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Puzzling Locations of Mildly Metal-Poor Stars in the HR Diagram

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Abstract: It is now possible with Hipparcos parallaxes to locate very precisely nearby subdwarfs in the HR diagram. Spectroscopic and theoretical studies (Nissen et al. 1997, Cayrel et al. 1997, Lebreton et al. 1997) have shown that serious difficulties arise when trying to fit observed data to theoretical isochrones : models appear hotter than real objects. Several effects have recently been proposed to explain this discrepancy (Morel and Baglin 1999, Lebreton et al. 1999). We have selected about one hundred metal-poor stars with accurate parallaxes and metallicities and we have compared their location in the HR diagram with the Bergbusch and Vandenberg (1992) isochrones. The shift in effective temperature was estimated for five metallicity bins. A slight trend with metallicity seems to emerge. Moreover, as already noted by Nissen et al. (1997), some stars near [Fe/H] ~ -1.0 still lie significantly above the corresponding isochrones. A possible explanation in the frame of the EASE scenario is proposed.

1 Introduction

The problem of fitting single stars to theoretical isochrones in the HR diagram is a very difficult one since errors do exist in both the observed luminosities and effective temperatures while at the same time lacks in the input physics affect the theoretical models. Moreover, even if the observed value of [Fe/H] is taken for granted from spectroscopic analyses, the metallicity can only be derived assuming some hypothesis on the chemical mixture such as proportional to solar or α-enhanced for instance. On the other hand, the ignorance of the He content is most of the time a sufficient reason to give up trying to fit stars on isochrones. However, for metal-poor stars, which must have formed in the early history of the Galaxy, the He content should be close to the cosmological value. In this case, therefore, a confrontation between theory and observation becomes possible and the age of these stars can be estimated.

Using Hipparcos parallaxes, Nissen et al. (1997) have determined surface gravities of 54 metal-poor stars and thoroughly discussed their location in the HR diagram. This analysis has clearly set the existence of two problems. First, a shift in effective temperature must be applied to the isochrones in order to fit the main sequence stars. Second, while most of the stars are nicely located on the shifted isochrones, some of them, in the mildly metal-poor interval, lie

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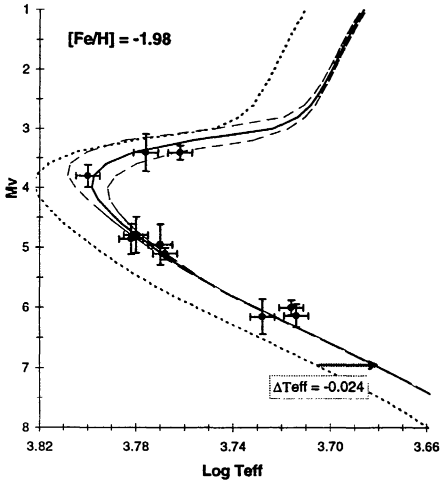

Figure 1: Location in the HR diagram of stars in the metallicity range [−2.2 < [Fe/H] < −1.8] and comparison with the [Fe/H] = −1.98 Bergbusch and Vandenberg (1992) 14 Gyrs isochrone (dotted line). The shift needed in $T_{\rm eff}$ is indicated by the arrow. Dashed lines show 12 and 16 Gyrs similarly shifted isochrones.

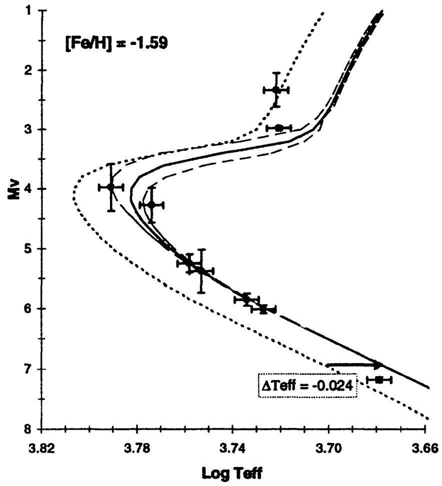

Figure 2: Same as Fig. 1. for the metallicity bin [−1.8 < [Fe/H] < −1.5].

significantly above the isochrones. According to Nissen et al. (1997), if these stars appear not to be binaries, their anomalous location in the HR diagram is a fundamental problem.

Similar studies (Cayrel et al. 1997, Lebreton et al. 1997) have checked the validity of theoretical models confronted to high accuracy observations and have led to estimations of the ages of metal-poor stars. In particular, Lebreton et al. (1997), using their own isochrones, have shown that mildly metal-poor stars lie close to stars of solar metallicity, quite far to the right of their corresponding theoretical isochrones. They stressed the point that the He content required to obtain a fitting would be far below the cosmological He abundance. In a recent paper, Morel and Baglin (1999) have shown that microscopic diffusion could be an explanation for the shift in effective temperature. As a result of diffusion, the metallicity observed at the surface of the star is smaller than the interior value and a fitting can only be achieved with isochrones computed with higher values of the metallicity. Lebreton et al. (1999) have also added the effect of NLTE corrections on the iron abundances determinations proposed by Thévenin and Idiart (1999).

2 Shift in Effective Temperature

We have attempted to gather a larger sample of metal-poor stars with high quality parallaxes, effective temperatures ($T_{\rm eff}$) and metallicities, in order to investigate the importance of the shift in $T_{\rm eff}$ as a function of [Fe/H]. The data for these stars come from different sources : Edvardsson et al. 1993 (6 stars), Nissen and Schuster 1997 (20 stars), Nissen et al. 1997 (41 stars), Jehin et al. 1999 (21 stars). The absolute magnitudes have been derived using the Hipparcos parallaxes, and have a precision better than 30%, while the effective temperatures, obtained from the colour indices b-y (Schuster and Nissen 1989) using the calibration of Alonso

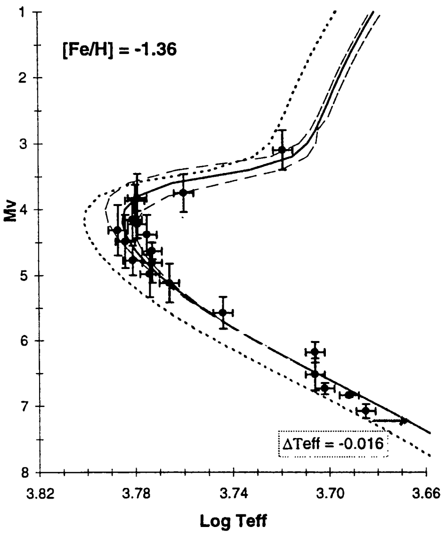

Figure 3: Same as Fig. 1. for the metallicity bin [$-1.5 <$ [Fe/H] < -1.2].

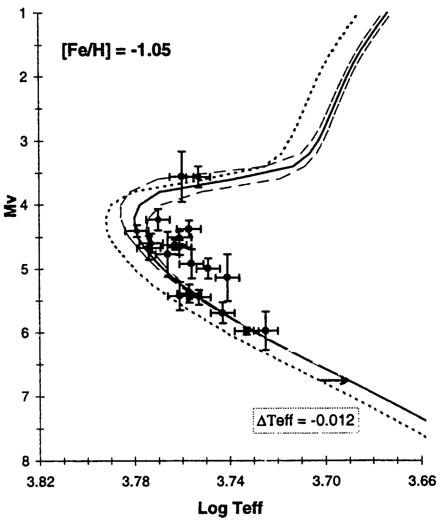

Figure 4: Same as Fig. 1. for the metallicity bin [$-1.2 <$ [Fe/H] < -0.9].

et al. (1996) have a good internal precision, of the order of 70K. For each sample the internal precision on the spectroscopic [Fe/H] is better than 0.1 dex but systematic corrections, based on stars common to all the samples, have been applied. The zero point was chosen arbitrarily from the analysis of Nissen et al. (1997).

We have distributed our sample stars among 5 metallicity bins indicated in figures 1 to 5. The isochrones (corresponding to the mean metallicity of the bins) are taken from Bergbusch and Vandenberg (1992), their helium abundance being adapted to the metallicity through an interpolation between the primordial value and the solar one. In each figure, the isochrone computed for 14 Gyr is taken as a reference.

Whatever the age, the main sequence should be well defined for stars within a metallicity bin (the scatter around the mean metallicity of the bin never exceeds 0.07 dex). It is obvious in each figure that a shift must be applied to reconcile observations and theory. The shifted isochrones are drawn for 12, 14 and 16 Gyr. Such a shift could actually result from a change in the mixing length parameter of the convection theory. However, we have tested that a rather large change in α, from 2.5 to 1.6, leads only to a shift of about -0.01 in log $T_{\rm eff}$. A missing source of opacity could also be held responsible for a shift of the isochrones towards lower effective temperature. From the observational point of view this shift could also be due to a bad zero point in the $T_{\rm eff}$-scale of metal-poor stars.

In figures 1 and 2, one can see that a shift of the theoretical isochrones of about -0.024 is required ($\sim$ 300 K). Taking this shift into account, an age estimation is possible with a value of 14 ± 2 Gyr. Figure 3 leads to similar results with a smaller shift (~ -0.016). The turn-off is much better defined which somewhat narrows the error bar on the age determination. At higher metallicity, shown in figure 4, the situation is much more complex. With a shift of about -0.012, a main sequence seems to emerge for one group of stars. The age given by the turn-off for the highest effective temperature stars is of the order of the age derived for lower metallicity. However, a distinct group of stars definitely cannot be fitted with this shift of the main sequence. A much larger shift, of the order of -0.030, would be required to fit the main

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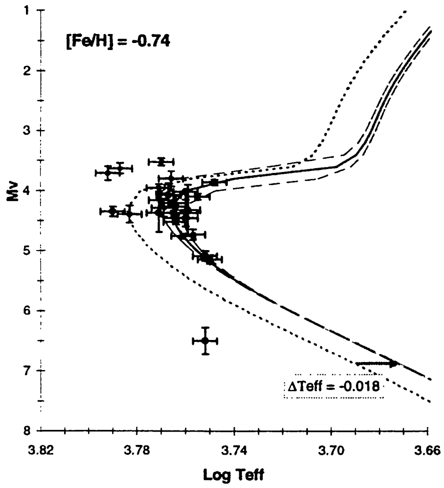

Figure 5: Same as Fig.1. for the metallicity bin [$-0.9 <$ [Fe/H] < -0.6].

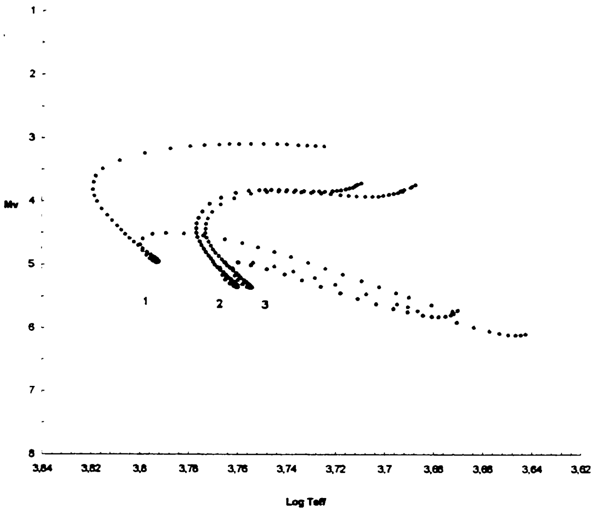

Figure 6: Evolutionary tracks for a 0.9 $M_{\odot}$ star with a metallicity of 0.001 (track 1) and 0.005 (track 3). A composite model with z=0.005 in the interior and z=0.001 in the external layer is also shown (track 2).

sequence stars as well as the lower effective temperature stars near the turn-off. This cannot be due to a different value of the helium abundance since the necessary decrease in Y would bring a helium content below the cosmological value. Anyway, it would be unlikely to find two distinct populations of stars with roughly the same metallicity and two very different Y values.

For still higher metallicity stars (Fig.5) the fitting becomes again quite good with a shift of the order of -0.018. The dispersion at the turn-off is however rather large here but in this range of metallicity, one can expect a more important contribution of younger disk stars.

3 EASE Scenario

The EASE scenario proposed by Jehin et al. (1999) (see also Jehin et al. 1999a, 1999b, Parmentier et al. 1999, Thoul et al. 1999) may shed some light on the problem of a possible bimodal distribution of stars in the metallicity range corresponding to figure 4. This scenario essentially builds a link between field halo stars and globular clusters through evaporation and/or disruption processes. After a phase of chemical self-enrichment resulting from the evolution of a first generation of mostly massive stars, a second generation of enriched stars form the bulk of the globular cluster. As these stars become AGB stars, they dredge newly processed *s*-elements up to their surface and loose their external layers. This material can then be accreted by lower mass main sequence stars (MS), which will exhibit an enrichment in *s*-elements at their surface.

Some first generation very low metallicity AGB stars could still be present in the cluster. The metal-poor matter they eject could be accreted by second generation MS stars, leading to inhomogeneous stars, more metal-rich in their central layers than their surface chemical composition would suggest. We have computed two evolutionary tracks for a 0.9 $M_{\odot}$ star with metallicities 0.001 and 0.005 throughout the whole stars. The results are presented in figure 6 where the increase in metallicity leads to a rightward displacement of the tracks. A composite evolutionary track has also been computed, for a metallicity of 0.005 in the central region and a lower metallicity of 0.001 in the external convective layers. As can be expected, the composite track is very close to the track of identical internal metallicity, i.e. to the right of the fully low metallicity track. Composite isochrones could thus fit the rightward group of stars in figure 4.

4 Conclusions

When trying to fit theoretical isochrones to metal-poor stars, a shift toward lower effective temperature must be applied to the isochrones. This shift seems slightly dependent on the metallicity and can be explained either by a bad T_{eff}-scale of metal-poor stars, a wrong choice of the mixing length parameter or a missing source of opacity at low temperature. Taking this shift into account, an age of the order of 14 Gyr can be estimated for the majority of stars in our sample. In the metallicity bin $[-1.2 < [\mathrm{Fe/H}] < -0.9]$ however, the stars seems to form two separate groups. In the frame of our EASE scenario, the rightward group could correspond to second generation MS stars polluted by first generation AGB stars.

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