FULL TITLE
ASP Conference Series, Vol. **VOLUME**, **YEAR OF PUBLICATION**
NAMES OF EDITORS

Atomic diffusion in old stars — helium, lithium and heavy elements

Andreas J. Korn and the ADIOS team[1]

Uppsala Astronomical Observatory (UAO), Institute of Astronomy and Space Physics, Uppsala University, Box 515, 75120 Uppsala, Sweden

Abstract. We present strong evidence from high-resolution observations of stars in NGC 6397 that the chemical abundances in the atmospheres of unevolved halo stars are systematically affected by atomic diffusion. The abundance trends identified are in good agreement with models of stellar evolution, if effects due to gravitational settling, radiative levitation and turbulent mixing below the outer convection zone are allowed for. An element-specific diffusion signature is identified for a variety of elements (Li, Mg, Ca, Ti and Fe), for the first time in this class of stars. The observed abundance trends empirically constrain the efficiency of turbulent mixing and the amount of helium settling.

This work has far-reaching implications for the interpretation of chemical abundances and age determinations of unevolved halo stars. In particular, the lithium abundance measured in warm halo stars must be corrected upwards by about a factor to two, bringing it into much better agreement with WMAP-based predictions of Big-Bang nucleosynthesis. Also, absolute isochrone ages of field turnoff and subgiant stars will require systematic downward revisions.

1. Introduction

Atomic diffusion in solar-type stars has been studied for several decades. Whether or not chemical abundances in stellar atmospheres are perfectly constant over billions of years became a question of cosmological relevance when a constant lithium abundance was found in warm halo stars (Spite & Spite 1982) and interpreted to be the relic of Big-Bang nucleosynthesis (BBN). In spite of the existence of an outer convection zone (fully mixed on a convective timescale), early theoretical models for such stars predicted lithium and other metals to sink appreciably towards the stellar centre under the force of gravity (Michaud et al. 1984). However, the efficiency of gravitational settling was shown to depend on stellar mass and model predictions were therefore in conflict with a constant lithium abundance in stars of different mass. Besides, systematic abundance differences between turnoff-point (TOP) stars (in which the accumulated diffusion effects are largest) and red-giant-branch (RGB) stars (in which convection has brought the chemical elements back to the surface) were not found in spectroscopic studies of nearby globular clusters (Gratton et al. 2001).

---

[1] As of 2006, the ADIOS (Atomic Diffusion In Old Stars) team consists of Paul Barklem (UAO), Remo Collet (UAO), Frank Grundahl (Århus, Denmark), Bengt Gustafsson (UAO), Lyudmila Mashonkina (Moscow, Russia), Nikolai Piskunov (UAO) and Olivier Richard (Montpellier, France). The project is led by the main author.

Table 1. Mean spectroscopic stellar parameters and chemical abundances

group (#)	T_{eff} [K]	$\log g$	$\log \varepsilon$ (Fe) [non-LTE]	$\log \varepsilon$ (Li) [LTE]
TOP (5)	6254	3.94	5.23 ± 0.04	2.24 ± 0.05
SGB (2)	5805	3.63	5.27 ± 0.05	2.36 ± 0.06
bRGB (5)	5456	3.37	5.33 ± 0.03	1.37 ± 0.12
RGB (6)	5130	2.56	5.39 ± 0.02	1.00 ± 0.10
Δ_{spec} (TOP – RGB)	1124	1.38	0.16 ± 0.05	1.24 ± 0.11
Δ_{phot} ($v - y$, IRFM)	1108	1.38	–	–
Δ_{phot} ($V - I$, IRFM)	1070	1.38	–	–

More recently, Richard et al. (2005) showed that the addition of turbulent mixing allows for a constant lithium abundance with stellar mass, at the same time lowering the initial lithium abundance by up to 0.5 dex (a factor of three). We show that these theoretical expectations are borne out by observations.

2. Observations and stellar-parameter analysis

To test these predictions, 18 stars in NGC 6397 were observed with the multi-object spectrograph FLAMES-UVES on the VLT in 2005: five TOP stars, two subgiants, 5 base-RGB (bRGB) and 6 RGB stars. The resolving power of the fibre-feed to UVES is $R = 48\,000$. For the TOP stars, total integration times of 12 h were needed to reach a S/N of 80 per pixel near Hα.

We made every effort to produce data as homogeneous as possible. By nature, the line strength of a given line varies between the four groups of stars with giants generally displaying stronger lines. We limited the analysis to lines weaker than 100 mÅ and chose the weakest well-observed line(s) of a given element. In choosing elements to analyse, we gave preference to those either represented in the spectra by lines of the majority species (e.g. titanium) or which can be treated in non-LTE (magnesium, calcium, iron).

We carried out spectroscopic and photometric stellar-parameter determinations, independent of one another. In short, Hα was used to constrain the effective temperature, while the Fe I/II ionization equilibrium in non-LTE was used to derive $\log g$. The analysis is entirely based on line synthesis. Strong constraints on the stellar parameters also come from broad-band and Strömgren photometry, e.g. Δ log g from ΔV. Table 1 summarizes the main results.

The agreement of both the effective-temperature differences and the surface-gravity differences between spectroscopy and photometry is excellent. Based on these stellar-parameter differences, relative abundance trends can be scrutinized.

3. Abundance results

We find significant and systematic trends of elemental abundance with evolutionary stage for a variety of elements. The size of these trends varies from

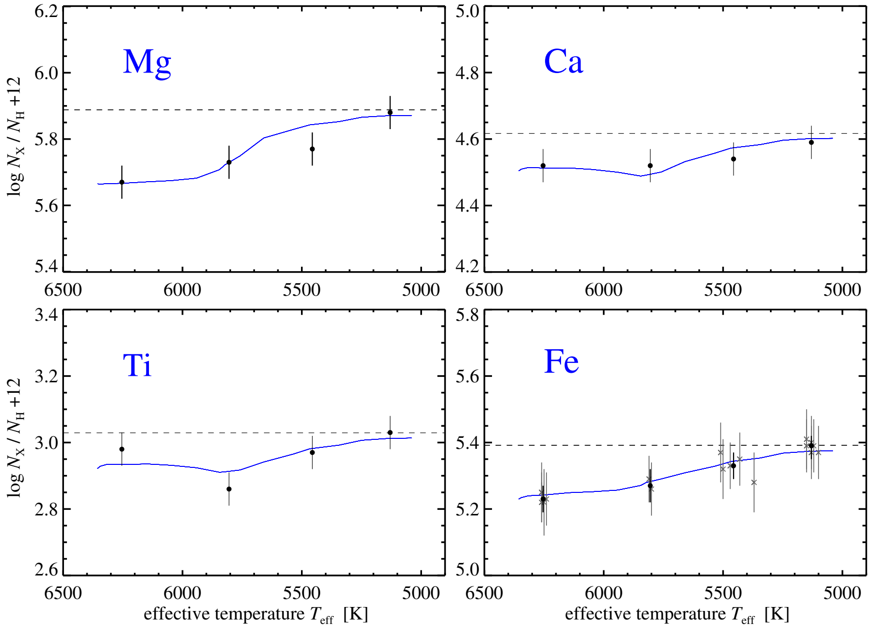

Figure 1. Observed trends of abundance (bullets) with evolutionary stage in NGC 6397. While the abundances of iron are given star-by-star (crosses), the other elements were analysed on mean stellar-group spectra using mean stellar parameters. The full-drawn line gives the element-specific prediction from the diffusion model with turbulent mixing.

elements to element, e.g. it is flatter for calcium and titanium and steeper for magnesium and iron. Based on these abundance trends, we empirically adjust the one free parameter of the stellar-structure model: the overall strength of turbulent mixing (for details see Korn et al. 2006a,b).

Figure 1 compares the measured abundances with the predictions from the diffusion model with turbulent mixing. The overall trends are well-matched, more pronounced trends are clearly predicted for magnesium and iron than for calcium and titanium. This agreement gives strong support to the diffusion interpretation of these abundance trends.

The non-detection of these trends by Gratton et al. (2001) can be explained by data-reduction problems related to échelle blaze removal and order merging that severely bias the effective-temperature determination for the TOP stars (see Korn et al. 2006c for more details).

4. Discussion

We now turn to the implications of our findings. First we address some of the criticism that our results met with.

4.1. Are the abundance trends caused by contrived T_{eff} values?

Bonifacio et al. (2006) comment that “This result is very suggestive [...] albeit inconsistent with the cluster photometry.” As shown in Section 2, this state-

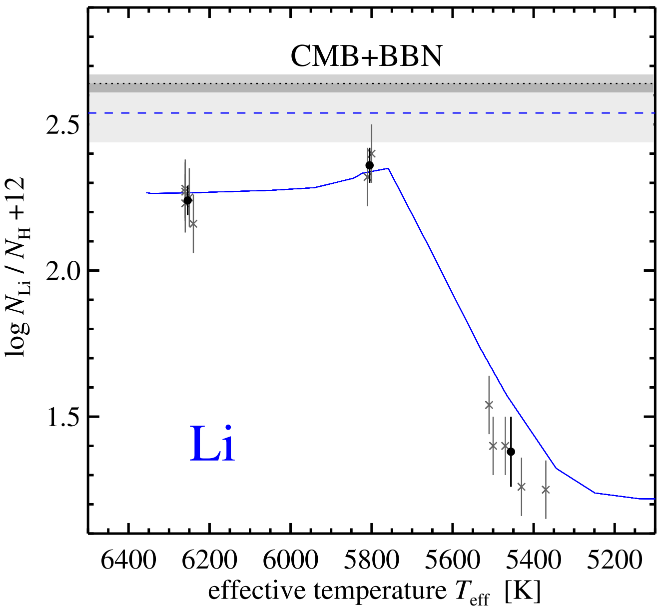

Figure 2. Lithium abundances in the TOP and SGB stars (crosses) with mean values indicated by the bullets. The full-drawn line gives the prediction from the diffusion model with turbulent mixing while the dashed line indicates the inferred initial lithium abundance of these stars.

ment finds no support from the colour indices and calibrations we use. In the present study, the stellar parameters are constrained by means of different and independent techniques. This scientific approach was not adopted by Gratton et al. (2001) or Bonifacio et al. (2002).

In another article, Bonifacio (2006) argues that "An increase of 100 K of the assumed TO temperature would effectively erase the abundance differences found." This statement is not even true when only comparing the iron abundances of the TOP and bRGB stars (the only two groups analysed by Gratton et al. 2001). Moreover, to remove the overall trends between TOP and RGB stars would require an increase in the TOP $T_{\rm eff}$ values of between 120 K (calcium) and 490 K (magnesium). There is no single $T_{\rm eff} - \log g$ combination capable of removing all trends simultaneously (see also the next subsection).

4.2. Lithium and the Big Bang

Lithium is a special case, as its fragility to proton capture prevents it from surviving the diffusive trip through the star. When the outer convection zone expands inward, it first encounters lithium-rich layers. But as the inward expansion continues, the convection reaches lithium-free layers and the photospheric abundance drops rapidly.

This is precisely the behaviour observed in NGC 6397, cf. Figure 2. Again, raising the TOP-star effective temperatures by 100 K does not remove this diffusion signature, 170 K would be needed. It is highly improbable that we misestimate the effective-temperature difference between two groups of stars 450 K apart by as much as 35 %.

What initial lithium abundance did these stars have, before diffusion altered it? From the diffusion model, the initial abundance is determined to be log $\varepsilon\,(\mathrm{Li})_0 = 2.54 \pm 0.10$, higher by 0.3 dex than in the TOP stars. Within 1σ error bars, this value is in agreement with WMAP-based predictions of BBN (log $\varepsilon\,(\mathrm{Li})_0 = 2.64 \pm 0.03$, Spergel et al. 2007). As John Bahcall once put it: "The Big Bang is bang on".

4.3. Isochrone ages for halo field stars

Another implication concerns stellar ages. Helium and metal diffusion have effects on stellar structure which lead to lower predicted TOP effective temperatures. Furthermore, for halo field TOP and SGB stars, a spectroscopic abundance analysis will underestimate the true metallicity due to gravitational settling. The neglect of these diffusion effects is thus likely responsible for isochrone ages of halo field stars well in excess of 13.7 Gyr (e.g. Gehren et al. 2006). Note that globular-cluster ages are less affected, as helium diffusion is usually considered and the cluster metallicity is derived from RGB stars. The effect on absolute ages of halo field stars and on a potential age spread in the halo remains to be quantified.

5. Outlook

We will continue to investigate effects of diffusion and turbulent mixing in halo stars. ESO recently awarded 46 h to our study of NGC 6752 ($[\mathrm{Fe/H}] \approx -1.5$). Like in NGC 6397, we will analyse stars from the TOP to below the bump on the RGB. If turbulent mixing is as efficient as found in NGC 6397, then abundance trends of similar size should also be present in NGC 6752.

Acknowledgments. A.J.K. acknowledges research fellowships by the German Leopoldina Foundation and the Swedish Research Council.

References

Bonifacio P. 2007, in: Chemodynamics – from first stars to local galaxies", Emsellem, Wozniak, Massacrier, Gonzalez, Devriendt & Champavert (eds.), EAS Publications Series [astro-ph/0611147]

Bonifacio P., Pasquini L., Spite F. et al. 2002, A&A 390, 91

Bonifacio P., Molaro P., Sivarani T. et al. 2007, A&A, accepted [astro-ph/0610245]

Gehren T., Shi J.R., Zhang H.W. et al. 2006, A&A 451, 1065

Gratton R.G., Bonifacio P., Bragaglia A. et al. 2001, A&A 369, 87

Korn A.J., Grundahl F., Richard O. et al. 2006a, Nature 442, 657

Korn A.J., Grundahl F., Richard O. et al. 2006b, The Messenger 125, 6 [astro-ph/0610077]

Korn A.J., Piskunov N., Grundahl F. et al. 2006c, in: Chemical Abundances and Mixing in Stars in the Milky Way and its Satellites, Randich & Pasquini (eds.), Springer (Heidelberg), pp. 294-297 [astro-ph/0608338]

Michaud G., Fontaine G. & Beaudet G. 1984, ApJ 282, 206

Richard O., Michaud G. & Richer J. 2005, ApJ 19, 538

Spergel D.N., Bean R., Dore O. et al. 2007, ApJ, submitted [astro-ph/0603449]

Spite M. & Spite F. 1982, Nature 297, 483