Beryllium, Lithium and Oxygen Abundances in F-type Stars

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Abstract. Beryllium and oxygen abundances have been derived in a sample of F-type field stars for which lithium abundances had been measured previously, with the aim of obtaining observational constraints to discriminate between the different mixing mechanisms proposed. Mixing associated with the transport of angular momentum in the stellar interior and internal gravity waves within the framework of rotating evolutionary models, appear to be promising ways to explain the observations.

1. Introduction

We present new beryllium and oxygen abundances in old disk-population F-type field stars with available Li abundances derived by Balachandran (1990). Stellar parameters ($T_{\text{eff}}$, $\log g$, [Fe/H], $M_V$, and $v \sin i$) were also taken from this work. Their masses were estimated by dividing the stars into three similar groups of metallicity and

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comparing their \((M_V, T_{\text{eff}})\) values with the evolutionary tracks of VandenBerg (1985) corresponding to \([\text{Fe/H}] = 0.00, -0.23,\) and \(-0.46\), respectively.

The 51 stars observed span from 5900 to 7000 K in \(T_{\text{eff}}\), from \(-0.65\) to \(0.20\) in \([\text{Fe/H}]\), and from \(0.9\) to \(1.7\) \(M_\odot\). Recently revised ages, based on \(M_V\) values derived from \textit{Hipparcos} parallaxes (Ng & Bertelli 1997) are available for 17 stars in the sample (covering the whole range of metallicity), showing that the ages of the stars are within the interval of 1.8 to 6.6 Gyr.

3. Observations and Analysis

A detailed abundance analysis via LTE spectral synthesis has been carried out to derive beryllium abundances, using the \(^9\text{Be II} \lambda 3131\) Å doublet, in 21 stars observed with \(\lambda/\Delta\lambda \sim 5 \times 10^4\) and \(\sim 4 \times 10^4\), using the Utrecht Echelle Spectrograph at the 4.2 m William Herschel Telescope, and the IACUB echelle spectrograph (McKeith et al. 1993) at the 2.5 m Nordic Optical Telescope (NOT), respectively, of the Roque de los Muchachos Observatory (La Palma, Spain). Similar analyses have been carried out previously for the Sun, metal-poor stars, and the Hyades (García López et al. 1995a,b), showing the reliability of the method. The left panel of Figure 1 shows the observed and synthetic spectra for one of the stars.

![Figure 1. Left panel: fitting of a synthetic spectrum to the observed one in the beryllium region of the star HR6541. The feature corresponding to the Be II \(\lambda 3131.065\) Å line (weaker than the other Be line in the doublet but more isolated) is indicated. Right panel: observed spectrum of the same star corresponding to the O I infrared triplet at \(\lambda\lambda 7771–7775\) Å.](image)

Very recently, Balachandran & Bell (1997) have argued that the continuous opacity in the UV region could have not been fully accounted for in previous works, providing abundances smaller than the actual ones. If this were the case, there would be an overall change of scale in the beryllium abundances derived from the Be II \(\lambda 3131.065\) Å line.

Oxygen abundances of 37 stars have been derived using an NLTE analysis of the O I infrared triplet at \(\lambda\lambda 7771–7775\) Å, following the prescriptions employed
by García López et al. (1993). The observations were carried out in two runs using IACUB at the NOT, with resolutions \( \lambda/\Delta \lambda \sim 2.9 \times 10^4 \) and \( \sim 1.8 \times 10^4 \), respectively. An example of the spectra in the O I region is shown in the right panel of Figure 1.

4. Abundances vs. Stellar Parameters

Figure 2 shows the Be and Li abundances (where \( \log (X) = \log(X/H) + 12 \)), as well as the O abundances with respect to the Sun ([O/H]), against stellar mass. All plots have been made with the same range of abundances, and a large scatter can be seen within the Be and Li measurements (filled circles) and upper limits (inverted open triangles), while the dispersion in oxygen abundances is much smaller.

Figure 2. Beryllium, lithium and oxygen abundances (in the latter case with respect to the Sun) against stellar mass for the F-type stars studied. Filled circles represent detections and open inverted triangles upper limits. Different colors correspond to the three bins of metallicity in which the sample has been divided. Note the large scatter for the Li and Be, while O abundances show a tight correlation with mass.

All Be-depleted stars are also Li-depleted, as is expected from their different nuclear reaction temperatures. HR6467 is the star with the least Be detected.
(log N(Be)= −0.55), and there are eight stars with detections in both Be and Li whose abundances are plotted in Figure 3. While the initial or “cosmic”

Figure 3. Upper panel: lithium and beryllium abundances against effective temperature for those stars with clear detections of both elements. Lower panel: beryllium against lithium abundances for these stars.

lithium abundance of these F-type stars can be estimated around log N(Li)~ 3.1 − 3.3, the initial Be abundance for the eight stars could vary, in principle, depending on their metallicity (due to the steep relation observed between Be and [Fe/H] and associated with spallation reactions between cosmic rays and C, N, and O nuclei in the interstellar medium; e.g. Rebolo et al. 1995; Molaro et al. 1997). However, given that their range in [Fe/H] is very small (−0.30 to 0.20) it is conceivable that their initial abundances were not very different. If so, the correlation seen in the lower panel of Figure 3 and the mean ratio log (Li/Be)= 1.7 ± 0.3 obtained from these stars could be used to constrain the mechanism responsible for the Li and Be depletions among them. This ratio would change to a smaller value if the UV continuous opacity were wrong as suggested by Balachandran & Bell (1997).

While there is no qualitative change in the distribution of Be or Li abundances against $T_{\text{eff}}$ and mass, indicating that the depletion mechanism is not related only to the stellar structure, the scatter of the oxygen abundances decreases and a significant correlation appears when plotting them against mass...
instead of against effective temperature. We have no clear explanation for this at present, and the radiative accelerations on oxygen computed by González et al. (1995) for A- and F-type stars do not even reproduce the observed abundances.

5. Mixing Mechanisms

The mechanisms proposed for explaining the Li depletion in F-type stars can be divided into two different groups: those which invoke nuclear burning of the Li atoms and those in which this is not necessary.

From the latter group, superficial mass loss (Schramm et al. 1990) has been shown not to be a reliable mechanism (e.g. Swenson & Faulkner 1992). Microscopic diffusion (Michaud 1986; Richer & Michaud 1993) operates where the material sinks below the surface convection zone because the internal radiation pressure is not capable of supporting the weight of the nuclide concerned. Michaud (1988) suggested that if the radiative acceleration is insufficient to support Li in the outer layers of an F-type star, the same could then hold for nitrogen and oxygen. However, not only do the oxygen abundances shown in Figure 2 not show any sign of depletion (either in F-type stars of open clusters; García López et al. 1993), but neither do the radiative accelerations computed by González et al. (1995) reproduce the observed abundances for these elements. Furthermore, recent work (e.g. Balachandran 1995) provides complementary information which suggests that the Li depletion in old clusters is not related to microscopic diffusion.

Rotation plays an important role in late-type stars of open clusters, where high rotational velocities seem to inhibit the Li depletion (e.g. García López et al. 1994; Barrado y Navascués & Stauffer 1996). Mixing mechanisms directly related to rotation, such as meridional circulation (Charbonneau & Michaud 1988) or rotationally induced turbulent mixing (Vauclair 1988; Charbonnel et al. 1992), have been proposed within the former group. While meridional circulation faces several problems in explaining the Li abundances in F-type stars (e.g. Balachandran 1990), rotationally induced mixing (after adding an important amount of pre-MS Li depletion) would marginally reproduce the Li and Be abundances observed in the Hyades (García López et al. 1995b).

Pinsonneault et al. (1989, 1990) and Deliyannis & Pinsonneault (1992) computed rotating evolutionary models including angular momentum loss, in which mixing of material is associated with the transport of angular momentum in the interior of the star. Although the models of Pinsonneault et al. can reproduce the light-element depletion trends observed in Figure 2, they can explain the observed Li and Be abundances in the Hyades (where the age is fixed) only if the initial angular momenta of the late-type stars were progressively larger for decreasing stellar mass (García López et al. 1995b). Very recently, however, Deliyannis et al. (1997; private communication) show that the predictions from rotating models can follow the Be vs. Li trend observed in an independent sample of stars. A different constraint on the rotation-induced turbulent diffusion used by Pinsonneault et al. (1989) comes from the fact that this model fails to extract sufficient angular momentum from the radiative solar interior to achieve the flat rotation profile revealed by helioseismology (Brown et al. 1989).
García López & Spruit (1991) proposed a mixing mechanism for F-type stars based on a weak turbulence induced by internal gravity waves, which is able to explain the Li abundances in the Pleiades and Hyades, as well as the Be measurements in the Hyades. The waves are generated by the fluctuating pressure of the convective cells at the base of the convection zone. A different version of this formalism was developed and successfully applied to the Sun (Montalbán 1994) and to late-type stars of the Hyades (Montalbán & Schatzman 1996).

However, the published mechanism for F-type stars, which was developed using several simplifying assumptions and aimed at testing the importance of the waves in inducing mixing in these stars, does not predict a large Be depletion for stars of about 1 Gyr (such as those observed in Figure 2). This is now under revision by applying a more refined convection treatment. Furthermore, the mechanism was linked to the stellar mass and age providing abundances which depend only on these parameters, in contradiction with the observations. However, a high rotational velocity could change the temperature distribution in the stellar interior (Martín & Claret 1996), or it could also block the mechanical energy transfer and/or the generation of internal waves at the base of the convection zone (Spruit 1987; Schatzman 1993), thus providing ways in which the mixing induced by the waves is linked to the rotational velocities, and not only to the stellar structure.

Very recently, Zahn et al. (1997) and Kumar & Quataert (1997) have found that internal gravity waves are also able to transport angular momentum in the stellar interior, operating on a time scale of $10^7$ yr for the solar case, and being consistent with the rotation profile provided by helioseismology.

6. Conclusions

A similar large scatter ($> 2$ dex) have been found for Li and Be abundances in the sample of old F-type stars studied. There is a similar distribution of light element abundances when plotted against $T_{\text{eff}}$ and mass, indicating that the depletion mechanism is not related only to the stellar structure.

Oxygen abundances are within $\pm 0.5$ dex of the solar value (except for the most massive star showing $[\text{O/Fe}]= 0.73$), and appear to be correlated with increasing stellar mass. The abundances are much higher than those predicted by theoretical radiative accelerations and do not show any dramatic sign of microscopic diffusion.

Beryllium and lithium have been simultaneously detected in eight stars with a $\sim 1.5$ dex range of depletions. Assuming similar Li and Be initial abundances for all of them (within a small range of $[\text{Fe/H}]$), their Li/Be ratio would serve to constrain proposed mixing mechanisms.

Since there are physical mechanisms linking the transport of angular momentum and mixing of material in late-type stars to the presence and propagation of internal gravity waves in the stellar interior, which satisfy observational constraints imposed by the solar rotation profile and the light element abundances in the Sun and in two open clusters, and ways have been suggested of relating the production and/or efficiency of the waves to the stellar rotational velocity, the internal gravity waves within the framework of rotating evolution-
ary models appear as a very promising consistent explanation for the Li and Be abundances observed in different open clusters and the field, including the dispersions found at a given $T_{\text{eff}}$ or mass. Mixing directly associated with the transport of angular momentum in the stellar interior is considered also as a possible explanation.

References

Balachandran, S. 1990, ApJ, 354, 310
Balachandran, S. 1995, ApJ, 446, 203
Balachandran S., & Bell, R. A. 1997, this volume
Barrado y Navascués, D., & Stauffer, J. R. 1996, A&A, 310, 879
Brown, T. M., Christensen-Dalsgaard, J., Dziembowski, W. A., Goode, P., Gough, D. O., & Morrow, C. A. 1989, ApJ, 343, 526
Charbonneau, P., & Michaud, G. 1988, ApJ, 334, 746
Charbonnel, C., Vauclair, S., & Zahn, J.-P. 1992, A&A, 255, 191
Deliyannis, C. P., & Pinsonneault, M. H. 1992, in IAU Coll. 137, Inside the Stars, ed. W. W. Weiss, ASP Conf. Series, 40, 174
García López, R. J., & Spruit, H. C. 1991, ApJ, 377, 268
García López, R. J., Rebolo, R., & Martín, E. L. 1994, A&A, 282, 518
García López, R. J., Rebolo, R., & Pérez de Taoro, M. R. 1995b, A&A, 302, 184
García López, R. J., Severino, G., & Gomez, M. T. 1995a, A&A, 297, 787
García López, R. J., Rebolo, R., Herrero, A., & Beckman, J. E. 1993, ApJ, 412, 173
González, J.-F., Artru, M.-C., & Michaud, G. 1995, A&A, 302, 788
Kumar, P., & Quataert, E. J. 1997, ApJ, 475, L143
Martín, E. L., & Claret, A. 1996, A&A, 306, 408
McKeith, C. D., García López, R. J., Rebolo, R., Barnett, E. W., Beckman, J. E., Martín, E. L., & Trapero, J. 1993, A&A, 273, 331
Michaud, G. 1986, ApJ, 302, 650
Michaud, G. 1988, in IAU Coll. 108, Atmospheric Diagnostic of Stellar Evolution: Chemical Peculiarities, Mass Loss, and Explosion, ed. K. Nomoto (New York: Springer), 3
Molaro, P., Bonifacio, P., Castelli, F., & Pasquini, L. 1997, A&A, 319, 593
Montalbán, J. 1994, A&A, 281, 421
Montalbán J., & Schatzman, E. 1996, A&A, 305, 513
Ng, Y. K., & Bertelli, G. 1997, A&A (in press)
Pinsonneault, M. H., Kawaler, S. D., & Demarque, P. 1990, ApJS, 74, 501
Pinsonneault, M. H., Kawaler, S. D., Sofia, S., & Demarque, P. 1989, A&A, 338, 424
Proffitt, C. R., & Michaud, G. 1991, in IAU Symp. 145, Evolution of Stars: The Photospheric Abundance Connection, ed. G. Michaud, A. Tutukov, & M. Bergevin (Montreal: Univ. of Montreal), 41
Rebolo, R., García López, R. J., & Pérez de Taoro, M. R. 1995, in The Light Element Abundances, ed. P. Crane, ESO Astrophysics Symposia, 420
Richer, J., & Michaud, G. 1993, ApJ, 416, 312
Schatzman, E. 1993, A&A, 271, L29
Schramm, D. N., Steigman, G., & Dearborn, D. S. P. 1990, ApJ, 359, L55
Spruit, H. C. 1987, in The Internal Solar Angular Velocity: Theory and Observations, ed. B. R. Durney & S. Sofia (Dordrecht: Reidel), 185
Swenson, F. J., & Faulkner, J. 1992, ApJ, 395, 654
Vauclair, S. 1988, ApJ, 335, 971
VandenBerg, D. A. 1985, ApJS, 58, 711
Zahn, J.-P., Talon, S., & Matias, J. 1997, A&A, 322, 320
Mass ($M_\odot$)

$[\text{O/H}]$

Log $N(\text{Li})$

Log $N(\text{Be})$

$[\text{Fe/H}]>−0.1$

$−0.1>\text{[Fe/H]}>−0.3$

$\text{[Fe/H]}<−0.3$

[Fe/H] $>−0.1$

$−0.1 \text{[Fe/H]} >−0.3$

$\text{[Fe/H]} <−0.3$
