Carnegie Observatories Astrophysics Series, Vol. 4:
Origin and Evolution of the Elements, 2004
ed. A. McWilliam and M. Rauch (Pasadena: Carnegie Observatories,
http://www.ociw.edu/ociw/symposia/series/symposium4/proceedings.html)

Unbiased Stellar Parameters

A. J. KORN
Universitäts-Sternwarte München (USM) &
Max-Planck Institut für extraterrestrische Physik (MPE) Garching, Germany

Abstract

I report about ongoing efforts of the USM cool-star group to refine our ability to derive fundamental stellar parameters $T_{\rm eff}$, $\log g$ and $[X_i/H]$ (chemical composition) for solar-type stars. In this contribution the focus lies on a universal gravity indicator, namely the iron ionization equilibrium. It is shown that a kinetic equilibrium or non-LTE approach for Fe I succeeds in fulfilling the trigonometric constraints coming from the HIPPARCOS satellite mission *if and only if* inelastic collisions with hydrogen are properly accounted for.
Our model makes testable predictions for the gravities of metal-poor globular cluster giants in which non-LTE corrections are expected to reach up to +0.5 dex.

1.1 Introduction

The rapid increase in stellar spectrum quality (and quantity) over the course of the 1990s has not been matched by a similar rise in the quality of abundance determinations (cf. Gustafsson, these proceedings). When it comes to archival data, every astronomer nowadays has access to an ever-increasing database of high resolution, high signal-to-noise spectra of stars tracing the chemical evolution of our Galaxy from its birth to the present day.

The exploitation of these advances requires improvements on the modeling side: We would like to be able to analyze hundreds or even thousands of stars without investing several man years. An extreme example in this context is the work of Fuhrmann (2004) who has spent the equivalent of 3 to 4 man years analyzing 300 local dwarf stars using semi-automated procedures: one could argue in this particular case that the quality of the results does justify the time invested (see Fig. 1.1).

Improvements are also needed when it comes to deriving stellar parameters. The vast majority of unevolved F and G stars in the solar vicinity can safely be analyzed using standard techniques (plane-parallel, static atmospheres in local thermodynamic equilibrium (LTE) in combination with LTE line formation). This is because they are sufficiently similar to the Sun in their stellar parameters (including the metallicity) such that the requirements of a differential analysis are warranted. The combination of Balmer profile temperatures for $T_{\rm eff}$ and pressure-broadened lines of Mg I for $\log g$ have been shown to yield distances in superb agreement with fundamental measurements like the HIPPARCOS astrometry (Fuhrmann 1998b, 2004). An offset of 2 % between the two distance scales translates into departures from physical effective temperatures of 40 K *or* of 0.02 dex from physical logarithmic gravities. A remarkable accuracy!

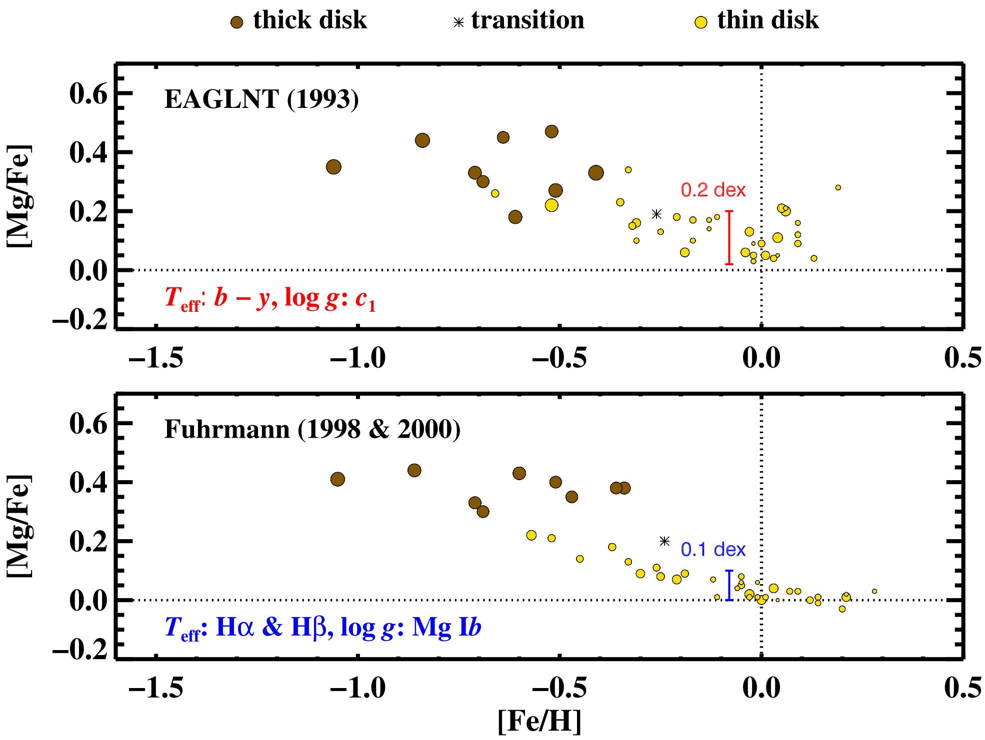

Fig. 1.1. A star-to-star comparison for 44 stars in common between Edvardsson et al (1993) and Fuhrmann (1998b & 2000, priv. comm.). Symbol sizes are proportional to the derived age of the object. In the analyses of Fuhrmann, the scatter is significantly reduced and the artificially high Mg abundances in the thin disk removed. The three main results from Fuhrmann: *a)* The Sun is a typical thin-disk star, *b)* thick-disk stars are systematically older than thin-disk stars and *c)* abundance-abundance diagrams like these can be used (in conjunction with kinematics and age estimates) to distinguish between the two disk populations.

Fuhrmann (1998a) has also shown that the iron ionization equilibrium Fe I/Fe II returns results which are incompatible with HIPPARCOS, especially for hot, evolved and/or metal-poor stars. A prime example is HD 140283, *the* halo subgiant: Fuhrmann (1998a) derives a gravity of $\log g = 3.20$ on the basis of Fe I/Fe II in LTE, but 3.52 using the Mg Ib lines. The latter value is in much better agreement with current (post-HIPPARCOS) estimates for the gravity. As I will show below, the situation becomes worse when going up the red giant branch where gravity corrections can reach +0.5 dex.

1.2 The Model

Details of our computations are given in Gehren et al. (2001a, b), Korn & Gehren (2002) and Korn et al. (2003). Here, I only summarize the most important aspects:

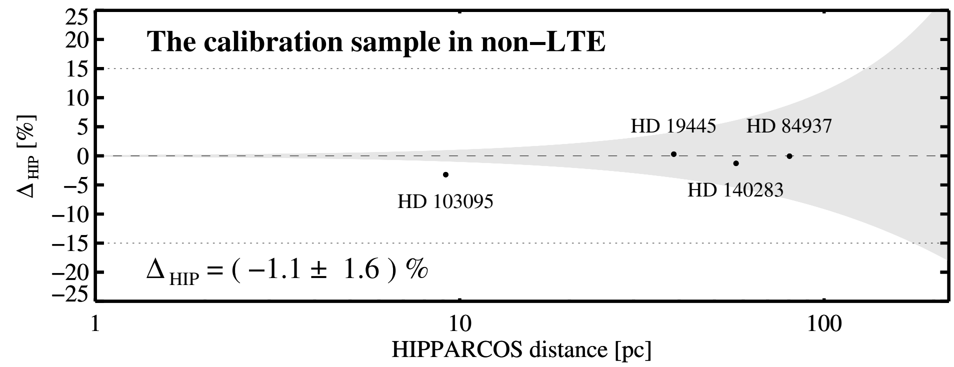

Fig. 1.2. Comparison of the spectroscopic distances with the trigonometric ones of HIPPARCOS. $\Delta_{\rm HIP} = 100\,(d_{\rm spec} - d_{\rm HIP})/d_{\rm HIP}$ with $d_{\rm spec}$ calculated from $\log\pi_{\rm spec} = 0.5\,([g]-[M]) - 2\,[T_{\rm eff}] - 0.2\,(V + {\rm BC} + A_V + 0.25)$, where $[X] = \log(X/X_\odot)$.

- The Fe I/Fe II model atom is extensive consisting of 236 terms in Fe I and 267 terms in Fe II
- Photo-ionization of Fe I is treated by implementing the large bf cross-sections computed by Bautista (1997)
- Both discrete and continuous sources of opacity are considered for the UV (line) blocking.
- The a priori unknown strength of hydrogen collisions as a thermalizing process (parameterized by S_H times the Drawin (1968, 1969) formula) is calibrated by means of metal-poor HIPPARCOS stars whose gravity can be inferred from the parallax once a temperature has be deduced (an iterative process).

It is worth noticing that we are currently applying the same non-LTE code to re-evaluate non-LTE effects in magnesium, sodium and aluminum. For these atoms we find S_H values of 0.1 and below. The difference with respect to iron may arise from the fact that the entire Fe I term system is photo-ionization dominated, whereas Mg I or Al I are ruled by ground-state photoionization only.

Fig. 1.2 shows how successful our calibration procedure is: when $S_H = 3$ is adopted the offset with respect to the trigonometric distances vanishes to within the uncertainties. This result is an order of magnitude more precise that previous attempts (cf. Korn et al. 2003).

1.3 Do We Need Inelastic Hydrogen Collisions?

To persuade the disbelieving, Fig. 1.3 shows the stellar parameters I derive for two values of S_H. If $S_H = 0$ is assumed, $T_{\rm eff} = 5550$ K, $\log g = 4.25$ and [Fe/H] = −2.26 result. The temperature is exclusively based on Hα (our primary temperature indicator), as this gravity leads to discordant temperatures from the higher Balmer lines. Had I chosen Hβ instead, the gravity correction would have been even larger.

These stellar parameters are to be compared with the best values derived on the basis of the $S_H = 3$ model: $T_{\rm eff} = 5810$ K, $\log g = 3.68$, [Fe/H] = −2.43 which result in a spectroscopic distance a mere 1.3 % shorter than the HIPPARCOS parallax indicates.

For the $S_H = 0$ model parameters, a stellar mass can no longer be inferred from the evolutionary tracks, as the star falls in the middle of "no star's land". But even if a sensible mass

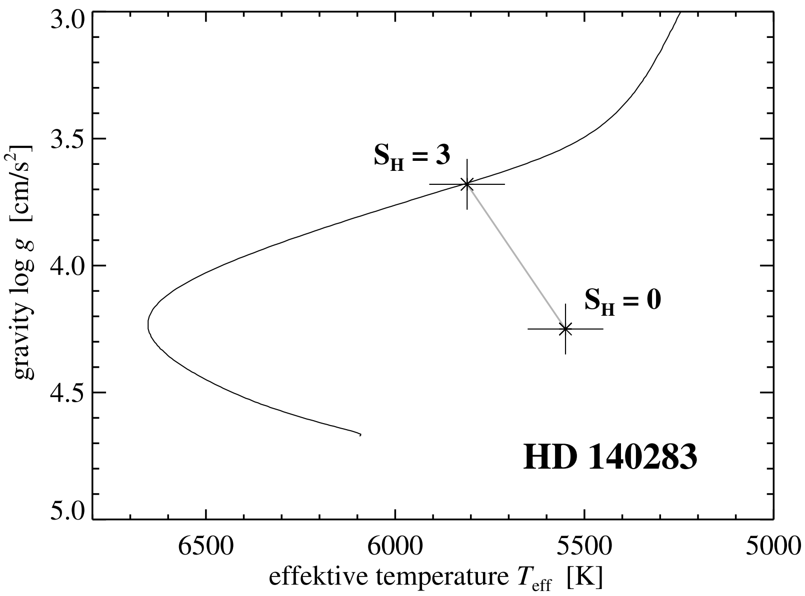

Fig. 1.3. Loci of HD 140283 in the Kiel diagram using different values for S_H. The track refers to calculations of VandenBerg et al. (2000) for a $M = 0.8\,M_\odot$ star with [Fe/H] = −2.31 and [α/Fe] = +0.6. $S_H = 0$ is entirely ruled out by the unphysical position which produces a spectroscopic distance a factor of 2 smaller than the astrometry does.

of $0.8\,M_\odot$ is assumed, a spectroscopic distance a factor of 2 too short results ($d_{\rm spec} = 26.5$ pc vs. $d_{\rm HIP} = 57.3$ pc). It is therefore clear that a non-vanishing S_H is required for consistent results.

Further reasons why S_H turns out to be larger than expected (by "sheep-like" astronomers) are discussed in Korn et al. (2003). Without much hope for experimental verification, it is upon the theoreticians to model the details of this collisional interaction, i.e. the transient formation of the quasi-molecule FeH. A challenge for the future!

1.4 Predictions

Let's check to what extent the gravity scale of halo objects is affected by departures from LTE in Fe I. For this purpose, I have computed theoretical LTE line profiles for Fe I lines one would typically use for an analysis ($W_\lambda < 100\,$mÅ) at four positions along evolutionary tracks for the metallicities [Fe/H] = −1.01 and −2.25. The non-LTE abundance change can then be estimated by matching this profile to theoretical profiles computed using the $S_H = 3$ non-LTE model for Fe I. As abundance corrections translate into gravity corrections with a multiplication factor of close to three ($3 \times \Delta \log \varepsilon \approx \Delta \log g$), I have adopted this factor for the derivation of the gravity corrections in Fig. 1.4 and 1.5.

As can be appreciated from inspecting Fig. 1.4, the gravity corrections are quite moderate at mild metal deficiencies. It is interesting to see that there seems to be a compensating effect of temperature (photo-ionization) and gravity (density, collisions) from the turnoff all the way to the giant branch.

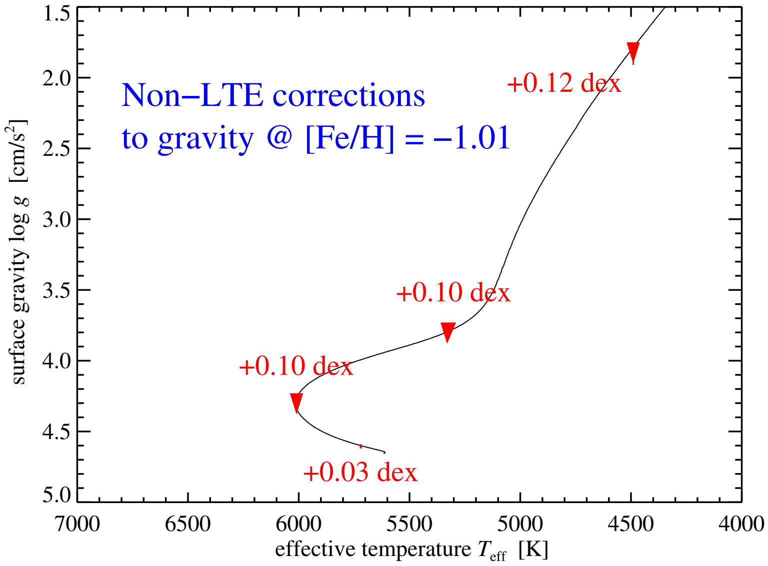

Fig. 1.4. Gravity correction for a metallicity of [Fe/H] = −1.00. The track refers to calculations of VandenBerg et al. (2000) for a $M = 0.8\,M_{\odot}$ star with [Fe/H] = −1.01 and [α/Fe] = +0.3. Abundance corrections are a factor of 3 smaller.

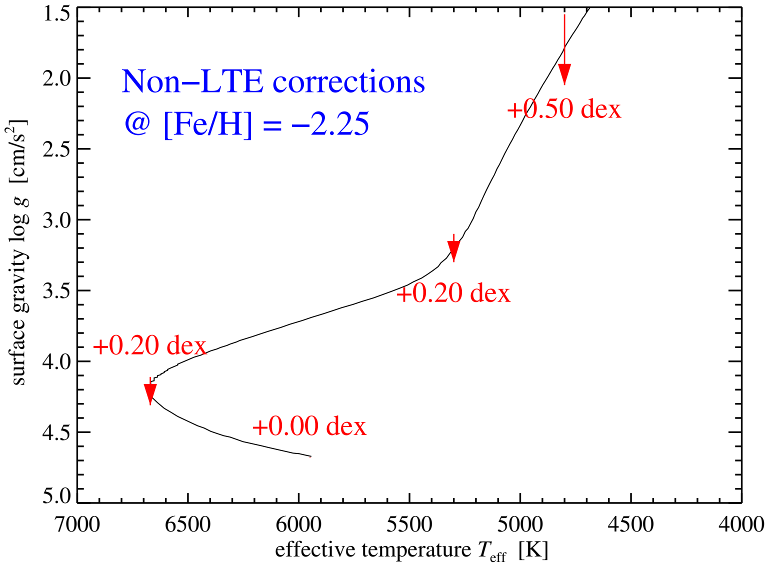

Fig. 1.5. Gravity correction for a metallicity of [Fe/H] = −2.25. The track refers to calculations of Cassisi & Salaris (1997) for a $M = 0.8\,M_{\odot}$ star with [Fe/H] = −2.25 and [α/Fe] = +0.3. Abundance corrections are a factor of 3 smaller.

Fig. 1.5 shows similar computations, this time for a metallicity one finds in the most metal-poor globular clusters. Here, non-LTE corrections are much larger and are a much clearer function of gravity.

The main question here obviously is: Have these non-LTE effects been "observed"? The answer is "maybe". Ramírez & Cohen (2003) recently analyzed 25 stars in M5 ([Fe/H] ≈ -1.3) of which 15 have gravities ≤ 3.25 (the first 15 entries in their Table 4). Their Table 5A gives [Fe I/H] and [Fe II/H] for all of these 15 giants. The mean values for this sample turn out to be -1.32 ([Fe I/H]) and $-$ 1.28 ([Fe II/H]). In other words, the average imbalance amounts to 0.04 dex in abundance or 0.12 dex in gravity. These values are indeed very close to what our model predicts.

Ivans & Kraft (2003) recently presented a re-evaluation of a large number of high-resolution analyses of globular cluster stars (see also Kraft, these proceedings). Their Group 1 (the best studied) contains 7 clusters with metallicities ranging from -1.26 (M5) to -2.42 (M15). The estimates for [Fe I/H] and [Fe II/H] always agree to within the mutual 1σ errors. Yet in five of the clusters the stars seem to show overionization of Fe I with respect to Fe II between 0.03 dex (M3) and 0.12 dex (M92), while two clusters (NGC 362 and NGC 288) show the opposite effect. Especially the most metal-poor clusters (M92 and M15) lend support to the notion that overionization is at work: 0.12 dex (M92) and 0.08 dex (M15) translate into gravity corrections of 0.36 dex and 0.24 dex. These values are in the range of corrections presented in Fig. 1.5.

It is worth noticing that I have analyzed the iron spectrum of CD $-38°$ 245, the most metal-poor star known prior to 2002. In this star, non-LTE corrections to gravity are +0.4 dex at a metallicity of close to -4. Why are non-LTE corrections not increasing towards lower metallicities? The answer lies in the competing effects of photo-ionization (aggravating non-LTE) and line strengths: the latter decrease towards lower metallicities shifting the depth of formation inward where departures from LTE are less pronounced.

In the analysis of the most metal-poor giant star known (HE 0107$-$5240 @ -5.3, Christlieb et al. 2002), an abundance correction of +0.1 dex was derived using the $S_H = 3$ model. Since no Fe II lines were detected in the optical spectrum, the ionization equilibrium could only be applied to derive upper limits on the gravity. We hope to remedy this drawback by looking at UV lines of Fe II calibrated against optical lines observable in CD $-38°$ 245.

1.5 Conclusions

I have presented applications of our non-LTE model atom for Fe I/Fe II to the analysis of metal-poor stars. In the framework of our modeling (static 1D model atmospheres with Böhm-Vitense convection and no overshooting) the constraints from local halo stars require an efficiency for inelastic hydrogen collisions of 3 (with respect to the Drawin formula) in the Fe I kinetic equilibrium calculations. $S_H = 0$ (no hydrogen collisions at all) is in irreconcilable conflict with the known evolutionary status of HD 140283 (on whatever temperature scale one adopts), even if $S_H = 3$ is an unexpected ("goat-like") result.

Our predictions for non-LTE gravity corrections for metal-poor giants are in good agreement with recent analyses. I caution the reader about the use of these corrections at face value: the calibration of S_H is only valid in combination with *a)* our Balmer profile temperature scale and *b)* our choice of $\log C_6$ values (to mention two of the most critical ingredients). Therefore further testing is required to quantitatively pin down the extent of overionization. In this respect globular cluster giants are ideal test particles.

This is but one contribution towards a better understanding of halo stars as tracers of the chemical enrichment that took place very early on in the history of the Universe. These stars still pose unsolved challenges for stellar astrophysicists and every effort should be made to model them even more accurately. This way we will gain refined insight into Galactic chemical evolution while learning more about the physics of stars.

Acknowledgements

It is a pleasure to thank the USM cool-star group members which have contributed to this work in one way or another: Jan Bernkopf, Klaus Fuhrmann, Zhao Gang (as a guest from Beijing), Thomas Gehren, Frank Grupp, the late Michael Pfeiffer to whom we owe the FOCES spectrograph, Johannes Reetz and Jianrong Shi (also Beijing). It's been a jolly-good time!
I would also like to thank Andy McWilliam for inviting me to take part in the forth and ultimate Carnegie Centennial bash.

References

Bautista M.A. 1997, A&AS, 122, 167
Cassisi S. & Salaris M. 1997, MNRAS, 285, 593
Christlieb N., Bessell M.S., Beers T.C., Gustafsson B., Korn A., Barklem P.S., Karlsson T., Mizuno-Wiedner M., Rossi S. 2002, Nature, 419, 904
Drawin H.W. 1968, Z. Physik, 211, 404
Drawin H.W. 1969, Z. Physik, 225, 483
Edvardsson B., Anderson J., Gustafsson B., Lambert D.L., Nissen P.E., Tomkin J. 1993, A&A, 275, 101
Fuhrmann K. 1998a, A&A, 330, 626
Fuhrmann K. 1998b, A&A, 338, 161
Fuhrmann K. 2004, AN, *submitted*
Gehren T., Butler K., Mashonkina L., Reetz J., Shi J. 2001a, A&A, 366, 981
Gehren T., Korn A.J. & Shi J. 2001b, A&A, 380, 645
Korn A.J. & Gehren T. 2002, in Modelling Stellar Atmospheres (IAU Symposium 210), ed. N.E. Piskunov, W.W. Weiss, D.F. Gray (San Francisco: ASP), *in press*
Korn A.J., Shi J. & Gehren T. 2003, A&A, 407, 691
Kraft R.P. & Ivans I.I. 2003, PASP, 115, 143
Ramírez S.V. & Cohen J.G. 2003, AJ, 125, 224
VandenBerg D.A., Swenson F.J., Rogers F.J., Iglesias C.A., Alexander D.R. 2000, ApJ, 532, 430