Light Elements in the Universe
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Boron depletion in 9 to 15 $M_\odot$ stars with rotation

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Abstract. The treatment of mixing is still one of the major uncertainties in stellar evolution models. One open question is how well the prescriptions for rotational mixing describe the real effects. We tested the mixing prescriptions included in the Geneva stellar evolution code (GENEC) by following the evolution of surface abundances of light isotopes in massive stars, such as boron and nitrogen. We followed 9, 12 and 15 $M_\odot$ models with rotation from the zero age main sequence up to the end of He burning. The calculations show the expected behaviour with faster depletion of boron for faster rotating stars and more massive stars. The mixing at the surface is more efficient than predicted by prescriptions used in other codes and reproduces the majority of observations very well. However two observed stars with strong boron depletion but no nitrogen enrichment still can not be explained and let the question open whether additional mixing processes are acting in these massive stars.

Keywords. Stars: rotation, abundances, interiors

1. Introduction

Rotation is beside the stellar mass and the initial chemical composition the most important parameter in the evolution of single stars. It affects the physical and chemical structures of the stars and therefore quantities such as lifetime, luminosity, surface temperature etc. Recent models including rotation reproduce a wide range of observations better than those without (e.g. Meynet & Maeder 2003, 2005; Vázquez *et al.* 2007; Georgy *et al.* 2009). Still, the treatment of transport of angular momentum and chemical species is thought to be one of the main uncertainties in stellar evolution models.

Light elements and in particular boron and nitrogen can constrain the mixing induced by rotation and help distinguish between single stars and interacting binaries (Brott *et al.* 2009). Boron is destroyed at relatively low temperatures ($6 \cdot 10^6$ K) where the CNO-cycles are not yet efficient. Therefore shallow mixing due to rotation leads to a depletion of light elements such as Li, Be and B at the surface without considerable nitrogen enrichment. This effect can not be explained by mass transfer in a binary system, since there the accreted material is depleted in boron and enriched in nitrogen. An increasing number of boron surface abundances from O- and early B-type stars became available in the last few years (Proffitt & Quigley 2001; Venn *et al.* 2002; Mendel *et al.* 2006). The comparison in Mendel *et al.* (2006) of observational data with the models of Heger & Langer (2000) shows a good agreement with the exception of two stars. The strong boron depletion in these two young B-type stars raises the question if the efficiency of surface mixing due to rotation should be stronger or if there is another mixing effect which should be accounted for. We examined this question because GENEC includes the effect of rotation in a different way. The main difference comes from the fact that the transport of angular momentum is properly accounted for as an advection process and not as diffusion.

2. Models and comparison

We calculated 9, 12 and 15 $M_\odot$ models, each with different rotational velocities, to study the influence of rotational mixing on the light elements. A detailed description of the treatment of the transport of chemical species and angular momentum in GENEC can be found e.g. in Hirschi *et al.* (2004). In all our models shear turbulence is the dominant mixing process close to the stellar surface. In radiative zones, the gradient in angular momentum leading to shear mixing results from the concomitant effects of meridional currents, shear turbulence and from envelope expansion occurring on the main sequence.

In massive stars boron is only destroyed. The observations of boron in young massive stars in the solar vicinity show variations in log(B/H) from 2.9 down to unobservable quantities below 1. The large boron surface variations cannot be explained only by variation of initial composition (Venn *et al.* 2002). The boron vs nitrogen relation of the models is almost independent of the rotation velocity and initial stellar mass and therefore a good way to compare with observations since usually only $v \cdot \sin(i)$ is known from them. The early boron depletion and only subsequent enrichment of CN-cycle processed material is the main characteristic of rotational mixing. Most of the observations can be well reproduced. However the observed stars with boron depletion of about 1.5 dex or more and no enrichment of CNO-processed material at the surface are hard to explain with our and previous models. To reproduce these stars (HD 30836, HD 36591) the models would have to mix very efficiently the outermost envelope to destroy boron while at the same time not dredging nitrogen from the central regions up to the surface. Rotational mixing as it is treated in the current models does not seem to explain all the observations, meaning that additional physics like magnetic fields could play a role.

In comparison to the models of Heger & Langer (2000) ours show considerably more mixing for the outer part of the envelope at the end of central hydrogen burning, i.e. boron is in general more depleted at the end of the main sequence in our models with similar initial angular momentum. This means also that observed stars are better reproduced with our models since most of them are intrinsically slow rotators (Morel *et al.* 2008). The stronger surface mixing in our models originates in the meridional circulation, which is implemented as an advective process, whereas it is treated as a diffusive process in the models of Heger & Langer (2000). This allows meridional circulation to build stronger angular velocity gradients in the envelope instead of just diffusing the gradient away.

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