THE HR DIAGRAM IN THE PLANE LOG($T_{\rm eff}$), $M_{\rm bol}$ OF POPULATION II STARS WITH HIPPARCOS PARALLAXES

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ABSTRACT

An HR diagram in the plane (log$T_{\rm eff}$, $M_{\rm bol}$) is presented for population II subdwarfs and subgiants having Hipparcos parallaxes known with an accuracy better than 15 per cent. The effective temperatures and the apparent bolometric magnitudes have been taken from measurements made by Alonso et al. (1996), by the IRFM method for the effective temperatures, and direct integration of the fluxes for the bolometric fluxes. This has allowed to bypass the use of bolometric corrections, and the resulting errors. The resulting diagram is interpreted with two sets of isochrones computed with OPAL opacities enhanced in alpha-elements, updated equations of state, a helium abundance close to the primordial value, and a mixing length to pressure scale height ratio calibrated on the Sun. For the first time it has been possible to check the validity of theoretical models for metal-poor stars against accurate observations, and to derive the age of halo stars independently of any globular cluster data.

Key words: space astrometry; population II HR diagram; stars: chemical composition.

1. INTRODUCTION

In 1982 two proposals (among others) aiming at measuring parallaxes of halo stars were submitted and accepted by ESA. One of them, No. 153 was presented by R. Cayrel as PI, and J. Delhaye, F. Spite, M. Spite, B. Jones and J. Jones as CoIs. The other one No. 190, was presented by M. Mayor (PI) and C. Turon. In 1992 an internal proposal, INCA094, 'Magnitudes and kinematics of subdwarfs' was presented by C. Turon (PI) and R. Cayrel and M. Mayor (CoIs) using the data of proposals 153 and 190. The present paper gives partial results of the internal proposal INCA094, essentially based on the parallaxes of proposal 153, plus a few objects of proposal 132 (M.-N. Perrin, 1982).

Out of the 134 stars of proposal 153, 122 were observed by Hipparcos. Three stars have negative parallaxes, two have a 'blank' parallax, and Figure 1 shows the histogram of the ratio σ_π/π of the standard error on the parallax σ_π over the Hipparcos parallax π itself. The Hipparcos data represents an impressive jump in the number of distances known with an accuracy of the order of 10 per cent or better, from a handful of stars to 25 objects. In Figure 2, the Hipparcos positions of the 8 closest metal-poor stars are plotted in the (log$T_{\rm eff}$, $M_{\rm bol}$) plane, with the positions which would have been obtained from the Yale Catalogue (van Altena et al. 1995). The statement that Hipparcos parallaxes are systematically making stars brighter is not particularly true for this sample, but would be true if older parallaxes (for example those quoted in the Hipparcos Input Catalogue) would have been used, instead of the 1995 data.

Our first aim here is to use these new distances for checking the validity of the theoretical evolutionary tracks and isochrones produced by the present state of the art in the modeling of the internal structure of metal-poor stars. We do not intend to discuss the use of Hipparcos parallaxes for redetermining the distance of the globular clusters here, but only to find the implications of the new data on the local sample of population II stars with very good distances. We have one less degree of freedom than with globular clusters, because we cannot trade off the position of the theoretical isochrones with distance and reddening, as the distances are unflexible, and the reddening the most often negligible.

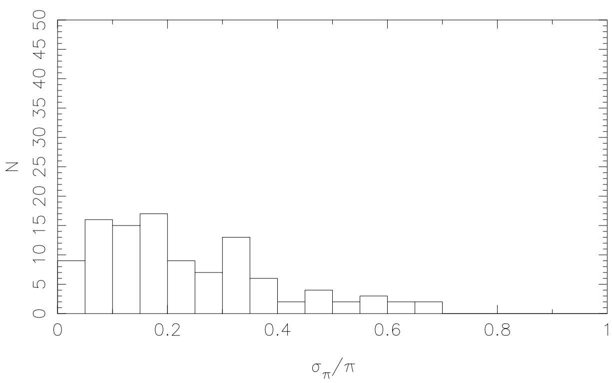

Figure 1. Histogram of the ratio σ_π/π. A few stars are beyond the limit of the figure.

2. DETERMINATION OF $T_{\rm eff}$, $M_{\rm bol}$ AND METALLICITY

Internal structure computations use as data the initial composition of a star, its mass, and predict at any age the bolometric luminosity and the radius of the star. In order to have a most direct comparison of these predictions with observations it is necessary to obtain the chemical composition (which can be reduced to a few numbers as the iron/hydrogen ratio, the α-elements/iron ratio and the mass-fraction Y of helium) the absolute bolometric luminosity, and the radius of the star, or equivalently the effective temperature defined by:

$$\sigma T_{\rm eff}^4 = L_*/(4\pi R^2)$$

Throughout this paper we use, for bolometric magnitudes, the zero-point (Allen 1973):

$$M_{\rm bol} = 4.75 - 2.5\log(L/L_\odot)$$

with:

$$L_\odot = 3.846 \times 10^{33}$$

in CGS units.

If we want to take advantage of distances accurate to 10 per cent, producing errors of about 20 per cent in the transformation of apparent to absolute bolometric fluxes, it is wise to aim at an accuracy twice or three times better on the other sources of uncertainties. It is current practice to derive $\log T_{\rm eff}$ and $M_{\rm bol}$ from colour indices and V magnitudes, using various calibrations of effective temperature versus colour indices and bolometric corrections. In view of the conflicting current temperature scales for metal-poor stars (Carney et al. 1994, King 1993, Fuhrmann et al. 1994, Spite et al. 1996) and similar uncertainties in the dependence of bolometric correction upon metallicity, we have decided, in a first step, to bypass these difficulties in using the most direct determination of both quantities by Alonso et al. (1996). These authors have first determined the apparent bolometric fluxes $f_{\rm bol}$ by integrating the $UBVRIJHK$ Johnson photometry, with an expected accuracy of 3 per cent. Then they have determined the effective temperature using the Infrared Fluxes Method (IRFM), averaging the effective temperatures derived from the J, H, and K bands. They quote the expected error in $T_{\rm eff}$ for each individual object, on the average of the order of 80 K. They give data for 475 G and K stars, spanning a complete range of metallicities. Their data constitute the largest sample of homogeneous determinations of the fundamental parameters $T_{\rm eff}$ and $f_{\rm bol}$ for metal-poor stars.

The metallicities of the stars obtained by intersection of our Hipparcos objects and the Alonso list have been derived from the new edition of the 'Catalogue of [Fe/H] determinations' (Cayrel de Strobel et al. 1997). The new edition contains all recent determinations based on CCD or Reticon, high signal/noise spectroscopic observations. Only those high S/N data have been averaged, to produce the adopted metallicity, used in this paper.

3. REMOVAL OF CONTAMINATED DATA

It is of course essential that the data compared to theoretical models pertain to truly single stars. Alonso's infrared photometry being made with an aperture of 15 arcsec or so, not only spectroscopic binaries, but close visual binaries must be excluded from the sample, or corrections must be applied if the flux-ratio of component A and B is sufficiently accurately known. Dereddening has been applied to stars with moderate reddening. Stars with an $E(B-V)$ larger than 0.05 have been excluded, because of the resulting uncertainty in the magnitudes. Eventually, when the difference between the effective temperature in Alonso et al. (1996) and the effective temperature from Cayrel de Strobel et al. (1997) was larger than 150 K, we decided to remove the object, as either the metallicity or the effective temperature was suspicious.

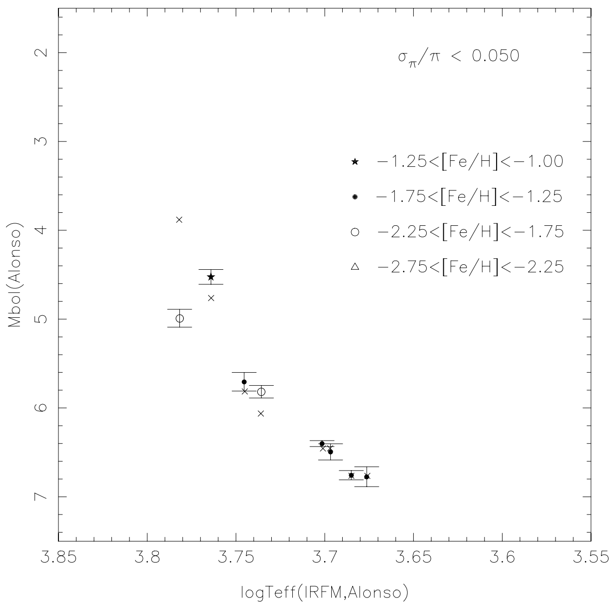

Figure 2. The 8 stars with the smallest relative error on their distance. The error bars on $\log T_{\rm eff}$ *and* $M_{\rm bol}$ *are given. Different symbols are used for different metallicities (stars, dots, circles and triangles). The crosses represent the positions of the same objects if the Yale (1995) parallaxes, instead of Hipparcos parallaxes would have been used.*

4. THEORETICAL MODELS

Our Hipparcos data are compared to two sets of theoretical models. The first set was computed by one of us (Y.L.) with the CESAM code (Morel 1997), the second set was kindly supplied by Don VandenBerg (VandenBerg et al. 1997) before publication. Both sets have rather similar input physics. They both use OPAL Iglesias & Rogers (1996) and Alexander & Fergusson (1994) opacities, and they calibrate the parameters $Y_\odot$ and the ratio $\alpha = \ell/H_p$ of the mixing length to pressure scale-height by fitting the Sun. The equation of state in Y.L. models is CEFF

Christensen-Dalsgaard (1991) and by Swensson in VandenBerg models (VandenBerg et al. 1997). A difference exist in the alpha-elements to iron ratio: +0.3 dex in VandenBerg models, +0.4 dex in Y.L. The VandenBerg grid has the advantage of a smaller step in the variation of the metallicity between consecutive models in the grid. A more detailed description of the physics of Y.L. models is given in Lebreton et al. (1997).

5. THE OBSERVATIONAL DIAGRAM

Figure 2 shows the position of the 8 stars with a relative error (one σ) less than 0.05 in the distance and the position that the same stars would have if ground-based measurements had been used instead (the parallaxes are taken from van Altena et al. 1995). It is clear that the general statement that Hipparcos moves away the objects does not apply to this sample, *if up-to-date ground-based measurements are used*. Figure 3 gives the positions of a much larger sample allowing relative errors on distances as large as 25 per cent. Note that unfortunately most subgiants have fairly large error bars.

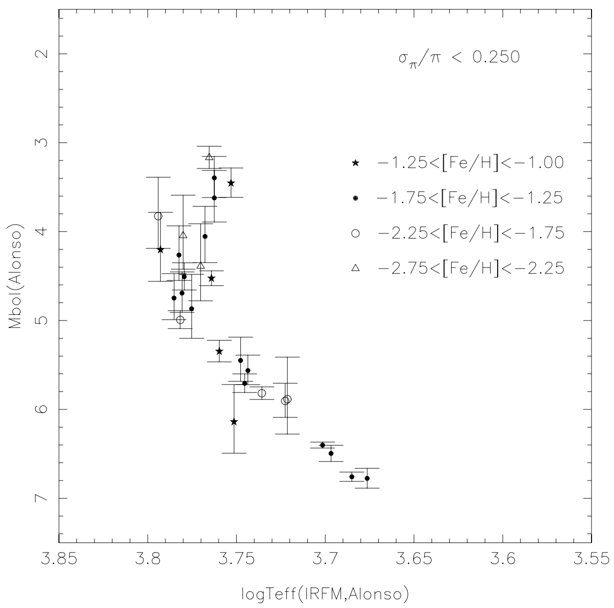

Figure 3. The 28 stars with a relative error less than 25 per cent on the distance. A bunch of subgiants emerges, with an isochrone-like shape.

6. THE CONFRONTATION BETWEEN THE OBSERVATIONAL DIAGRAM AND THE MODELS AND THE AGE OF THE SAMPLE

In order to compare model predictions with the observational diagram based on Hipparcos data we have selected stars with a reasonable accuracy in their distances (σ_π/π less than 0.125) and in a narrow range of metallicity, near the most frequent metallicity in the halo ([Fe/H] = -1.5 ± 0.3). This leaves 13 stars that we compare with Y.L. isochrones having the metallicity of the mean of the sample, and an helium content (mass fraction) $Y = 0.23$, nearly the primordial abundance. Figure 4 gives the result. It is immediately visible that the unevolved stars are above the isochrones. A similar situation results with VandenBerg set of isochrones. There is here an obvious problem, that we find exacerbated in Lebreton et al. (1997), for stars with metal deficiencies near [Fe/H] = -0.8. It is not possible to solve the problem by using a different mixing-length/scale-height ratio, because this affects somehow the turnoff region but does not move the isochrones near $\log T_{\rm eff} = 3.7$, where the discrepancy still exists. The use of a different approach for convective transfer, (Canuto & Mazzitelli (1991), for example) suffers from the same defect. One way out would be to blame the zero-point of our effective temperature scale.

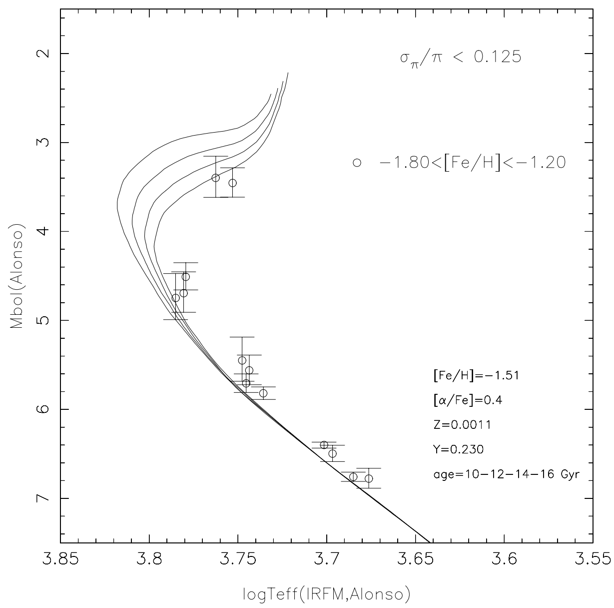

Figure 4. Y.L. isochrones compared to the observational diagram for metallicities near [Fe/H] = −1.5. Note the systematic shift of the observational points versus the theoretical curves.

The horizontal shift needed to bring the unevolved stars on their theoretical sequence is 0.01 in $\log T_{\rm eff}$, corresponding to about +120 to 140 K in the temperature range under consideration. Figure 5 shows the result. An age of 10 or 12 Gyr (under the standard physics assumed in the models, no sedimentation, etc...) is ruled out, whereas an age of 14–16 Gyr is favoured.

Figure 6 shows the same as Figure 5, but this time with VandenBerg isochrones. Exactly the same shift has been applied.

The shift in abcissa we have just tried is by no means the only possibility to solve the discrepancy we have found between theory and observations. Our zero-point is already on the high-temperature side (similar to Fuhrmann et al. (1994) scale), and there is no independent argument to support the 0.01 shift.

Another possibility is that the thin convective layer of

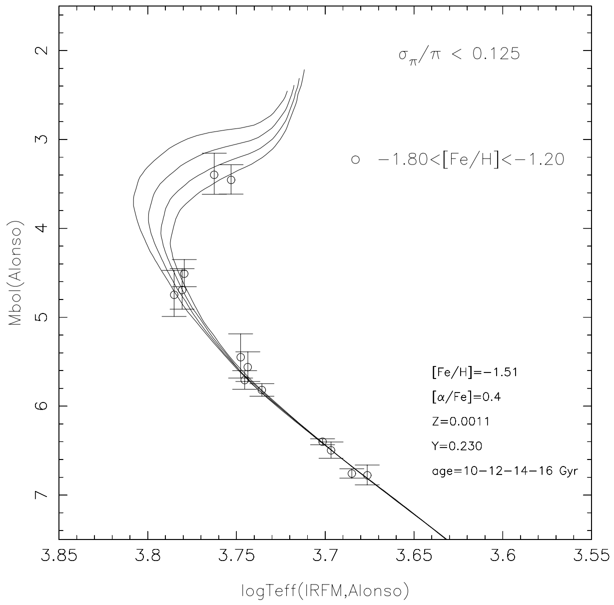

Figure 5. Same as Figure 4 but with a shift of 0.01 in $\log T_{\rm eff}$ *in the observed data.*

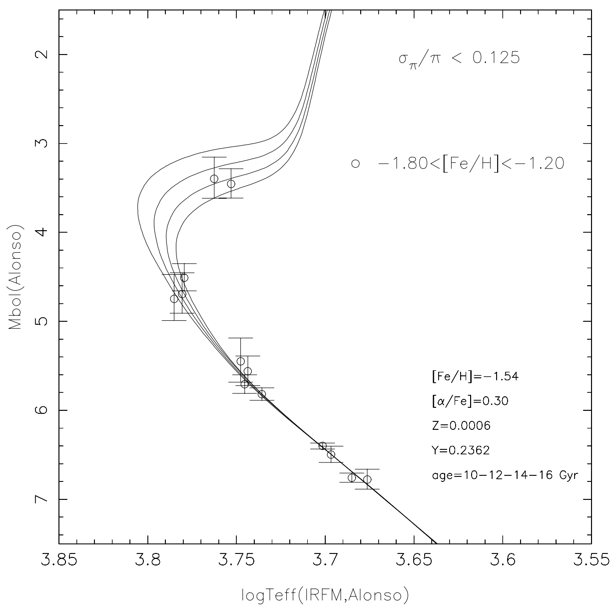

Figure 6. Same as Figure 5 but with VandenBerg isochrones. An age of 14 Gyr is favoured.

metal-poor stars has lost part of its heavy elements by sedimentation. This has been computed already for helium in the Sun (Richard et al. 1996) and in metal-poor stars (D'Antona et al. 1997). If other heavy elements are exposed to sedimentation the metalliciy of the atmosphere is less than the mean internal metallicity. We can then try to see if an isochrone of higher metallicity fits better than the isochrone computed with the atmospheric metallicity. Figure 7 shows the result with the unshifted VandenBerg isochrone with the metallicity [Fe/H]= −1.31. The fit with the observations is excellent for the isochrone 14 Gyr.

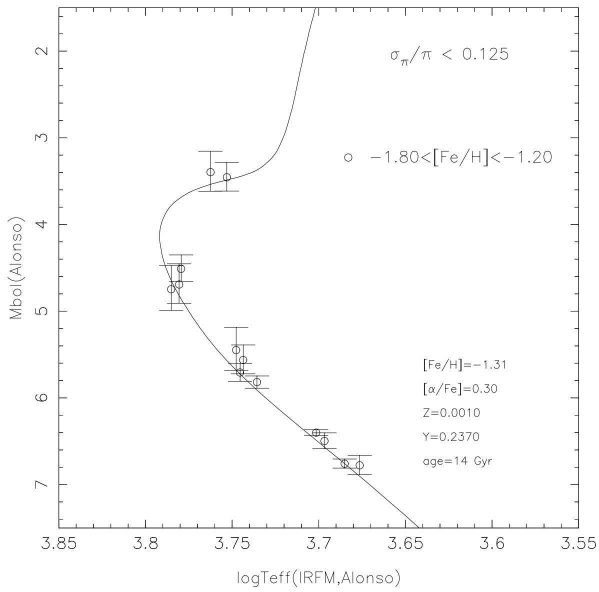

Figure 7. Fit between the data and the VandenBerg isochrone 14 Gyr, computed with a metallicity slightly higher than the atmospheric mean metallicity of the sample.

Finally, we show (Figure 8) the position of all stars with σ_π/π less than 0.15, with Y.L. isochrones 15 Gyr and metallicities −1.0, −1.5, and −2.0 to check the position of the stars as a function of their metallicity. As in Figure 5, a shift of 0.01 in $\log T_{\rm eff}$ has been applied to fit the unevolved stars. The sample contains unfortunately only four very metal-poor stars, and no firm conclusion can be drawn at present.

7. CAN WE GET THEM YOUNGER?

The answer is of course, yes.

But contrary to a common assertion at this meeting it is not because the main sequence of subdwarfs has become brighter, after Hipparcos. We have seen that the 1995 parallaxes of the new Yale Catalogue, measured from the ground, do not depart significantly from the Hipparcos parallaxes. But, as stated by D'Antona et al. (1997), changing the physics in the models can substantially alter the age. Among the things already pinpointed, there is taking into account the full spectrum of turbulence in computing the convective transport, taking into account the sedimentation of helium, and the use of a different equation of state (Rogers et al. 1996). We have suggested that if helium actually sinks in the Sun it does it even more in metal-poor stars, because the time available is larger, the speed of diffusion greater, and the mass of the convective zone smaller. Also, if helium sinks, other elements should do it too, in particular C, N, O. The question of the age of the halo, will be settled when the input physics will be such that the age determined by isochrone fitting will be the same as the age determined by the new method of Padoan & Jimenez (1997). For the time being it is not so.

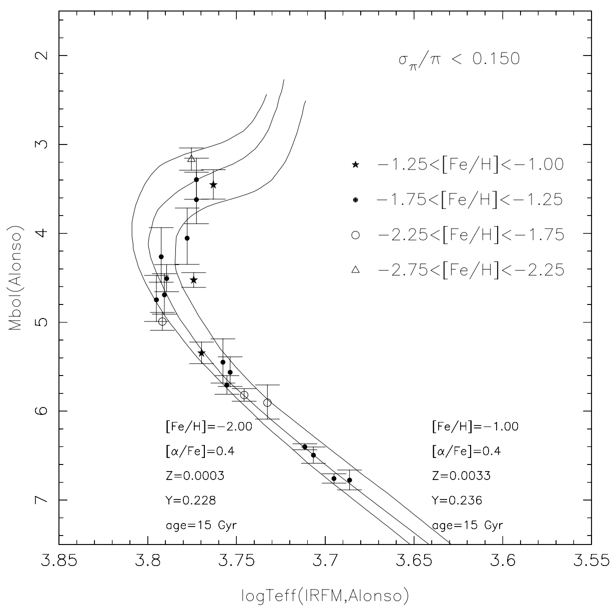

Figure 8. Comparison of the sample with σ_π/π less than 0.15, with three Y.L. isochrones of the same age (15 Gyr), but different metallicities. From left to right the metallicities are [Fe/H] = -2, -1.5, -1. Note the unequal spacing of the isochrones.

8. CONCLUSIONS

For the first time it has been possible to check theoretical models of metal-poor stars against observation. Before the absolute magnitudes of these stars were just too poorly known.

For the first time an age of halo stars can be determined independently of any globular cluster data.

However, age determinations of the local halo is still severly limited by the accuracy on the distances of subgiants. The sample of halo stars with good distances remains small, even after Hipparcos.

This strongly supports the need for GAIA, actually the only hope to obtain the distances of halo giants, one hundred times rarer in space than subdwarfs!

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