The ($\log T_{eff}$, M_{bol}) diagram of metal-poor stars with Hipparcos parallaxes: comparison with theoretical isochrones using NLTE iron abundances

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Abstract: From an initial sample of a few hundred stars selected for an Hipparcos program, a subsample of 33 objects with direct determination of their effective temperature, bolometric magnitude and [Fe/H] has been derived. An accurate observational ($\log T_{eff}$, M_{bol}) HR diagram has been obtained, and compared to theoretical isochrones. Attention has been concentrated on the cool part of the HR diagram, for which evolutionary effects are negligible. Whereas solar metallicity stars show a reasonable agreement with theoretical expectation, a clear discrepancy occurs for stars more metal-poor than [Fe/H] = -0.5. This discrepancy is reduced to practically zero, if corrections to LTE abundances are taken into account for Fe, and if sedimentation effects are included in stellar evolution computations.

1 Introduction

One great potentiality of the Hipparcos mission was to obtain accurate absolute magnitudes of stars, and to check the validity of internal structure theory, which predicts both total luminosity and radius for a star of given initial chemical composition, given mass and given age.
Before any age can be safely determined, the unevolved part of the HR diagram must be correctly accounted for by the theory. This is why a program directed towards this goal was proposed by one of us (MNP), in 1982 (Hipparcos proposal No. 132). In particular, Perrin et al. (1977) had found that, on the basis of distances obtained with trigonometric parallaxes available at this epoch, there was a curious lack of separation of unevolved main sequences for different metallicities, from the solar metallicity down to a metallicity [Fe/H] = -0.7. It was conjectured that the expected move of the main sequence with metallicity was offset by a proportional variation of the He abundance, acting in the opposite way on the position of the ZAMS. More precisely a ratio $\Delta Y/\Delta Z$ of 5 was needed to accomplish the needed offset(Y and Z are respectively the fractional abundances by mass of He and of the heavier elements). Needless to say that there was a large scatter on the absolute magnitudes derived from trigonometric parallaxes, and it was thought that a much clearer picture could be obtained from Hipparcos

parallaxes. Also the ratio of 5 which looked acceptable when the abundance of He was still uncertain in metal-poor stars (let us recall that Carney was finding Y= 0.19 in subdwarfs), began to appear incompatible with the predictions of the Big-Bang cosmology ($\approx$ 0.24) and the value currently accepted for the Sun ($\approx$ 0.28). The interval between these two values is too small to accomodate $5 \times Z_{\odot}$. So a sample of stars of metallicity between -0.7 and 0.3 was proposed as an Hipparcos program, and accepted. We shall deal now with the results.

As there is a paper in press for A&A on this, available from the Net as the astro-ph/9908277 file, we shall present here a shorter version, without technical details.

2 The observational diagram

Hipparcos proposal 132 was containing practically all F, G, K stars submitted to a detailed spectroscopic analysis at the time of the proposal, and expected to be nearer than 25 pc (($\approx$ 150 objects). Most of these stars were observed by the satellite, and the parallaxes made available in January 1997. Before plotting them in a ($\log T_{eff}$, M_{bol}) diagram, we had to derive T_{eff} and m_{bol} (transformed into M_{bol} with the Hipparcos parallax) in a coherent and uniform way. Fortunately we could circumvent the itching question of conversion of color indices into these fundamental parameters by using the *direct* determination of them by Alonso et al. (1995, 1996). This has limited the number of possible objects. But the most severe restriction was that of using only stars with a relative error on the parallax less or equal to 0.05, corresponding to an error of 0.1 on the absolute magnitude M_{bol}. Then, we had to remove stars known or suspected to be spectroscopic binaries, stars with significant reddening (occurring only for subgiants), and stars for which detailed analysis effective temperature was strongly conflicting with Alonso's IRFM effective temperature. The remaining set was 33 stars, whose HR diagram is presented in fig. 1. The striking feature is a confirmation of the finding of Perrin et al. (1977): whereas there is clear separation of the real subdwarfs (-1.8< [Fe/H] <-1.2) with near solar composition stars , stars of the intermediate population (-1 < [Fe/H] < -0.5) are nearly mixed with solar metallicity objects. The interpretation of this empirical constatation must of course be searched in a comparison with theoretical evolutionary models, the object of the next section.

3 Comparison of the observational HR diagram with theoretical isochrones

In order to understand the meaning of the observational diagram we compare it to theoretical isochrones, computed with updated equation of state and opacities. The theoretical details can be found in astro-ph/9908277. This comparison is shown in fig. 2.

The major free parameter is of course the abundance of helium , which is known at the two ends of the metallicity range but which is precisely what we intended to find out for the intermediate metallicities. The value of the fractional helium content by mass Y , can be reasonably expected to be close to the primordial cosmological value Y_p in very metal-poor stars, and close to the solar value ≈ 0.28 in solar metallicity stars. In first approximation it is often assumed that:

$$Y(Z) = Y_p + Z/Z_{\odot}(Y_{\odot} - Y_p)$$

but a more complex behaviour is expected as the yields during the first metal enrichment by

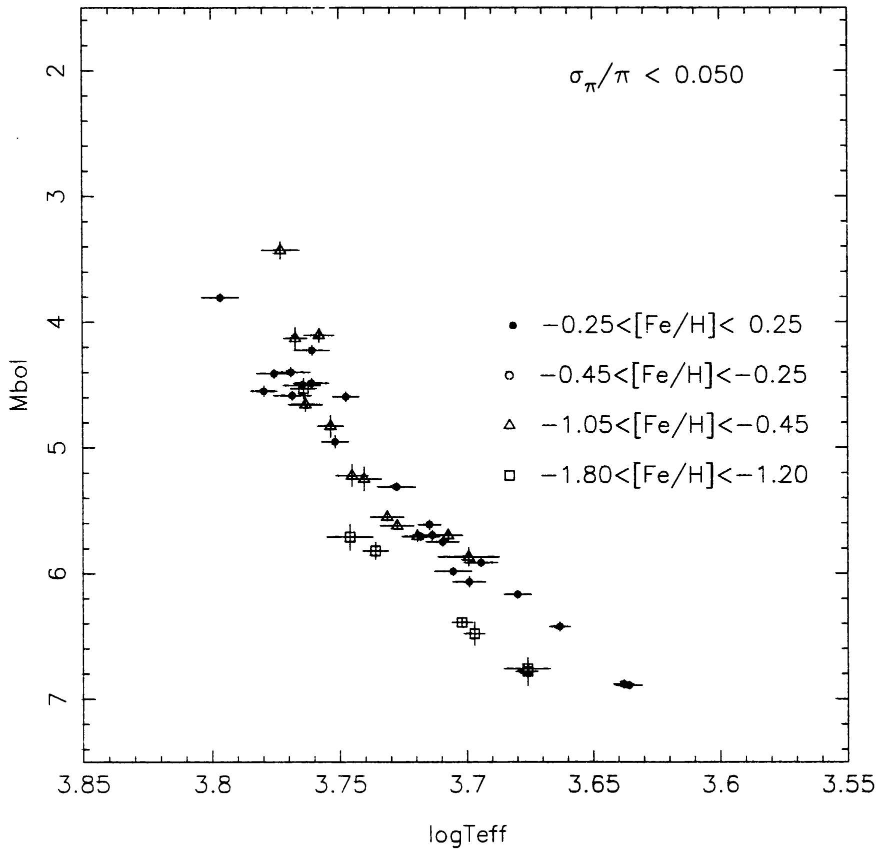

Figure 1: Observational HR diagram showing the effect of metallicity. The subdwarfs (square symbols) are the only stars showing a clear separation on the lower main sequence, where evolutionary effects are negligible. All stars with metallicity above -1.0 show little separation from the solar metallicity sequence (dots). The error bars represent one sigma.

SN II ejectae are different of the yields when other contributors as AGBs and SN Ia play a role. Anyhow, we started with the simple linear relation above as template.

No obvious problem arises for stars with solar metallicities. The observational points are all between the isochrones for metallicity [Fe/H] = 0.3 and the isochrone for [Fe/H] = -0.5, computed with the maximum enrichment in α elements of 0.4 (see caption for the ages of the isochrones, which have no influence for $\log T_{eff} < 3.75$).

On the contrary, all stars with [Fe/H] between -1 and -0.5 fall outside the lane between the corresponding isochrones, and the subdwarfs with mean metallicity [Fe/H] ≈ -1.5 fall on the isochrone -1.0 instead of -1.5. There is a clear problem with the metal-poor stars, which needs careful consideration. It is what is done in the next section.

4 How to solve the metal-poor star problem?

The first idea which came to our mind was a possible effect of sedimentation of the heavy elements in old metal-poor stars (see Lebreton et al. 1997). Then Thévenin&Idiart (1999) computed departure from LTE for iron, and found that at the metallicity [Fe/H] $\approx -.7$, an upwards correction of the LTE iron abundance of 0.15 dex was needed. We have investigated the two effects, and found that each of them alone is insufficient to solve the discrepancy, but

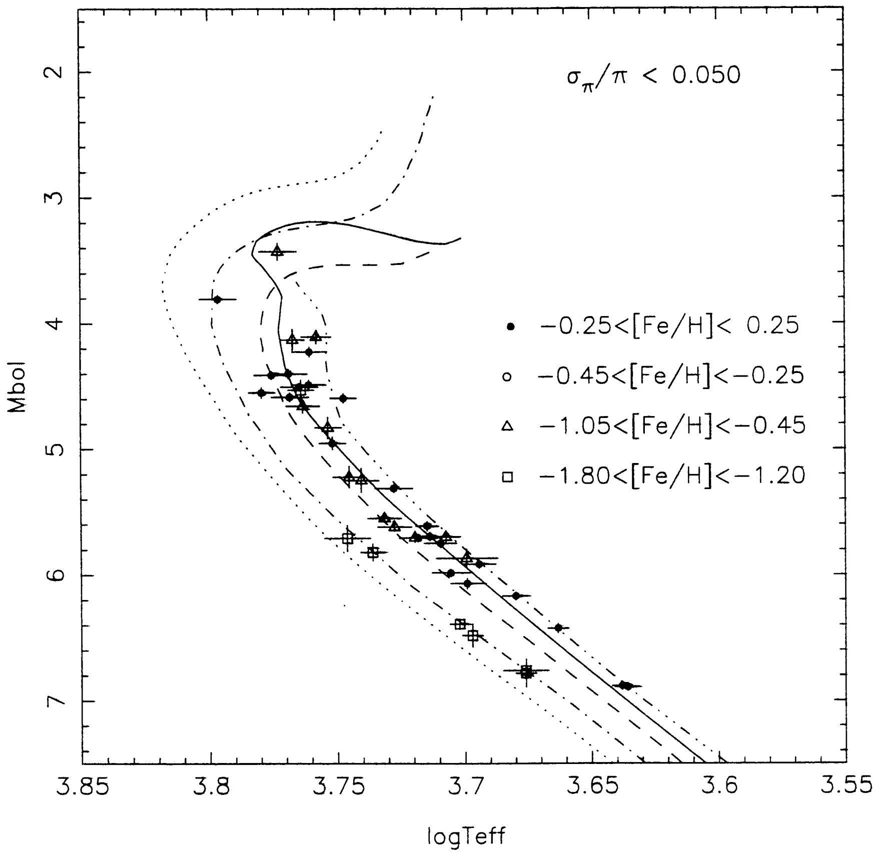

Figure 2: The observational data are the same as in fig. 1. But isochrones ,computed by Y.L., have been superimposed. The code for reading these isochrones is as follows: full line : solar metallicity 6 Gy; 3 dots-dash line: metal-rich by 0.3 dex, 6 Gy; dashed line [Fe/H] = −0.5, α-el. enriched (0.4 dex), 10 Gy; dot-dash line: [Fe/H] = −1.0, α-el. enriched 10 Gy; dotted line: [Fe/H]= −1.5 , α-el. enriched, 13 Gy. Only one star out of twelve in the metallicity range [Fe/H] −1.05 to −0.45 falls in the proper region. Note that the subdwarfs fall along the isochrone [Fe/H] = −1.0 instead of −1.5. In the portion of the diagram with $\log T_{eff} < 3.75$ evolutionary effects are negligible, and the age of the isochrones is irrelevant. The Pop. I star at the very left of the diagram is a young star (γ Lep) , and falls on the ZAMS, rather than on an 6 Gy isochrone.

that the cumulated effect of both is just about what is needed to restore agreement between theoretical prediction and observations.

Before, we had of course tried simpler things, which failed. For example we have tried to adjust the helium abundance, but found that values below the primordial value Y_p were needed, a very unattractive solution. We also tried to change the mixing length to pressure scale-height ratio, but found that the effect was much too small in the most relevant part of the diagram at $\log T_{eff} < 3.75$.

Fig. 3 shows the effects of correcting the LTE abundance of iron (Thévenin&Idiart's work) , and the cumulated effect of this correction plus the inclusion of sedimentation of the heavy elements in the internal structure evolution code , for an age of 10 Gy, appropriate to the thick-disk stellar population.These last computations were made by Morel&Baglin (1999), and made available before publication. A single star has a significant deviation from the theoretical isochrone: it is HD 132142, which has only one spectroscopic abundance analysis ([Fe/H] =-

0.55), and a Strömgren photometric [Fe/H], slightly positive instead. The binary stars μ Cas fits quite well the expected isochrone, for a mass within the error bars of the astrometric determination (0.757 ± 0.06 solar mass).

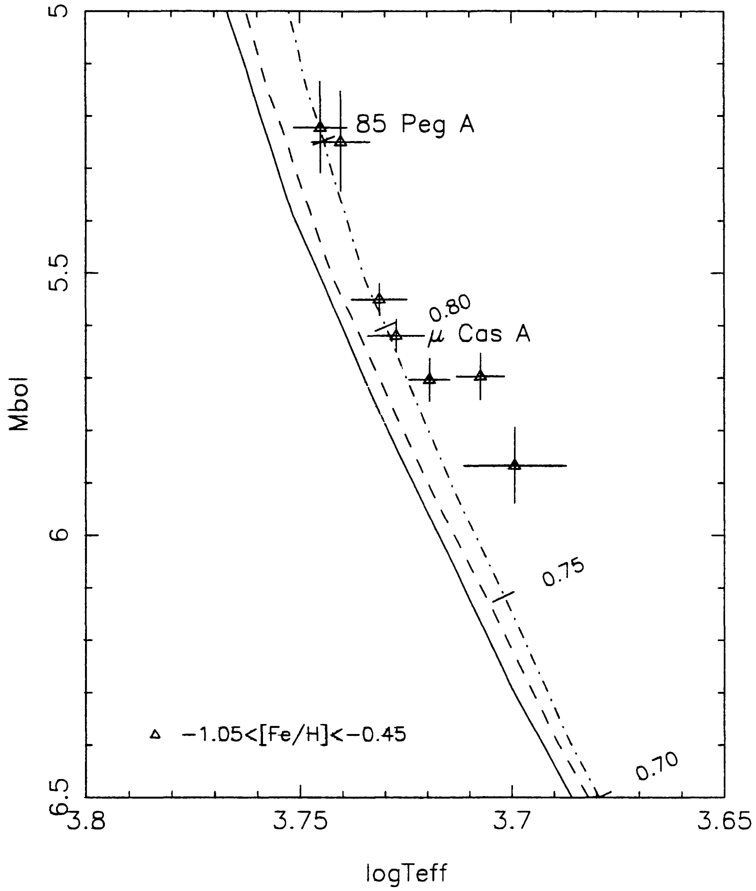

Figure 3: Zoom of the HR diagram for the stars of intermediate metallicity (LTE [Fe/H] between -1.05 and -0.45). The mean metallicity of the sample is -0.72. The full line is the standard 10 Gy isochrone for [Fe/H] = -0.70 (enriched in α elements by 0.4). The observed data are all to the right of the line. If the NLTE abundance of iron is used ([Fe/H] = -0.55), the isochrone moves to the dashed line. Not enough! If sedimentation of heavy elements is also taken into consideration, the isochrone moves to the dot-dashed line. The progress is now substantial, especially if one notes that the deviant star at coordinates (3.707, 5.70) has only one detailed analysis, giving [Fe/H], conflicting with the photometric metallicity from Strömgren photometry.

5 Conclusions

Hipparcos data have firmly established the surprising location of stars with intermediate metallicities with respect to the sequences of solar metallicity stars, and the sequence of the real subdwarfs. The separation of intermediate metallicity stars from the solar metallicity stars is considerably smaller than theoretical expectations, based on *standard* isochrones. This fact can be explained if NLTE abundances of iron are used, and if sedimentation of heavy elements (from He upwards) is included in the internal structure computations.

Acknowledgements

We are indebted to F. Thévenin and T. Idiart for making available their NLTE results before publication, and to P. Morel and A. Baglin for doing the same for their non-standard isochrone computations.

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Discussion

R. Gratton: The comparison between gravities from ionization equilibrium and Hipparcos is not a robust test of non-LTE effects, since it is very sensitive to the adopted temperature scale (and even details in the stellar models). On the other side, if such large non-LTE effects are present for dwarfs, they should be very large, for e.g. RR Lyraes (due to the lower gravities, metallicities and larger UV-fluxes). Such large effects are not observed. So I think these non-LTE computations should be considered with care.

R. Cayrel: Even if there is some degeneracy between a zero-point shift on the effective temperature scale and the size of NLTE effects, I think that an unevolved dwarf is a simpler object than an RR Lyrae to study NLTE. The parameters ($T_{\rm eff}$, $\log g$) are so different for the two types of stars that little can be infered on what happens for one type object from the other one.

I. Iben: What is the major influence of sedimentation ? Is it an opacity effect : Fe, etc... diffuse out of the surface convective layer, increasing the opacity in deeper radiative layers, which now expand, increasing the stellar radius ?

R. Cayrel: Yes, the major influence is through opacities, but CNO abundances are also slightly modified in the burning region, and that sets on the luminosity too.

R. Peterson: The results of an analysis of a blue horizontal branch star in NGC 6752, presented as poster IV.9, emphasizes the concern raised by R. Gratton that such large non-LTE corrections must be operating in dwarfs but not in more luminous stars with lower pressures. In the cool blue HB stars in NGC 6752, we find that the ionization equilibrium is satisfied simultaneously for Fe, Ca, Si and Mg at a surface gravity appropriate for the horizontal branch : $\log g = 3.0$ at $T_{\rm eff} = 8000$ K. Thus this LTE analysis shows no sign of non-LTE effects in a star of much lower pressure.