Convection in Metal-Poor Stars as Traced from Spectral Line Asymmetries

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Abstract. Convection leaves an elusive, but observable signature in the stellar spectral line shifts and shapes. It sways the line formation in a way impossible to understand through experience with homogeneous model atmospheres. However, improvements in both observing and modelling capabilities are helping to answer the challenge. It is possible now to observe the subtle characteristic marks left by convection in the stellar spectra, with extremely high resolving power and signal-to-noise ratio, as well as to accomplish realistic, three-dimensional, time-dependent, hydrodynamical simulations of surface convection.

Metal-poor halo stars are of particular interest, as their atmospheric abundances trace the chemical evolution of the early Galaxy, and are of key importance to comprehend the Big Bang nucleosynthesis. We have accurately measured line asymmetries in two metal-poor stars, finding some interesting peculiarities. We have, in parallel, carried out hydrodynamical simulations for the most metal-poor of the observed stars, HD140283, which perform very satisfactorily in reproducing the observed line asymmetries.

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1. Observations

Two well-studied halo stars were chosen for this study: HD103095 (T$_{\text{eff}} = 5030$ K/ log $g = 4.7$ / [Fe/H] = −1.3) and HD140283 (T$_{\text{eff}} = 5690$ K/ log $g = 3.7$ / [Fe/H] = −2.5). For comparison purposes the two solar-metallicity stars ε Eridani (T$_{\text{eff}} = 5180$ K/ log $g = 4.6$ / [Fe/H] = −0.1) and HR3775 (T$_{\text{eff}} = 6380$ K/ log $g = 3.9$ / [Fe/H] = −0.2) were included in the program, as well as the Sun. Observations were carried out during three campaigns from 1995 to 1997, with the 2dcoudé spectrograph (Tull et al. 1995) coupled to the McDonald 2.7m telescope. The set-up provided resolving powers ($\lambda/\Delta\lambda$) in the range 170,000-220,000. As many 1/2 hour exposures were acquired as were needed to reach a final signal-to-noise ratio (SNR) of ~ 300–800.

A very careful data reduction was applied using the IRAF software package, and consisted in: overscan (bias) and scattered light subtraction, flatfielding, extraction of one-dimensional spectra, wavelength calibration, and continuum normalization. Wavelength calibration was performed for each individual image on the basis of ~ 300 ThAr lines spread over the detector. Before co-adding the individual one-dimensional spectra, they were first cross-correlated to correct for the change in doppler shifts due to the Earth motion and instrumental displacements.

The ability of the 2.7m to acquire day-light spectra allows us to carry out an empirical estimate of the accuracy of the observations: a comparison of the wavelengths of 60 lines with those measured in the Solar Flux Spectrum of Kurucz et al. (1984) by Allende Prieto & García López (1998), gives a r.m.s. difference of 58 m s$^{-1}$ ($\sim \frac{1}{25}$ pixel), giving confidence in the adopted procedure.

2. Observed asymmetries in metal-poor stars

Gray (1982) found that the velocity span of the bisectors for late-type stars of the same luminosity type was a smooth function of the stellar spectral type. For dwarfs and sub-giants of solar metallicity there is a minimum of the velocity span around G8. The metal-poor case has, however, previously never been investigated.

We have measured the bisectors of 34, 36, 26, and 16 (apparently) clean lines in the spectral range available for HD103095, ε Eri, HD140283, and HR3775. The individual bisectors were averaged for each star, computing what we have defined as the average mean bisectors (see Allende Prieto et al. 1999 for details).

HD103095: the mean bisector of the star (G8V) fits in the general description for solar-metallicity stars and, therefore, the typical velocity spans are smaller than those for the Sun (G2V), and ε Eri (K2V), as shown in Fig. 1(left panel). We do not detect any metallicity effect, although it could be caused by the modest size of the velocity span ($\sim 60$ m s$^{-1}$), close to our measurement error, as well as the moderately low metallicity of the star.

HD140283: for this extremely metal-poor sub-giant (G0IV) the measured line asymmetries are, surprisingly, significantly larger than the bisectors of HR3775 (F3IV), though the opposite would be expected based on their $T_{\text{eff}}$. As shown in Fig. 1(right panel) the typical velocity span is ~ 300 m s$^{-1}$, about twice as large as in HR3775 and the Sun. It seems likely that this reflects the low metallicity
Figure 1. Left panel: mean line bisector in the spectrum of the metal-poor dwarf HD103095 (G8; solid line), as compared with the hotter Sun (G2; dashed line), or the cooler ε Eri (K2; dashed line). Right panel: mean line bisector in the spectrum of HD140283 (G0; solid line) compared with that for the solar-metallicity star HR3775 (F3; dashed line) and the Sun (G2; dashed line).

making the granulation more transparent to photons escaping from the bottom layers of the photosphere.

3. Theoretical line asymmetries in HD140283

In order to better understand convection in low-metallicity stars, 3D convection simulations of HD140283 have been performed. The simulation details are similar to those of the Sun (see Asplund et al. and Trampedach et al. in this volume). Theoretical line profiles have been computed from a sequence of snapshots covering 40 minutes of stellar time.

The broadening due to the stellar rotation is calculated by integrating over the disk, from the intensity profiles at various aspect angles (μ and φ). In order to obtain the correct line broadening with the observed equivalent widths, a stellar rotation of \( \sin i = 3.0 \pm 0.5 \) km s\(^{-1} \) is required; all investigated lines (Fe I, Fe II, Ba II, Ca I, and Li I) result in the same value. According to our preliminary calculations, the predicted bisectors show very gratifying agreement with the observed profiles, as apparent in Fig. 2. The significantly larger temperature and intensity contrasts in HD140283 compared with the Sun, together with the larger photospheric velocity field, are responsible for the greater line asymmetries.

Finally, it is interesting to note that the 3D simulations require \( \sim 0.4 \) dex lower iron abundance, as judged from the Fe I lines, than with one-dimensional model atmospheres, as a result of the steeper temperature gradient. Undoubtedly, this will have implications, for example, in the derived lithium abundances in metal-poor stars, if validated by subsequent tests. A full account of this and following studies will be presented elsewhere.
Figure 2. Theoretical line profile and bisector (solid line) for Fe I λ5232 Å computed from a three-dimensional hydrodynamical convection simulation of HD140283 compared with the observations (diamonds and line with error bars).

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References