Abundances of light elements in metal-poor stars. I.

Atmospheric parameters and a new $T_{\text{eff}}$ scale

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Abstract. We present atmospheric parameters for about 300 stars of different chemical composition, whose spectra will be used to study the galactic enrichment of Fe and light elements. These parameters were derived using an homogeneous iterative procedure, which considers new calibrations of colour-$T_{\text{eff}}$ relations for F, G and K-type stars based on Infrared Flux Method (IRFM) and interferometric diameters for population I stars, and the Kurucz (1992) model atmospheres. We found that these calibrations yield a self-consistent set of atmospheric parameters for $T_{\text{eff}} > 4400$ K, representing a clear improvement over results obtained with older model atmospheres. Using this $T_{\text{eff}}$ scale and Fe equilibrium of ionization, we obtained very low gravities (implying luminosities incompatible with that expected for RGB stars) for metal-poor stars cooler than 4400 K; this might be due either to a moderate Fe overionization (expected from statistical equilibrium calculations) or to inadequacy of Kurucz models to describe the atmospheres of very cool giants. Our $T_{\text{eff}}$ scale is compared with other scales recently used for metal-poor stars: it agrees well with those obtained using Kurucz (1992) models, but it gives much smaller $T_{\text{eff}}$'s than those obtained using OSMARCS models (Edvardsson et al. 1993). This difference is attributed to the different treatment of convection in the two sets of models. For the Sun, the Kurucz (1992) model appears to be preferable to the OSMARCS ones because it better predicts the solar limb darkening; furthermore, we find that our photometric $T_{\text{eff}}$'s for metal-poor stars agree well with both direct estimates based on the IRFM, and with $T_{\text{eff}}$'s derived from Hα wings when using Kurucz models.

Key words: Stars: fundamental parameters - Stars: atmospheres - Stars: abundances - Stars: population II

1. Introduction

The determination of elemental abundances in metal-poor stars is a basic constraint for models of the chemical evolution of our Galaxy, and provide wealth of data about the history of star formation (see e.g. Wheeler et al. 1989). A very important role is played by C, N, O, Na, Mg, and Fe, which are amongst the most abundant elements, likely produced in a variety of astronomical sites. The determination of accurate abundances for these elements in a large sample of stars of different metallicities, and their discussion within the framework of galactic evolution is the main purpose of the present series of papers. In the course of this investigation, we found it necessary to discuss a number of important, related issues in order to obtain more reliable results: some of them (e.g. the solar abundances and the applicability of the adopted model atmospheres in abundance analyses) were treated in a parallel study of the spectra of RR Lyrae stars at minimum light (Clementini et al. 1995), and in more depth by Castelli and Gratton (1996). The present paper is devoted to the presentation of the adopted atmospheric parameters; these were obtained using an iterative procedure which exploits both photometric and spectroscopic data. The most relevant feature is a new, hopefully improved calibration of colours against effective temperatures ($T_{\text{eff}}$'s). In other papers of this series (and with the contribution of other authors) we will present a discussion of non-LTE effects, using specially devoted statistical equilibrium computations and a new empirical calibration of the collisional cross-sections, and a discussion of the adopted abundance indices and of the derived abundances within the framework of models of the galactic chemical evolution.

The colour-$T_{\text{eff}}$ calibrations are by themselves a very interesting output of the present investigation: they have an important impact on a broad class of topics, including e.g. abundance analyses and comparisons between theoretical isochrones and cluster colour-magnitude (c-m) di-
agnars. Our new $T_{\text{eff}}$ scale is close to that determined by King (1993: hereinafter K93); it is based on empirical determinations for population I stars, applying corrections for non-solar metallicities drawn from the same Kurucz (1992) model atmospheres used in the analysis. A quite extensive discussion of this $T_{\text{eff}}$ scale is given in Sect. 5; we conclude that it gives reliable and consistent results for $T_{\text{eff}} > 4600$ K, while either the $T_{\text{eff}}$ scale or the same Kurucz models seem inadequate for stars cooler than 4400 K.

2. Program stars

Before discussing the derivation of the atmospheric parameters adopted in our analysis, a short presentation of the observational data used in this series of papers is required. The original material consists in about 400 high resolution ($R \sim 50,000$), high S/N ($> 150$) spectra of 19 metal-poor stars acquired with the Short Camera of the Coudé Echelle Spectrograph (CES) at the ESO Coudé Auxiliary Telescope, La Silla, and with the Coudé Spectrograph at the 2.7 m telescope of the McDonald Observatory. The stellar sample is the same used by Gratton & Sneden (1991, 1994: hereinafter GS1 and GS2) in order to derive abundances of Fe-group and n–r elements. However, the initial observations were carried out during ESO test time, kindly made available by Dr S. D’Odorico: the available observing time forced us to concentrate on the brightest ($V \leq 8$) southern metal-poor stars accessible during the observing run. This sample included only 19 stars; furthermore, all extremely metal-poor stars are giants, with the only exception of the subgiant HD 140283. This sample is too small for the present purposes and important biases are present. For this reason, we decided to increase it by adding data (equivalent widths $EW$) from a number of literature sources, reanalyzing them in the most homogeneous way possible: these additional data allow to better understand the selection biases present in our data, and to obtain a sample large enough for a statistically significant analysis of the results.

The additional sources of $EW$’s were selected from papers based on high resolution, high S/N observational material; we only considered studies giving $EW$’s for both Fe I and Fe II lines, since we used the Fe equilibrium of ionization to derive gravities: for this reason, only papers dealing with data having a rather large wavelength coverage were considered. The following works were then considered:

1. Tomkin et al. (1992: hereinafter TLLS): analysis of high excitation C and O permitted lines in 34 unevolved metal-poor stars;
2. Sneden et al. (1991) and Kraft et al. (1992) (hereinafter collectively SKPL): abundances of O from forbidden lines and Na from the doublet at 6154-60 Å in 27 field halo giants.
3. Edvardsson et al. (1993: hereinafter E93): analysis of high excitation O, Na, and Mg lines in about 180 field dwarfs with metallicity $[Fe/H] > -1$. Their data were integrated with $EW$’s for high excitation C lines from Clegg et al. (1981) and Tomkin et al. (1995), and forbidden O lines from Nissen & Edvardsson (1992) in a smaller number of stars.
4. Zhao & Magain (1990: hereinafter ZM90): abundances of Na and Mg in 20 metal-poor dwarfs.

Since there is some overlap amongst these different samples, on the whole, data for almost 300 stars over a wide range in luminosity and metal-abundance are considered. In the remaining part of this paper, we will discuss the derivation of the atmospheric parameters used in the analysis of all this material.

3. Derivation of atmospheric parameters

When preparing the present series of papers, the grid of model atmospheres by Kurucz (1992, hereinafter K92) became available to us. Since these models are able to reproduce various solar features (flux distribution, photospheric abundances, limb darkening, etc.) much better than the Bell et al. (1976; hereinafter BEGN) atmospheres, they were adopted in the present analysis. We decided to revise the whole derivation of atmospheric parameters (effective temperature $T_{\text{eff}}$, surface gravity log $g$, model metal abundance $[A/H]$, and microturbulent velocity $v_t$) for the program stars, in order to put them on a self-consistent scale. $T_{\text{eff}}$’s were derived from dereddened colours using semiempirical calibrations obtained through a procedure similar to that of K93; however standard $T_{\text{eff}}$’s obtained by means of the IRFM (Blackwell & Shallis 1977) were taken from Blackwell & Lynas-Gray (1994: hereinafter BLG), who used new calibrations based on the K92 model atmospheres. Furthermore, corrections for gravities were also obtained empirically by interpolating among values obtained for dwarfs and giants. The adopted iterative procedure (which requires approximate initial values for log $g$, $[A/H]$, and $v_t$) is as follows:

1. We first obtained empirical colour-$T_{\text{eff}}$’s calibrations using a compilation of $T_{\text{eff}}$’s derived with the IRFM for $\sim 140$ population I stars from the lists of BLG and Bell & Gustafsson (1989); these last $T_{\text{eff}}$’s were corrected to put them into the same scale of those of BLG. A first correction is required because Bell & Gustafsson derived $T_{\text{eff}}$’s from the IRFM using the BEGN models rather than the K92 models used here; we notice that on this respect, our calibrations represent an improvement over that of K93, who used $T_{\text{eff}}$’s derived from the IRFM calibrated against BEGN models (Saxner & Hammarbäck 1985). The $T_{\text{eff}}$’s from Bell & Gustafsson were then lowered by 122 K to put them on the same scale of those by BLG. This last correction might be due to the different ways fluxes in the IR are determined within broadband colours. Figure 2 shows the colour-$T_{\text{eff}}$ (IRFM)
Table 1. Polynomial coefficients of the empirical colour-$T_{\text{eff}}$ calibrations for population I stars (valid for $n < \text{colour} < m$). Two relations are given for giants; the first one should be preferred for stars with colours smaller than the following limits: $B - V = 1.48$, $V - R = 1.10$, $R - I = 0.94$, $J - K = 0.92$, $V - K = 3.10$, $b - y = 0.739$. The second one should be preferred for stars with colours larger than these limits. Errors are standard deviations from fits.

| Class | Stars | $a_0$ | $a_1$ | $a_2$ | $a_3$ | n  | m  |
|-------|-------|-------|-------|-------|-------|----|----|
| $B - V$ | III 81 | 8843  | -6982.5 | 3961.8 | -980.78 | 0.08 | 1.54 |
|       |       | ±95   | 401.7  | 530.5  | 206.09  |     |    |
| $B - V$ | III 22 | -228  | 7992.9  | -3466.5 | 1.20    | 1.64 |
|       |       | ±93   | 4281.2  | 1511.8  |         |     |    |
| $B - V$ | V 33  | 8905  | -6730.4 | 3173.8  | -552.07 | 0.12 | 1.35 |
|       |       | ±91   | 522.5   | 903.9   | 434.6   |     |    |
| $V - R$ | III 81 | 9245  | -8392.3 | 3247.6  | -85.49  | 0.10 | 1.23 |
|       |       | ±140  | 887.6   | 1473.8  | 722.71  |     |    |
| $V - R$ | III 22 | 7060  | -3879.5 | 1046.7  | 0.89    | 2.03 |
|       |       | ±77   | 476.7   | 168.2   |         |     |    |
| $V - R$ | V 29  | 9065  | -8067.3 | 3568.5  | -131.30 | 0.07 | 1.17 |
|       |       | ±182  | 1328.0  | 2605.5  | 1431.50 |     |    |
| $R - I$ | III 81 | 8824  | -11747.6 | 7920.2  | -1123.14 | 0.03 | 0.94 |
|       |       | ±75   | 373.9   | 649.0   | 400.52  |     |    |
| $R - I$ | III 22 | 5932  | -3109.0 | 969.0   | 0.63    | 1.91 |
|       |       | ±88   | 389.3   | 159.3   |         |     |    |
| $R - I$ | V 33  | 8764  | -11850.9 | 9310.1  | -2265.45 | 0.05 | 0.85 |
|       |       | ±182  | 1328.0  | 2605.5  | 1431.50 |     |    |
| $J - K$ | III 68 | 8553  | -10456.7 | 9613.5  | -3886.47 | 0.17 | 0.97 |
|       |       | ±84   | 1202.7  | 2233.7  | 1260.56 |     |    |
| $J - K$ | III 16 | 10071 | -10088.2 | 3843.5  | 0.85    | 1.22 |
|       |       | ±50   | 2073.6  | 1017.7  |         |     |    |
| $J - K$ | V 19  | 9850  | -17774.9 | 23374.3 | -12170.60 | 0.11 | 0.83 |
|       |       | ±164  | 2887.6  | 6894.7  | 4901.1  |     |    |
| $V - K$ | III 78 | 8992  | -2887.9 | 556.9   | -40.02  | 0.19 | 3.67 |
|       |       | ±43   | 78.9    | 44.3    | 7.20    |     |    |
| $V - K$ | III 13 | 6733  | -1136.0 | 99.3    | 3.10    | 6.01 |
|       |       | ±63   | 325.1   | 35.1    |         |     |    |
| $V - K$ | V 33  | 8890  | -2782.4 | 523.1   | -31.79  | 0.29 | 3.32 |
|       |       | ±60   | 136.2   | 97.1    | 19.10   |     |    |
| $b - y$ | III 32 | 8736  | -9595.6 | 6135.2  | -1428.90 | 0.96 | 0.95 |
|       |       | ±103  | 781.4   | 1738.9  | 1108.00 |     |    |
| $b - y$ | III 14 | 11754 | -15965.3 | 8172.8  | 0.70    | 0.96 |
|       |       | ±60   | 5430.3  | 3261.7  |         |     |    |
| $b - y$ | V 30  | 8592  | -7044.5 | -2200.5 | 5248.20 | 0.06 | 0.79 |
|       |       | ±94   | 966.8   | 2786.9  | 2251.70 |     |    |

2. We derived $T_{\text{eff}}$'s from each observed colour for the program stars using a cubic polynomial interpolation in the theoretical $T_{\text{eff}}$-colour planes. However, before doing this interpolation we transformed both theoretical $T_{\text{eff}}$'s and observed colours, to consider the difference between the empirical and theoretical calibrations for population I stars, and the variation of colours with metallicity. This was done in two steps: (i) By assuming that the zero-point calibrations of the various theoretical colors may be in error and the IRFM yields the right temperatures, we replaced $T_{\text{eff}}$'s of the K92 models with those $T_{\text{eff}}$'s that give the same value of the colours but using the empirical calibrations ob-
tained from population I stars: this coordinate transformation corresponds to the application of systematic corrections, function of $T_{\text{eff}}$, to the K92 temperatures, equal to the differences between the empirical and theoretical calibrations for solar metallicities. (ii) We then replaced the colours of K92 models for solar metallicity at each temperature, with the colours of K92 models for the approximate input value of the metallicity; these colours were obtained by means of a cubic polynomial interpolation through theoretical colours given by K92; this second coordinate transformation corresponds to the application of systematic corrections, still a function of $T_{\text{eff}}$, to the observed colours to consider the individual metallicity of the star under consideration. Note that this step implies that though the K92 models may give uncorrect colours at a given temperature, they correctly predict the dependence of colours on metal abundances. This last assumption was made also by K93.

3. We applied the previous transformations separately for both giants and dwarfs; when comparing theoretical and empirical calibrations, we assumed $\log g = 4.5$ for luminosity class V; for luminosity class III, we assumed $\log g = 2$ for $T_{\text{eff}} > 4500$ K, and $\log g =$


\( (T_{\text{eff}} - 3500)/500 \) for \( T_{\text{eff}} < 4500 \text{ K} \). These values approximately match the observed \( \log g \) for dwarfs and giants respectively; however, this assumption is not critical, since gravity corrections are generally small. The best temperature for each colour as function of gravity was then derived by linear interpolation/extrapolation between the values obtained for the two different logarithmic gravities, using the approximate input value for the stellar gravity.

4. Atmospheric parameters for reanalyzed stars

For all program stars, new values for the atmospheric parameters were derived, following the iterative procedure described in Sect. 3. We used the \( EW \)'s from the various sources cited in Sect. 2, and photometric data from Hauck & Mermilliod (1990), Schuster & Nissen (1988), Twarog & Anthony-Twarog (1994), Laird et al. (1988), Stone (1983), Pilachowski (1978), Arribas & Martinez-Roger (1987), and Alonso et al. (1994); however, only \( V - K \) colours were available, since they are only weakly dependent on gravity and metallicity; one or two iterations were required for the other cases.

5. Discussion of the adopted parameters

5.1. Kurucz 1992 and Kurucz 1995 model atmospheres

After the draft of this paper was ready, we were aware that the convective flux in Atlas 9 version used to compute the 1992 models stored on the CD-ROM 13 generated discontinuities in the grids of the colour indices for \( T_{\text{eff}} \) in the approximate range between 6700 K (for \( \log g = 2 \)) to 8000 K (for \( \log g = 4.5 \)). The convection formalism was improved (Castelli, 1996) and Kurucz (1995) recomputed most of the cool model atmospheres (K95 models). The 1995 models differ from the 1992 models mostly for an improved convection, for the larger number of layers (72
rather than 64) which extend toward lower optical depths, for a better treatment of the radiation emerging from the uppermost layers, and for a few changes in some opacity routines, as that for H$^{-}$. Furthermore, all the colours are recalibrated on a different ATLAS9 Vega model (Castelli & Kurucz 1994). Rather than redoing all our lengthy computations, we directly compared colour indices and abundances from the K92 and K95 models, made recently available to us by R. Kurucz. First we considered colors, and in particular Johnson $B - V$ and $V - K$, and Strömgren $b - y$ (these are the colors having the largest weight in our $T_{\text{eff}}$ determinations). We found small constant offsets of 0.004, 0.012 and 0.025 for $b - y$, $B - V$, and $V - K$ respectively between the original K92 colors and those we obtained using K95 models (in the sense that K95 colors are redder). These small offsets are due to slightly different assumptions about the atmospheric parameters for the reference star Vega. For the stars used in this series of papers, the theoretical $T_{\text{eff}}$-scale obtained using K95 models is $\sim 30$ K warmer. For all colors, there is a peak in the color residuals (amounting to $\sim 0.02$, 0.015, and 0.045 for $b - y$, $B - V$, and $V - K$ respectively, again K95 colors being redder) over a small range of $T_{\text{eff}}$ ($\sim 6750$ for $\log g = 2$, and $\sim 8000$ K for $\log g = 4.5$). The peak residual is smaller for metal-poor model atmospheres. Given the small $T_{\text{eff}}$ range where these larger corrections (corresponding to 30-120 K, depending on the colour used) apply, they have negligible impact on the polynomial fitting curves used in our semiempirical procedure. Furthermore, the peaks fall outside the $T_{\text{eff}}$ range for stars considered in this series (and in the parallel paper on RR Lyrae at minimum light by Clementini et al. 1995).

We then compared abundances obtained using K92 and K95 model atmospheres for a few typical cases, adopting in both cases the same set of atmospheric parameters. We found that K95 atmospheres yield larger abundances (by 0.008 dex) than K92 atmospheres for low excitation lines of easily ionized elements; and smaller abundances (by 0.003 dex) for high excitation lines of dominant species (like the OI IR triplet).

On the whole, we regard differences between results obtained using K92 and K95 model atmospheres as negligible with respect to other sources of error in our analysis, and in this series of papers we will keep the results obtained using K92 atmospheres.

5.2. Trends of Fe abundances with excitation potential

Use of K92 atmospheres and of the new sets of atmospheric parameters allows an homogeneous comparison to solar abundances; however, we noticed some inconsistencies, that are discussed in this section.

Dalle Ore (1992) found a systematic trends of abundances from individual Fe I lines with excitation potential for metal-poor giants, in the sense that temperature derived from line excitation is much lower than that derived from colours (that is, a negative slope $\delta \theta$ of Fe abundances with excitation potential). We found a similar trend using star in our original sample, that admittedly included a few stars; however the large spectral coverage allowed derivation of EWs for a large set of lines having accurate laboratory $gf$'s. We found the following average values for the slope $\delta \theta$ in the excitation-abundance plane:

- all stars: $-0.047 \pm 0.009$ dex/eV ($\sigma = 0.041$ dex/eV, 19 stars)
- $\log g > 4$: $-0.038 \pm 0.005$ dex/eV ($\sigma = 0.013$ dex/eV, 6 stars)
- $3 < \log g < 4$: $-0.052 \pm 0.016$ dex/eV ($\sigma = 0.040$ dex/eV, 6 stars)
- $\log g < 3$: $-0.050 \pm 0.022$ dex/eV ($\sigma = 0.058$ dex/eV, 7 stars)

On the whole, the value of the slope seems to be weakly dependent on surface gravity, while the scatter seems to be a function of gravity. This suggests that either the effective temperatures of giants are ill-defined (e.g. due to errors in the estimate of reddening), or that the atmospheres of giants are somewhat different one from the other, or both. On the other side, the average slope for stars in the large sample by E93 (all with $\log g > 3$) is quite different ($\delta \theta = +0.027 \pm 0.002$, $\sigma = 0.025$, 203 independent estimates for 187 stars); a clear trend with overall metal abundance is present: $\delta \theta = (0.051 \pm 0.005)[\text{Fe}/\text{H}] + (0.040 \pm 0.021)$. However, the determinations of the slope using stars in the E93 sample are based on a few lines with solar oscillator strengths. Contamination by blending features may cause spurious trends. This point should then be reexamined using an extended line list for a large sample of stars.

![Fig. 2. Differences between gravities derived from the position in the c-m diagram ($\log g_{\text{orig}}$) and from Fe equilibrium of ionization ($\log g_{\text{ew}}$) as a function of $T_{\text{eff}}$ for the globular cluster giants considered by Carretta & Gratton (1996). A mass of 0.8 $M_{\odot}$ was adopted for these stars](image-url)
5.3. Gravities and Fe equilibrium of ionization

For another program (Carretta & Gratton 1996), we applied this same procedure to the analysis of the spectra of globular cluster giants, where gravities can be determined from luminosities, masses and effective temperatures. That analysis showed that the difference between abundances given by neutral and singly ionized lines is a function of $T_{\text{eff}}$. This is illustrated by the data in Fig. 2 where we plotted the differences between the gravities for globular cluster giants obtained from the procedure described in this paper, and those derived from the position in the c-m diagram, assuming a mass of 0.8 $M_\odot$. While the agreement between the two sets of gravities is fairly good for $T_{\text{eff}} > 4600$ K, gravities derived from the Fe equilibrium of ionization are on average too low for stars cooler than 4400 K.

In the following we will consider three possible explanations for this discrepancy:

1. The IRFM cannot be reliably used for M-stars from ground-based observations alone, due to the strong molecular bands in the near-IR spectral region. It is then possible that our empirical calibration for population I stars, based on the application of the IRFM method to ground-based observations, is not accurate for the coolest stars. On the other side, $T_{\text{eff}}$'s for M giants can be derived from determinations of stellar angular diameters. We then tested the cool end of our $T_{\text{eff}}$-colour calibrations by comparing the $T_{\text{eff}}$'s derived using the IRFM with those that can be obtained from interferometric determinations of stellar diameters (Di Benedetto & Rabbia, 1987; see Fig. 3). We found however an excellent agreement between the two sets of $T_{\text{eff}}$'s; a calibration obtained by merging the two sets differs by $\leq 20$ K from that obtained using $T_{\text{eff}}$'s from the IRFM alone for $T_{\text{eff}} > 4000$ K.

2. Some Fe overionization is expected for the coolest, very low gravity giants. We performed an explorative statistical equilibrium computation for the coolest star in our own sample (HD 187111) using MULTI code (Scharmer & Carlsson, 1985; Carlsson 1986) and a 60-level Fe I model atom (for a full description of this model atom and the methods used in this and other statistical equilibrium computations, see Gratton et al. 1996). We parametrized the poorly known cross sections for collisions with H I atoms by matching observations of RR Lyrae at minimum light (see Clementini et al. 1995). We found that the maximum non-LTE correction to the Fe I abundance in HD 187111 compatible with the observations of RR Lyrae variables (where departures from LTE are expected to be larger than in the program stars) is 0.08 dex (abundances from Fe II lines are not influenced by departures from LTE). A smaller correction (0.04 dex) is expected for HD 136316, while non-LTE corrections to Fe abundances should be very small for the other program stars. If LTE abundances from Fe I lines for HD 187111 are corrected for this amount, we derive slightly larger surface gravities ($\sim 0.25$ dex). This correction is about half the value required to reduce the luminosity of this metal-poor star below that expected at the tip of the red giant branch. Hence, departures from LTE are a promising candidate to explain part of the observed discrepancy.

3. We finally tested the hypothesis that the model atmospheres may be responsible for the observed discrepancies. This was done by replacing BEGN models to the K92 ones for a few typical cases. Abundances for the Sun derived from the K92 models and updated laboratory $g f$'s are close to those given by the Holweger & Muller (1974) model, and to the meteoritic values (Anders & Grevesse 1989), while it is well known that abundances provided by BEGN solar model are too low by $\sim 0.08 - 0.15$ dex (the exact value depends on the line list used). Furthermore, K92 model reproduces the solar flux distribution much better than the BEGN model; hence K92 models should be preferred in the analysis of solar type stars. However, for all the species investigated, the K92 and BEGN models yield stellar abundances relative to the solar ones which differ less than 0.03 dex for $T_{\text{eff}} > 4400$ K. When doing a relative analysis for cooler stars, the ionization equilibrium given by BEGN model atmospheres is in agreement with the observations.
better agreement with that obtained using $T_{\text{eff}}$ ’s from IRFM and gravities from the c-m diagram, although the discrepancy is not completely canceled. Gravities obtained from the equilibrium of ionization are too low when using K92 models for these cool stars. This fact suggests that K92 models are not fully adequate for the analysis of stars with $T_{\text{eff}} < 4400$ K.

Since in the present series of papers we are mainly concerned with stars with $T_{\text{eff}} > 4400$ K, we will use K92 model atmospheres; however, results for the coolest stars require further investigations: whenever possible, conclusions will only be drawn using warmer stars (preferably dwarfs).

6. Comparison between empirical calibrations and theoretical colours

Figures 3 and 4 compare the present empirical $T_{\text{eff}}$ -colour calibrations for population I dwarfs and giants respectively with the theoretical calibrations directly based on K92 fluxes for the Johnson $B - V$, $V - R$, $R - I$, $J - K$, and $V - K$ colours, and for the Strömgren $b - y$ index. The agreement between the empirical and theoretical calibrations is very good for $V - K$; significant deviations can be noticed only at very low $T_{\text{eff}}$’s ($T_{\text{eff}} < 4500$ K) for dwarfs, and high $T_{\text{eff}}$’s ($T_{\text{eff}} > 6000$ K) for giants, where we have only a few calibrating stars. The comparison is also quite good for $B - V$, $R - I$, and $b - y$, although corrections (a few hundredths of mag) are not negligible. In particular, we notice that the $B - V$ colour for the Sun derived from our empirical calibration ($B - V = 0.62$) is 0.03 mag bluer than that provided by the theoretical calibration. Similar corrections should be applied when colours from K92 models are applied to theoretical isochrones. The comparison is poorer for the $V - R$ colour.

7. Comparisons with other $T_{\text{eff}}$-scales

Of particular interest is the comparison of the current $T_{\text{eff}}$-scale with those recently used by other authors for metal-poor stars.

7.1. Giants

7.1.1. Dalle Ore et al. (1996)

Dalle Ore et al. (1996) used the K92 models in an analysis of the chemical composition of HD 122563; their $T_{\text{eff}}$ (4590 K) derived with the IRFM agrees very well with our value for this star (4583 K).

7.1.2. Cohen et al. (1978)

Figure 3 compares the present calibration of $V - K$ with that obtained by Cohen et al. (1978), often used in the analysis of globular cluster giants. Cohen et al. scale is based on $JHK$ magnitudes and colours, calibrated against the old Kurucz (1979) model atmospheres: it predicts that $V - K$ colours are independent of gravity and metal abundance. The three panels of Fig. 3 compare the two scales in different abundance regimes and for different values of gravities. While the overall comparison is fairly good, the metallicity dependence is different in the two cases, since we are using the K92 models. Furthermore, the gravity dependence at low $T_{\text{eff}}$’s and metallicity seems not negligible; however, it is now clear that K92 models are not fully adequate in the analysis of the coolest, very metal-poor giants.

7.1.3. Clementini et al. (1995)

It is useful to compare our $T_{\text{eff}}$ scale with that adopted by Clementini et al. (1995), since results of the abundance analysis in that paper will be used in the second paper of this series to calibrate our own statistical equilibrium computations. Figure 4 compares the two empirical calibrations of the $V - K$ index: the relations are virtually identical in the typical temperature range for RR Lyrae at minimum light (6000-6300 K).

7.1.4. Blackwell & Lynas Gray (1994)

The comparison between the $T_{\text{eff}}$ scale of this paper and that of BLG is shown in Fig. 5; the agreement is excellent, but the range of validity of the BLG scale is smaller than the present scale.

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Fig. 6. Comparison between the present $T_{\text{eff}}$ -colour calibrations for giants (GCC96) and the calibrations by Cohen et al. (1978: CFP). Panel a shows results for $[\text{Fe/H}]=0$, panel b for $[\text{Fe/H}]=-1.5$, and panel c for $[\text{Fe/H}]=-2$. Different line types are used for models with different values of log $g$. 

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Fig. 4. Comparison between the present empirical $T_{\text{eff}}$-colour calibrations for population I dwarfs (dashed line) and the theoretical calibrations directly based on K92 fluxes (Kurucz 1992) (solid line) for various colours. For brevity, only the comparisons for $B-V$ (panel a), $b-y$ (panel b), and $V-K$ (panel c) are shown in this figure.

7.2. Dwarfs

7.2.1. King (1993)

More intriguing is the situation for metal-poor dwarfs. The present $T_{\text{eff}}$ scale agrees fairly well with that of K93, as shown by the comparisons of Fig. 4: this is not surprising, since they were derived using the same model atmospheres and a similar procedure.

7.2.2. Edvardsson et al. (1993)

Recently, E93 published the results of the analysis of a very extensive spectroscopic survey of field dwarfs. All stars considered by E93 have $\text{[Fe/H]} > -1$; however, Nissen et al. (1994) presented the results of the analysis of a few more metal-poor dwarfs whose atmospheric parameters were derived with a similar technique. A star-to-star comparison between our and E93 and Nissen et al. sets of atmospheric parameters shows large discrepancies in the adopted $T_{\text{eff}}$'s for a few stars. This effect is systematic, as shown by Fig. 11, which displays the difference between
Fig. 5. The same as Fig. 4 but for population I giants

the $T_{\text{eff}}$’s derived by the two techniques for the stars observed by E93 and Nissen et al. against [Fe/H]. The best fit regression line with [Fe/H] is:

$$
\Delta T_{\text{eff}} = -(174.9 \pm 7.5)[\text{Fe/H}] - (81 \pm 30),
$$

(1)

based on 187 stars. The Persson linear regression coefficient is $r^2 = 0.746$, but there are minor, not negligible correlations with gravity and $T_{\text{eff}}$; the regression using all three variables is:

$$
\Delta T_{\text{eff}} = (-171.5 \pm 7.2)[\text{Fe/H}] - (45 \pm 14) \log g
- (0.0492 \pm 0.0074)T_{\text{eff}} + (405 \pm 27),
$$

with $r^2 = 0.798$, a marginal but significative improvement. This comparison shows that $T_{\text{eff}}$’s may be different by as much as $\sim 400$ K for the most metal-poor stars, even though the same colours are used; this is an enormous difference causing discrepancies as large as $0.4 \div 0.5$ dex in the derived [Fe/H]. A small part of this discrepancy can be attributed to the rather large values of reddening $E(b-y)$ adopted by Nissen et al. (1994), and for individual stars there are colour indices yielding slightly different $T_{\text{eff}}$’s using our prescriptions. However most of this discrepancy is real, and at prima facie surprising, since both $T_{\text{eff}}$ scales are linked to accurately determined $T_{\text{eff}}$’s for Population I stars, for which a good agreement exists among determinations by different authors. However, a major difference is the use of different grids of model atmospheres: E93 and Nissen et al. used the new (unpublished) OSMARCS
Abundances of light elements in metal-poor stars. I.

Fig. 7. Comparison between the \( T_{\text{eff}} \) scale of this paper (GCC96) and that of Clementini et al. (1995: RR) for population I dwarfs.

Fig. 8. Comparison between the \( T_{\text{eff}} \) scale of this paper (GCC96) and that of BLG; the agreement is excellent, but the range of validity of the BLG scale is smaller than the present scale.

Fig. 9. Comparison between the \( T_{\text{eff}} \) scale of this paper (GCC96) and K93 for population I dwarfs.

Fig. 10. Plot of the differences between original \( T_{\text{eff}} \)'s for stars in the Edvardsson et al. (1993) and Nissen et al. (1994) samples and those derived using our calibration, as a function of our value for \([\text{Fe/H}]\) stars; the consequence is that the two models predict a very different dependence of colours on metal abundance: e.g. at \( b-y = 0.35 \), OSMARCS models with \([\text{Fe/H}]=0\) are \( \sim 210 \) K warmer than models with \([\text{Fe/H}]=-1\), while the analogous difference for the K92 models is only \( \sim 40 \) K. The discrepancy between the two grids is smaller for low \( T_{\text{eff}} \) stars, but these are not included in the E93 and Nissen et al. papers.

The most sensitive test for model atmospheres is the comparison between predicted and observed solar limb-darkening relations. Blackwell, Lynas-Gray and Smith (1995) show that this comparison clearly favors the K92 model atmospheres with respect to the OSMARCS models.
Fig. 11. $T(\tau)$ relations for the Sun (panel a) and a metal-poor dwarf (panel b) using different model atmospheres: K92 (solid line), OSMARCS (dot dashed line), Holweger & Müller (1974: HM, dotted line in panel a), and BEGN (dotted line in panel b).

Fig. 12. Comparison of our $T_{\text{eff}}$ calibration (GCC96) with $T_{\text{eff}}$’s deduced from the wing of Balmer lines (Fuhrmann et al. 1993, 1994: F94) for some metal-poor dwarfs.

7.2.3. $T_{\text{eff}}$’s from IRFM for subdwarfs

Magain (1987) derived $T_{\text{eff}}$’s for eleven metal-poor dwarfs using the IRFM and the BEGN model atmospheres; it must however be noticed that his $T_{\text{eff}}$’s derived from $J$ and $K$ magnitudes are quite different (those derived from $J$ being lower by $131 \pm 12$ K on average). His $T_{\text{eff}}$-scale is lower than ours by $\sim 140$ K, with no trend with metal abundance; this difference is equal to the difference between the $T_{\text{eff}}$-scale of Magain and that of Saxner & Hammarbäck (1985) at $[\text{Fe/H}]=-0.5$, the lower edge of validity of this last scale (see also K93). However, to make a meaningful comparison, Magain’s $T_{\text{eff}}$’s should be corrected for the systematic differences between $T_{\text{eff}}$’s derived using the IRFM with BEGN and K92 model atmospheres. These have been computed only for population I stars (BLG: Mégessier 1994); if these corrections are applied, Magain’s $T_{\text{eff}}$’s are increased by 90 K on average (the correction is rather large for $T_{\text{eff}}$’s derived from $J$ magnitudes, while it is quite small for those obtained from $K$). The mean difference with the current $T_{\text{eff}}$-scale is then reduced to $46 \pm 14$ K. Furthermore, $T_{\text{eff}}$’s derived from $J$ and $K$ magnitudes would now be in fair agreement with each other, the mean difference being reduced to $21 \pm 12$ K. This test should be repeated with values for the $R$ ratio of the IRFM appropriate for metal-poor stars; however, these early results suggest that the dependence of colours on metal abundance given by K92 models should not be far from correct.

7.2.4. $T_{\text{eff}}$’s from Balmer line profiles for subdwarfs

While the far wings of H$_\alpha$ are quite independent from gravity, metallicity and convection of the model atmo-
Table 7. \( T_{\text{eff}} \)'s from \( \text{H}_\alpha \) for seven subdwarfs

| Star      | \( (V-K) \) | \( \text{Fe/H}\) | \( T_{\text{eff}} \) \( (V-K) \) | \( T_{\text{eff}} \) \( (\text{H}_\alpha) \) |
|-----------|-------------|------------------|-------------------------------|------------------|
| HD 19445  | 1.37        | -1.91            | 6112                          | 6250              |
| HD 64090  | 1.72        | -1.69            | 5510                          | 5500              |
| HD114762  | 1.41        | -0.87            | 5964                          | 5750              |
| HD194598  | 1.35        | -1.11            | 6077                          | 6100              |
| HD201891  | 1.39        | -1.08            | 6009                          | 6000              |
| LTT10733  | 1.525       | -1.04            | 5788                          | 5900              |
| LTT111819 | 1.79        | -1.56            | 5406                          | 5400              |

Subdwarfs (and are then good temperature indicators for solar type stars), those of the other Balmer lines are strongly dependent on how convection is handled when computing model atmospheres, due to its effect on the temperature stratification of the model. Fuhrmann et al. (1993) employed this dependence to determine the best value for the pressure scale height in the mixing length formalism, to be used when modelling atmospheres for metal-poor dwarfs. Unfortunately, they used the old Kurucz (1979) model atmospheres, and their results cannot be directly used in the present context. We note, however, that our \( T_{\text{eff}} \)-scale compares quite well with the \( T_{\text{eff}} \)'s determined by Fuhrmann et al. (1994; see Fig. 12).

For another program, we acquired spectra of several subdwarfs at a resolving power of \( \sim 15,000 \) and \( S/N \sim 250 \) using the REOSC Echelle spectrograph at the 182 cm Copernicus reflector of Asiago Observatory. This spectrograph uses a 79 gr/mm echelle grating and a large format front illuminated Thomson CCD detector, with no appreciable diffraction fringes. These spectra are then quite well suited for the determination of \( T_{\text{eff}} \)'s from the \( \text{H}_\alpha \) profiles. Preliminary reduced spectra for seven subdwarfs were used by Clementini et al. (1995) to derive \( T_{\text{eff}} \)'s from \( \text{H}_\alpha \) profiles using K92 model atmospheres. Details about data reduction are given in Clementini et al.: here we only remind that particular care was devoted to flat fielding and subtraction of the telluric lines. For two stars (HD 19445 and HD 114762) we could directly compare the \( \text{H}_\alpha \) profiles derived from our spectra with those by Fuhrmann et al. The agreement is excellent: profiles from the two sources agree within \( \sim 0.5\% \).

The observed \( \text{H}_\alpha \) profiles were compared with synthetic profiles computed using K92 models and our own spectral synthesis code, which included Doppler, natural damping, resonance (Ali & Griem 1965, 1966), and Stark (Vidal et al. 1970) broadening, following prescriptions similar to those adopted by Fuhrmann et al. (1993, 1994). These prescriptions should be correct for electron densities above \( 10^{11} \) electrons per cm\(^3 \), that is throughout most of dwarf atmospheres. However, line formation in the outer part of the atmospheres may be affected by appreciable deviations from LTE: hence these part of the profiles (as well as those contaminated by other lines) were not considered in the \( T_{\text{eff}} \) derivations. A comparison with the solar flux spectrum (Kurucz et al. 1984) showed that our computed profiles with the K92 model atmospheres reproduce observations very well (incidentally, good agreement is also obtained when using the OSMARCS and Holweger & Müller, 1974, atmospheres).

A comparison of observed and computed profiles for three stars is given in Fig. 12. Our \( T_{\text{eff}} \)'s from \( \text{H}_\alpha \) profiles for the seven subdwarfs are listed in Table 7 where metal abundances are from Schuster & Nissen (1989) In this table we also give \( T_{\text{eff}} \)'s from our photometric calibrations (averaging \( V-K \) colors from Alonso et al. (1994) and Laird et al. (1988), both transformed into the Johnson system using the relations given by Alonso et al. (1994). The agreement between \( T_{\text{eff}} \)'s derived from spectroscopy...
and photometry is excellent: the mean difference is 6 ± 43.
The r.m.s. scatter of star-to-star residuals (114 K) indicate that internal errors are ~ 100 K; we attribute these errors to small (~ 1%) uncertainties in the location of the continuum level. We conclude that the comparison with $H_\alpha$ profiles supports our colour-temperature calibrations.

8. Comparison with parameters used in the original analyses

8.1. GS1 and GS2

The new temperatures and gravities are larger for dwarfs and smaller for giants with respect to the values used in GS1 and GS2. Metal abundances and microturbulent velocities are also larger for dwarfs, while they are close to the old values for giants. We computed linear regression fits through the residuals between new and old values of the atmospheric parameters as a function of surface gravity; the relations are as follows:

$$T_{\text{eff,us}} - T_{\text{eff,old}} = (45.7 \pm 6.1) \log g_{\text{us}} - (100 \pm 41) \text{ K}$$

$$\log g_{\text{us}} - \log g_{\text{old}} = (0.147 \pm 0.027) \log g_{\text{us}} - (0.35 \pm 0.18)$$

$$v_t_{\text{us}} - v_t_{\text{old}} = 0.088 \pm 0.049 \log g_{\text{us}} - (0.23 \pm 0.32) \text{ km/s}$$

$$[\text{Fe/H}]_{\text{us}} - [\text{Fe/H}]_{\text{old}} = (0.046 \pm 0.011) \log g_{\text{us}} + (0.101 \pm 0.076)$$

We notice that the main conclusions of the present series of papers are not influenced by these variations of the atmospheric parameters, although abundances for individual stars may be different by as much as 0.3 dex.

8.2. TLLS

These atmospheric parameters are rather different from the original ones; on average, our $T_{\text{eff}}$’s are larger than those found in TLLS by 165 ± 16 K, the log $g$’s by 0.31 ± 0.03, the [Fe/H]’s by 0.29 ± 0.02, while the $v_t$’s are smaller by 0.67 ± 0.03 km s$^{-1}$. We found no significant trend for these offsets with $T_{\text{eff}}$, log $g$, and [Fe/H], except of course for $v_t$.

8.3. SKPL

Differences with SKPL are much smaller (on average differences in the sense us-SKPL are −78 ± 18 K, −0.24 ± 0.07 dex, 0.02±0.02 dex, and −0.12±0.03 km s$^{-1}$ for $T_{\text{eff}}$, log $g$, [Fe/H] and $v_t$ respectively), but there are trends with $T_{\text{eff}}$.

8.4. E93

Significative trends with metal abundances are present when we compare our adopted parameters for the stars considered by E93 with those adopted in their preliminary analysis:

$$T_{\text{eff,us}} - T_{\text{eff,E93}} = -(180 \pm 9)[\text{Fe/H}]_{\text{us}} - (81 \pm 35) \text{ K},$$

$$\log g_{\text{us}} - \log g_{\text{E93}} = -(0.31 \pm 0.04)[\text{Fe/H}]_{\text{us}} - (0.11 \pm 0.17) \text{ dex},$$

$$[\text{Fe/H}]_{\text{us}} - [\text{Fe/H}]_{\text{E93}} = -(0.165 \pm 0.008)[\text{Fe/H}]_{\text{us}} - (0.024 \pm 0.045) \text{ dex}.$$}

These trends may be explained by the differences in the $T_{\text{eff}}$ scales (see Sect. 7.2.2).

8.5. ZM90

No trend with metallicity is present when we compare our parameters with those originally adopted by ZM90. Mean differences (20 stars) are:

$$T_{\text{eff,us}} - T_{\text{eff,ZM90}} = 137 \pm 4 \text{ K},$$

$$\log g_{\text{us}} - \log g_{\text{ZM90}} = 0.65 \pm 0.02 \text{ dex},$$

$$[\text{Fe/H}]_{\text{us}} - [\text{Fe/H}]_{\text{ZM90}} = 0.30 \pm 0.01 \text{ dex},$$

with standard deviations of 20 K, 0.09 dex, and 0.03 dex respectively. The temperature difference corresponds to the use of the calibration by Magain (1987) by ZM90.

9. Conclusions

We have presented a new, self-consistent set of atmospheric parameters for about 300 metal-poor stars, that will be analyzed for the abundances of Fe and light elements (C, N, O, Na, and Mg) in forthcoming papers of this series. The most important aspect of this derivation is the determination of a new $T_{\text{eff}}$ scale, based on the K92 model atmospheres. Our $T_{\text{eff}}$ scale is based on $T_{\text{eff}}$’s determined empirically using the IRFM for about 140 population I stars. We considered separately dwarfs and giants, so that $T_{\text{eff}}$’s for stars of any gravity can be derived by interpolation/extrapolations. Cubic polynomials drawn through the observational points allows to correct theoretical $T_{\text{eff}}$’s from the K92 models: $T_{\text{eff}}$’s appropriate for any star can then be obtained by an iterative procedure by using the theoretical dependence of colours on
metal abundance, once abundance determined from the line analysis and gravities given by Fe equilibrium of ionization are known.

A discussion of our $T_{\text{eff}}$ scale shows that it gives consistent results for stars with $T_{\text{eff}} > 4500$ K, while gravities determined from the equilibrium of ionization for Fe are too low for giants cooler than this limit. We discuss several possible causes of this discrepancy: we found that departures from LTE may explain part of it. However, K92 models are likely not adequate matches to the atmospheres of the coolest metal-poor giants.

We compared our $T_{\text{eff}}$ scale with others from the literature. We found excellent agreement with other $T_{\text{eff}}$ scales based on the K92 model atmospheres (in particular, the agreement is good with K93 $T_{\text{eff}}$’s), while there is a serious discrepancy with the $T_{\text{eff}}$’s determined for metal-poor dwarfs using the new OSMARCS models. We attribute this discrepancy to the different way convection is handled in the two set of models. K92 model atmospheres better reproduces the solar limb darkening than the OSMARCS models. We find that additional confirmations of the present $T_{\text{eff}}$ scale for metal-poor dwarfs are provided by independent determinations of $T_{\text{eff}}$’s obtained by both the IRFM and the wings of $H_{\alpha}$.

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