HE 1327−2326 – stellar parameters, atomic diffusion and lithium abundance

Andreas J. Korn*, Lyudmila Mashonkina†, Olivier Richard**, Anna Frebel‡, Wako Aoki§ and Norbert Christlieb*

*Department of Astronomy and Space Physics, Box 515, 75120 Uppsala, Sweden
†Institute of Astronomy, Russian Academy of Science, Pyatnitskaya 48, 119017 Moscow, Russia
**GRAAL-UMR5024/IPM (CNRS), Université Montpellier II, Place E. Bataillon, 34095 Montpellier, France
‡McDonald Observatory and Department of Astronomy, University of Texas at Austin, 1 University Station, C1400, Austin, TX 78712, USA
§National Astronomical Observatory of Japan, 2-1-21 Osawa, Mitaka, Tokyo, 181-8588 Japan

Abstract. The recent discovery of systematic trends of elemental abundances with evolutionary stage in the globular cluster NGC 6397 [1] has given support to the theoretical expectation that the abundances of elements in the atmospheres of unevolved halo stars are significantly affected by atomic diffusion. HE 1327−2326, one of the two known hyper-metal-poor (i.e., [Fe/H] < -5) stars, is in a near-turnoff stage of evolution [2, 3] and seemingly has no lithium ($\log \varepsilon\,(\mathrm{Li}) < 0.7$, [4]). Based on various techniques we derive improved stellar parameters for this star. In particular, we derive a spectroscopic surface gravity based on the calcium ionization equilibrium in non-LTE [5]. HE 1327−2326 is found to be a subgiant. Calculations show that, while atomic diffusion may have significantly altered the surface abundances of this star, the large deficit of lithium (relative to other metal-poor stars and the amount produced in Big-Bang nucleosynthesis) cannot be explained in this way.

Keywords: <Enter Keywords here>
PACS: <Replace this text with PACS numbers; choose from this list: http://www.aip.org/pacs/index.html>

STELLAR PARAMETERS

Based on broad-band photometry calibrated on the infrared-flux method (IRFM) of [6], an effective temperature of 6180 K is derived for HE 1327−2326 [3]. At this T_{eff}, two surface gravity solutions are possible from the inspection of an isochrone: main sequence ($\log g = 4.5$) and subgiant ($\log g = 3.7$).

To constrain the surface gravity spectroscopically, an ionization equilibrium can be used. However, the only element detectable in two ionization stages is calcium. Assuming local thermodynamic equilibrium (LTE), the abundances derived from lines of Ca I and Ca II differ by 0.57 dex. This could indicate significant departures from LTE (non-LTE effects).

Here we apply the NLTE model atom of [5] to the observed lines of calcium in HE 1327−2326. Establishing the ionization equilibrium of Ca I 4226 with the log g-sensitive line Ca II 8498 (see Figs. 1 & 2) we find a surface gravity close to 3.7. This result is supported by Balmer-profile analyses (see Fig. 3).

Using the revised infrared-flux method of [7], a higher effective temperature is obtained: 6450 K [8]. Assuming $T_{\mathrm{eff}} = 6450$ K, a $\log g$ of 4.0 is derived. Both solutions are therefore possible from the point of view of stellar evolution. The turnoff-point solution is, however, disfavoured by the analysis of Balmer lines.

ATOMIC-DIFFUSION CALCULATIONS

Using stellar-structure models including atomic diffusion (that is, gravitational settling, diffusion due to concentration gradients, thermal diffusion and radiative acceleration; see [9] for details), we evolve a star with initial [Fe/H] $= -6$ to reach the subgiant branch at $T_{\mathrm{eff}} \approx 6200$ K (the turnoff at $T_{\mathrm{eff}} \approx 6450$ K) after 13.5 Gyr. At that point, atomic diffusion has modified the abundances of, e.g., Li, C, N, O and Fe in the following way ($\Delta \log \varepsilon$ values rounded to the nearest tenth of a dex): −1.2, +0.2, −0.6, −1.0 and +0.6 (−0.9, −0.3, −0.8, −0.8 and +0.8 for the turnoff solution). The predicted surface abundances of iron are thus compatible with the observed one in both cases. Lithium is particularly interesting: starting from the upper limit of $\log \varepsilon\,(\mathrm{Li}) < 0.7$ [4], the atomic-diffusion model for the subgiant solution predicts an original abundance of $\log \varepsilon\,(\mathrm{Li}) \leq 1.9$. However, this is still a factor of five below the primordial value.

These calculations show that atomic diffusion may have significantly altered the chemical surface composition of HE 1327−2326.

From the study of stars in NGC 6397 [1], it seems likely that the effects of atomic diffusion are moderated by mixing below the convective envelope. We have not considered this effect here, as we do not know how it varies with metallicity. It is conceivable that it diminishes

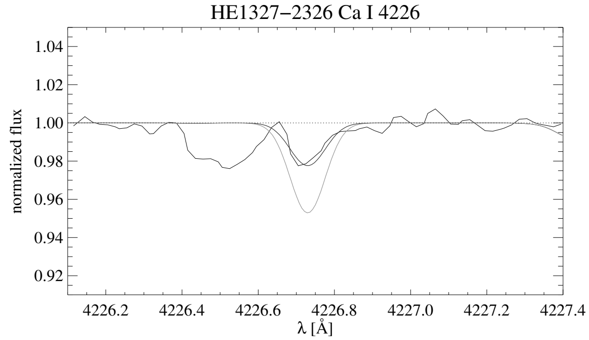

FIGURE 1. Fit to the observed profile of Ca I 4226 (equivalent width W_λ = 2.7 mÅ) At $T_{\rm eff}$ = 6180 K, the calcium abundance is determined to be log ε (Ca) = 1.24 (black: non-LTE, grey: LTE). In spite of the line's weakness, the non-LTE effect amounts to +0.34 dex.

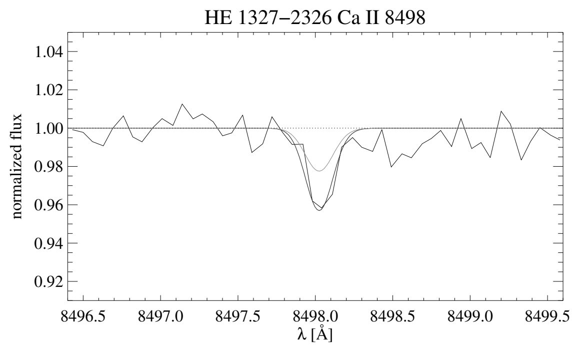

FIGURE 2. Fit to the observed profile of Ca II 8498 (equivalent width W_λ = 10 mÅ) at a calcium abundance of log ε (Ca) = 1.28 (black: log g = 3.7, grey: log g = 4.5). Assuming $T_{\rm eff}$ = 6180 K, the Ca I/II ionization equilibrium requires a surface gravity of around 3.7. Thus, HE 1327−2326 is a subgiant.

towards lower metallicities. In this sense, the results presented here constitute upper limits to the abundance changes expected from atomic diffusion.

CONCLUSIONS

The analysis of the Balmer lines and the Ca I/II ionization equilibrium in non-LTE points towards a subgiant stage of evolution for HE 1327−2326. We hence recommend to use the subgiant solution of [3, 4] when modelling the abundance pattern.

Non-LTE effects on calcium lines can be rather large in stars as metal-poor as HE 1327−2326.

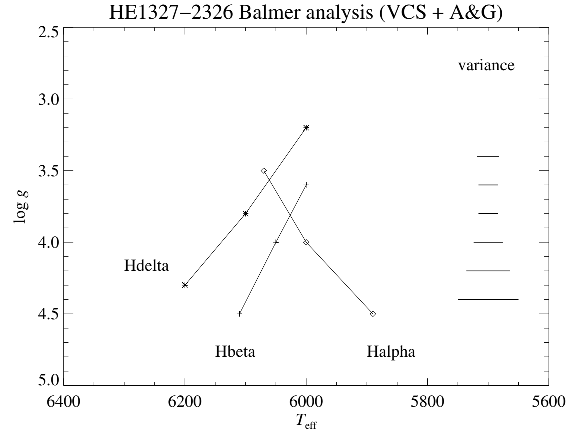

FIGURE 3. Different lines of the Balmer series depend differently on effective temperature and surface gravity. In particular, an analysis of Hα vs. the higher-order Balmer lines provides constraints on the surface gravity. Like the calcium ionization equilibrium, this analysis points to the subgiant solution for HE 1327−2326. For details about the broadening theories applied here (VCS + A&G), see [10].

Atomic diffusion may have significantly altered the surface abundances of HE 1327−2326, but it is unlikely to explain the non-detection of lithium.

REFERENCES

1. A. J. Korn, F. Grundahl, O. Richard, P. S. Barklem, L. Mashonkina, R. Collet, N. Piskunov, and B. Gustafsson, *Nature* **442**, 657–659 (2006)
2. A. Frebel, W. Aoki, N. Christlieb, H. Ando, M. Asplund, P. S. Barklem, T. C. Beers, K. Eriksson, C. Fechner, M. Y. Fujimoto, S. Honda, T. Kajino, T. Minezaki, K. Nomoto, J. E. Norris, S. G. Ryan, M. Takada-Hidai, S. Tsangarides, and Y. Yoshii, *Nature* **434**, 871–873 (2005)
3. W. Aoki, A. Frebel, N. Christlieb, J. E. Norris, T. C. Beers, T. Minezaki, P. S. Barklem, S. Honda, M. Takada-Hidai, M. Asplund, S. G. Ryan, S. Tsangarides, K. Eriksson, A. Steinhauer, C. P. Deliyannis, K. Nomoto, M. Y. Fujimoto, H. Ando, Y. Yoshii, and T. Kajino, *Astrophysical Journal* **639**, 897–917 (2006)
4. A. Frebel, N. Christlieb, K. Eriksson, and W. Aoki, *Astrophysical Journal*, submitted
5. L. Mashonkina, A. J. Korn, and N. Przybilla, *Astronomy & Astrophysics* **461**, 261–275 (2007)
6. A. Alonso, S. Arribas, and C. Martinez-Roger, *Astronomy & Astrophysics* **313**, 873–890 (1996).
7. I. Ramírez, and J. Meléndez, *Astrophysical Journal* **626**, 465–485 (2005)
8. J. Meléndez, N. G. Shchukina, I. E. Vasiljeva, and I. Ramírez, *Astrophysical Journal* **642**, 1082–1097 (2006)
9. O. Richard, G. Michaud, and J. Richer, *Astrophysical Journal* **580**, 1100–1117 (2002)
10. A. J. Korn, J. Shi, and T. Gehren, *Astronomy & Astrophysics* **407**, 691–703 (2003)