THE H-R DIAGRAM FOR LATE-TYPE NEARBY STARS AS A FUNCTION OF HELIUM CONTENT AND METALLICITY

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ABSTRACT

Recent theoretical stellar models are used to discuss the helium abundance of a number of low-mass stars for which the position in the Hertzsprung-Russell diagram and the metallicity are known with high accuracy.

Hipparcos has provided very high quality parallaxes of a sample of a hundred disk stars, of type F to K, located in the solar neighbourhood. Among these stars we have carefully selected those for which detailed spectroscopic analysis has provided effective temperature and [Fe/H] ratio with a high accuracy.

We have calculated evolved stellar models and their associated isochrones in a large range of mass, for several values of the metallicity and of the helium abundance and we took into account an α-element enrichment in the metal-deficient stars. The input physics is recent and appropriate to the considered stellar mass range.

We discuss the position in the H-R diagram of those stars which can be considered as non-evolved. Once the physics of the models has been fixed, this position only depends on metallicity and helium abundance.

We find that the thickness of the observational main sequence is of about 0.25 magnitude, for stars spanning a metallicity range from [Fe/H] $= -1$ to $+0.2$, while theoretical stellar models predict a width of about 0.45 magnitude.

The position in the H-R diagram of stars of solar metallicity or close to it is well accounted for by theoretical stellar models. Problems arise with the moderately metal deficient stars which lie quite close to the stars of solar metallicity and very far from the theoretical isochrones corresponding to their expected chemical composition. To reconcile theory and observations very low values of the helium abundance, well below the primordial helium abundance, would be needed. We briefly discuss the possible reasons of this discrepancy: improvements to bring to the physics of the models, inaccuracies of observations.

Key words: Galaxy: solar neighbourhood; stars: abundances; stars: low-mass; stars: HR diagram; Galaxy: abundances.

1. INTRODUCTION

The knowledge of the initial helium abundance of stars born in different sites with different metallicities is of great importance for many astrophysical studies. The lifetime of a star and its internal structure very much depend on its initial helium content and this has important consequences not only for stellar astrophysics but also in cosmology or in studies of the chemical evolution of galaxies.

Direct measurement of the helium abundance in the photosphere of a low mass star cannot be made since there are no helium lines in the spectra. In a few objects the helium abundance can be determined by means of theoretical stellar models. In the Sun the initial helium abundance can be drawn from the careful calibration of the solar model, which with given input physics, has to yield at solar age the observed luminosity and radius which enforces its initial helium abundance (Christensen-Dalsgaard 1982). Moreover the present helium abundance in the convection zone of the Sun can be determined from helioseismological measurements (Pérez Hernández & Christensen-Dalsgaard 1994). This value is different from the one obtained by calibration which can be explained by invoking transport processes at work in the solar convection zone (Cox et al. 1989).

Stellar models can also be used to determine the initial helium abundance of visual binary stars of known mass and metallicity. The method is similar to that used for the Sun; models have to satisfy the constraints on luminosity and effective temperature for the two stars of the system which are assumed to have same age, metallicity and initial helium content (Noels et al. 1991).

In single low-mass stars, neither the mass, nor the age are known. For a few stars the [Fe/H] ratio is measured. To model these stars an assumption has to be made on the value of the initial helium content. Very often it is supposed that the metallicity Z and helium Y in mass fraction are related by the so-called helium to metal enrichment ratio $\Delta Y/\Delta Z = (Y - Y_{\rm p})/Z$, where $Y_{\rm p}$ is the primordial helium abundance and $\Delta Y/\Delta Z$ is constant from star to star.

However the assumption that $\Delta Y/\Delta Z$ is a 'universal' constant can be questioned. Many attempts have been made to estimate $\Delta Y/\Delta Z$. Investigations in different sites of observations as well as theoretical nucleosynthesis predictions have been made and were reviewed by Fernandes et al. (1996). Values of $\Delta Y/\Delta Z$ from 2. to 6. were found. A simultaneous increase of helium and metallicity is always found but with large variations of $\Delta Y/\Delta Z$.

$\Delta Y/\Delta Z$ can also be calculated from the metallicities and helium contents found in the Sun and in the few binary stars which can be calibrated. The recent work by Fernandes et al. (1997) shows that $\Delta Y/\Delta Z$ is of about 3.0, slightly depending on the input physics of the theoretical stellar models. Lebreton et al. (1997) used similar theoretical stellar models to calibrate simultaneously the Sun and the lower main sequence of the Hyades and found that $\Delta Y/\Delta Z$ is higher in the Sun than in the Hyades although the metal content [Fe/H] is higher in the Hyades.

The solar neighbourhood is a very interesting site to study the relationship between helium and metallicity: it is constituted of the nearest stars which have been thoroughly observed. Perrin et al. (1977) first studied the HR diagram of a selected sample of the nearest low-mass stars and found that $\Delta Y/\Delta Z$ is constant and equal to 5.0 in the solar neighbourhood. Recently Fernandes et al. (1996) measured the observational lower main sequence width in the solar neighbourhood. They estimated the associated value of $\Delta Y/\Delta Z$ using theoretical stellar models. They found that if the observed width is entirely due to a chemical composition dispersion in the solar neighbourhood then any value of $\Delta Y/\Delta Z$ greater than 2.0 could account for this width.

Our purpose here is to go further in that study using the recent results of the Hipparcos mission. It is now possible to work on a very well defined sample constituted of stars of the solar neighbourhood. This sample was selected by M.-N. Perrin and then by A. Baglin et al. (Hipparcos Proposals 132, 1982 and INCA011, 1992). The sample is composed of about 100 late-type nearby dwarfs of spectral type from F to late K. The location of those stars in the HR diagram is known with high accuracy: the Hipparcos satellite has provided their parallaxes and high resolution spectroscopy has given their effective temperatures and metallicities.

In this very preliminary work, we compare observations to stellar models calculated with appropriate updated input physics to draw information on the helium content and on the eventual relationship between helium and metallicity in those stars.

In Section 1 we describe the observational sample and focus on the high accuracy of the observational data. In Section 2, models relevant for the interpretation of the observations are described. The results are presented and discussed in Section 3.

2. OBSERVATIONAL MATERIAL

We study an homogeneous sample of late-type nearby stars which has been carefully selected by M.-N. Perrin. These stars are closer than about 25 parsecs which ensures an excellent accuracy of their parallax determination by Hipparcos. Moreover these stars are among those which were best studied from the ground: they all have been submitted to photometric measurements and to detailed spectroscopic analysis.

Among the 114 stars selected there are 38 stars which are very well known and which are not suspected to be unresolved binaries. Their parallax has been determined by Hipparcos with an accuracy better than 5 per cent. Their bolometric flux has been derived by Alonso et al. (1995) with an accuracy of about 3 per cent by integrating UBVRIJHK photometry. This provides the bolometric magnitude with no need of bolometric corrections ($\Delta M_{\rm bol} < 0.03$ magnitude). The effective temperature has been obtained by Alonso et al. (1996) from the bolometric flux and using a grid of theoretical model line-blanketed flux distributions (Kurucz 1991). The resulting accuracy on effective temperature is of about 1.5 per cent. The metal content [Fe/H] has been obtained through detailed spectroscopic analysis (Cayrel de Strobel et al. 1997), the mean error on [Fe/H] being of the order of 0.1 dex.

3. THEORETICAL MODELS

The stellar evolution calculations have been computed with the CESAM code (Morel 1997) in which we have included appropriate input physics. In the range of mass considered the CEFF equation of state (Eggleton et al. 1973, Christensen-Dalsgaard 1991), which includes Coulomb corrections to the pressure is appropriate. We use the Caughlan & Fowler (1988) nuclear reaction rates. To determine the initial composition we used either the Grevesse & Noels (1993) solar mixture (GN93 mixture) or a GN93 mixture where the α-elements O, Mg, Si, S, K, Ca, Ti are enriched relative to the Sun ($[\alpha/{\rm Fe}] = +0.4$ dex). An enrichment of α-elements is observed in metal deficient stars with metallicities [Fe/H] lower than -0.5 (Wheeler et al. 1989).

We used the most recent OPAL opacities (Iglesias & Rogers 1996) complemented at low temperatures ($T \leq 10000$ K) by atomic and molecular opacities from Alexander & Fergusson (1994) for the GN93 mixture or from Kurucz (1991) for the α-enriched mixture. We use the Eddington's $T(\tau)$ law to describe the atmosphere after a comparaison with the ATLAS9 models (Kurucz 1991) and the mixing-length theory of Böhm-Vitense (1958) to describe convection. With the input physics described above the calibration in luminosity and radius of a solar model having $Z/X = 0.0244$ where X is the hydrogen abundance by mass (Grevesse & Noels 1993) requires a mixing-length $\ell = 1.64\ H_{\rm p}$, an initial helium abundance $Y = 0.266$ and a metallicity $Z_\odot = 0.0175$. We adopt the solar mixing-length value in all our calculations in accordance with results of Fernandes et al. (1997).

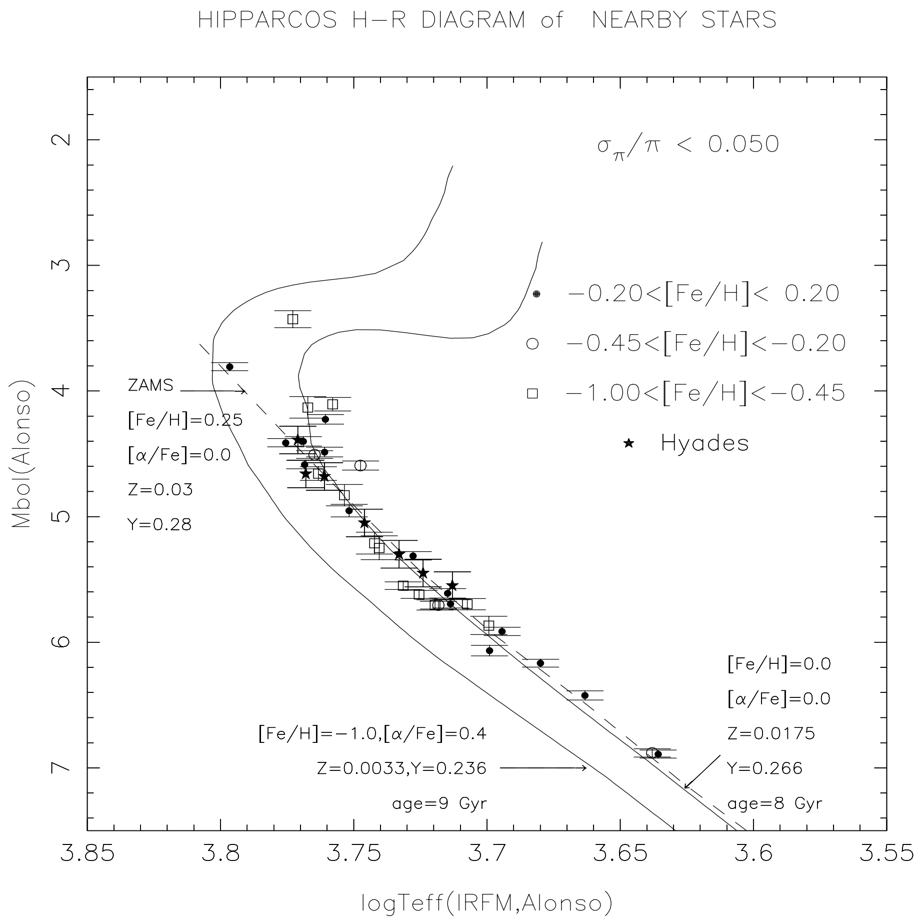

Figure 1. The Hipparcos Hertzsprung-Russell diagram of nearby stars.

We calculated several grids of evolutionary models and associated isochrones. The mass range covers masses from 0.5 to 5.0 $M_\odot$. We considered different metallicities corresponding to the observational range ([Fe/H] in the interval -1.0 to 0.5). The metallicity Z in mass fraction is related to [Fe/H] by the relation $[Fe/H] = \log(Z/X) - \log(Z/X)_\odot$. In these models the helium abundance is derived from the metallicity Z using the $\Delta Y/\Delta Z$ relationship and the solar value of $\Delta Y/\Delta Z$. Two distinct grids of models were calculated in the metal deficient cases ([Fe/H] $= -0.5$ and -1.0): a grid with normal solar mixture and a grid with an α-elements enrichment of 0.4 dex. In order to obtain the sensitivity of zero-age main sequence location with chemical composition we also calculated non-evolved models of masses from 0.5 to 1.4 $M_\odot$ for 8 values of Z ranging from 0.004 to 0.06 and 6 values of Y ranging from 0.18 to 0.43, therefore corresponding to different values of $\Delta Y/\Delta Z$.

4. RESULTS AND DISCUSSION

We present in Figure 1 the Hertzsprung-Russell diagram of the 38 stars of the selected sample which have an observed metallicity [Fe/H] between -1.0 and +0.20 and a very accurate parallax ($\sigma_\pi/\pi \leq 0.050$). We have superimposed on that diagram two 'extreme' theoretical isochrones. The isochrone located on the left of the H-R diagram has been calculated with the lowest metallicity value ([Fe/H] $= -1.0$) and an helium abundance close to the primordial value and it corresponds to an α-elements enriched mixture. The isochrone located on the right has been obtained with models of solar metallicity and solar helium abundance. We also plotted on Figure 1 a metal enriched zero age main sequence (Z = 0.03 corresponding to [Fe/H] = +0.25).

If we first consider the whole sample focusing at the non-evolved stars (i.e. those which have an effective temperature lower than about 3.74) it is clear that the available space between the two extreme theoretical isochrones corresponding to the observed metallicity interval is not filled. On the contrary the stars have a tendancy to gather close to the solar isochrone even when their metallicity is quite low. The thickness of the observational main sequence, measured on the non-evolved lower part, is of about 0.25 magnitude while the theoretical thickness is of 0.45 magnitude.

It is also worth to note that the slope of the theoretical main sequence agrees very well with the observational slope. This is in favour of the unicity of the mixing-length parameter in low-mass stars.

If we examine the stars which have a solar metallicity or close to it ($-0.20 <$ [Fe/H] < 0.20) and the very moderately deficient stars ($-0.45 <$ [Fe/H] < -0.20)

it appears that theoretical models fit the observations satisfactorily. Each star can be placed on a theoretical ZAMS corresponding to its metallicity and to a Y value different from the solar one but not smaller than the primordial helium abundance $Y \simeq 0.23$.

On the other hand no agreement can be found for stars with metal deficiencies in the range ($-1.05 <$ [Fe/H] < -0.45). These stars cannot be placed on a theoretical isochrone corresponding to their metallicity unless the helium abundance is decreased to an unacceptable value ($Y \simeq 0.10$) very much smaller than the primordial helium abundance.

To solve the problem related to the metal deficient stars one has to question the validity of the theoretical stellar models as well as the accuracy of observations. The position of the theoretical ZAMS would have to be shifted either rightwards by an amount of about 250 K or upwards by an amount of about 0.2 magnitude to be in agreement with observations. The effect of the chemical mixture used for the calculations has already been taken into account: we found that changing the metal mixture from a solar mixture to an α-enriched mixture with $[\alpha/\mathrm{Fe}] = +0.4$ dex shifts the ZAMS in the right way by an amount of about 120 K for [Fe/H] $= -0.5$ and only 50 K for [Fe/H] $= -1.0$. Nothing more can be expected since $[\alpha/\mathrm{Fe}] = +0.4$ dex appears to be an upper observational limit (Wheeler et al. 1989) and the effects of the α-elements enrichment on the models decreases as [Fe/H] decreases. We examined the effects of a change of the mixing-length parameter and found that decreasing α from the solar value 1.64 to 1.2 produces a change of 70 K only. We also looked at the effects of a change in the atmosphere model using the sophisticated ATLAS 9 models (Kurucz 1991) instead of the usual grey atmosphere but we did not find a difference of more than about 30 K.

Among the processes that are neglected in standard stellar evolution theory, microscopic diffusion of helium and heavy elements in the stars during their evolution could play a role: gravitational settling is more active in metal poor stars than in stars of solar metallicity because the density at the bottom of the convective zone is smaller and the mass of the convective zone is also smaller so that it is easier to modify the surface abundances. These stars are expected to have ages of about 9 Gyr (expected age of the galactic disk) so that diffusion could have been efficient and could have modified the atmospheric abundances which would differ from the initial abundances determining their structure. From the models we find that stars with an atmospheric chemical composition [Fe/H] $= -0.8$ are located on a theoretical isochrone of [Fe/H] $= -0.3$.

Work is in progress to quantify the effects of microscopic diffusion in the metal deficient stars of the sample. Actually there is an indication that an isochrone more metal-rich than the metallicity of -0.8 (which is the atmospheric metallicity of the binary star μ Cas A) not only resolves the isochrone discrepancy but also gives the right mass for μ Cas A. A detailed paper on this subject is in preparation (Lebreton et al. 1997). As discussed by Cayrel et al. (1997) there is also a problem for the very low metallicities corresponding to subdwarfs ([Fe/H] $\simeq -1.5$).

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