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Thermohaline Convection in Main Sequence Stars

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Abstract. Thermohaline convection is a well known subject in oceanography, which has long been put aside in stellar physics. In the ocean, it occurs when warm salted layers sit on top of cool and less salted ones. Then the salted water rapidly diffuses downwards even in the presence of stabilizing temperature gradients, due to double diffusion between the falling blobs and their surroundings. A similar process may occur in stars in case of inverse μ-gradients in a thermally stabilized medium. Here we describe this process and some of its stellar applications.

Keywords. stars:evolution, convection, stars: abundances

1. What is thermohaline convection?

Thermohaline convection is a wellknown process in oceanography : warm salted layers on the top of cool unsalted ones rapidly diffuse downwards even in the presence of stabilizing temperature gradients, due to the different diffusivities of heat and salt. When a warm salted blob falls down in cool fresh water, the heat diffuses out more quickly than the salt. The blob goes on falling due to its weight until it mixes with the surroundings. This leads to the so-called salt fingers (Figure 1). Thermohaline convection is a double diffusive convection. When the gradients are reversed, another kind of double diffusive convection occurs, which is generally referred to as semi convection.

The condition for the salt fingers to develop is related to the density variations induced by temperature and salinity perturbations. Two important characteristic numbers are defined :

• the density anomaly ratio

$$R_\rho = \alpha \nabla T / \beta \nabla S \tag{1.1}$$

where $\alpha = -(\frac{1}{\rho}\frac{\partial \rho}{\partial T})_{S,P}$ and $\beta = (\frac{1}{\rho}\frac{\partial \rho}{\partial S})_{T,P}$ while ∇T and ∇S are the average temperature and salinity gradients in the considered zone

• the so-called "Lewis number"

$$\tau = \kappa_S / \kappa_T = \tau_T / \tau_S \tag{1.2}$$

where κ_S and κ_T are the saline and thermal diffusivities while τ_S and τ_T are the saline and thermal diffusion time scales.

The density gradient is unstable and overturns into dynamical convection for $R_\rho < 1$ while the salt fingers grow for $R_\rho \geqslant 1$. On the other hand they cannot form if R_ρ is larger than the ratio of the thermal to saline diffusivities τ^{-1} as in this case the salinity difference between the blobs and the surroundings is not large enough to overcome buoyancy.

Salt fingers can grow if the following condition is satisfied :

$$1 \leqslant R_\rho \leqslant \tau^{-1} \tag{1.3}$$

In the ocean, τ is typically 0.01.

2. The stellar case

Thermohaline convection may occur in stellar radiative zones in the presence of inverse μ-gradients. In this case $\nabla_\mu = \mathrm{dln}\mu/\mathrm{dln}P$ plays the role of the salinity gradient while the difference $\nabla_{ad} - \nabla$ (where ∇_{ad} and ∇ are the usual adiabatic and local (radiative) gradients $\mathrm{dln}T/\mathrm{dln}P$) plays the role of the temperature gradient. The medium can become dynamically unstable if (Ledoux criterion):

$$\nabla_{crit} = \frac{\phi}{\delta}\nabla_\mu + \nabla_{ad} - \nabla < 0 \qquad (2.1)$$

where $\phi = (\partial \ln \rho/\partial \ln \mu)$ and $\delta = (\partial \ln \rho/\partial \ln T)$. When ∇_{crit} vanishes, marginal stability is achieved and thermohaline convection may begin as a "secular process", namely on a thermal time scale (short compared to the stellar lifetime!).

As for the ocean case, salt fingers will form if the following condition is verified:

$$1 \leqslant \left|\frac{\delta(\nabla_{ad} - \nabla)}{\phi(\nabla_\mu)}\right| \leqslant \tau^{-1} \qquad (2.2)$$

with $\tau = D_\mu/D_T = \tau_T/\tau_\mu$ where D_T and D_μ are the thermal and molecular diffusion coefficients while τ_T and τ_μ are the corresponding time scales.

In stars the value of the τ ratio is typically 10^{-10} if D_μ is the molecular (or "microscopic") diffusion coefficient but it can go up by many orders of magnitude when the shear flow instabilities which induce mixing between the edges of the fingers and the surroundings are taken into account.

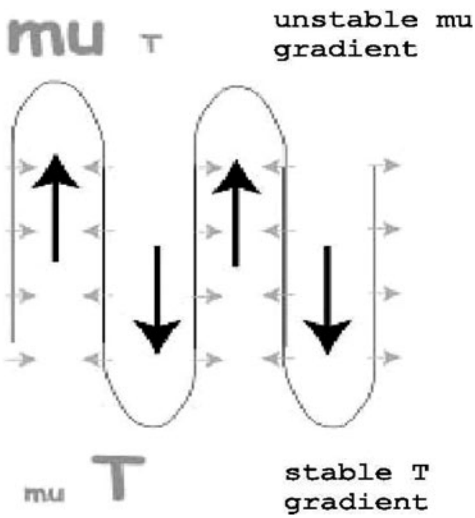

Figure 1. Schematic graph of thermohaline convection (salt or mu fingers). An important effect to take into account in the computations of thermohaline diffusion is the shear flow instabilities which occur at the edge of the fingers.

The effects of thermohaline convection as a mixing process in stars are far from trivial. Many detailed studies in the water case have been published, for example Gargett & Ruddick 2003) who gave precise comparisons between numerical simulations and laboratory experiments. However the stellar case is different as mixing then occurs in a compressible fluid.

As pointed out by Charbonnel & Zahn 2007, two different parametrisation recipes, as given by Ulrich 1972 or Kippenhahn *et al.* 1980 can differ by two orders of magnitude. This illustrates enough that treating thermohaline convection as a simple diffusion process, using a simple diffusion coefficient, may lead to wrong results.

Vauclair 2004 gave a discussion of these parameterisation procedures. The basic problem here concerns the vertical shear flow instability which occurs between the fingers and the inter-fingers medium, which is not taken into account in the Ulrich 1972 procedure. This instability leads to local turbulence which increases the mixing at the edge of the fingers. Consequently, a process of self destruction appears for the blobs, so that fingers eventually reach a regime where they cannot form anymore: this effect is taken into account in the Kippenhahn *et al.* 1980 procedure.

All this becomes much more complicate if one wants to take into account the competition between thermohaline convection and other macroscopic motions. This question has recently been addressed by Canuto *et al.* 2008

3. Where does thermohaline convection take place in stars?

Thermohaline convection may occur and has to be taken into account any time inverted μ-gradients are built. The first situation which was pointed out concerned ^{3}He burning regions (Abrams & Iben 1970, Ulrich 1971). It has recently been revisited by Eggleton *et al.* 2006 and Charbonnel & Zahn 2007 for the case of red giants: this is treated in other contributions to this meeting.

Situations with ^{4}He enhancement in stellar outer layers were also discussed several times, e.g. due to mass transfer (Stothers & Simon 1969). Another case occurs in main sequence helium rich stars, observed with effective temperatures around 20000 degres, which are helium rich only in their outer layers. This may be explained by helium diffusion in a stellar wind (Vauclair 1975). The observations, which show that helium is enhanced by a factor two in average, prove that thermohaline mixing must be important in this case, otherwise the helium overabundance would be much larger. However thermohaline mixing must not be completely efficient, otherwise no helium enhancement would be left at all. The reason may be due to the presence of a magnetic field in this case. Extension of this kind of studies have been discussed for roAp stars by Balmforth *et al.* 2001.

In more recent work, detailed computations of iron accumulation in stars, due to atomic diffusion processes, have been performed in several frameworks. Charpinet *et al.* 1996 found that, in the case of sdB stars, iron accumulation could help triggering stellar oscillations due to the iron-related kappa-mechanism. Richard *et al.* 2001 found that such an iron accumulation can lead to a special iron-induced convective zone which may drastically change the internal stellar structure during main sequence evolution. As the iron accumulation leads to an inverted μ-gradient, the effects of thermohaline convection should be tested in all these computations, which has not been done yet.

Other cases where thermohaline convection must occur are related to accretion of metal-rich matter onto main sequence stars. Let us discuss two quite different cases. The first case is related to planetary formation and migration in the early times of planetary systems. The question arises whether the overmetallicity observed in exoplanets-host stars may be due to accretion of planetary material. One of the arguments against this was that the observed overabundances in exoplanets host stars is constant for main sequence stars, whatever their masses, while the depth of their convective zones were highly variable. Vauclair 2004 showed that this argument does not hold, due to thermohaline convection. Now the question arises whether some overmetallicity can remain in the outer layers of the stars or not. This question is not solved yet. It seems however, for other statistical reasons, that the overmetallicity must be primordial.

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The second case is quite different. It concerns carbon enhanced main-sequence stars (CEMPs). These stars with abundance anomalies are supposed to have suffer some accretion of material coming from an AGB companion. Stancliffe *et al.* (2007) pointed out that in case of accretion of metal-rich matter, this material would subsequently fall down inside the star due to thermohaline convection. In a more recent paper (Thompson *et al.* 2008), we suggested that, between the stellar birth and the time when the AGB sends its processed material onto it, the main sequence star had time to suffer helium and heavy element diffusion below its convective zone, thereby creating a stabilizing μ-gradient. In the presence of this diffusion-induced μ-gradient, outside matter may accumulate in the convection zone until the overall μ-gradient becomes flat. This effect can save the whole process in this case (Figure 2).

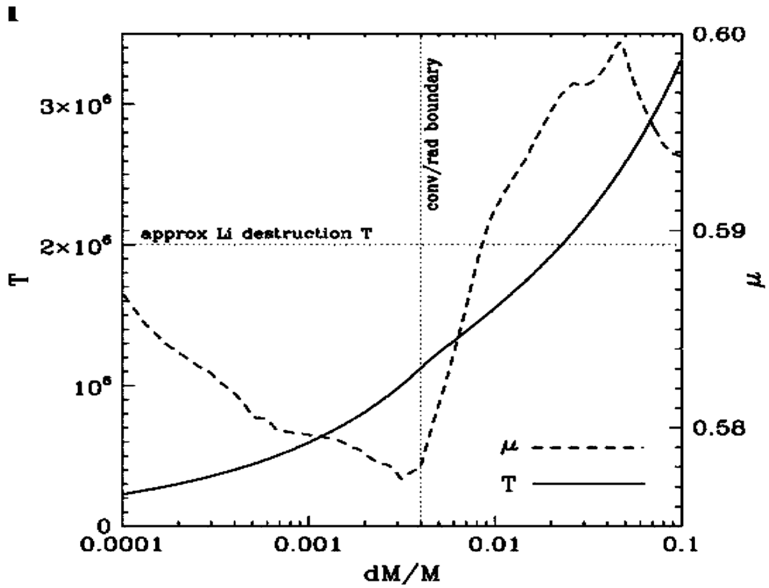

Figure 2. Mean molecular weight (including partial ionisation) and temperature profiles, as a function of the fractional mass, in a 0.78 Msun star with [Fe/H] = −2.3, at an age of 3.75 Gyr. This may correspond to the internal structure of a main sequence star just before the accretion of heavy material from an AGB companion. Helium depletion due to gravitational settling leads to a pre-existing stabilizing μ-gradient, which then allows a large part of the accreted matter to remain in the convective zone (after Thompson *et al.* 2008)

In summary, thermohaline convection, which has long been forgotten in astrophysics, has to be taken into account in several important cases during stellar evolution. Its competition with other processes like meridional circulation, magnetic fields, etc. will have to be computed and discussed thoroughly for a better understanding of stellar evolution.

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Discussion

Charbonnel: It's certainly important to look at the effect of atomic diffusion on the inhibition of thermohaline in MS stars, and the case of carbon stars should bring important constraints on these interactions. However, it is not relevant in the case of red giants, because the first dredge-up erases completely the effects of atomic diffusion that occurred on the main sequence.

Vauclair: Yes of course, I agree and I did not speak of giants, only main-sequence stars. Matteo Cantiello will speak about giants just after me.

Stepień: You mentioned that the diffusion rate determines the extent of fingers (or, equivalently their life time). Is friction peeling off the original bullet not more important?

Vauclair: Yes indeed, this why I said that the particle transfer between the interior and exterior of the fingers was more rapid that original atomic diffusion and that this had to be taken into account in the computation.

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