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Metal-rich accretion, thermohaline instabilities, extra lithium depletion in stars

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Abstract. The early evolution of planetary systems is expected to depend on various periods of disk matter accretion onto the central star, which may include the accretion of metal-rich matter after the star settles on the main sequence. When this happens, the accreted material is rapidly mixed within the surface convective zone and induces an inverse mean-molecular-weight gradient, unstable for thermohaline convection. The induced mixing, which dilutes the metal excess, may also have important consequences on the light elements abundances. We model and analyze this process, and present the results according to various possible accretion scenarios. We give a detailed discussion of the different ways of treating thermohaline mixing, as proposed by previous authors, and converge on a consistent view, including the most recent numerical simulations. We show how the observations of light elements in stars can be used as tracers of such events.

Key words. convection - planetary systems - planet-star interactions - stars: abundances - stars: solar-type

1. Introduction

It is now well established that stars may experience episodic accretion along their evolution through different processes. The planet formation period which extends from the stars's birth to the end of the pre-main sequence phase (Ida & Lin 2008) is a favourable epoch for such event since efficient planet migration processes may lead to accretion phenomena onto the central star (Terquem 2010; Lubow & Ida 2010).

At the end of the protoplanetary disk phase, the planetary system architecture is not necessarily set. Current models for planetary system evolution indicate that various instabilities may commonly arise within the first gigayear after the system's birth. During this phase, the system experiences quasi-stable periods interrupted by more or less violent restructuring episodes. These events may result in orbital reconfigurations, collisions, gravitational captures or ejections. During these catastrophic events, planetesimals, asteroids or debris may be pushed towards the central region and fall onto the inner objects and/or the central stars.

Evidence for such phenomena are observed in our solar system. Planetary formation theories suggest that the giant planets formed on orbits different from their current path (Tsiganis et al. 2005). The mass(Stern 1996, O'Brien et al. 2007), the location (Gomes et al. 2005; Thommes et al. 2007) and the dynamical structure of the Kuiper and asteroids belts (Chiang et al. 2007; Morbidelli et al. 2008) are also expected to have changed over time. Moreover its has been known that the inner solar system experienced about 700Myr after its birth a 50-200Myr period of planetesimals bombardment that probably originated from the existing asteroid belt. This catastrophic episode is referred to as the Large Heavy Bombardment (Gomes et al. 2005; Morbidelli et al. 2005; Tsiganis et al. 2005).

2. The thermohaline instability

The accretion of planetary (metal-rich) material onto a star produces a brutal increase of its surface metal content. The metal-rich accreted material is rapidly mixed within the surface convective zone: a metal-enriched zone may then overlay lighter layers which produces a positive molecular weight gradient (with $d\ln\mu/dr > 0$) in the external regions of the star. This situation is highly unstable against thermohaline convection. This process leads to partial mixing of the stellar material which proceeds until a stable stratification has been restored.

The modelling of the thermohaline mixing has been a matter of debate for more than 30 years. It may generally be described as a diffusion process. Several expressions for the corresponding diffusion coefficient have been given in the literature (see a general discussion in Théado & Vauclair 2012) but recent determinations of the diffusion coefficient deduced from 2D and 3D simulations (Denissenkov 2010, Traxler et al. 2011) seem to converge towards comparable expression of the mixing coefficient.

In this context, the aim of this work is to investigate the effects of accretion and thermohaline mixing on the stellar lithium and beryllium, using the most recent determinations for the thermohaline diffusion coefficient .

3. Computations

We computed stellar models using the Toulouse-Geneva stellar evolution code. These models have masses ranging between 0.7 and $1.3M_\odot$, they include:

- Atomic diffusion: computed for H, He, Li, Be, B, C, N, O, Ne, Mg, Ca, Fe.
- Accretion episode : we assume that stars could swallow planetary material during their early main sequence life. The accretion of a given amount of matter is modelled through an instantaneous increase of the metal content of the convective envelope. The composition of the impacting object is assumed similar to the solar mixture determined by Grevesse & Noels (1993) but devoid of H and He. The composition of the surface convective zone is computed again after each accretion episodes taking into account the newly accreted material but the stellar structure is supposed unaltered by the accretion phenomenon.
- Thermohaline convection: the thermohaline mixing is modelled as a diffusion process following the prescription proposed by Traxler et al. (2011).

We tested various accretion scenarios: 1 to 15 accretion events were introduced in our models with various accretion rates for a total accreted mass ranging from $1M_\odot$ to $1.5M_{Jup}$ (where M_{Jup} represents the mass of Jupiter). We present here a choice of our models, representative for all the computations done.

4. Results: accretion phenomena onto solar type stars

We present results obtained for several $1.10M_\odot$ models (with Y_0=0.29, [Fe/H]=0.20 and the Grevesse & Noels (1993) initial metal mixture) experiencing 1, 5 or 10 accretion episodes each of $1M_\oplus$ or of one Jupiter core ($\simeq 0.03M_{JUP}$). The accretion period starts at 2 Myr on the ZAMS and the accretion episodes are tentatively separated by 2Myr. Figure 1 presents the variations of the surface metallicity of the models during the accretion/mixing period. It shows that each accretion event induces a metallicity increase which depends on the accretion rate. For the considered accretion rates and number of impacts, the overmetallicity does not exceed 0.08 dex. After the end of the accretion period, the overmetallicity decreases under the combined effects

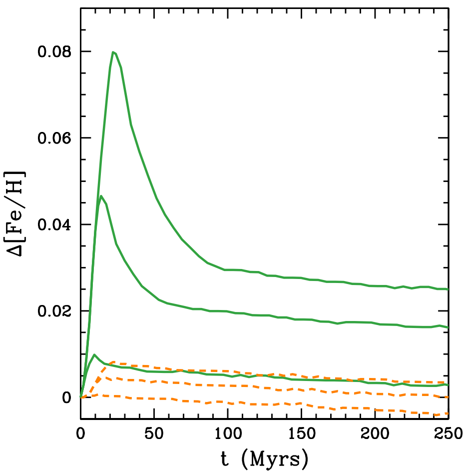

Fig. 1. Variations of the surface metallicity over the accretion/mixing period. Δ[Fe/H] is the difference between the current surface metallicity and its initial value. Orange lines are models experiencing (from bottom to top): 1, 5, or 10 accretion events of $1M_{\oplus}$. Green lines are models experiencing (from bottom to top): 1, 5, or 10 accretion events of $0.03M_{Jup}$.

of thermohaline mixing and atomic diffusion, which makes heavy elements diffuse out of the surface convective zone. When the mixing stops (i.e. before 250 Myr for all the presented models), the remaining metallicity increase is smaller then 0.03 dex and is unable to explain the average overmetallicity of 0.2dex observed in EHS.

Figure 2 displays the lithium and beryllium abundances variations over the accretion/mixing period. The thermohaline mixing induced by the accretion of planetesimals allows connecting the stellar surface with the Li/Be nuclear burning region. This process may decrease the surface Li and Be abundances, with a depletion rate depending on the accretion rate and the number of impact events. The Be nuclear-depleted zone being deeper than the Li one, the obtained Be destructions are smaller than the Li ones. At the end of the accretion/mixing period, a large dispersion in the Li/Be abundances is expected depending on the accretion scenario experienced by the star.

5. Conclusions

Accretion of planetary matter onto solar type stars is probably a common phenomenon. In this framework we have investigated the effects of this process on the surface chemical composition of young main sequence stars. We have shown that the dilution of metal-rich material in the surface convective zone creates an unstable μ-gradient at the transition between the convective and radiative zones. The induced thermohaline instabilities result in a mixing which dilutes the metal-rich matter until the μ-stratification becomes stable. The combined effects of thermohaline convection and atomic diffusion soften the μ-gradient on a few tens of million years, depending on the considered accretion scenario. At the end of the accretion/mixing period, only a very small overmetallicity increase may remain, consistent with a primordial origin of the 0.2 dex overmetallicity observed in EHS. On the other hand, the thermohaline mixing allows connecting the stellar surface with the Li/Be-nuclear burning region which may lead to rapid Li-depletion depending notably on the accretion rate, the frequency and the number of impacts experienced by the star. In this context, we suggest that the accretion/thermohaline mixing process may be an important parameter in the description of the Li dispersion in solar type stars. Stars which accrete more than 10 Earth masses are expected to be subject to strong Li depletion. This process could be an elegant explanation for the observations of stars in which strong Li depletion is found.

A large dispersion in the lithium abundances is also observed in the extremely metal poor stars (i.e. with $[Fe/H] < -2.8$) (cf. Ryan et al. 1999; Bonifacio et al. 2007; Aoki et al. 2009, Sbordone et al. 2010, Sbordone et al. 2012a,b). Some of these stars are located on the Spite Plateau, whereas a growing number of them are detected with a smaller abundance. Moreover the main sequence stars with $[Fe/H] < -4$, present large Li destructions allowing to determine only upper limits for their Li abundances. Accretion phenomena could also bring an explanation for these observations.

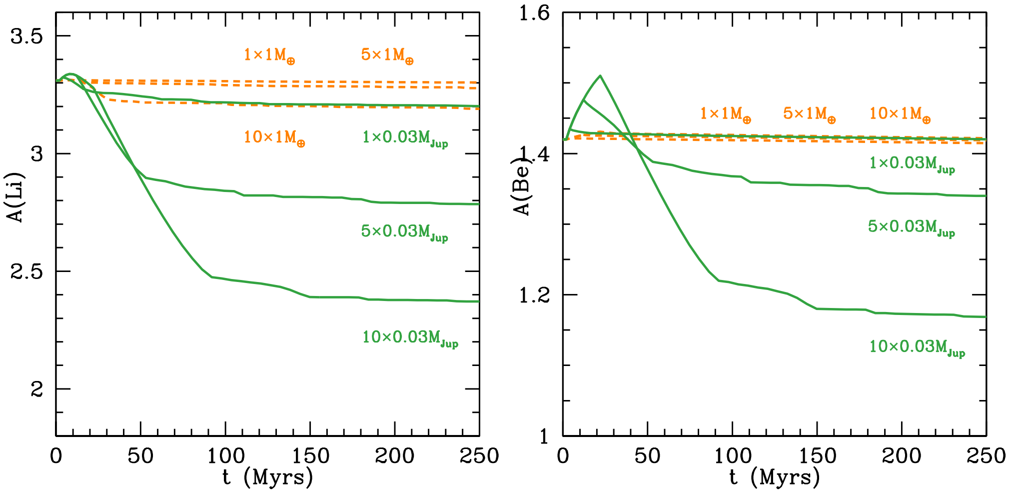

Fig. 2. Variations of Li and Be abundances along the accretion/mixing period. The initial Li and Be abundances are taken from Grevesse & Noels (1993) and, respectively equal to 3.31 and 1.42. The curves are labelled according to the number of accretion episodes and the accretion rate undergone.

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