a Post-AGB Star

Anticipating other observational results, we may already make a guess on the nature of our star. Unlike normal supergiants, it is certainly not a massive star. Massive stars are young and therefore metal-rich. Moreover, they tend to be confined to the galactic plane, near the place where they were born, while HR 4049 is located at a galactic latitude of 26°. The only known possibility for a low-mass star to appear with $T = 10^4$ K and a low gravity is the rapid transition in the upper part of the HR-diagram that a star undergoes when it has terminated its evolution as a red giant.

At the end of its evolution as a red giant – on the so-called asymptotic giant branch or AGB – a star less massive than five solar masses has a degenerated CO core and is burning helium and hydrogen in shells around the core. In its cool and tiny outer layers molecules and dust are formed. Because of instabilities in the envelope these outer layers are gradually expelled from the star and eventually decouple from it. As long as the energy production by H and He burning shells is not influenced by what is going on in the outer layers, the star evolves at constant luminosity. But it shrinks as the envelope mass decreases and so the surface temperature increases. The star thus evolves leftwards in the HR diagram, at a luminosity of 10^3 to 10^4 solar. Once the temperature exceeds about 25,000 K, the outcoming photons are energetic enough to ionize the ejecta that now form an ionized shell far from the star. This shell, having been invisible at visual wavelengths so far, now shines through emission lines: a planetary nebula is born.

How then does HR 4049 fit into this picture? The very low metallicity indicates that the star is an old object of initial mass less than a solar mass. The high carbon abundance is probably due to dredge-up processes as a result of thermonuclear flashes in the He-burning shell when the star was still on the AGB. The temperature of 10^4 K indicates that the star has left the AGB and evolves to higher effective temperatures. In fact, we can locate the position of HR 4049 on the calculated evolutionary tracks for post-AGB stars by Schönberner (1981) and thus derive its mass. From a study of the wings of the Balmer lines we found that the surface gravity of the star is 100 cm/s^2. Since the post-AGB stars have a unique relation between gravity and temperature on the one hand, and between mass and luminosity on the other hand, we can derive a mass of 0.544 $M_\odot$ from T and g, and a luminosity of 1.3 10^3 $L_\odot$ from this mass. The luminosity and the apparent visual magnitude indicate a distance of 400 pc. So, despite its original classification as a massive early-type supergiant, the star consistently turns out to be an old low-mass star!

Although we are confident that the post-AGB scenario applies for our star, several problems remain. First, it turns out that HR 4049 is abnormally bright in the visual, compared with other post-AGB stars. Usually the post-AGB stars are embedded in a thick dust cloud ejected on the AGB, and the ratio of visible to infrared luminosity is very small. In contrast, HR 4049 suffers only little extinction in the visual. Second, the dust temperature of 1,250 K is fairly high and seems to contradict the hypothesis that this dust was ejected on the AGB. If the dust was ejected on the AGB, it would have reached a distance of the order of 1 pc, and have a temperature close to 30 K.

The first problem is probably related to the low mass of the star. The duration of the transition from the AGB to the left of the HR diagram is a strongly decreasing function of mass. So the dust which was ejected during the AGB phase may now be at such a large distance that it hardly affects the visual luminosity. In fact, we are not at all sure that our star eventually will manage to become a planetary nebula. When the lowest-mass stars finally reach the 25,000 K temperature necessary for ionizing their circumstellar component, this component is already too far away and too dispersed to be seen as a planetary nebula. Interestingly, some excess flux at 100 micron was detected by IRAS: there is evidence that an additional cool dust component which no longer behaves as a point source is present. Probably, this component is the dust shell ejected on the AGB.

As for the second problem, the high temperature indicates that the dust which emits the bulk of the IR radiation is still relatively close to the star. Maybe it is presently formed by mass loss from the star. But what can be the physical cause of this mass loss?

Will Variability Provide the Key?

So far we did not focus on the other way our interest arose in HR 4049: the variability. The photometric variability was detected in the Bright Star survey that was carried out in the Geneva system with the Swiss telescope at La Silla. Thanks to the generous awarding of telescope time for this long project by Professor Rufener, the star has been monitored with Swiss precision continuously since late 1982. The visual-magnitude data are shown in Figure 3. HR 4049 stands out among variable

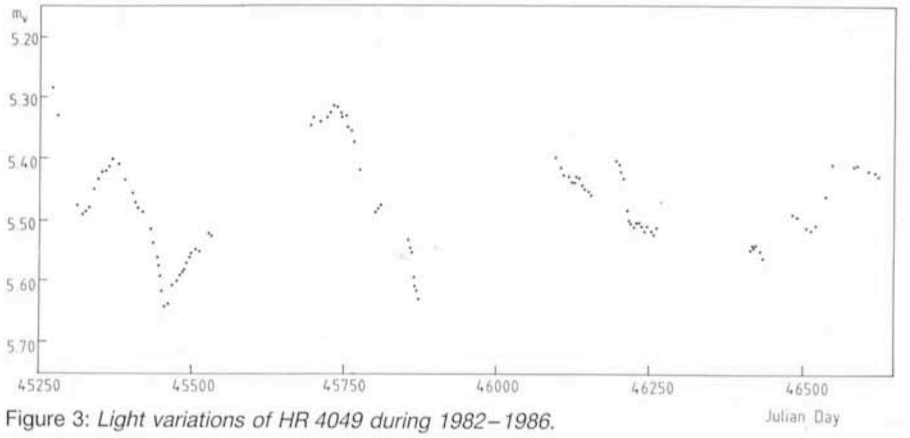

Figure 3: *Light variations of HR 4049 during 1982–1986.*

early supergiants by its large amplitude (up to 0.65 mag in U, 0.50 mag in B, and 0.35 mag in V) and its very long time scale (440 days). Since 1985 the star was also observed repeatedly in the infrared by ESO staff astronomer Thibaut Le Bertre. The variability is seen until 3.4 micron, where it amounts to 0.03 mag. Light curves are in phase over the whole spectral range observed. The amplitude roughly follows a $1/\lambda$ law.

It seems established that the variability is due to intrinsic variations of the underlying star, but what is going on is not clear at all. The period is much too long for radial pulsation, and colour variations are very large for nonradial pulsation. During the brightening of the star in early 1987 a series of high-resolution observations of the Hα-profile was obtained. There is a correlation between the photometric and spectral variability. The Balmer lines Hα and Hβ show (variable) emission components with central absorptions, and are best interpreted in terms of a decelerated outflow of mass from the star.

HR 4049 thus being a mass-losing variable star, it may indeed be that the dust envelope which is observed was not expelled during the AGB, but is of more recent origin. That could explain the high temperature of the dust and may be compatible with the faintness of the envelope relative to what is seen in candidate-proto-planetaries. This possibility raises the interesting questions whether other post-AGB stars also undergo a HR 4049-like phase, and, if so, how this phase does contribute to the planetary nebula.

More about the Dust of HR 4049

Unraveling the peculiarities of HR 4049 will need more observational efforts. These efforts may be rewarding in a broader scope than originally aimed at. As an example, it turns out that HR 4049 is a very interesting laboratory for the study of the interstellar medium. In general, interstellar dust contains various components which are not easily deconvolved. On the other hand, the composition of HR 4049 is so peculiar, that its dust may be expected to be peculiar as well. Indeed, although the UV deficiency of the object is extremely severe, there is no trace of the 2200 Å feature which is normally prominent in interstellar dust. On the other hand, the dust features at 7.4, 8.6, and 11.6 micron are clearly seen in the IRAS low-resolution spectrum. These last features have recently been attributed to the so-called "polycyclic aromatic hydrocarbons" or PAH's. The presence of PAH's in the dust of HR 4049 is not surprising, since hydrogen and carbon are so prominent; in fact the dust may be remarkably devoided of impurities. It is interesting to point out that the PAH's do not produce a significant 2200 Å absorption feature in the UV energy distribution of HR 4049. This supports the idea that PAH's are not responsible for the interstellar 2200 Å feature.

A Quest for Similar Objects

When an astronomer has encountered a strange object, he studies it, but also searches for other similar ones. If he is lucky enough and succeeds in finding a second one, he defines a class. Very soon, he has a class and some exceptions. That was also our experience. We think that it is probable that HR 4049 is related to some other supergiants with infrared excesses. Most of these stars are variable, many of them are high-latitude objects, some of them are metal-deficient. One of the most interesting stars in our sample may be the high-latitude ($b = 56°$) faint ($m_v = 8.8$) early-A supergiant HD 213985 (Waelkens et al., 1987). This star has an energy distribution not unlike that of HR 4049 and shows similar photometric variations; however, HD 213985 does not seem to present obvious spectral peculiarities. In fact, the more similar stars we find, the more pronounced does appear the peculiarity of HR 4049. So we found a class, but the exception is the very star we started with.

References

Morgan, W.W.: 1984, in "The MK Classification Process", Toronto, p. 18.

Schönberner, D.: 1981, *Astron. Astrophys.* **103,** 119.

Waelkens, C., Waters, L.B.F.M., Cassatella, A., Le Bertre, T., Lamers, H.J.G.L.M.: 1987, *Astron. Astrophys.*, in press.

Supernova 1987 A

A Summary of the ESO Workshop held from 6–8 July 1987

S. VAN DEN BERGH, Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, Victoria, Canada

This has been a really exciting meeting! Not only have we heard many new results, but it has also provided a fine example of how science should be done. In particular we had vigorous interplay between theory and observation, contributions from a variety of wavelength regions and intense international collaboration.

In his introductory paper West showed that astrometry of SN 1987A places this object within $\Delta\alpha.\cos\delta = 0\farcs00 \pm 0\farcs04$ and $\Delta\delta = -0\farcs04 \pm 0\farcs05$ of the star Sk −69°202. This close positional agreement, plus the disappearance of Sk −69°202 in recent IUE spectra (Gilmozzi, Kirshner) shows beyond reasonable doubt that the B3I star Sk −69°202 was the progenitor of SN 1987A.

Sk −69°202 (star 1) has close companions (White and Malin) with V = 15.3, d = 2″65 (star 2) and V = 15.7, d = 1″4 (star 3). The a priori joint probability that Sk −69°202 should have two such close companions is $\sim 10^{-5}$ i.e. it is virtually certain that Sk −69°202 was a member of a physical multiple system. Since members of such a system are coeval, the progenitor of SN 1987A must have had a larger mass than the relatively unevolved star number 2. Assuming this star to be a main sequence object its magnitude $M_V = -3.6$ places a lower limit of $\sim 10\ M_\odot$ on the main sequence mass of the supernova.

A pre-outburst objective prism spectrum of Sk −69°202 (Wamsteker et al.) shows that NII λ3995 was significantly stronger in the supernova progenitor than in the B3Ia star Sk −67°78. Furthermore Kudritzky reported finding that Sk −65°21 and Sk −68°41 have helium abundances (by number) $y = 0.35 \pm 0.05$ and $y = 0.23 \pm 0.05$, respectively. This high helium abundance shows that at least some LMC blue supergiants are highly evolved post red giant objects. This conclusion is greatly strengthened by Cassatella's recent IUE spectra of SN 1987A which show that [N/C] ~50 to