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BERYLLIUM IN LITHIUM-DEFICIENT F STARS : CONSTRAINTS ON STELLAR EVOLUTION

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ABSTRACT Standard stellar evolution predicts that F stars should retain their initial surface lithium (Li) abundance because their convection zones are too shallow to destroy it at their base. Yet, observations reveal a severe Li depletion (the "Boesgaard Gap"), perhaps by as much as about two orders of magnitude, in a narrow T_{eff} range. Several physical mechanisms, not usually included in stellar evolution calculations, have been proposed to account for this Li deficiency. These include diffusion, mass loss, meridional circulation, and rotationally-induced mixing driven by angular momentum loss. Identifying which of these (if any) might really be at work is not only of vital interest to stellar evolution, but may also have serious implications elsewhere (e.g. cosmology, Deliyannis *et al.* 1991). We bring attention to beryllium (Be) observations in F stars, which are crucial for discriminating between scenarios. Particularly important is the star 110 Her, which is depleted in Be by about a factor of 5 - 10, but still has a *detectable* Li abundance (depleted by a factor of 100 - 200). Depleting surface Be without having depleted nearly all of the surface Li requires specific circumstances ; we discuss how *this depletion property severely constrains or eliminates most of the proposed mechanisms*. One mechanism, rotationally-induced mixing, predicts relative depletions for these elements that agree well with what is observed.

1. INTRODUCTION

Boesgaard and Tripicco (1986) discovered that, in a narrow T_{eff} region of a few hundred degrees, F stars deplete severely their surface Li abundance, and do so primarily during the main sequence (Boesgaard *et al.* 1988). This startling discovery blatantly contradicted standard stellar evolution theory. Already at the ZAMS, the model surface convection zone (SCZ) occupies only a small fraction of the Li preservation region ; hence, surface Li is not affected. To explain the Li gap, proposed additional physical mechanisms have proliferated, and it is not yet clear which (if any) are correct. Using Li and Be together to decipher the signature of the responsible mechanism(s) is powerful because Be survives to about twice the ZAMS depth that Li does. Thus, the effect of each mechanism on surface Be will in general be different.

We assume that solar metallicity stars typically formed with the Li and Be abundances measured in meteorites : 3.31 ± 0.04 and 1.42 ± 0.04 (Anders and Grevesse 1989, where abundance = $12 + \log [N_{\text{element}} / N_H]$). In the Hyades, mid-F stars are depleted in Be by a factor of 0 – 2 relative to late-F stars, and by a factor of 1.5 – 4 relative to Be_{met}. Field G dwarfs are depleted by 0 – 4 and in the same stars Li depletion ranges from 5 - 200 (Fig. 1). *F stars show a Be gap,* and Be depletion factors range from 2 – >100. *Especially important is the star 110 Her, which is (definitively) depleted in both Li and Be,* **but still preserves a detectable amount of Li.** Its depletion factors of 100 - 200 and 5 - 10 provide serious constraints for stellar evolution theory.

2. CONSTRAINTS ON STELLAR EVOLUTION

Simple Microscopic Diffusion. Diffusion mechanisms not related to rotation ("simple diffusion") include gravitational settling and thermal diffusion (downward), and radiative acceleration (upward) ; their efficiency increases with model radius, but can be inhibited (completely) by sufficient mixing. At a given age, the depth of the SCZ decreases with increasing T_{eff}. For Li, settling and thermal diffusion dominate for internal $T > 2 \times 10^5$ K where Li is fully ionized, creating the cool side of the gap (Michaud 1986). For smaller T, Li retains an electron so radiative acceleration dominates, creating the hot side (the availability of more Li to be pushed into the SCZ also helps). However, for $T_{\text{eff}} > 7000$ K, this creates an overabundance of Li by at least an order of magnitude, in contradiction with observation. A small rate of (finely tuned) mass loss has been proposed to eliminate the Li overabundance. *Below 6400 K, Be and Li are predicted to diffuse downward at comparable rates (Michaud and Charbonneau 1991), in contradiction with the observations of field stars (Fig. 1).* Particularly striking is 110 Her, which is at least 10 times more depleted in Li than in Be. At higher T_{eff}, an overabundance is also predicted for Be, *which is not observed.* Since Be retains an electron at higher T than Li, its radiative acceleration begins at lower T_{eff}. It is thus difficult for mass loss to be invoked to eliminate simultaneously both the Li and Be overabundances.

Main Sequence Mass Loss. To produce the morphology of the Li gap (Schramm *et al.* 1990), and with the correct timing, mass loss rates must vary across the Li gap in an exceedingly finely tuned manner. To deplete Be, mass loss must first deplete **all** the observable Li. *This is in stark contrast to 110 Her.* Furthermore, the high Li abundances of the stars in Fig. 1 contradict mass loss if ANY of these stars are in fact depleted in Be by a factor of 2-3.

Meridional Circulation plus Radiative Acceleration. In this model (Charbonneau and Michaud 1988), circulation increases with model radius and rotation rate, creating the cool side of the Li gap. For hotter stars, radiative acceleration must be invoked to overcome circulation and create the hot side of the gap ; the objections raised above apply here as well.

Rotationally-Induced Mixing. The Yale models spin-down through angular momentum (J) loss, and include a comprehensive treatment of instabilities that result in the transport of J and mixing (see Pinsonneault in this volume). Li destruction is related to J(total) lost. Initial J (J_0) in F stars is observed to increase with mass ; its loss results in the cool side of the gap. Hotter stars are not observed to spin down ; this results in the hot side of the Li gap. A spread in Li abundances is the natural result of a spread in J_0. Mixing time scales are roughly comparable to the evolutionary time scale, so mixing can resemble a dilution process. Thus, Be and Li can both be depleted at the same time, without catastrophic depletion of Li. *The Yale models match the depletion of Li and Be in 110 Her* (e.g. for an age of ~ 5 Gyr and a normal J_0, or younger ages and a higher J_0). The models also agree well with stars that have (Li,Be) depletion of (5-50,1.5-3), and can severely deplete Be at advanced ages.

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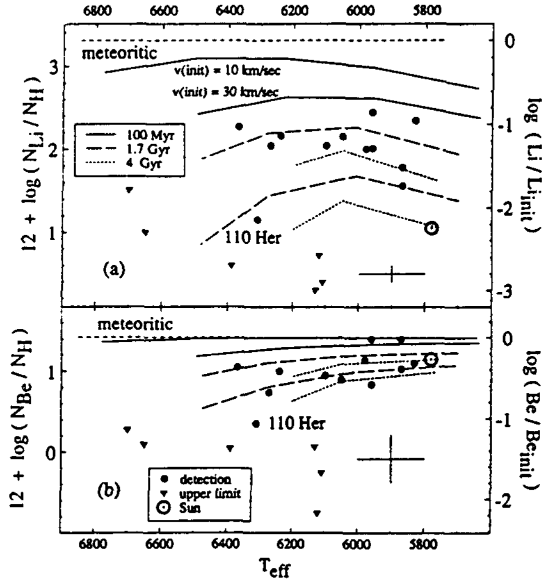

Figure 1. Li (a) and Be (b) abundances (left scale) in field F and early G stars (Boesgaard and Lavery 1986, ApJ, 309, 762, and references therein) plotted against isochrones from models with rotationally-induced mixing (right scale), with a likely range in v(initial) at each age. It is crucial that new observations determine whether other stars have the properties of 110 Her.