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CONSEQUENCES OF THE ACCRETION OF PLANETARY MATTER ON THE CHEMICAL COMPOSITION OF THE STARS.

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Abstract. The question of the possible modification of the abundances observed at the surface of stars in case of accretion of planetary matter has been debated for several years. Here we present some recent studies on this subject. At the beginning of the stars' life on the main sequence, contrary to what was assumed in the past, heavy matter accretion cannot lead to any overabundance of heavy elements because of the double-diffusive instability induced by the inversion of the mean molecular weight. This instability leads to partial extra-mixing which, in some cases, may induce lithium destruction. On the other hand, helium settling leads to stabilizing μ-gradients inside the stars during stellar evolution, so that heavy matter accretion can modify the observed chemical composition as long as the global μ-gradient does not become unstable.

Keywords: stars, accretion, chemical composition, hydrodynamics, mixing processes, lithium

1 Introduction

The question of the possible modifications of the metallic abundances in stellar outer layers as a result of the accretion of heavy planetary matter has been a subject of debate for many years. The observed exoplanet-host stars are, on average, metal-rich compared to stars without observed planets (Santos et al. (2001), Ghezzi et al. (2010a)). This average metal excess was a subject of discussion during at least one decade. Two options could arise at first sight. The high metallicity could be pristine, which means that a high metallicity in the original nebula helps planet formation, or it could be due to the accretion of planetary matter onto the star. Nowadays, this second possibility is completely excluded, for several reasons, one of them being that the metal-rich accreted matter cannot remain inside the outer convective zone. It rapidly falls down inside the star due to double-diffusive (thermohaline) convection (Vauclair (2004)), in such a way that no overabundance can remain (Garaud (2011)). On the other hand, this leads to extra mixing which may have some importance for the lithium destruction problem (Théado & Vauclair (2012)). We also have evidences of accretion of planetary matter onto white dwarf stars, due to observed heavy elements in their atmospheres, in relation to the presence of debris disks (Farihi et al. (2012)). Here again, double-diffusive (thermohaline) convection occurs below the outer convection zones and must be taken into account in the computations. In this paper, we give a short review of the hydrodynamical process referred to as thermohaline convection. Then we discuss its consequences in the case of accretion of heavy matter onto the stars, first for exoplanet-host stars, second for the special case of very old stars which accrete matter from a companion, and finally for white dwarfs.

2 The double-diffusive instability

In oceanography, the double-diffusive convection is a well-known physical process. In this context it is refereed to as thermohaline convection. The instability is induced by warm salted water lying on top of colder fresh water. The instability produces the so-called salt-fingers (see for instance Stern (1960), Veronis (1965), Kato (1966), Turner (1973), Shen & Veronis (1997), Turner & Veronis (2000), Yoshida & Nagashima (2003), Ruddick & Gargett (2003)).

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A density anomaly ratio is defined as: $\mathrm{R}_\rho = \alpha \nabla \mathrm{T}/\beta \nabla \mathrm{S}$, with $\alpha = (1/\rho)(\partial\rho/\partial \mathrm{T})_{S,P}$ and $\beta = (1/\rho)(\partial\rho/\partial \mathrm{S})_{T,P}$, where ρ, T and S are the density, the temperature and the salinity respectively. The thermohaline instability develops when $1 \leq \mathrm{R}_\rho \leq \tau^{-1}$, where the inverse Lewis number τ is the ratio of the salt to the temperature diffusivity: $\tau = \kappa_S/\kappa_T$.

Similar situations occur in stars. The role of the salt is played by the mean molecular weight, μ. Two kinds of double-diffusive instabilities may occur inside stars. The first one is the semi-convection which may develop when a stable μ gradient occurs in a region of unstable temperature gradient. The second one is the equivalent of the thermohaline convection, also called ‘ ‘ fingering convection” in this case, which may happen when an unstable μ gradient develops in a region of stable temperature gradient. These instabilities occur when the medium is stable against dynamical convection.

In stars, the equivalent of R_ρ is R_0 defined as: $\mathrm{R}_0 = \delta(\nabla_{ad} - \nabla_{rad})/\phi\nabla\mu$, where $\delta = (\partial \mathrm{ln}\rho/\partial \mathrm{lnT})$, $\phi = (\partial \mathrm{ln}\rho/\partial \mathrm{ln}\mu)$, and $\nabla\mu = \mathrm{dln}\mu/\mu$. In this case the inverse Lewis number τ is the ratio of the particles to the temperature diffusivities: $\tau = \kappa_\mu/\kappa_T$. The fingering instability develops when $1 \leq \mathrm{R}_0 \leq \tau^{-1}$. It has recently been explored through 3D numerical simulations for a range of characteristic physical parameters (Traxler et al. (2011), Brown et al. (2013), Zemskova et al. (2014)).

The fingering instability may develop under various conditions. It may occur when the stars accrete heavy material. This happens in the case of the exoplanet host stars accreting planetary matter, in the case of stars accreting enriched matter from an evolved companion as in the carbon enriched metal poor (CEMP) stars and in the case of the white dwarfs accreting heavy material from a debris disk.

It may also develop due to the accumulation of heavy elements in specific layers. This happens when the radiative acceleration on such elements exceeds gravity and decreases upwards (Richard et al. (2001), Vauclair & Théado (2012)). 3D numerical simulations have been done to refine the detailed hydrodynamics and give prescriptions to be used in 1D stellar models(see Zemskova et al. (2014)).

Fingering convection has also been invoked to explain abundance anomalies in red giant branch stars but it has been proved to have too small an effect to account for the observations (Wachlin et al. (2014) and references therein).

3 The case of the Exoplanet-Host Stars

As pointed out by (Santos et al. (2001), the overmetallicity of exoplanet-host stars does not depend on their effective temperatures, which means that they are independent of the depth of the convective zones. Vauclair (2004) showed how the accreted matter builds an inverse μ-gradient which leads to thermohaline (fingering) convection, so that the heavy elements are rapidly mixed inside the star. When this effect is taken into account, the accreted heavy elements are expected to be mixed down to similar depths, much below the convective zone, for all stars. At the end, a very small μ-gradient may remain, which is now proved much too small to account for the observed overmetallicity (Garaud (2011)).

This result is consistent with the detailed observations of Ghezzi et al. (2010c) who found that the overmetallicity of the subgiant exoplanet host stars was very similar to that of the main sequence ones, which would not be the case if it was due to accreted matter remaining inside the convective zone. It is also consistent with the observations by Teske et al. (2013) of the two stars of a binary system, one holding a planet contrary to the second (see also Schuler et al. (2011) for a similar case, as discussed below). The two stars are found quite similar for all astrophysical parameters, including detailed chemical composition. On the other hand, Ghezzi et al. (2010b) found that the overmetallicity is different for stars holding jovian planets and stars holding neptunian planets, which would be an indication that the type of planets which may form depend of the initial metallicity. All these considerations converge on the fact that the overmetallicity observed in exoplanet-host stars is pristine. This does not mean that accretion did not take place, but that the accreted material did not stay in the stellar outer layers.

An important consequence of the mixing process induced by the accretion of heavy elements is that it can modify the internal stellar structure, and also destroy some lithium at the beginning of the star's life on the main sequence. This was already suggested by Théado, Bohuon & Vauclair (2010) and confirmed by Garaud (2011) and Théado & Vauclair (2012). Lithium depletion in solar-type stars remains a challenge for stellar models. Extra mixing below the outer convective zone is needed to explain the observed abundances in the Sun, the solar analogs and the solar twins (e.g., Do Nascimento et al. (2009)). Several processes have been invoked in the past to account for this lithium depletion, like rotational induced mixing, but they fail to account for all the observed features and observed abundance dispersion.

The lithium abundance differences between exoplanet-host stars and stars without detected planets is still a subject of debate. Ghezzi et al. (2010a) gave a recent review on that subject and showed that an overall comparison between the two samples gives no obvious differences except in the range 5700 K $< T_{eff} <$ 5850 K where the lithium abundance is $\approx$ 0.26 dex lower in stars with planets than in stars without planets. This is the typical effective temperature range where the bottom of the convective zone becomes close enough to the lithium destruction region, so that the final lithium abundances are very sensitive to the mixing processes occuring there.

A spectacular result in that respect was obtained by Schuler et al. (2011) who determined the detailed astrophysical parameters and chemical compositions of the two components of the binary system 16 Cygni. The main particularity of that system is that 16 Cyg B hosts a giant planet whereas 16 Cyg A has no detected planet. The two stars are very similar, with effective temperatures of 5796±34 K for 16 Cyg A and 5753±30K for 16 Cyg B. They also have similar gravities, log g = 4.38±0.12 for 16 Cyg A and 4.40±0.12 for 16 Cyg B. The abundances of 15 elements were derived with high signal to noise ratio echelle spectra. They were found indistinguishable between the two stars... except for lithium, which is depleted by a factor at least 4.5 in 16 Cyg B compared to 16 Cyg A. According to the Théado & Vauclair (2012)'s results, this could be an indication of the accretion of planetary matter onto 16 Cyg B followed by thermohaline convection.

4 The case of the Carbon-Enhanced Metal Poor stars

Carbon-enhanced metal poor stars (CEMPs) show abundance anomalies which could be accounted for in case of accretion 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 (see also Stancliffe & Glebbeek (2008), Stancliffe et al. (2009), Stancliffe (2010)). In this case, the thermohaline mixing is strongly limited by the pre-existing stable μ-gradient, induced by helium settling. This is not expected to occur in the case of exoplanets-host stars which accrete matter at the very beginning of their lives, when atomic diffusion has not yet had time to build important helium gradients.

5 The case of the white dwarfs

A large fraction of DA and DB white dwarfs, maybe as large as ≈50%, shows absorption lines of heavy elements in their spectra (Desharnais et al. (2008), Zuckerman et al. (2010), Zuckerman et al. (2011), Gänsicke et al. (2012), Koester et al. (2014)). Many of these stars also show evidence of infrared-excess in their spectral energy distribution. This proves the existence of debris disks orbiting the white dwarfs. It also proves that an ongoing accretion of material originating from the disk is polluting the chemical composition of the white dwarf outer layers. These polluted DA and DB white dwarfs are then classified as DAZ and DBZ. When different heavy elements are present, their relative abundance ratios are similar to those measured for the rocky planetesimals, asteroid-type, in the solar system (Melis et al. (2011), Dufour et al. (2012), Gänsicke et al. (2012), Xu et al. (2014)). It strongly suggests that these debris disks are the remnants of the primordial planetary system.

From the derived abundances of the heavy elements it is possible to estimate the accretion rates. To derive such rates, it was previously assumed that the accreted heavy elements are mixed in the outer convection zone, or in the radiative atmosphere when there is no convection zone, and then diffuse downwards due to the efficient gravitational settling. Accretion rates were then estimated by assuming a steady state between accretion and gravitational settling (see for instance Farihi et al. (2012)).

However, the importance of the thermohaline (fingering) convection induced by the increase of heavy elements abundances in the outer stellar layers has been overlooked in these estimates. Due to this process, the accreted material is mixed much deeper in the outer layers of the white dwarf. As a consequence larger accretion rates are required in order to reproduce the observed heavy elements abundances. A preliminary study of the consequences of the fingering convection on the derived accretion rates shows that the effect may be important for the accretion rates on DAZ white dwarfs but not in the case of the DBZ (Deal et al. (2013)). According to this study, the fingering convection starts in the DAZ as soon as the relative increase of the mean molecular weight in the polluted layers, $\Delta\mu/\mu$, exceeds $\approx 10^{-6}$.

As an example, in a typical DA white dwarf of $0.59M_{\odot}$, with an effective temperature of 10600 K, the accretion rate needed to reproduce an observed Ca abundance [Ca/H]= -7.2, is four times larger when thermohaline convection is taken into account, than when it is estimated with gravitational settling only. This discrepancy rises to a factor 200 for a DA model with 12800 K. On the contrary, for the DB white dwarfs, the simulations show no or only marginal fingering instability. The main reason is that in DB white dwarfs the depth of the convection zone is much deeper than in DA white dwarfs. As a consequence of the physical conditions which prevail below the convection zone, the parameter R_0 exceeds the inverse Lewis number so that fingering convection is not triggered. This effect is a very simple and straightforward explanation of the apparent paradox raised by the DAZ and DBZ observations.

6 Conclusions

The important conclusions of these studies are :

- The abundances observed at the stellar surfaces are not always representative of the original abundances. This is important in the framework of the chemical evolution of galaxies.
- When computing the abundances evolution at the surface of stars, it is not enough to take into account microscopic diffusion processes and accretion of external matter. The induced thermohaline (fingering) process and its consequences have also to be investigated.
- Thermohaline convection induced by accretion of heavy matter and/or internal accumulation of heavy elements in specific layers leads to extra-mixing which may help understanding the observed lithium abundances, and may also modify the internal stellar structure.
- At the epoch of precise determination of the internal structure of stars with the help of asteroseismology, this microscopic-macroscopic connexion cannot be ignored.

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