Beryllium abundances in old open clusters

Sofia Randich

*Osservatorio di Arcetri, Large E. Fermi 5, I-50125, Firenze, Italy*

Francesca Primas and Luca Pasquini

*European Southern Observatory, Karl Schwartzschild Str. 2, D-80457, Garching bei München, Germany*

Roberto Pallavicini

*Osservatorio di Palermo, Piazza del Parlamento 1, I-90134, Palermo, Italy*

**Abstract.** Thanks to the very high near-UV performances of UVES at VLT UT2, we have obtained for the first time high resolution spectra in the Be II resonance doublet region of solar-type stars in the old open clusters M 67 and IC 4651. The comparison with the solar Be abundance and the abundance of a solar-analog in the young cluster IC 2391 suggests that solar-type stars, including the Sun, do not undergo any Be depletion during their first \( \sim 5 \) Gyr on the main sequence, implying a rather shallow mixing. We do not find any evidence of correlated Li and Be depletion; in addition, none of the available models can reproduce the light element patterns observed among cluster stars.

1. Introduction

Standard models of stellar evolution include convection only as a mixing mechanism and are not able to explain observed lithium patterns among field and cluster stars (e.g., Jeffries 2000). The factor of 140 Li depletion in the Sun itself cannot be explained as due to the action of convection since, according to standard models, the convective zone of solar-type stars on the main sequence (MS) does not reach deep enough layers to enable Li destruction (e.g., Pinsonneault 1997). Whereas several models have been developed, which take into account a more complex physics, including mass loss, diffusion, slow mixing driven by rotation or gravity waves (Swenson & Faulkner 1992, Chaboyer et al. 1995, Deliyannis & Pinsonneault 1997, Montalbán & Schatzman 2000), these models are still very poorly constrained; in particular, the question remains how deep in the stellar interior the mixing extends.

Since Be burns at temperatures \( 10^6 \) deg higher than Li (Li and Be are destroyed by proton capture at the temperatures of 2.5 and \( 3.5 \times 10^8 \) K, respectively), the simultaneous determination of Li and Be abundances in the same star traces stellar mixing to different depths, thus providing stringent observa-
Figure 1. Comparison of the spectra in the Be (top panel) and Li (bottom panel) spectral regions of the stars S1252 (solid line) and S1256 (dashed line) in the old cluster M 67. The figure clearly shows the lack of correlated Li and Be depletion; whereas a large difference in Li strengths is evident, the spectra in the Be region do not show a significant disagreement.
Figure 2. log n(Be) vs. T_{eff} for our sample stars (circles: M 67, triangles: IC 4651, star: α Cen A). Model predictions are shown in the figure. Dot-dashed curves indicate the predictions of gravity waves (kindly provided by J. Montalbán), dotted and dashed curves indicate the predictions of rotationally induced mixing with initial rotations of 10 and 30 km/sec (Deliyannis & Pinsonneault 1997). Upper and lower curves are for ages of 1.7 and 4.0 Gyr, respectively. The curves have been normalized to the initial abundance log n(Be)= 1.11 obtained for the young star in our sample.

Additional constraints on model predictions. Evidence exists that Be is undepleted in the solar photosphere (Balachandran & Bell 1998), indicating that mixing in the solar interior is shallower than previously thought; the finding of little or no Be depletion in the Sun however cannot be regarded as a general conclusion since it relies on absolute abundance measurements, which are hampered by large uncertainties (Balachandran & Bell 1998) and it is based on one star only. Beryllium measurements in homogeneous samples of stars, such as stellar clusters, with well determined evolutionary status, chemical composition, and age, are instead crucial in order to constrain proposed mixing models.

The best observable Be feature, the Be II resonance doublet (λλ = 3130.420 and 3131.064 Å), lies close to the atmospheric UV cutoff; observations of Be are thus very challenging and have so far been limited to the brightest stars observable in the field (e.g., Primas et al. 2001) and in the close-by Hyades and Ursa Major clusters (Boesgaard & Budge 1989, García López, Rebolo, and Perez de Taoro 1995, Boesgaard & King 2001). Thanks to the superior near-UV capabilities of UVES on VLT Kueyen (Dekker et al. 2000), we acquired for the first time high resolution spectra of the Be region of 14th magnitude solar–analogs in old clusters. We present here our main results.
2. Sample stars and observations

Our sample includes five solar-type members of the solar age M 67 cluster (4.5 Gyr), three solar-type members of the 1.7 Gyr old IC 4651, the solar-analog α Cen A, and one member of the young (50 Myr) cluster IC 2391. This star has just arrived on the zero age main sequence and it is undepleted in Li (Randich et al. 2001); under the fully reasonable assumption that it is also undepleted in Be, it provides an indication of the initial Be abundance and a zero point to our abundance scale. No known binaries are included in our sample.

The observations were carried out using UVES on VLT UT2 (KUEYEN); UVES was operated in Dichroic Mode using Cross Dispersers #1 and #3 in the Blue and Red arms, respectively. Such a combination allowed us to cover the spectral ranges from \( \sim 3115 \) to 3940 Å in the blue and from \( \sim 4780 \) to 6810 Å in the red, covering both the beryllium and the Li 6707.8 Å regions. We used a 1 arcsec wide slit and CCD binning 2 x 2 and 1 x 1 in the blue and red, respectively, providing resolving powers R ~ 40,000 and R ~ 45,000. The spectra were reduced using MIDAS and following the usual steps. Typical S/N ratios range between 30 and 50 in the Be region and between 150 and 200 in the Li region. In Fig. 1 we show the comparison of the spectra of two M 67 members in the Be and Li spectral regions.

3. Analysis

Effective temperatures were determined based on B–V colors using the same calibration employed in similar studies (Soderblom et al. 1993). A surface gravity \( \log g = 4.44 \) and microturbulence \( \xi = 1.1 \) km/sec were assumed for all sample stars. Li and Be abundances were derived in a consistent way using Kurucz model atmospheres (including overshooting) and codes (ATLAS9, SYNTHE, and WIDTH9 –Kurucz 1993). Be abundances were determined by spectrum synthesis; a consistent spectrum synthesis of the solar spectrum provides solar Be abundance \( \log n(\text{Be})_\odot = 1.11 \). Li abundances were instead derived from the measured equivalent widths of the Li I 6707.8 Å feature. Errors in the derived abundances include the sensitivity of both Be and Li abundances to uncertainties in all the stellar parameters, to the placement of the continuum (in the case of Be), and to errors in the measured Li EWs. Most important, thanks to our choice of targets of very similar nature and macroscopic parameters, we can safely compare the relative light element abundances of our sample stars without being affected by systematic effects and possible problems such as that of the “missing continuum opacity” (Balachandran & Bell 1998), which affected the determination of the solar Be abundance.

4. Results

In Fig. 2 we plot \( \log n(\text{Be}) \) vs. effective temperature, while \( \log n(\text{Be}) \) vs. \( \log n(\text{Li}) \) is plotted in Fig. 3. Model predictions are also shown in the figures. Figure 2 clearly indicates that all our sample stars and the Sun have, within the errors, the same Be abundances. For the three clusters we derive similar, about solar, metallicity which is indicative of a similar initial Be abundance (Boesgaard

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the finding of a similar present-day Be abundance thus implies that solar-type stars, including the Sun, do not burn Be while on the MS. Our result strongly supports the hypothesis of a shallow mixing process that can transport surface material down to the Li burning layer, but not deep enough to destroy Be. Cluster stars behave as our Sun, indicating that it is not peculiar.

Be surveys among field stars (e.g., Stephens et al. 1997) have suggested the existence of a correlation between Li and Be depletion which was interpreted as the proof of the action of slow mixing driven by rotation; a similar result was found by Boesgaard & King (2001) for Hyades dwarfs warmer than 5850 K \(^1\). At odds with this finding, Fig. 3 does not show any evidence of correlated Li and Be depletion. However, this contradiction may be only apparent, since the detection of a Li-Be correlation among field stars is based on samples including stars much warmer than the Sun for which the same mixing mechanism may not necessarily be at work; in agreement with our results, no correlation between Li and Be is indeed found for Hyades stars cooler than 5850 K, although this is not explicitly discussed by Boesgaard & King (2001).

The comparison with model predictions clearly shows that none of the currently available and best elaborated models, at least in their current formulation, is able to fit all the observed patterns. Models including rotational mixing do not reproduce the Be vs. Li observed distribution nor the Be vs. temperature

\(^1\)We mention that the effective temperatures adopted by Boesgaard & King, (2001) do not seem to be completely consistent with each other, since various stars are present in their sample with the same B−V color, but different \(T_{\text{eff}}\).
pattern. In particular, mixing driven by rotation is not as shallow as required by our observational results and, in contrast with our results, models including rotational mixing predict that a dispersion in Be should be observed when a dispersion in Li is present. Diffusion implies simultaneous Li and Be depletion and thus does not fit the observed Be vs. Li diagram. Gravity wave induced mixing is shallow enough not to burn Be; models including waves indeed provide the best fit to the observed Be vs. Li diagram. Mixing driven by waves, however, is not able to reproduce the Li vs. temperature morphology of M 67 and, in particular, the dispersion in Li observed among clusters stars. We have not taken into account in this discussion Li depletion due to mass loss. Models including mass loss (Swenson & Faulkner 1992) predict that Be depletion starts only when Li has been completely depleted and thus they would be qualitatively in agreement with our results. Mass loss, however, has been convincingly shown not to work when applied to Li data alone (Swenson & Faulkner 1992).

In conclusion, our new high-quality data show that the problem of depletion of light elements during the MS phases of solar–type stars, Sun, needs further investigation on theoretical grounds.

References

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