Fingering instabilities induced by the accretion of planetary matter onto stars :

The lithium case. Application to the 16 Cygni stellar system.

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Context

The bright solar analogs 16 Cyg A and 16 Cyg B represent a very interesting stellar system for many reasons. The two stars are separated enough to be studied in the same way as two isolated stars, with no common dynamical effects. This situation allows for precise differential studies between a planet-host star and a non-planet-host star with similar birth conditions. The presence of the brown dwarf around 16 Cyg A may be the reason why no accretion disk could have developed around it, whereas a planetary disk remained around 16 Cyg B, including the observed giant planet, and probably smaller still unobserved bodies. The metallic abundances of these two stars are very close but the surface lithium abundance of 16 Cyg B is smaller than that of 16 Cyg A by at least a factor 4,7. The interest of this study is that these stars have the same birth site and the same age, with masses of the same order, so that their past evolution is similar for most aspects. The observed differences between them must basically be due to the presence of a planetary disk around B. We studied the properties of these two stars by computing models with the Toulouse Geneva Evolution Code (TGEC). We identified the stellar oscillation frequencies (computed with the PULSE code) with the Kepler observations to derive the best models. We then tested the effect of accreting planetary matter on the lithium abundance of 16 Cyg B.

	16 Cyg A	16 Cyg B
T_{eff}(K)	5821 ± 25	5747 ± 25
Log(g)	4.293 ± 0.001	4.359 ± 0.001
Mass ($M_\odot$)	1.102 ± 0.010	1.058 ± 0.010
Radius ($R_\odot$)	1.239 ± 0.010	1.129 ± 0.010
Age (Gyrs)	6.400 ± 0.025	6.400 ± 0.025
Z_i	0.024 ± 0.001	0.024 ± 0.001
Y_i	0.26 ± 0.01	0.26 ± 0.01

Table 1: Characteristics of 16 Cygni A and B modelled in this work

Fingering (thermohaline) convection

In stars, fingering (thermohaline) convection occurs every time heavy matter comes upon lighter one, in the presence of a stable temperature gradient. This may happen in the case of accretion of planetary matter (Vauclair et al. 2004, Garaud et al. 2011, Théado et al. 2012, Deal et al. 2013), in the case of a local heavy element accumulations due to radiative accelerations which lead to an increase of μ and in some other cases.

Fingering convection is characterised by the so-called density ratio R_0 which is the ratio between thermal and compositional gradients:

$$R_0 = \frac{\nabla - \nabla_{ad}}{\nabla_\mu}.$$

This instability can only develop if the thermal diffusivity is larger than the molecular one. This means that a heavy blob of fluid falls in the star and keeps falling because heat diffuses more rapidly than the chemical elements. Fingering convection cannot occur if the ratio of the diffusivities becomes smaller than ratio of the gradients, which leads to the following condition:

$$1 < R_0 < \frac{1}{\tau}$$

where τ is the inverse Lewis number, ratio of molecular and thermal diffusivity. For values of $R_0 < 1$ the region is dynamically convective (Ledoux criteria) and for values of $R_0 > 1/\tau$ the region is stable.

Accretion

We computed models of 16 Cyg A and B with initial parameters as given in Table 1, which fit precisely the observed oscillation frequencies (Deal et al. 2015). Here we show how the accretion of planetary matter (earth composition) on B at the beginning of the MS induces fingering convection, which decreases the surface lithium abundance (Fig 1).

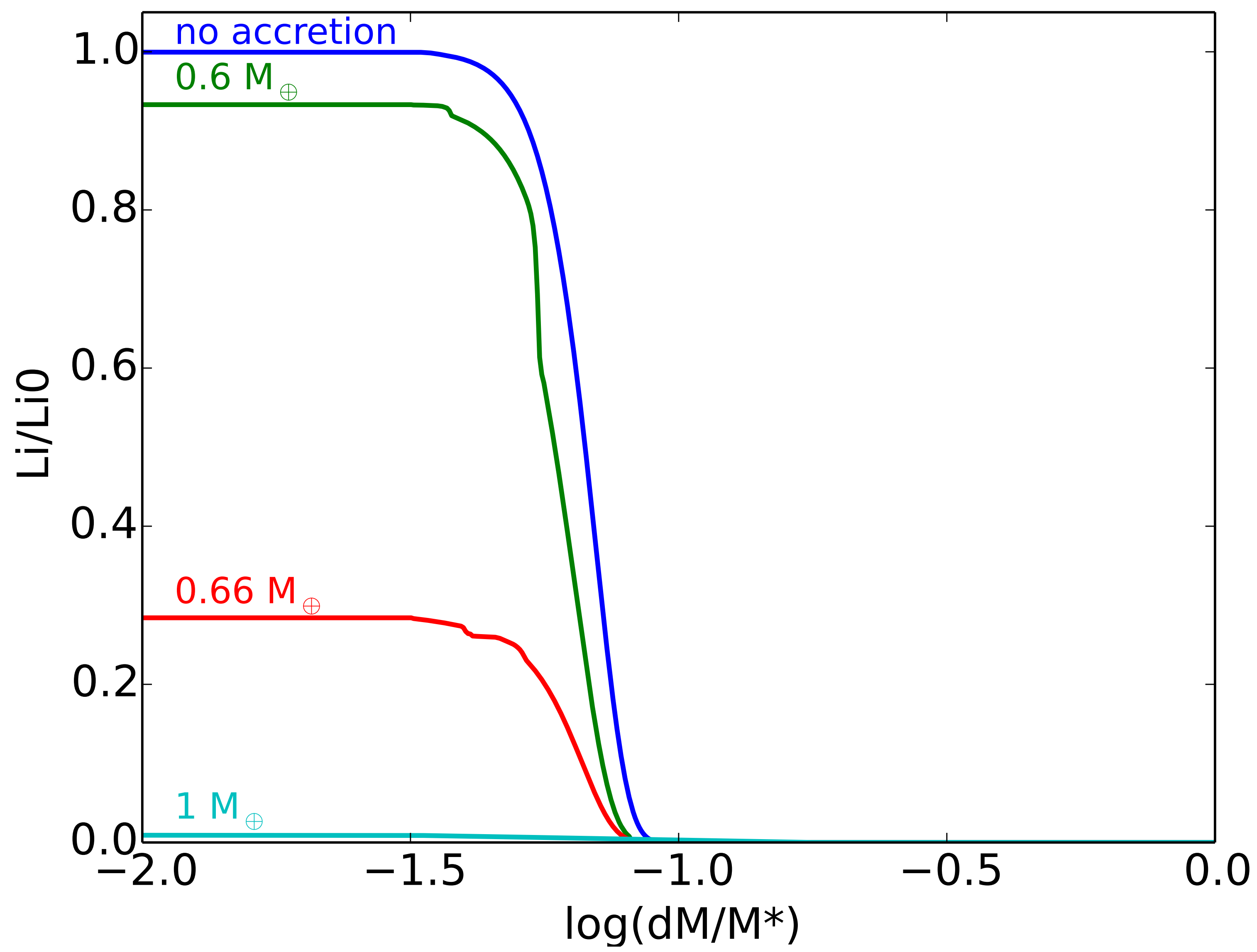

Figure 1: Li abundance profiles just after accretion of different mass at the beginning of the MS for 16 Cygni B models.

Accreted masses lighter than 0.6 $M_\oplus$ only have a small impact on the Li surface abundance because the μ-gradient is not large enough. For larger accreted masses, fingering convection mixes elements down to the lithium destruction zone and may reduce significantly the Li surface abundance.

Results

The Li abundance ratio between 16 Cyg A and B is too large to be accounted for by traditional mixing processes (rotation, internal waves, ...) when it is adjusted to obtain the right depletion for A. If we begin with the same initial lithium, the ratio at the age of the stars is less than 3, whereas the observed ratio is larger than 4.7 (Fig 2). We computed models of B in which we assumed accretion-induced fingering convection at the beginning of the evolution. Then the Li abundance was followed in the same way for the two stars. We show that in this case, an accretion mass of 2/3 $M_\oplus$ is enough to account for the larger depletion observed in B.

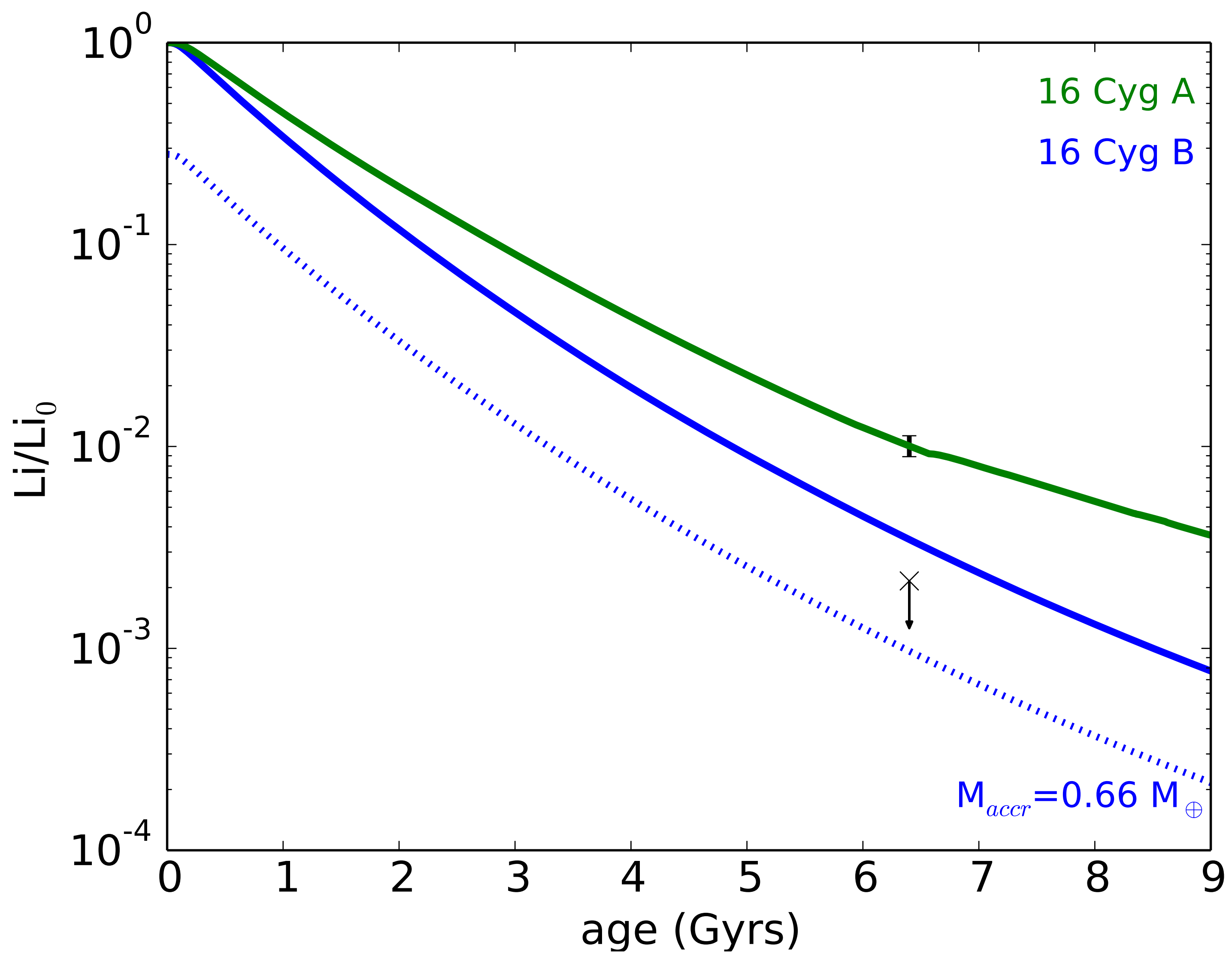

Figure 2: Time variation of Li surface abundance. Black crosses are Li abundances from observations (King et al. 1997).

Furthermore the observed Li surface abundance of 16 Cygni B is an upper limit so that a larger accretion mass may be needed to explain the observations.

Conclusions

- The accretion of planetary matter onto stars leads to fingering convection which has to be taken into account when computing the abundance variations of the elements. Due to this extra mixing, the accreted heavy elements are diluted inside the star, so that no overabundance remain at the surface. On the other hand, lithium may be destroyed if the mixing zone reaches the lithium destruction region.
- Only a fraction of earth mass is needed to account for the observations in the 16 Cygni system.

Forthcoming Research

This extra mixing may happen in many cases, every time stars accrete heavy matter. The 16 Cygni system is very instructive in that respect. We are going to study this effect in more details, for other stars, including very metal poor stars, CEMPs and other cases. We will also computed models with the Montreal-Montpellier code, which treats the diffusion processes with a numerical scheme different from the TGEC one, to test the robustness of our results.

References

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