SN 1987A - Presupernova Evolution and the Progenitor Star

S. E. Woosley

Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064

Alexander Heger

Max Planck Institut für Astrophysik, D–85740 Garching, Germany

Thomas A. Weaver

General Studies Group, Physics Department, Lawrence Livermore National Laboratory, Livermore, CA 94550

Norbert Langer

Institut für Theoretische Physik und Astrophysik, Universität Potsdam, D–14415 Potsdam, Germany

Abstract. Ten years later, astronomers are still puzzled by the stellar evolution that produced SN 1987A — a blue supergiant. In single star models, the new OPAL opacities make blue solutions more difficult to achieve, though still possible for certain choices of convection physics. We also consider rotation, which has the desirable effect of producing large surface enhancements of nitrogen and helium, but the undesirable effect of increasing the helium-core mass at the expense of the envelope. The latter makes blue solutions more difficult. Still, we seek a model that occurs with high probability in the LMC and for which the time-scale for making the last transition from red to blue, ~20 000 years, has a physical interpretation — the Kelvin-Helmholtz time of the helium core. Single star models satisfy both criteria and might yet prove to be the correct explanation for Sk -69 202, provided new rotational or convection physics can simultaneously give a blue star and explain the ring structure. Some speculations on how this might be achieved are presented and some aspects of binary models briefly discussed.

1. Introduction

Following the explosion of SN 1987A, a large variety of models were proposed that sought to explain both the light curve and the identification of the presupernova star, Sk -69 202, a blue supergiant. Many of these fell by the wayside as more data were obtained and detailed models constructed. The idea of mass loss as the explanation of a blue star (e.g., Maeder 1987; Chevalier & Fransson

1987; Shigeyama et al. 1987) failed to explain the long delay before the second light peak and the slow velocity of the ejecta. SN 1987A, unlike SN 1993J, was not a Type IIb supernova. The suggested low metallicity of the LMC offered an explanation of why many blue supernova progenitors might exist (Shklovskii 1987; Truran & Weiss 1987; Arnett 1987; Hillebrandt et al. 1987), but, by itself, failed to explain the existence of a nitrogen rich circumstellar shell surrounding the supernova. This low velocity material was and still is taken as evidence that Sk -69 202 lived for a time as a red supergiant, making the (last) transition back to the blue just shortly, about 20,000 years, before its death.

More successful models considered some alteration to the physics of convective mixing, the dredge up of helium by rotation for example (Saio et al. 1988; Weiss et al. 1988; Wang 1991; Langer 1991, 1992), or altered convective mixing plus low metallicity (Woosley et al. 1988; Langer et al. 1989; Weiss 1989), or else invoked the effects of close binary membership on the late evolution (Podsiadlowski & Joss 1989; Barkat & Wheeler 1989; Hillebrandt & Meyer 1989; Chevalier & Soker 1989; de Loore & Vanbeveren 1992; Braun & Langer 1995). The rotational models (e.g., Saio et al.) suffered from an *ad hoc* prescription for the timing and extent of the mixing process, essentially substituting one puzzle for another (though, as we shall see later, they *may* have been essentially correct). The "restricted semiconvection" plus low metallicity models (e.g., Woosley et al. 1988) also employed several assumptions that have yet to be proven - that convection follows the Ledoux criterion more closely than the Schwartzschild and that the LMC is metal poor to the required extent (a factor of 3 or more in oxygen). But they were still regarded as successful until the complicated ring structure, revealed by Space Telescope, called all single star models into doubt. The binary star models suffered perhaps from a too great diversity of possible outcomes and the unavoidable conclusion that SN 1987A was an unusual event, even in the LMC.

Today, ten years later, we revisit this subject. Little has been learned about the (central) supernova itself that changes our views of the presupernova star. Its light has continued to decline at a steady rate and is currently powered by some combination of ^{44}Ti, a compact collapsed remnant, and circumstellar shock interaction, just as was expected. However, the discovery of the complicated double ring structure and the need to break spherical symmetry prior to the explosion shows that, at minimum, rotational effects must be included and, at a maximum, that SN 1987A was a consequence of binary merger. The latter possibility is discussed in detail elsewhere (and in this volume) by Podsiadlowski. Here we will concentrate on single star models. During the last ten years our understanding of stellar opacities also has improved. The new OPAL opacities (Iglesias & Rogers, 1996) are considerably different from what was used ten years ago and, as we shall see, this has important consequences for Sk -69 202. It has also become possible to include, in a preliminary way, the effects of rotation on massive stellar evolution and we do so for Sk -69 202 for the first time here.

We begin with a brief discussion of what causes a star to become a blue supergiant and then present new calculations of massive star evolution in the mass range 16 to 22 $M_{\odot}$. These are non-rotating models that employ either solar composition or a composition that might be appropriate to the LMC. The degree of semiconvection is varied, either reduced throughout the star's life or, for some cases (Table 2) only after hydrogen burning. There is no obvious need that the parameters of mixing should be exactly the same on the main sequence and during advanced burning stages. Both, red and blue solutions are obtained and discussed. Next, we consider the modification to these models caused by an appreciable amount of rotation. Rotation leads to mixing, especially in regions of large velocity shear like those at the boundaries of convective shells, and this changes the evolution. Velocity shear also leads to angular momentum transport which is followed in the calculations. For the most part, rotation suppresses the blue solution and makes it harder to understand SN 1987A. But in the conclusions, we discuss how additional angular momentum transport by magnetic fields might lead to the appreciable dredge up of helium into the envelope. This would help make the star blue and also explain large surface abundance enhancements in nitrogen.

2. Some generalities

It was agreed then and still is that the star that exploded, Sk -69 202, a B3 Ia supergiant, had a luminosity of $3 - 6 \times 10^{38}$ erg s^{-1} and a radius of $3 \pm 1 \times 10^{12}$ cm. The luminosity implies the helium-core mass was 6 $\pm$ 1 M$_\odot$, which if the effects of mass loss, rotation, and overshoot mixing are ignored, corresponds to a mass on the main sequence of 18 - 22 M$_\odot$. For a credible explosion kinetic energy, $1 - 2 \times 10^{51}$ erg, consistent with the velocity history observed for SN 1987A and the very early light curve, the star must also have had a hydrogen envelope mass around 10 M$_\odot$ in order that the secondary maximum of the light curve occurs at the right time (e.g., Woosley 1988). Certainly envelope masses below 5 and above 15 M$_\odot$ are excluded. Analysis of the neutrino signal gives a mass for the iron core that collapsed of 1.2 - 1.7 M$_\odot$ (e.g., Burrows 1988) which is reasonable for progenitor helium core masses around 6 M$_\odot$. The inner ring of slow moving nitrogen-rich material alluded to previously also implies that Sk -69 202 was a red supergiant for some time before making a transition to a blue star about 20,000 years prior to exploding. While a red supergiant, the star lost at least 0.045 M$_\odot$ (Lundquist & Fransson 1996) and perhaps as much as several M$_\odot$ (see elsewhere in these proceedings). The nitrogen enhancements observed in the inner ring are N/C $\approx$ 5.0 $\pm$ 2.0 (about 14 times solar) and N/O $\approx$ 1.1 $\pm$ 0.4 (about 10 times solar, Lundquist & Fransson 1996). The outer rings also appear to be nitrogen rich though less so by a factor of three indicating ejection at an earlier epoch (Panagia et al. 1996).

In general, increasing the helium core mass makes it harder to get a blue progenitor. Larger helium cores have larger luminosities to inflate their hydrogen envelopes. On the other hand a large envelope mass favors a blue solution. The hydrogen burning shell does not contribute appreciably to the presupernova luminosity, but its mass does add to gravity. Making the low density envelope rich in helium also helps to achieve a blue solution by reducing the opacity and increasing the mean molecular weight. The envelope will always be enriched in nitrogen and helium if the star has been a red supergiant with a deeply convective envelope, but this mixing can be amplified by rotational effects or perhaps in the common envelope stage of binary merger. Reducing the metallicity tends to produce a blue supergiant, both by reducing the envelope opacity and the efficiency of hydrogen shell burning by the CNO cycle shortly before the supernova. Obviously, raising the envelope opacity, e.g., because of new calculations of the relevant atomic physics, also tends to make a red star. Reduced semiconvection helps make a blue solution, in part by decreasing the gravitational potential at the hydrogen burning shell (Lauterborn et al. 1971) and by reducing the carbon-oxygen core mass developed by a helium core of given size.

One obvious consequence of these rules is that any process that tends to increase the helium-core mass relative to the hydrogen-envelope mass will tend to make a red supergiant. Examples of such processes are mass loss (short of removing the entire envelope) and rotation.

3. Computer Models: 16 - 22 $M_\odot$

We now present a series of model calculations to illustrate the range of outcomes one might expect for various assumptions regarding the composition, convection, and rotation. All models in Section 3.1 were calculated using the KEPLER computer code (Weaver, Zimmerman, & Woosley 1978) modified to use, on request, the new OPAL opacities (Iglesias & Rogers, 1996) and low-temperature opacities (Alexander & Fergusson, 1994).

Where a composition appropriate to the LMC was called for, we used 74.6% H, 25% He, 0.052% C, 0.012% N, 0.25%O, 0.056%Ne, and 0.08% Fe, all by mass. This is roughly a metallicity of 1/4 solar consistent with the sum of CNO being (0.30 ± 0.5)% in the inner ring around the supernova (Lundquist & Fransson 1996). Where used, *solar* abundances were from Anders & Grevesse (1989). The critical reaction rate for $^{12}C(\alpha,\gamma)^{16}O$ was taken equal to the Caughlan & Fowler (1988) value except where otherwise noted. Mass loss rates, where included, were from Nieuwenhuijzen et al. (1990) scaled by a factor $(Z_{surf}/Z_\odot)^{0.65}$ with $Z_{surf} \approx 5.6 \times 10^{-4}$ for the LMC models.

3.1. Non-rotating Models

Table 1 gives the results for a variety of stellar models. All of these models used "restricted semiconvection" in the sense of Woosley et al. (1988). That is the mixing criterion, while not quite Ledoux, did use a small value of semiconvective mixing coefficient, $\alpha = 10^{-4}$ throughout the evolution (here α is a multiplier on the diffusion coefficient used for transporting composition; $D_{semi} \approx \alpha D_{rad}$). This is to be contrasted with the standard value used e.g., in Woosley & Weaver (1995), of 0.1. We call the latter here "full semiconvection". If there is an entry for τ_{blue}, the star died with a surface temperature over 10,000 K and this was the time spent that way following the latest episode as a RSG. An accompanying entry for τ_{red} is then the time spent with surface temperature less than 5,000 K *prior to this last blue stage* or prior to the SN explosion, if there was no such blue stage. The lifetimes may sum to much less than the helium burning lifetime, about $0.5 - 1 \times 10^6$ yr in all cases, if the star experienced a blue loop or spent an extended period burning helium in the blue before becoming red.

We see that using the old opacities - the same as in the code ten years ago - blue solutions are still obtained for 18, 20, and 22 $M_\odot$ stars. The 18 $M_\odot$ model (for zero mass loss) is blue much too long before the explosion. The inner ring would be much farther out than observed. In the case of the 20 and 22

$M_\odot$ models evolved without mass loss, the final red state just before the last transition to the blue is short, a feature not emphasized in previous discussions. Each star actually spends several hundred thousand years as a RSG burning helium, but has an extended blue loop that "resets the clock" insofar as Table 1 is concerned. The short last red phase might eject as much as $\sim$0.1 $M_\odot$ which might be enough to explain the inner ring, or at least that position visible so far, but it is expected that the actual mass in the ring is much larger (McCray, these proceedings). The star most like the earlier calculations of Woosley and Weaver is the 22 $M_\odot$ model that includes mass loss (de Jager, Nieuwenhuijzen, & van der Hucht 1985). This loss suppresses the blue loop and the star spends most of its helium burning lifetime as a RSG then moves to the blue a proper 20,000 years before exploding. For the other models the implication of a previous RSG phase with lots of mass loss followed by a blue wind then a red wind then a blue wind have yet to be explored, but might be related to the complicated inner and outer ring structure.

Table 1. New models — no rotation

M ($M_\odot$)	$\dot{M}$	κ	τ_{red} (ky)	τ_{blue} (ky)	M_α ($M_\odot$)	M_{env} ($M_\odot$)	L_{38} erg/s	He_s	$^{14}N/^{12}C$ ($\odot$)	$^{14}N/^{16}O$ ($\odot$)	note
18	0	old	190	460	5.5	12.6	3.81	25	2.4	1.1	
18	0	OPAL	700	-	5.3	12.8	3.33	27	6.4	2.6	a
18	yes	OPAL	710	-	5.2	11.7	3.28	27	6.8	2.7	a
18	0	OPAL	640	25	5.5	12.6	3.91	25	3.6	1.5	c
18	acc	OPAL	690	-	5.3	14.9	4.05	27	5.5	2.4	d
18	0	OPAL	680	-	5.2	12.9	3.42	26	4.3	1.8	e
18	yes	OPAL	710	-	5.2	11.9	3.29	26	5.8	2.3	f
18	0	OPAL	700	-	5.3	12.8	3.34	25	3.8	1.6	g
20	0	old	50	30	6.5	13.6	5.12	25	2.6	1.2	b
20	0	OPAL	600	-	6.2	13.9	4.51	27	6.8	2.8	a
20	yes	OPAL	580	-	6.1	12.3	4.27	27	6.3	2.8	a
20	0	OPAL	560	-	6.4	13.7	4.63	26	4.1	1.8	a,c
22	0	old	40	12	7.4	14.7	6.52	25	2.8	1.3	b
22	yes	old	450	20	7.2	13.6	5.95	25	3.4	1.5	h
22	0	OPAL	540	-	7.1	15.0	5.87	28	7.3	3.0	a
22	yes	OPAL	520	-	6.9	13.0	5.47	28	7.6	3.1	a

[a] Spends entire post main sequence lifetime in the red.

[b] Extended blue loop after being red since hydrogen exhaustion.

[c] Metallicity divided by 5 in opacity routine only.

[d] Accretion of 2 $M_\odot$ at 3×10^{-6} $M_\odot$ y^{-1} during helium burning.

[e] $^{12}C(\alpha,\gamma)^{16}O$ rate times 1.7.

[f] Scale height in mixing length multiplied by 1.5.

[g] Scale height in mixing length multiplied by 2.5.

[h] de Jager, Nieuwenhuijzen, & van der Hucht (1985) mass loss rate; see also Chiosi & Maeder (1986)

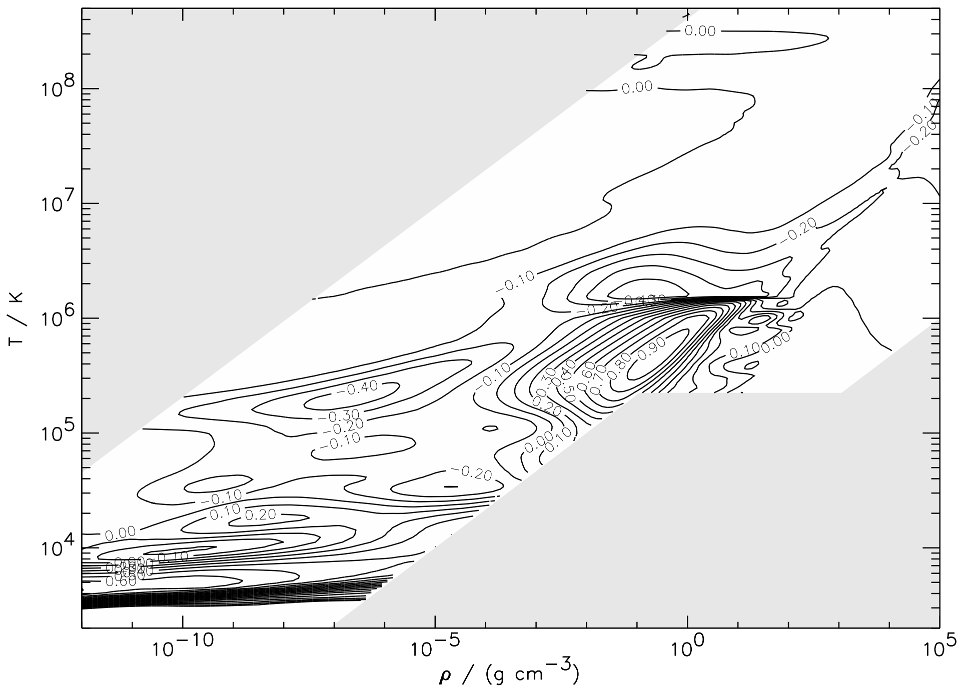

Figure 1. The logarithm of the ratio of the old opacities used in KEPLER to the new OPAL opacities.

Unfortunately though, the nitrogen enhancements in the outer atmospheres of all these models are too small to agree with observations of the circumstellar shell. But at least the stars are blue. Even this appealing trait is unfortunately lost with the new OPAL opacities (Table 1). Figure 1 shows the log of the ratio of the old opacities to the OPAL opacities. A substantial increase in opacity around 2 10^5 K, $\rho \approx 10^7$ g cm^{-3} due to iron has an important effect on the atmospheric structure. It would be nice to vary iron separately in the opacity calculation but, as it is, the opacity tables assume solar ratios and scale according to the total metallicity. In one case we decreased the metallicity passed to the opacity routine by an additional factor of 5, but did not change the abundances used for energy generation. This gave a very nice model at least with respect to red and blue lifetimes, but we do not believe the LMC is that metal poor. The calculation only indicates the sensitivity to the opacity. Another calculation that reduced the metallicity by only a factor of two (more than the assumed LMC value) stayed red.

We also experimented with mass accretion during core helium burning to investigate the effect of massive hydrogen envelopes. Interestingly, a model with a 15 $M_\odot$ envelope, all that the SN 1987A light curve would allow, stayed red (cf. Table 1). In our code at least, simply adding matter to the star does not necessarily make it turn blue. This constrains some varieties of binary models. We did not experiment with adding helium rich matter however.

Some binary models (Podsiadlowski, this volume) invoke "Case C" mass transfer after helium burning in order to provoke a common envelope merger just before the explosion. The timing of this late time expansion is also governed by the Kelvin-Helmholtz time-scale of the helium core — about 20,000 years — as in the single star case. In the models we calculated, though, this expansion was always very small (sometimes zero). The greatest expansion observed was for an 18 $M_\odot$ model having solar composition and restricted semiconvection, $\lesssim$40%. More typically the expansion was $\lesssim$10%. The necessary coincidence that this small expansion led to mass exchange would make such events rare. However, we have only calculated a limited number of models and the results are sensitive to the treatment of convection.

Table 2. Opal opacities - restricted semiconvection only for $\bar{A} \geq 4$

M ($M_\odot$)	$\dot{M}$	comp	τ_{red} (ky)	τ_{blue} (ky)	M_α ($M_\odot$)	M_{env} ($M_\odot$)	L_{38} erg/s	He_s (%)	note
16	0	LMC	60	95	4.2	11.9	2.72	25	
16	yes	LMC	100	85	4.2	11.5	2.61	25	
18	0	LMC	-	80	4.8	13.3	3.96	25	a
18	yes	LMC	100	35	4.8	12.7	3.79	25	
18	2x	LMC	75	45	4.7	12.4	3.59	25	
18	0	LMC	-	-	5.0	13.1	4.16	25	b
18	yes	solar	450	-	4.7	11.3	3.76	36	c
18	yes	solar	1000	-	5.2	8.7	4.80	37	c,d
19	yes	LMC	-	50	5.3	13.3	4.37	25	a
20	0	LMC	30	20	5.7	14.4	5.40	25	
20	yes	LMC	50	7	5.7	13.7	5.15	26	

[a] Surface T drops below 10,000 K, but the star moves back to blue very quickly

[b] Old opacities. Surface T has a dip at the end of central He burning but never drops below 10,000 K.

[c] Star does not get blue before supernova occurs

[d] Semiconvective mixing parameter 0.1 rather than 10^{-4} even after hydrogen burning.

We also experimented with the convection prescription. The uncertainty regarding semiconvection is such that there is no compelling reason that the multiplier on the diffusion coefficient should be the same on the main sequence and during advanced stages. We calculated a series of models in which reduced semiconvection was only employed in regions where the mean atomic weight $\bar{A} \geq 4$. The results were appreciably different from the α = constant cases. Table 2 summarizes the results.

Even using the OPAL opacities there are now a number of blue solutions and some of these, e.g., the 18 $M_\odot$ models, are red for a long time moving to the blue only at the end. The low surface abundance enhancements of nitrogen remain of some concern however. Only the solar metallicity models had sufficiently

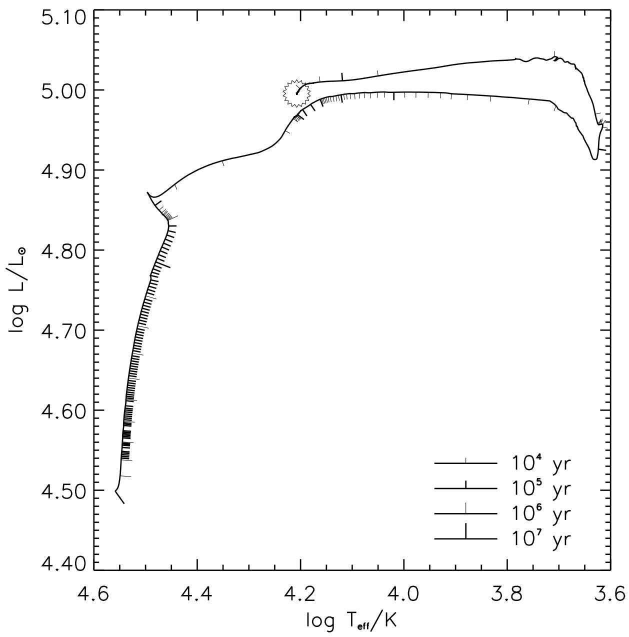

Figure 2. The HR-diagram for an 18 $M_\odot$ star evolved using OPAL opacities and restricted semiconvection only for $\bar{A} \geq 4$. The toothed circle marks the position in the HRD where the star would explode as SN. It spends its last $\approx$35,000 yr as a blue supergiant.

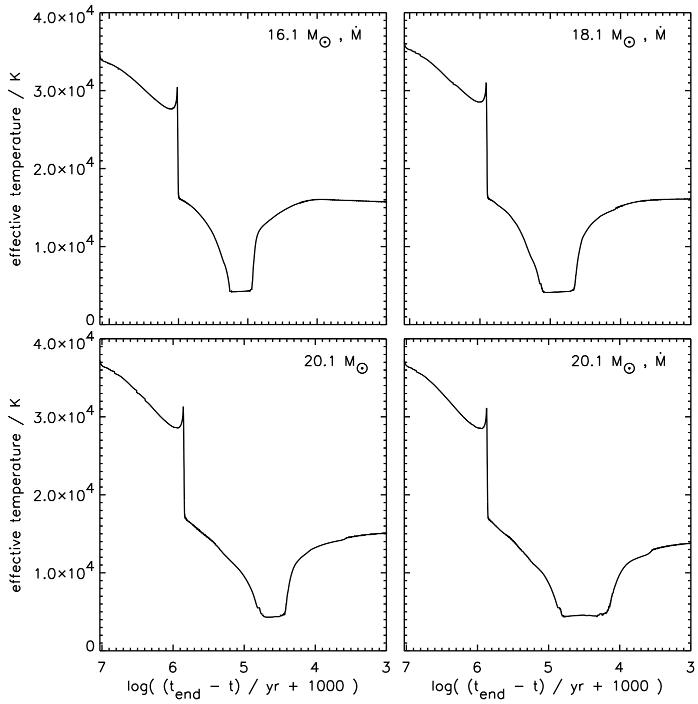

Figure 3. Effective temperature as a function of time for four models with blue SN progenitors. They are calculated starting with LMC composition and using OPAL opacities, restricted semiconvection only for $\bar{\mathrm{A}} \geq 4$ (full semiconvection otherwise) and mass loss (see text) where indicated by "$\dot{\mathrm{M}}$". The time-scale of the blue phase before the SN ranges from about 10,000 yr (20 $\mathrm{M}_{\odot}$ with mass loss) to almost 100,000 yr (16 $\mathrm{M}_{\odot}$).

deep convective envelopes to give large values, as indicated by the large helium abundances in the table.

Table 3. Nucleosynthesis and remnant masses

Element	LMC-18	SOL-18	LMC-20	SOL-20	LMC-22	SOL-22
Fe core	1.27	1.42	1.62	1.74	1.36	1.82
Remnant	-	1.76	-	2.06	-	2.02
H	8.71	7.89	9.31	8.24	9.91	8.79
He	7.02	6.28	8.07	6.72	8.82	7.51
C	0.19	0.25	0.27	0.21	0.34	0.24
N	0.015	0.057	0.017	0.060	0.019	0.067
O	0.28	1.13	0.66	1.94	1.02	2.38
Ne	0.27	0.28	0.10	0.11	0.063	0.07
Mg	0.058	0.055	0.026	0.031	0.047	0.042
Si	-	0.14	-	0.29	-	0.36
S	-	0.055	-	0.15	-	0.17
Ar	-	0.0087	-	0.026	-	0.028
Ca	-	0.0068	-	0.014	-	0.017
^{56}Ni	-	0.066	-	0.088	-	0.205

The nucleosynthesis in Table 3 is taken from the 18, 20, and 22 $M_\odot$ models that used old opacities, no mass loss, and no rotation. They were the only models evolved so far to the presupernova state. The solar metallicity versions of these models used the large semiconvection parameter and are taken from Woosley & Weaver (1995). Oxygen is an interesting diagnostic of the models, a value appreciably less than 1.0 $M_\odot$ being strongly suggestive of restricted semiconvection.

All numbers in Table 3 are in solar masses. All "SOL" stars ended their lives as *red* supergiants. The "LMC" models used the LMC composition, old opacities, and small semiconvection parameter. They all ended their lives as *blue* supergiants.

3.2. Rotating Models

As the complicated ring structure around SN 1987A indicates, spherical symmetry has been broken. If the star was not a binary, rotation must have played a role. Rotation can also enhance deep mixing and that might help to enrich the atmosphere in helium and nitrogen (Langer 1991).

A recent analytic model by Meyer (1997) suggests that the outer rings of SN 1987A are formed as a result of an aspheric slow RSG wind which has been heated and ionized during the pre-SN blue phase of SK -69 202. Whether a single star carries enough angular momentum to form the density contrast between equator and pole (at least ~ 4) needed in Meyer's model is not yet clear but might not be excluded (see e.g. Asida & Tuchman 1995).

A series of rotating models were calculated using the Göttingen stellar evolution code (Table 4). This had a similar, though not identical treatment of

Table 4. Models that include rotation

M ($M_\odot$)	$\dot{M}$	comp	v_{rot} km/s	τ_{red} (ky)	τ_{blue} (ky)	M_α ($M_\odot$)	M_{env} ($M_\odot$)	L_{38} erg/s	He_s (%)	$^{14}N/^{16}O$ ($\odot$)	$^{14}N/^{12}C$ ($\odot$)
18	yes	LMC	0	615	-	5.0	12.0	3.24	28	6.3	4.2
18	yes	LMC	20	240	-	5.8	11.0	5.36	39	7.9	11.3
18	yes	LMC	200	715	-	7.2	8.0	7.77	46	13.6	25.1

semiconvection to the "restricted" cases done with KEPLER and a similar treatment of mass loss (cf. Langer et al. 1989). The assumed starting model was rigidly rotating on the main sequence with an equatorial velocity given in Table 4. Angular momentum transport was treated as described in Langer et al. (1997; see also Endal & Sofia 1976, 1978, 1981; Pinsonneault et al. 1989) and included terms for convection, semiconvection, Eddington Sweet circulation, the Solberg-Hoiland instability, as well as secular and dynamic shear instability. Although the transport of angular momentum is treated in diffusion approximation, convective regions tended to rotate rigidly, because the convective turnover time-scale is usually small in comparison to the live-time of convective regions and the time-scale on which the convective region changes its properties, e.g. its density structure and total angular momentum.

Sample model results at carbon depletion are given in Table 4 for two rotating 18 $M_\odot$ stars (the zero rotation case is also given for comparison). Both rotating stars developed deep convective envelopes and had large helium and nitrogen enhancements. However, both ended up as red supergiants. The main culprit here is the growth of the helium core (Figure 4) due to additional rotationally induced mixing (Langer et al. 1997). A larger helium core implies a bigger luminosity which is bad enough, but the larger luminosity also causes more mass loss. Both effects make a blue solution difficult.

4. Speculations and Conclusions

Our conclusions here are mostly negative - without incredibly large decreases in metallicity, the new opacities preclude an acceptable blue solution for Sk -69 202 even if the old treatment of restricted semiconvection is used. Using restricted semiconvection only after hydrogen burning gives more acceptable results, but the surface abundances of N and He remain problematic. A moderate amount of rotation and a reasonable - but poorly understood - prescription for angular momentum transport gives the desired deep mixing, but too large helium cores to make a blue progenitor.

Before surrendering the possibility of a single star solution, however, and accepting that SN 1987A was a very improbable event, we consider another possibility - that rotation was the cause of the ring structure, the abundance anomalies in the rings, and the blue progenitor.

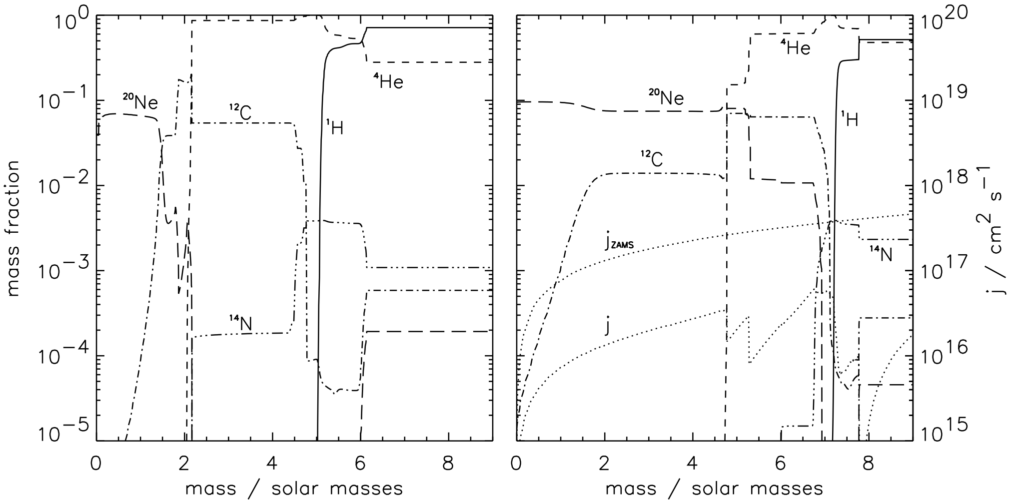

Figure 4. Composition and specific angular momentum of two LMC 18 $M_{\odot}$ stars evolved to carbon depletion with (right, last line in Table 4) and without (left, first line in Table 4) rotation. The rotating model had a ZAMS equatorial rotation velocity of 200 km/s at the surface and was rigidly rotating (upper dotted line, indicated by "j_{ZAMS}"). The final distribution of j pictured is a result of angular momentum loss of the star due to mass loss from the surface and redistribution of the angular momentum due to convetion and rotational instabilities. The convective envelope of the RSG, which reaches down to about 7.8 $M_{\odot}$, is chemically homogeneous and rigidly rotating, i.e. the major part of the angular momentum of the star is located close to the surface of the star.

Our rotating presupernova stars (Fig. 4) end up with very large velocity shears at the outer edge of the helium core. Inclusion of magnetic fields, or other mixing mechanisms not considered so far (Acheson 1978, Spruit & Phinney 1997), might lead to additional helium being dredged up into the envelope. Some kind of additional angular momentum transport is indicated because the continued evolution of these stars, using the same angular momentum transport scheme, ends up making iron cores with 100 times the specific angular momentum of the Crab pulsar (Heger, Woosley, & Langer 1997). While we can provide no models at the present time, any mechanism that reduced the helium core while simultaneously increasing helium in the envelope would tend strongly towards a blue solution. Whether this would naturally occur 20,000 years prior to the explosion remains to be demonstrated (see also, e.g., Saio et al. 1988).

A rotating RSG with a deeply convective envelope that moved back to the blue would also concentrate a large fraction of the angular momentum in the outer few hundredths of a solar mass (Heger & Langer 1997). This would lead to near Keplerian motion in the outer layers and asymmetry in the mass loss. Of special interest is the *first* time this occurs for stars which experience blue loops, as many of our models do. Whether this asymmetry could be enough to explain the complex outer ring structure is unknown, at least it might be an explanation for the inner ring, but we consider the single star models for SN 1987A worthy of continued study.

Acknowledgments. We are grateful to F. Meyer and H.C. Spruit for delighting discussions. This work has been supported by the National Science Foundation (AST -94 17171) and NASA (NAG5 3434). A. Heger was supported by a "DAAD-Doktorandenstipendium aus den Mitteln des 2. Hochschulprogramms" while in Santa Cruz.

References

Acheson, D.J. 1978, *Phil. Trans. R. Soc. London, Ser. A*, **289**, 459.

Anders, E., & Grevesse, N. 1989, *Geochim. Cosmochim Acta*, **53**, 197.

Arnett, W. D. 1987, ApJ, **319**, 136

Asida, S.M., Tuchman, Y. 1995, ApJ, **455**, 286

Barkat, Z., & Wheeler, J. C. 1989, ApJ, **342**, 940.

Braun, H., Langer, N. 1995, A&A, **297**, 483.

Burrows, A. 1988, ApJ, **334**, 891.

Caughlan, G. A., & Fowler, W. A. 1988, *Atomic Data and Nuc. Data Tables*, **40**, 283.

Chevalier, R. & Fransson, C. 1987, ApJ, **322**, L15.

Chevalier, R. A., & Soker, N. 1989, ApJ, **341**, 867.

Chiosi, C., & Maeder, A. 1986, *ARAA*, **24**, 329

de Jager, C., Nieuwenhuijzen, H., & van der Hucht, K. A. 1985 in *Luminous Stars and Associations in Galaxies*, eds. C. De Loore, A. Willis, & P. Laskarides, IAU Symp. 116, (D. Reidel: Dordrecht), p. 109

de Loore, C., & Vanbeveren, D. 1992, A&A, **260**, 273.

Endal, A. S., & Sofia, S. 1976, ApJ, **210**, 184.

Endal, A. S., & Sofia, S. 1978, ApJ, **220**, 279.

Endal, A. S., & Sofia, S. 1981, ApJ, **234**, 645.

Heger, A., & Langer, N. 1997, A&A, in preparation.

Heger, A., Woosley, S. E., & Langer, N. 1997, ApJ, in preparation.

Hillebrandt, W., & Meyer, F. 1989, A&A, **219**, L3.

Hillebrandt, W., Höflich, P., Truran, J. W., & Weiss, A. 1987, *Nature*, **327**, 597.

Kippenhahn, R., & Möllenhoff, C. 1974, *Ap. Spac. Sci.*, **31**, 117.

Langer, N. 1991, A&A, **243**, 155.

Langer, N. 1992, A&A, **265**, L17.

Langer, N., El Eid, M., & Baraffe, I. 1989, A&A, **224**, L17.

Langer, N., Fliegner, J., Heger, A., & Woosley, S. E. 1997, in *Nuclei in the Cosmos IV*, M. Wiescher et al., eds., Nuc. Phys. A, in press

Lauterborn, D., Refsdal, S., Weigert, A. 1971, A&A, **10**, 97.

Lundquist, P., & Fransson, C. 1996, ApJ, **464**, 924.

Maeder, A. 1987, in *Proc. ESO Workshop on SN 1987A*, ed. J Danziger, ESO, 251.

Meyer, F. 1997, MNRAS, **285**, L11

Panagia, N., Scuderi, S., Gilmozzi., R., Challis, P. M., Garnavich, P. M., & Kirshner, R. P. 1996, ApJ, **459**, L17.

Pinsonneault, M. H., Kawaler, S. D., Sofia, S., DeMarque, P. 1989, ApJ, **338**, 424.

Podsiadlowski, Ph., & Joss, P. C. 1989, *Nature*, **338**, 401.

Podsiadlowski, Ph., Joss, P. C., & Rappaport, S. 1990, A&A, **227**, L9.

Saio, H., Nomoto, K., & Kato, M. 1988, *Nature*, **334**, 508.

Shklovskii, I. S. 1987, *Sov. Astr. Lettr.*, **10(5)**, 302.

Shigeyama, T., Nomoto, K., Hashimoto, M., Sugimoto, D. 1987, *Nature*, **328**, 320.

Spruit, H.C., & Phinney, E.S. 1997, preprint

Truran, J. W., & Weiss, A. 1987, in *Proc. ESO Workshop on SN 1987A*, ed. J. Danziger, ESO, 271.

Weaver, T. A., Zimmerman, G. B., & Woosley, S. E. 1978, ApJ, **225**, 1021.

Weiss, A. 1989, ApJ, **339**, 365.

Wang, L. 1991, A&A, **246**, L69.

Weiss, A., Hillebrandt, W., & Truran, J. W. 1988, A&A, **197**, L11.

Wood, P. R., & Faulkner, D. J. 1988, *Proc. Astr. Soc. Australia*, **7**, 75.

Woosley, S. E. 1988, ApJ, **330**, 218.

Woosley, S. E., Pinto, P. A., & Ensman, L. M. 1988, ApJ, **324**, 466.

Woosley, S. E., & Weaver, T. A. 1995, *Ap. J. Supp.*, **101**, 181.