Evolution and Nucleosynthesis in rotating massive stars

A. Heger[1], *N. Langer*[2], *S.E. Woosley*[3]

[1] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85740 Garching, Germany*
[2] *Institut für Physik, Universität Potsdam, D-14415 Potsdam, Germany*
[3] *Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, U.S.A.*

We investigate the evolution of rotating stars with initial masses above $\sim 8\,\mathrm{M}_\odot$. The evidences for rotation being important in the evolution of massive stars are manifold. First, massive main sequence stars show average equatorial rotation rates of $200\,\mathrm{km\,s^{-1}}$ or more [4], i.e. they rotate, on average, at about half of their break-up velocity. Second, the surface-abundance patterns show signs of nuclear processing [5]. This cannot be explained by mere mass loss, as it would require loss rates in excess of what is expected from both observations and stellar evolution calculations. Also, the observed surface abundance patterns themselves are not compatible with this picture [3]. Thus rotationally induced mixing processes must be employed. Finally, the axisymmetric shapes of circumstellar shells and rings around many stars can be understood when rotation is the cause for breaking the spherical symmetry in the stellar mass loss. A famous example of this is the progenitor of supernova SN 1987A [11, 15].

For our calculations we use hydrodynamic stellar evolution codes [9, 14], which are modified to include specific angular momentum as a local variable. Centrifugal terms are also included in the force equation [1, 7]. The transport of angular momentum and mixing of chemical species are both modeled as diffusive processes [2, 13]. In addition to convection and semi-convection, rotationally induced instabilities are also taken into account, especially the dynamical and secular shear instabilities, the Goldreich-Schubert-Fricke instability, the Eddington-Sweet circulation and the Solberg-Høiland instability [2, 13]. Uncertain efficiency parameters are adjusted for each so that the observed surface abundance patterns for theses stars [5] are reproduced. Obviously there is some ambiguity in the choice of these parameters.

In Fig. 1, the evolutionary tracks of rotating and non-rotating stars of solar composition are compared in the Hertzsprung-Russell diagram [6]. The slightly lower luminosities and surface temperatures of the rotating models at the onset of central hydrogen burning are caused by the reduction of the effective gravity due to centrifugal forces. However, during the main sequence evolution, the rotating stars become more luminous than non-rotating stars of the same mass because the rotationally induced instabilities lead to the mixing of helium into layers above the core. Some even rises to the surface. This leads to an increase of the average mean molecular weight of the star and therefore to a higher luminosity [8]. Thus rotation broadens the main-sequence.

The mixing of helium on the main sequence is responsible for an increase in the mass of the helium core. Moreover, the layers above the core are depleted in hydrogen, causing the helium core to grow faster during central helium burning, so the stars also have a larger helium core at the time of core collapse. E.g., our rotating $12\,\mathrm{M}_\odot$ stars ends up with a helium core of about the same mass as our non-rotating star of $15\,\mathrm{M}_\odot$. This strongly affects the nucleosynthetic yields of the stars as a function of their initial mass.

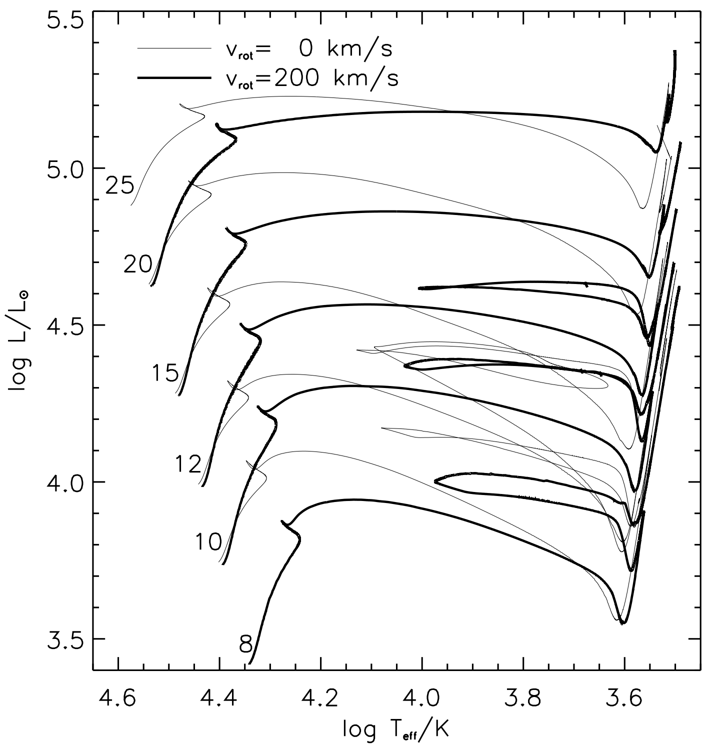

Figure 1: Evolutionary tracks for rotating (thick lines) and non-rotating (thin lines) stars in the mass range 8...25 $M_\odot$ from the ignition of central hydrogen burning to the pre-supernova stage (from [6]). The tracks are labeled with the initial masses (in $M_\odot$). The rotating models have an initial equatorial rotation rate at the surface of $200\,\mathrm{km\,s^{-1}}$

.

From central helium burning onwards, the evolutionary time-scales of the stars become shorter than those for rotationally induced mixing processes. This inhibits the transport of angular momentum or mixing of chemical species over large distances. That is, the products of central helium burning are *not* transported up to the hydrogen burning shell, nor is there any important loss of angular momentum from the helium core to the stellar envelope (neglecting magnetic fields). Therefore after central helium burning the central regions of rotating stars evolve similar to the cores of more massive non-rotating stars.

However, in some models we find that after the hydrogen shell source has become extinct, protons can be mixed down into the helium burning shell source (i.e. after termination of central helium burning) and this opens new channels of nucleosynthesis [10].

Because of the inefficiency of angular momentum transport by rotationally induced instabilities from central helium burning onwards, only convection is able to transport angular momentum on scales large enough to be important for the redistribution of angular momentum in the late evolutionary stages. The subsequent convective regions of central and shell burning of carbon, neon, oxygen, and silicon thus leave their fingerprints in the angular momentum profile and lead to the spiky structures that can be seen in Fig. 2. However, the total angular momentum remaining in the cores of our models is large: It would be sufficient to bring the neutron stars, formed from the collape of the stellar iron core, close to critical rotation. That is, our models might result in pulsars with initial rotation periods around

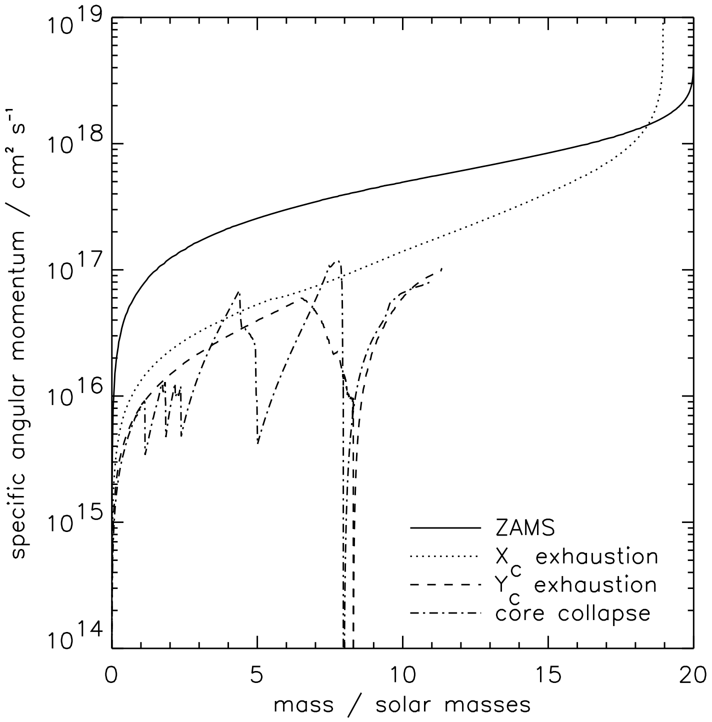

Figure 2: Specific angular momentum as a function of interior mass for the $20\,M_\odot$ star. The solid line gives the distribution at the onset of central hydrogen burning, the dotted line at the termination of central hydrogen burning, the dashed line at the termination of central helium burning and the dash-dotted line at the onset of core-collapse.

1 ms. On the other hand, the fastest known young neutron star, PSR J0537-6910, has a rotation period of 16 ms [12]. The cause of this discrepancy might be either an important angular momentum transport mechanism that is missing in our models, e.g., magnetic fields, or an indication that angular momentum has to be lost during the core collapse or the early evolution of the young neutron star.

Acknowledgments

This work has been supported by a "DAAD-Doktorandenstipendium aus den Mitteln des 2. Hochschulprogramms", the Deutsche Forschungsgemeinschaft through grant No. La 587/15-1, by the National Science Foundation (AST-94-17161) and NASA (NAG5-3434).

References

[1] A.S. Endal and S. Sofia, ApJ **210** (1976) 184.

[2] A.S. Endal and S. Sofia, ApJ **220** (1978) 279.

[3] J. Fliegner, N. Langer, K. Venn, A&A **308** (1996) L13.

[4] I. Fukuda, PASP **94** (1982) 271.

[5] D.R. Gies and D.L. Lambert, ApJ **387** (1992) 673.

[6] A. Heger, S.E. Woosley, and N. Langer, ApJ (1998) in preparation.

[7] R. Kippenhahn and H.-C. Thomas, in *Stellar rotation*, ed. A. Slettebak, Reidel, Dortrecht, (1970) 20.

[8] R. Kippenhahn, and A. Weigert, *Stellar Structure and Evolution*, Springer-Verlag, Berlin (1991).

[9] N. Langer, M. Kiriakidis, M.F. El Eid, K.J. Fricke, A. Weiss, A&A **192** (1988) 177.

[10] N. Langer, J. Fliegner, A. Heger, S.E. Woosley, Nuc. Phys. A **621** (1997) 457c.

[11] F. Meyer, MNRAS **285** (1997) L11.

[12] F.E. Marshall, E.V. Gotthelf, W. Zhang, J. Middleditch, Q.D. Wang, ApJL (1998) submitted.

[13] H.M. Pinsonneault, S.D. Kawaler, S. Sophia, P. Demarque, ApJ **338** (1989) 424.

[14] T.A. Weaver, G.B. Zimmerman, S.E. Woosley, ApJ **225** (1978) 1021.

[15] A. Weiss, W. Hillebrandt, J.W. Truran, A&A **197** (1988) L11.