Astron. Astrophys. 330, 626–630 (1998)

ASTRONOMY AND ASTROPHYSICS

Surface gravities of very metal-poor stars from Hipparcos parallaxes*

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Received 23 July 1997 / Accepted 29 September 1997

Abstract. We discuss some consequences for the determination of the surface gravity parameter of very metal-poor halo dwarfs in the new light shed upon these objects from the Hipparcos astrometry. Whereas it has become clear that standard spectroscopic LTE iron ionization equilibria are prone to systematic errors, in the sense, that stages of evolution are predicted that are actually not yet reached, the method that circumvents this shortcoming by means of pressure-dependent strong line wings, faces the problem that such tracers are considerably weakened, or even absent, in the visible spectra of very metal-poor stars. We exemplify this circumstance by means of two nearby halo stars, the well-known HD 140283 and the turnoff star G 84-29, both significantly below one hundredth of the solar metallicity.

Key words: stars: distances – stars: fundamental parameters – stars: subdwarfs – stars: atmospheres – stars: HD 140283; G 84-29

1. Introduction

Surface gravities of cool dwarf stars of type F and G may be determined from the LTE ionization equilibrium of abundant species such as iron, chromium, silicon or titanium. This has been the standard approach for spectroscopy in numerous analyses. But as soon as we investigate metal-poor stars of, say, [Fe/H]= -2, the number of available absorption lines diminishes significantly and in some cases only iron lines may withstand this dilution. The cooler the stars, the more tracers sustain, but at the same time these objects – though relatively numerous – are necessarily faint. At the hot end of stars that evolve on time scales relevant for galactic evolution studies, turnoff and subgiant objects are most attractive since they are intrinsically brighter, i.e. less volume-limited, and can be very useful for age determinations of e.g. the Galaxy.

However, it turns out that for these stars, standard iron ionization equilibria come up with log g's that are systematically too small, that is, an evolutionary stage is derived, which is actually not yet reached.

To circumvent this problem, we recently suggested to use instead the wings of strong absorption lines, a differential method, that in principle is well-known since the early days of spectroscopy and a basis for e.g. the luminosity classification of stars. Important advertisers for this method have been Cayrel de Strobel (1969) and Blackwell & Willis (1977) in the sixties and seventies, and, later on, Edvardsson (1988a, b), whose recommendation *"to check – when possible – surface gravity values from the ionization equilibria with gravities determined from the wings of pressure broadened metal lines"* cannot be overestimated.

Our own work (Fuhrmann et al. 1997) was initiated from the persisting discrepancies with the standard star Procyon and finally has led to abandon surface gravity determinations from ionization equilibria, at least for those F- and G-type dwarfs that are hotter than the Sun, or, more explicitly, possess an extreme iron ionization balance.

With the advent of the Hipparcos parallax data, one may realize that this notion is confirmed from a comparison with spectroscopically determined parallaxes. It is only for HD 140283, the classical halo star of our recent sample, that the surface gravity value derived from the strong line method is at best in marginal agreement with the astrometric data, but this can be explained and is detailed in Sect. 2. The surface gravity parameter of HD 140283, and hence its evolutionary stage, has been the subject of many investigations, a question, that now is fairly well settled from the accurate Hipparcos astrometry.

A second star that deserves considerable attention in the literature, is the even more extreme G 84-29, that will be discussed in Sect. 3. This object escapes the strong line method for gravity determinations since all tracers in question are scaled down to Doppler core dominated absorption lines. The star is also rather faint, and accordingly the Hipparcos data are less accurate, but nevertheless a turnoff stage of evolution is most probably indicated for this object.

* Based on observations collected at the German Spanish Astronomical Center, Calar Alto, Spain

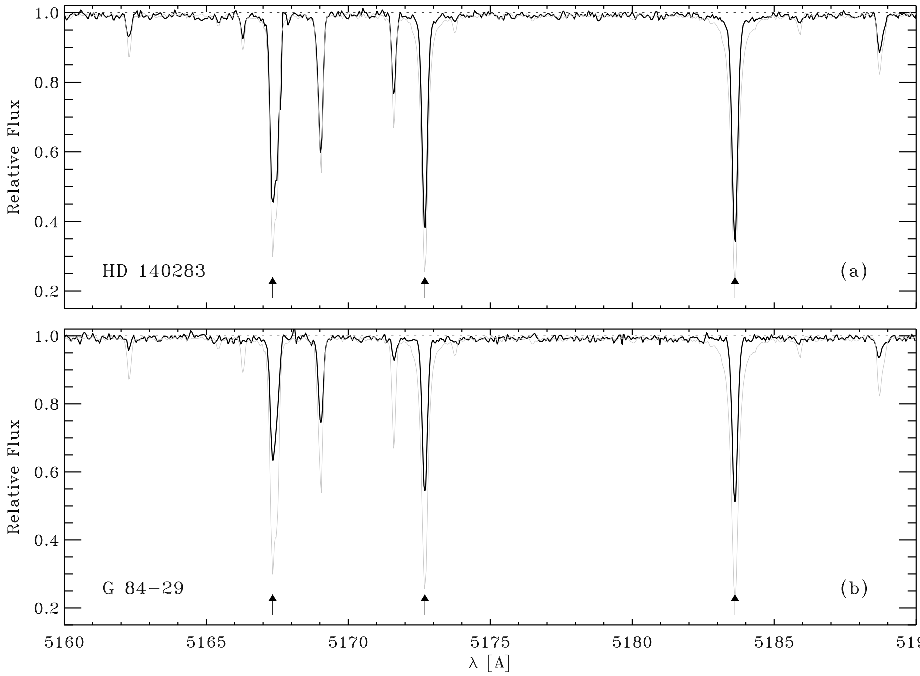

Fig. 1. The Mg Ib triplet (arrows) in the spectra of HD 140283 and G 84-29, and, for comparison, HD 19445 (dotted spectrum in both panels)

2. Observations

Two spectra of HD 140283 (V=7.21) and a single 1h-exposure of G 84-29 (V=9.81), obtained with the Calar Alto 2.2m telescope and the fiber optics Cassegrain échelle spectrograph FOCES (Pfeiffer et al. 1997), are our primary data set. These spectra cover the region 3900-6900Å at $\lambda/\Delta\lambda \sim 35000$. Signal-to-noise values are 100-200 longward of 5000Å, but of only restricted quality in the blue. Additional spectra of HD 140283, obtained in 1985 with the ESO CASPEC spectrograph at $\lambda/\Delta\lambda \sim 20000$ supplement our data, especially for a comparison of the Balmer line profiles.

3. The evolutionary stage of HD 140283

Being unconscious about the existence of metal deficient stellar atmospheres, astronomers in the 1920s misidentified HD 140283 to be as early as A2 (Adams & Joy 1922). But as more information became available about this star, we witnessed a steady decrease in the proposed effective temperature values that converged at $\sim$ 5600 K in the late eighties (e.g. Laird et al. 1988, Magain 1989). Most of these analyses were based on temperature sensitive photometric indices, such as $b-y$ or $V-K$, which depend however on the amount of interstellar reddening – normally assumed to be zero for nearby stars.

But as discussed in e.g. Nissen (1994), most stars are reddened to some degree and Ryan et al. (1991) point out that HD 140283 in particular *"is in a direction of very strong reddening"*. As a result, photometrically determined effective temperatures that make no allowance for this effect, have to be corrected to higher values. Estimates for the color excess of HD 140283 are given in McMillan et al. (1976), E_{b-y} = 0.056; Ryan (1989), E_{B-V} = 0.02; Schuster & Nissen (1989b), E_{b-y} = 0.020; and from the Strömgren data in Hauck & Mermilliod (1990), along with the $(b-y)_0$ calibration of Schuster & Nissen (1989a), we obtain E_{b-y} = 0.043. With $E_{B-V} \sim 1.35 \times E_{b-y}$ we adopt an average value E_{B-V} = 0.04. A reddening of that amount gives rise to an increase of $\Delta T_{eff} \sim$200 K, and, accordingly, the effective temperature of HD 140283 should be close to $\sim$ 5800 K.

Our early effective temperature determination of HD 140283 – based on the spectroscopic method of Balmer line wings (Hα...Hδ) – resulted in T_{eff} = 5814 K. This is in complete agreement with the photometric results, if, in fact, reddening is at work. More recently, on the base of a new grid of model atmospheres and additional spectra obtained with the FOCES échelle spectrograph, we slightly revised this value to T_{eff} = 5843 K.

Until recent, the stellar surface gravity value of HD 140283 has been a longstanding enigma. Large discrepancies in trigonometric parallaxes prevailed (cf. Nissen 1994, and references therein) and a wide range of log g values (3.1...4.8) were advocated to be valid. Now, with the precise information from the Hipparcos astrometry at our disposal, possible surface gravity values – and hence the evolutionary stage of HD 140283 – are confined to a narrow range. It is now definitely confirmed that the star has left the main sequence and is in a subgiant stage on its way up to the red giant branch. From the Hipparcos parallax, π = 17.44 $\pm$ 0.97 mas, HD 140283 is situated at a distance 57.34 $^{+3.38}_{-3.02}$ pc. With $A_V = 3.2 \times E_{B-V} \sim 0.13$ and $BC_V = -0.12$, calculated from tables of bolometric corrections as given by VandenBerg (1992), the bolometric magnitude is found to be M_{bol} = 3.16 $\pm$ 0.14 (here we adopt ΔBC_V = $\Delta A_V \simeq$ 0.05 mag). If we take T_{eff} = 5810$\pm$80 K (see below), this results in a stellar radius of $R_\star$ = 2.04 $\pm$ 0.15 $R_\odot$.

Cohen & Strom (1968) may have been the first to *"assume that HD 140283 is an evolved subdwarf"*. Most interestingly,

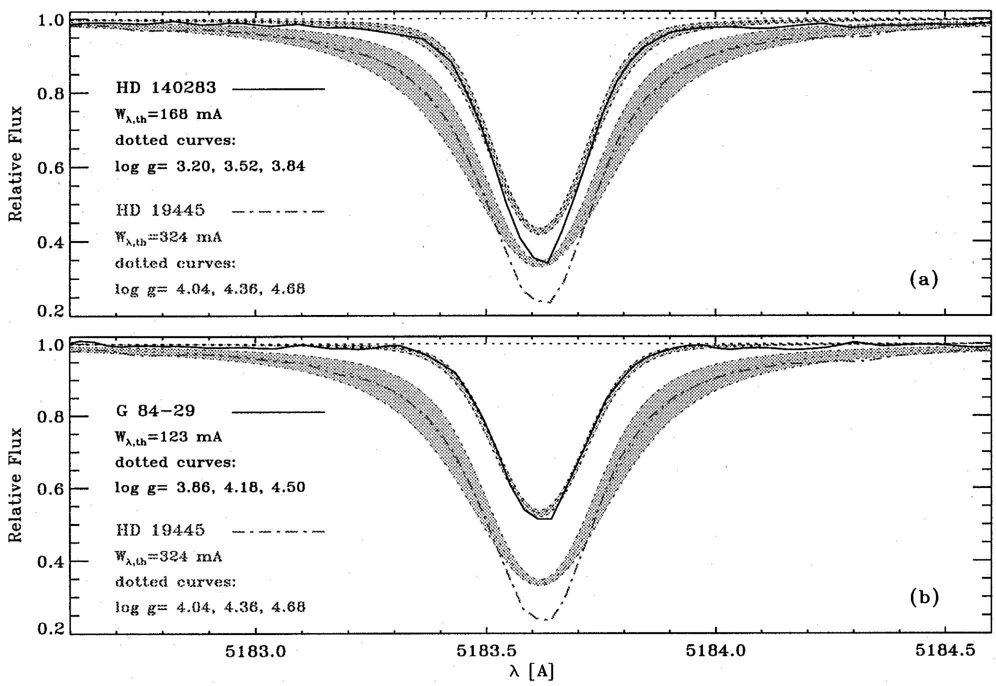

Fig. 2. Enlarged portion of Fig. 1 around λ5183.6, the strongest of the Mg Ib lines. Top: observed spectra are given for HD 140283 (continuous curve) and HD 19445 (dot-dashed curve). Theoretical calculations are depicted by the shaded regions that enclose the stellar spectra for log g = 3.52 $\pm$ 0.32 (HD 140283) and log g = 4.36$\pm$0.32 (HD 19445). The salient characteristic is the reduced sensitivity to a change in log g for HD 140283. The innermost (dotted) curve for HD 140283 is valid for log g = 3.20, the value obtained from the iron ionization equilibrium. Bottom: same analysis, but for G 84-29. The change in log g by 4.18 $\pm$ 0.32 is hardly detectable and the strong line method not applicable to this star with the Mg Ib lines. Note that the theoretical calculations reveal discrepancies in the line cores

their model with log g = 3.7 shows discrepancies in the iron ionization equilibrium, and for this reason they ultimately favour a model with log g = 3.3. A value as low, or even less, has been considered by several investigators. Magain's (1989) log g = 3.1 is among the lowest values, partly due to his lower effective temperature 5640 K. Our own work favours log g = 3.2, but only, if we rely on the LTE iron ionization equilibrium, and there are strong hints that this assumption may not be valid.

Instead, we recently made use of the strong line method for surface gravity determinations by means of the Mg Ib lines (Fig. 1). But, as detailed in Fig. 2 for λ5183, the line wings of HD 140283 are rather small ($W_{\lambda 5183}$ = 168 mÅ) and therefore not very sensitive to a change in log g (as opposed to HD 19445, which is also displayed for comparison). Nevertheless, the innermost (dotted) curve shows that for log g = 3.20 the computed magnesium line is too weak. Consequently, a higher log g is required, and log g = 3.52 was ultimately deduced.

But, as with HD 19445, our calculations show discrepancies in the cores of the Mg Ib lines and this renders the line profile fitting to become a somewhat difficult task, especially if the modeling of rotation, macroturbulence and the instrumental profile becomes important. For stars such as HD 19445, the Mg Ib lines are strong enough, that such details are almost negligible for the formation of the line wings. HD 140283, however, has to be considered as a critical case, where the strong line method for gravity determination is less reliable.

The comparison of the ionization equilibrium method and the strong line method indicates, that the log g of HD 140283 is higher by $\sim$ 0.32 dex if the latter applies. But from a comparison of the Hipparcos parallax data with our spectroscopically determined distance, Fig. 3 reveals that *a further increase in* log g *by* ~ 0.17 *dex is required.*

From the equation for the spectroscopic parallax

$$\log \pi_{\rm sp} = 0.5([g] - [M]) - 2[T_{eff}] - 0.2(V + BC_V - A_V + 0.26)$$

with $M_{bol,\odot}$=4.74 and the usual logarithmic notation $[X]$ = $\log(X/X_\odot)$, we can see that some uncertainty in the distance scale is introduced from the value of the stellar mass. On the other hand, HD 140283 is very metal-poor, and along with our good knowledge about T_{eff} and M_{bol}, its mass is fairly well fixed: contemporary stellar evolution calculations show that the mass must be as high as 0.7 $M_\odot$, but cannot be significantly above 0.8 $M_\odot$ (much larger uncertainties – as well as systematic errors – may be expected for the stellar *age* determination, which we defer for the moment until improved calculations are available; cf. Bernkopf 1997, VandenBerg 1997). As a result, the log g values differ by only 3.66 and 3.72, respectively, and we may thus assume that log g = 3.7$\pm$0.1 is a good approximation for HD 140283. Most recently Nissen et al. (1997) advocated a slightly higher value, log g = 3.79 $\pm$ 0.06. The difference is explained as the result of their neglect of the interstellar extinction A_V, along with a small contribution that is due to a slightly different value adopted for $M_{bol,\odot}$.

The upward shift in log g (3.69 vs. 3.52) entails a small adjustment of our published parameters of HD 140283. Instead of [Fe/H]= -2.34, we now obtain -2.29, with a 2σ rms error of 0.06 dex and a microturbulence ξ_t = 1.49 km s^{-1}. A slight revision is also indicated for the effective temperature of HD 140283, for which we derive T_{eff} = 5810 $\pm$ 80 K.

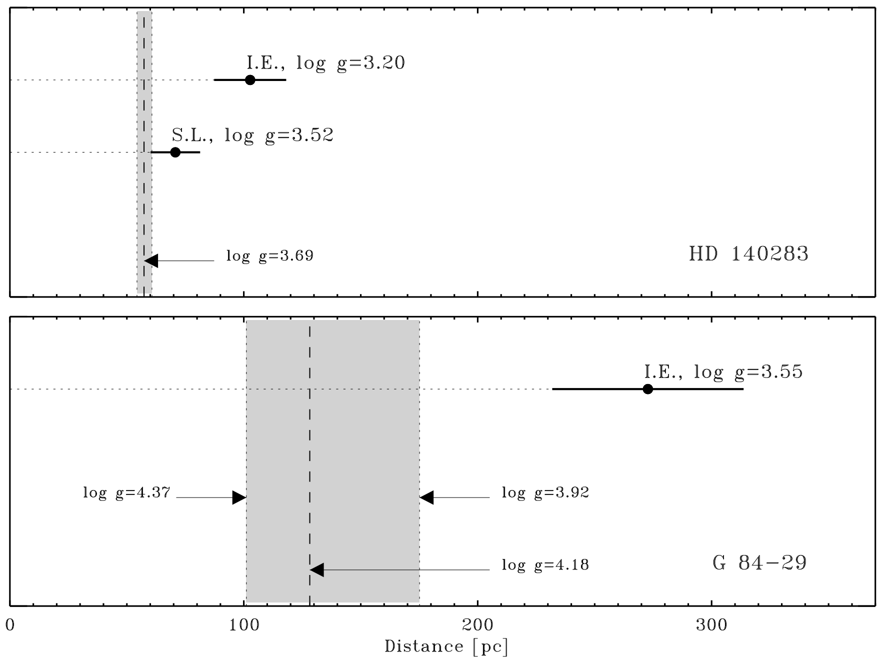

Fig. 3. The spectroscopic distance of HD 140283 and G 84-29 (filled circles) compared to the astrometric data (vertical dashed lines) from the Hipparcos satellite. Internal errors of the spectroscopic distance scale are about 15%. Astrometric errors are displayed by the shaded area. For both stars the spectroscopic distances, derived from the ionization equilibrium (I.E.) are too large by a factor of two. This error is reduced for HD 140283 from the analysis of the strong Mg Ib lines (S.L.), but due to the reduced efficiency of the method for this star, an additional correction of ∼0.17 dex is required. For G 84-29 the Hipparcos parallax implies log $g \sim 4.18$, and a lower limit for the gravity of log $g \sim 3.92$

4. Constraints on G 84-29

This star is hotter and at the same time more metal depleted than HD 140283. Therefore, lines of neutral magnesium are comparatively weaker, which is demonstrated in Fig. 1. In fact, the Mg Ib lines of this star show no wings, as we also infer from the model calculations in Fig. 2, that is, the strong line method fails for this star – at least as far as the Mg Ib lines are concerned.

When we applied the ionization equilibrium method to G 84-29, the surface gravity was found to be log g = 3.55, with a metallicity [Fe/H]= −2.70, and for the effective temperature we obtained T_{eff} = 6330 K. This set of stellar parameters inevitably meant that we had found a very metal-poor, but also quite luminous, i.e. comparatively young subgiant. This would have been a rather unexpected result. At that time we were however aware that most of our so-derived surface gravity values were most likely to be erroneous, and since there was no way to apply the strong line method to this star, we refrained from publishing our results for G 84-29. But, as we will see in what follows, there are now certain constraints on the characteristics of this halo star.

G 84-29 is more distant than HD 140283. Thus its Hipparcos parallax, π = 7.80 mas, is much smaller, and unfortunately this value is also accompanied by a relatively large error of 2.09 mas. As a result, the distance remains rather uncertain, as is also depicted in Fig. 3 by the large shaded area that reaches from 101 to 175 pc. Nevertheless, even if the latter value applies, a *lower limit* of log g = 3.92 is derived (here we assume $M_\star$ = 0.75 $M_\odot$ for the stellar mass), and if d = 128 pc applies – which corresponds to π = 7.80 mas – log g = 4.18 is inferred. This would be a correction of Δ log g = 0.63 dex, compared to the result from the LTE iron ionization equilibrium (although, upon suggestion of the referee R. Cayrel, the asymmetric distance error of G 84-29 makes a larger distance more probable than the value which corresponds to the observed parallax, and thereby, may lessen part of the log g discrepancy).

A gravity log g = 3.92 would also give rise to changes of the other stellar parameters: the effective temperature is lowered to T_{eff} = 6290 K and the metallicity increased to [Fe/H]= −2.54. If instead log g = 4.18 is the correct value, this results in T_{eff} = 6260 K and [Fe/H]= −2.46. In both cases we estimate the microturbulence to $\xi_t \simeq 1.4$ km s^{-1}.

The colors of G 84-29 suffer a certain amount of interstellar reddening. The presence of interstellar material in front of the star is most evident from the work of Hobbs & Pilachowski (1988), who identified strong sodium D lines of interstellar origin (cf. their Fig. 2) that are nicely Doppler-displaced from the stellar spectrum, for G 84-29 is a high-velocity star. Their estimate of the color excess is E_{B-V} = 0.04. Schuster & Nissen (1989b) measure E_{b-y} = 0.019, which translates to E_{B-V} = 0.025 and is also confirmed from the photometry given in Hauck & Mermilliod (1990). As with HD 140283, the reddening of G 84-29 requires an increase of photometrically determined effective temperatures that are based on the zero-reddening assumption. The effect amounts to $\sim$ 150 K and can therefore explain the discrepancy with the somewhat lower value, T_{eff} = 6110 K, derived by Magain (1989) from $V-K$.

If we adopt E_{B-V} = 0.03, the interstellar extinction is $A_V \sim 0.10$ and with $BC_V = -0.11$ we get $M_{bol} = 4.06\,^{+0.52}_{-0.68}$. With T_{eff} = 6260 ± 100 K the star is close to the turnoff region, but the exact position remains uncertain due to the relatively large parallax error. This also affects our knowledge of the stellar radius, which is found to be $R_\star = 1.16\,^{+0.42}_{-0.25}\,R_\odot$.

5. Conclusions

The investigation of very metal-poor stars is a challenge not only to our understanding of the early cosmological epochs and

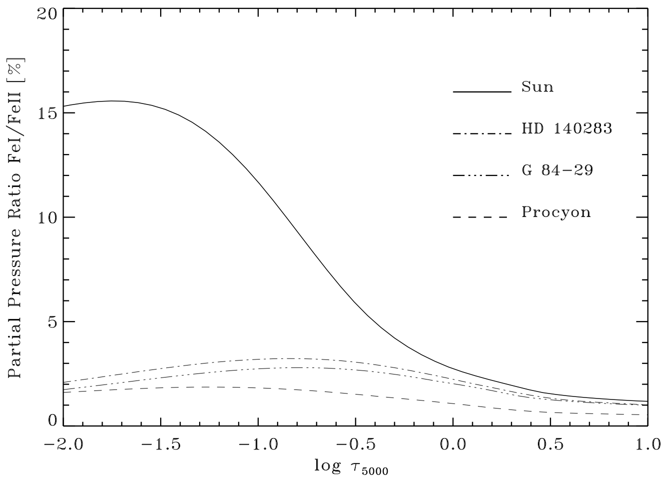

Fig. 4. Ratio of Fe I / Fe II partial pressures vs. optical depth for the Sun, Procyon, HD 140283, and G 84-29. The latter three stars reveal a similar extreme ionization balance

the formation of galaxies, but also to the employed methods of analyses. The spectra of these stars are considerably erased from the bulk of absorption lines that normally plague the proper placement of the continuum. This, at first glance, seemingly advantageous property is however outweighed by the fact, that many line wings, essential for diagnostic purposes, are absent, whereas other lines are as weak that only the highest quality spectra can provide useful informations – by no means an effortless matter since these stars are rare and accordingly faint. Two of the brightest of these extreme halo stars have been the subject of this paper and were investigated taking the recently published astrometric data from the Hipparcos mission into account.

The distance to HD 140283 is now well-known and this poses genuine constraints on the nature of this object: the *subgiant* stage is definitely confirmed, the surface gravity must be close to log $g \sim 3.7$.

The evolutionary stage of G 84-29 is not that well determined. Nevertheless, the star is situated somewhere near the *turnoff* region and must have a surface gravity to which log $g \sim 4.0$ is most probably a lower limit.

If we compare these results with the surface gravities based on the LTE iron ionization equilibria, the deviations are most obviously methodic and of the order of ~0.5 dex, i.e. as large as they have been found for Procyon. Fig. 4 shows that all three stars share a similar extreme Fe I/II ionization balance and this is a clear indication that the deviations must be affiliated to the Fe I lines. From a qualitative point of view, we know that NLTE effects most probably take an active part in clarifying the existing discrepancies. But, on the other hand, we should also be aware of our somewhat crude modeling of stellar atmospheres, to which especially those species are most susceptible, that are not in the dominant stage of ionization.

In this respect, the wealth of the Hipparcos data is the precise constraints, or at least the stringent upper or lower limits, posed on some of the fundamental stellar parameters, which act as a landmark for our guidance.

Acknowledgements. This research was supported from the *BMBF* under grant 05 2MU114 7.

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