STELLAR INTERIORS AND ATMOSPHERES IN THE FRAMEWORK OF THE GAIA MISSION

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ABSTRACT

The understanding and modelling of the structure and evolution of stars is based on statistical physics as well as on hydrodynamics. Today, a precise identification and proper description of the physical processes taking place in stellar interiors are still lacking (one key point being that of transport processes) while the comparison of real stars to model predictions, which implies conversions from the theoretical space to the observational one, suffers from remaining uncertainties in model atmospheres. That results in uncertainties on the prediction of stellar properties needed for galactic studies or cosmology (in particular stellar ages and masses). In the years to come, considerable progress is expected in the field simultaneously from the theoretical, experimental and observational sides. The Gaia harvest will consist of complete and homogeneous astrometric, photometric and spectroscopic observations of hundreds of millions of stars spanning the whole ranges of masses, chemical compositions and evolutionary stages. I illustrate some of the difficulties to overcome and, on the basis of a few selected examples, I discuss how Gaia data associated with independent observational material (for example from asteroseismology or interferometry) will contribute to a better knowledge of stellar interiors and atmospheres and to more precise determinations of the stellar parameters.

Key words: Stars: fundamental parameters, atmospheres, internal structure, evolution.

1. INTRODUCTION

The objectives of the stellar (astro)physicist are on the one hand to understand the physics of matter in the extreme conditions encountered in stars and on the other hand to determine some stellar properties that are crucial to understand and describe the history and evolution of galaxies and to constrain cosmological models.

To achieve these goals and to support theoretical studies, we mainly rely on astronomic observations, multi-dimensional simulations and laboratory experiments.

Astronomic observations provide global stellar parameters (like luminosity, radius, mass, effective temperature, gravity or surface abundances), seismic parameters (such as oscillation frequencies or amplitudes) and other parameters (for example the solar neutrino fluxes). The quality of observed data has been very much improved recently with the development of modern ground-based or space telescopes equipped with high quality instrumentation. In the years to come, the determination of global parameters is expected to be further improved with, for instance, the VLT–VLTI or JWST telescopes and instrumentation, while accurate asteroseismic data for increasing numbers of stars will be obtained from ground-based instruments like HARPS (Bouchy & Carrier 2002) and space missions like MOST (Walker et al. 2003) and COROT (Auvergne et al. 2003). During the next decade, Gaia will make precise astrometric, photometric and spectroscopic observations of a huge number of stars that will cover the whole range of stellar masses, compositions and evolutionary stages (ESA 2000; Perryman et al. 2001). In the following, I will illustrate how the homogeneity and completeness of Gaia observations will be crucial for stellar structure and evolution studies.

Multi-dimensional hydrodynamical simulations are now more easily accessible to modern computers. I will mention here some very important results obtained recently from 2 and 3D simulations of turbulent convection in stellar cores and envelopes.

Laboratory experiments such as fluid experiments or experiments using particle accelerators or high power lasers can also give access to data of astrophysical interest. Recently, experiments with intense lasers allowed the derivation of the opacities of iron for physical conditions corresponding to stellar envelopes (Chenais-Popovics et al. 2000) while high-pressure experiments with lasers gave access to the equation of state of matter in the dense regime corresponding to the interiors of brown dwarfs and giant planets (Collins et al. 1998). Ultra high intensity lasers are now under development like the Laser MegaJoule (LMJ, see Stehlé & Chieze 2002) or the National Ignition Facility (NIF, see Remington et al. 2000). As illustrated in Figure 1 these devices will give access to an extended – today still out of reach – region of the stellar temperature-density plane for determinations of stellar thermonuclear reaction rates, equation of state or opacities.

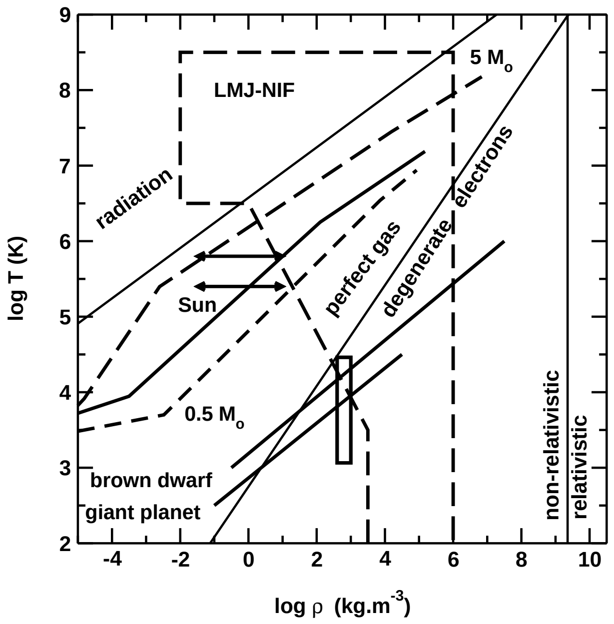

Figure 1. The density-temperature plane: The arrows delimit the region of stellar envelopes where the iron opacities have been derived from experiments with high power lasers, the rectangle corresponds to the region of the interiors of brown dwarfs and giant planets where the equation of state of dense matter has been studied with high pressure experiments using intense lasers, and the large region delimited by dashed lines is the region that will be accessible to the next generation of intense lasers like the LMJ or the NIF (see text).

2. STELLAR MODELS INPUT PARAMETERS

2.1. Input Physics and Boundary Conditions

A valid physical description of the microscopic and macroscopic processes at work in stellar plasmas is required for stellar models calculation. Concerning microscopic physics, the last decades have seen great improvements in the description of opacities, equation of state and thermonuclear reaction rates and this has brought models in better agreement with observations. However there are remaining difficulties. For instance, the molecular opacities are still incomplete and inaccurate and that leads to uncertainties in the modelling of cool objects. Also, some nuclear reaction rates for advanced evolution stages are still uncertain. Furthermore, in some cases, a better accuracy is needed when the stellar models are very strongly constrained by observations as it is the case for the solar model (see subsection 2.3). Concerning macroscopic physics great difficulties remain because the transport processes and resulting mixing are generally not well understood and even not characterized: there are problems with the description of pure diffusive mixing, convection, overshooting, rotation induced mixing and with the role of magnetic fields, mass loss, accretion, perturbations from binary companion, etc. Finally, stellar models calculation requires correct model atmospheres to fix the boundary conditions for the interior, and the conversion of the outputs of interior models into quantities that can be compared with observations is based on bolometric corrections or colour-temperature conversions that can be estimated from model atmospheres.

2.2. Outputs from Model Atmospheres

Stellar models calculation involves inputs and constraints derived from observations. Observational data (apparent magnitudes, colours, spectra, light curves, velocity curves) have to be analysed to get the stellar fundamental parameters. These analysis often rely on model atmospheres, for instance to predict fluxes in different bands, synthetic spectra or limb-darkening coefficients.

The last decade has seen great progress in atmosphere modelling : better atomic and molecular data have been obtained and faster computers and new algorithms have allowed to perform 2 and 3D hydrodynamical simulations and to include NLTE effects, spherical geometry, etc. We now have better model atmospheres to exploit the high quality spectra obtained with modern instruments. So we should expect better accuracy in quantities like temperatures, gravities and abundances (Recio-Blanco & Thévenin 2005). However, while the internal errors in the determination of stellar parameters are indeed becoming very small (see Table 1), systematic errors remain and they can be large. As discussed by Gustafsson (2004), the internal errors on metallicity may be as small as 0.02 dex but the typical systematic errors often amount to 0.2-0.3 dex. Similarly, the current formal error on effective temperature is around 50 K but, Gustafsson stresses that for some stars like cool giants or metal poor dwarfs, differences in $T_{\rm eff}$-scales can reach 200 to 400 K. Furthermore, although stellar models by different authors generally agree to within 0.05 mag in $M_{\rm bol}$, errors of 0.1 mag and even more are commonly introduced when converting these models from the $(M_{\rm bol}, T_{\rm eff})$-plane to various colour-magnitude diagrams through colour-temperature conversions or bolometric corrections (Robichon et al. 1999; Lebreton 2002).

2.3. Impact of Input Parameters: Solar Surface Abundances

Solar surface abundances have been recently derived from 3D radiative-hydrodynamical model atmospheres including better atomic data and NLTE effects (Asplund et al. 2004). When compared to the ‘old’ abundances derived from 1D hydrostatic models, the new solar surface abundances of C, N, O are reduced by 0.15–0.20 dex and the solar surface metallicity is decreased by $\sim$ 30%. Since a modification of C, N, O abundances induces a modification of opacities and energy generation, one expects consequences for the solar interior model. Indeed, Bahcall et al. (2004); Montalban et al. (2004); Turck-Chieze et al. (2004) have recently shown that the new solar model is now in large disagreement with the seismic model: the convection zone depth and helium abundance, the sound speed and density profiles all disagree with observations. As an example, Figure 2 shows the comparison of the square of the sound speed in solar models with

Table 1. Best internal precisions obtained on the determination of observational parameters of dwarfs, subgiants and giants of spectral types A to K.

		number of stars	source
σ_π/π	< 0.10	2×10^4	astrometry: Hipparcos
$\sigma_{\rm F_{bol}}/{\rm F_{bol}}$	~ 0.02	5×10^2	multi-colour photometry
$\sigma_{\rm T_{eff}}$	50–100 K	10^3	IRFM, SBM, spectroscopy
$\sigma_{\log g}$	0.1–0.2 dex	10^3	spectroscopy, photometry
$\sigma_{\rm [Fe/H]}$	0.02–0.10 dex	10^5	spectroscopy, photometry
$\sigma_{\rm M}/{\rm M}$	0.01–0.02	10^2	binaries: astrometry, photometry, spectroscopy
$\sigma_{\rm R}/{\rm R}$	0.01–0.02	10^2	binaries, HRA
seismic data		Sun and a few stars	

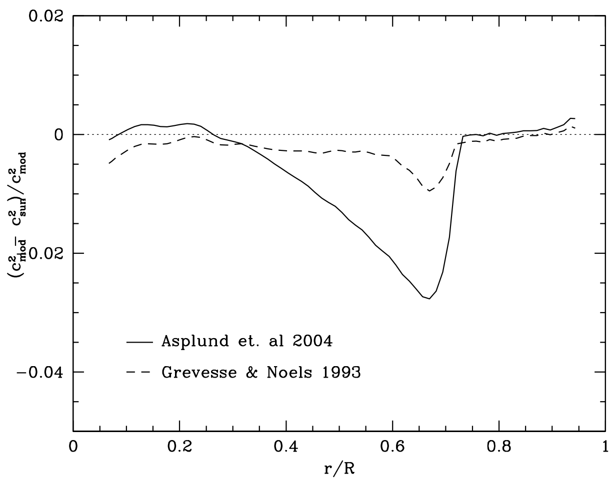

Figure 2. Comparison of the square of the sound speed in a solar model with the value derived from the inversion of heliosismic data from J. Montalban (2004, private communication). The dotted line corresponds to old abundances, the continuous one to new abundances.

the profile derived from inversion of seismic data. Clearly the revision of the abundances exemplifies the problems in the description of the region extending from $\sim$0.4$R_\odot$ to $\sim$0.7$R_\odot$ which corresponds to the upper part of the radiative zone and to the shear region between the convective and radiative zone called tachocline. If the validity of the new abundances is further confirmed, the physics in the solar model will have to be revised. The discrepancy could partially come from microscopic diffusion coefficients – which are known to be uncertain by $\sim$10–15% – or from inaccuracies in opacities. However, as recently discussed by Badnell et al. (2004), OPAL and OP opacities do not differ by more than 2.5% in the concerned zone. The origin of the discrepancy could also be related to missing physics, both in the radiative zone and tachocline, like rotational induced mixing (Mathis & Zahn 2004). In the future, it will be possible to probe this region of the solar interior with intense lasers.

2.4. The Future in the Context of Gaia

After the success of the 3D simulations of the solar atmosphere in reproducing granulation geometry, line profiles, assymetries and shifts, and heliosismic constraints (see Stein & Nordlund 2000), 3D hydrodynamical model atmospheres are now being developed for other stars. For example, M. Steffen and collaborators present simulations of the granulation in A stars on a web site[1] and simulations of cool giants atmospheres are presented in Hoefner et al. (2004).

Gaia will provide millions of spectra and broad and narrow band photometry for all spectral types. The present preparation of the mission is mainly based on 1D, LTE static model atmospheres (ATLAS, MARCS, PHOENIX, see Jordi 2005; Katz 2005). However it is very probable that Gaia actual data will have to be analysed using elaborate models accounting for NLTE effects and 2D or 3D hydrodynamics (Plez 2003).

3. MODELLING CALIBRATORS

The stellar modeller distinguishes two kinds of stars. The so-called calibrators are the very few stars for which constraints are strong and numerous. Calibrators are used to validate the models and learn on the physics. Then the knowledge learned from calibrators can be applied to stars whose observations are incomplete and not so accurate. This implies extrapolating to compositions, masses or evolution stages not covered by calibrators with the underlying hypothesis that the physical description we make is universal. Quantities of astrophysical interest such as age, helium content or distance scale can then be derived for very large numbers of stars.

3.1. Example 1: the Binary System α Centauri

The binary system α Centauri is the closest and best-known system and it has been modeled at least fourteen

[1] http://www.aip.de/groups/sternphysik/stp/convect.html

times in the past. Its observational global parameters $L, T_{\rm eff}$ and $[{\rm Fe/H}]$ are very accurate. In addition, masses have been revisited recently and are given with an accuracy $\sigma_{\rm M}/{\rm M} < 1\%$ (Pourbaix et al. 2002), direct angular diameters have been measured for the first time by interferometry with a precision better than 1% (Kervella et al. 2003). Finally, first seismic data have been obtained by Bouchy & Carrier (2001) and Carrier & Bourban (2003) who identified 28 low-degree p-modes for component A and 12 for component B respectively.

The modelling of a binary system consists in reproducing the observed constraints under the hypothesis that the two stars have same age and initial chemical composition. This allows to infer the values of the unknown parameters of the models: age, initial helium, and parameters entering the physical description like mixing-length parameter for convection or overshooting parameter. When playing the game one finds that a lot of models with different sets of parameters fit the $(L, T_{\rm eff})$ or $(L, log\ g)$ box in the HR diagram. As a result the constraints on the physics remain loose and ages between 2.7 and 7.6 Gyrs and initial helium abundances in the range 0.27–0.32 have been proposed (see Thévenin et al. 2002; Thoul et al. 2003; Eggenberger et al. 2004, for recent models).

The new constraint on the radii is very precious since it allows to reduce the number of suitable models (Kervella et al. 2003). But adding the seismic constraints complicates the problem since no model can now simultaneously fit all observations at the one sigma level: either the constraint on the interferometric radii has to be relaxed to the 2σ level (Eggenberger et al. 2004) or the constraint on the revisited α Cen B mass has to be relaxed to the 3σ level (Kervella et al. 2003).

It is important to point out that the present seismic observations are still rather coarse since the accuracy on the observed frequencies is of the order of $\Delta\nu \simeq 0.5\ \mu{\rm Hz}$ for α Cen A (Bouchy & Carrier 2001). To go further in the analysis, we have to wait for improved accuracies expected from future seismic observations. However, these studies already demonstrate that both asteroseismic and global constraints are essential and that the stronger the observational constraints are, the more difficult it is to constrain the models and to reach the ultimate goal which is to characterize and discriminate the physical processes.

Today very few calibrators are available to make fine tests of the physics of stellar interiors. In particular there are less than 200 stars for which Hipparcos measured distances with an accuracy better than 1% and less than $\sim$ 100 binary systems for which masses and radii are measured with an accuracy better than 1%. Gaia will drastically increase that number by providing a large set of global parameters including masses : with Gaia the parallax of 7×10^5 (21×10^6) stars will be measured with an accuracy better than 0.1% (1%) and the mass of stars in 17 000 binary systems will be obtained with an accuracy better than 1%. On the other hand, future interferometric observations will give access to enlarged stellar samples with very accurate angular radius measurements. Finally the precise seismic data expected for an appreciable number of stars from future missions will be crucial to probe the stellar models. For instance, COROT will reach an accuracy of $0.1\mu{\rm Hz}$ on oscillation frequencies for about 50 targets (G-F V-IV type stars and δ Scuti stars) and we still hope that a mission like Eddington will fly in the future to enlarge the seismic sample to 50 000 stars with accuracies on frequencies of 0.1–0.3$\mu{\rm Hz}$ (Roxburgh & Favata 2003).

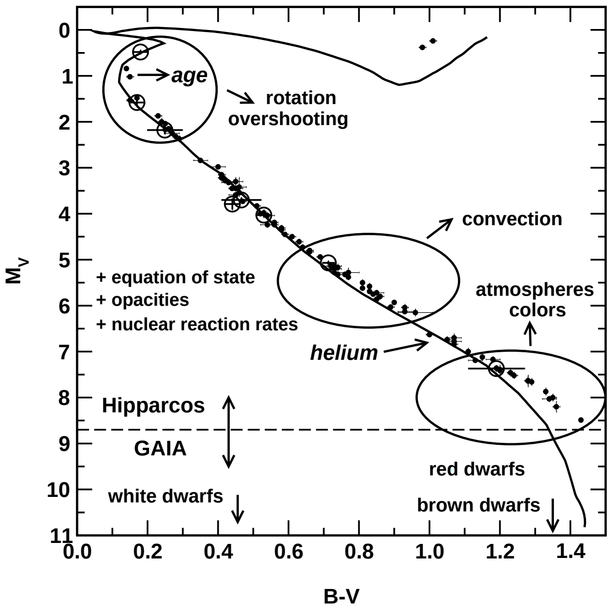

Figure 3. The Hyades colour-magnitude diagram. Observational data from Hipparcos (de Bruijne et al. 2001) are compared to a model isochrone (Lebreton et al. 2001). Different regions are indicated where the impact of the various physical inputs is crucial. The magnitude limit of Hipparcos – which will be pushed down by Gaia – is indicated by the horizontal dashed line

3.2. Example 2: Open Clusters Members: Hyades

Stars in open clusters can also be very interesting calibrators if their observational data are accurate enough. This is the case of the Hyades members that can be studied with the hypothesis that they all have the same age and initial composition but different mass. As illustrated in Figure 3, the comparison of a model isochrone with observations of the cluster members in a colour-magnitude diagram allows to derive the initial abundance and age of the cluster. The initial helium abundance can be derived from the position of the lower main sequence but this requires that the metallicity is very well-known because of the helium-metallicity degeneracy in the HR diagram (Perryman et al. 1998). The age can be derived from the position of the main sequence turn-off. However, depending on the considered cluster, helium and age determinations can be affected by uncertainties on the physics as envelope or core convection or mixing induced by rotation (Lebreton et al. 2001).

As illustrated in Figure 4, additional constraints on the models are provided if the mass-luminosity relation of the cluster can be derived from observations of stars in binaries. In that case the study of low-mass non evolved mem-

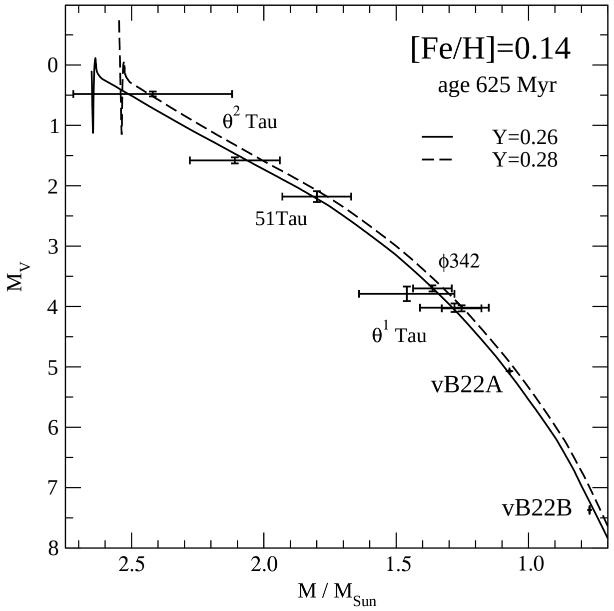

Figure 4. The Hyades mass-luminosity relation. Observed masses are from Torres et al. (1997c,a,b). The $\mathrm{vB22}$ *system is the only one which has observed parameters accurate enough to constrain the helium content of the models (Lebreton et al. 2001).*

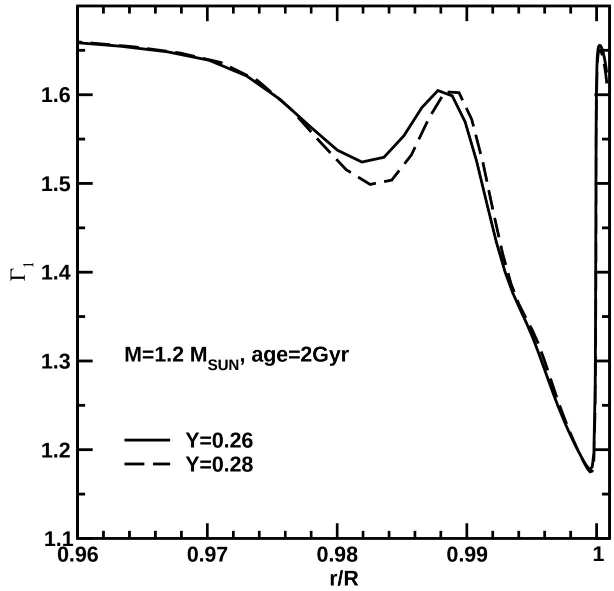

Figure 5. The profile of the adiabatic index Γ_1 *in a* $1.2M_\odot$ *model for two values of the helium abundance.*

bers allows to improve the accuracy on the helium abundance Y provided the masses and metallicites are very precise. Furthermore, constraints on the physics can be provided if several binaries are observed spanning a large mass range. In the case of the Hyades, only one system – vB22 – has masses accurate enough ($\sigma_{\mathrm{M}}/\mathrm{M} < 1\%$) to allow improvement in the determination of Y. But even in this case, the precision $\Delta\mathrm{Y}$ reachable on Y is limited by the uncertainty on the $[\mathrm{Fe/H}]$ determination, the helium-metallicity degeneracy in the M–L plane implying $\Delta\mathrm{Y}/\Delta[\mathrm{Fe/H}] \simeq 0.2$ (Lebreton et al. 2001).

After the successes of helioseismology, recent investigations have shown that the seismic analysis of solar-type stars should bring information on their inner structure as the convection zone depth and helium content (see for instance, Mazumdar & Antia 2001; Basu et al. 2004; Piau et al. 2005). In particular, as shown in Figure 5, the second helium ionization produces a depression in the adiabatic index Γ_1 in the outer convection zone of solar-type stars. Basu et al. (2004) have shown that this depression increases for increasing helium abundance and that its signature is detectable in the oscillation frequencies. With the hypothesis that low frequency acoustic modes of degree $l = 0$–3 are detected in low mass main sequence stars with an accuracy on the frequencies of 0.01% and that either the mass or the radius of the stars are known independently, Basu et al. performed a seismic analysis based on the second difference of the frequencies $\delta^2\nu_{n,l} = \nu_{n+1,l} - 2\nu_{n,l} + \nu_{n-1,l}$ and showed that the helium abundance can be determined with a precision $\Delta\mathrm{Y}$ ranging from 0.03 for $0.8\mathrm{M}_\odot$ stars to 0.01 for $1.2\mathrm{M}_\odot$ stars. These conditions should be fulfilled with future asteroseismic missions. We therefore expect that the detection of solar-like oscillations in stars members of open clusters will allow to determine their helium content more precisely (see also Piau et al. 2005, for an investigation of what we can expect from seismic analysis of stars in clusters). However, as in the Sun, seismic analysis will give access to the helium abundance in the present convection zone. To infer the initial helium abundance, we will still have to understand the transport processes that can modify the abundances in the convection zone during the life of the stars as microscopic diffusion or rotation induced mixing.

After Hipparcos, the number of open clusters that can be treated as calibrators is very small. Precise individual distances are available for the Hyades stars only. Binaries have been analysed in the Hyades and the Pleiades only. It is worth pointing out that in the Pleiades, the recent determination of the masses of the components of two binary systems has allowed to anchor the distance of the cluster more firmly (Munari et al. 2004; Zwahlen et al. 2004). Furthermore, there is no cluster star where solar-like oscillations have been detected.

Gaia will considerably enlarge the number of clusters calibrators by bringing $\sim$120 open clusters (up to distances of 1 kpc) to a level of precision ($\sigma_{\mathrm{M-m,G<15}} \leq 0.02$ mag) similar to or better than what is available in the Hyades today. Moreover, Gaia will observe $\sim$10 binaries per cluster. Combining Gaia data with the seismic data for cluster stars we hope to get in the future will certainly bring much progress in the field.

4. DERIVING ASTROPHYSICAL PARAMETERS

4.1. Ages of A and F Stars and the Size of their Mixed Cores

In our Galaxy, the ages of A and F stars are crucial inputs for studying the disc but these ages are still uncertain. In

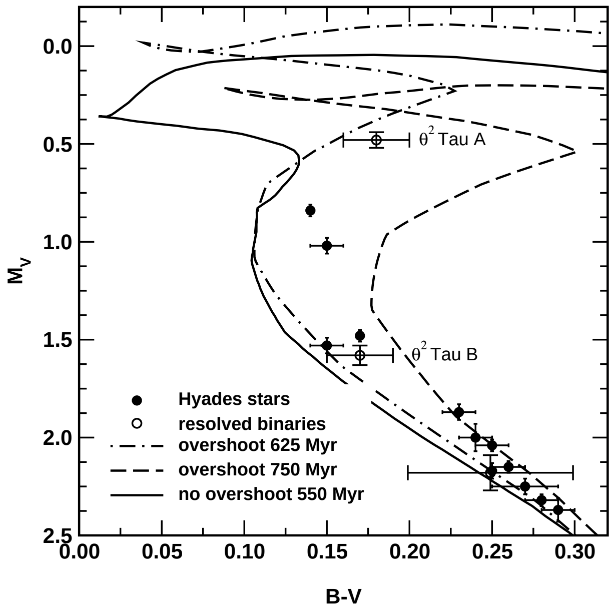

Figure 6. Effect of convective core overshooting on model isochrones for A-stars at Hyades turn-off.

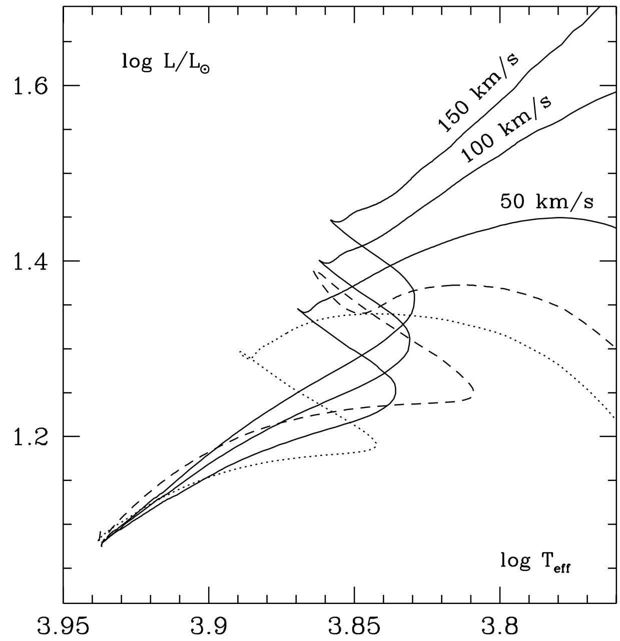

Figure 7. Effects of rotation induced mixing on the evolutionary tracks from Goupil et al. (2000). Continuous lines are tracks including rotation induced mixing for different rotation rates. The dotted track is a standard non-rotating one, the dashed-line is a non-rotating track but it includes convective core overshooting.

the Hyades, A-stars are located at the turn-off; they are fast rotators lying in the δ Scuti instability strip (see Figure 3). To model these stars, we are faced to difficulties in describing mixing by core convection overshoot, turbulent mixing induced by rotation and effects of rotation on photometry. These processes modify either the stellar models or the position of the observed star in the HR diagram and in turn affect the age determination. Figures 6 and 7 show the effects in the HR diagram of mixing due to convective overshooting and of mixing induced by rotation: these distinct processes have similar signatures and the difficulty is to discriminate them and to estimate the resulting uncertainty on age.

Stars of $M \gtrsim 1.2M_\odot$ have convective cores. The size of the mixed core determines the structure of the star and the fuel available for its evolution, it is therefore a crucial parameter for age determination. Today, we do not have any satisfactory hydrodynamical description of convective overshoot or of mixing induced by rotation so in stellar modelling the size of the mixed core is usually parameterized with a coefficient $\alpha_{\rm ov}$ that might depend on the mass, composition and evolutionary stage. Theoretical works have allowed to put an upper limit to the overshooting parameter (see Zahn 1991; Roxburgh 1992). On the other hand empirical calibrations of $\alpha_{\rm ov}$ have been performed on the basis of considerations on the main sequence width or on the calibrations of binaries (see Ribas et al. 2000; Young et al. 2001; Cordier et al. 2002). However, values of the overshooting parameter are very uncertain: modellers currently use $\alpha_{\rm ov} \simeq 0.20\pm0.15$ which represents an uncertainty of about 75% on $\alpha_{\rm ov}$. Progress is presently coming from various kinds of 2 or 3D hydrodynamical simulations of non linear convection in rotating stellar cores (see the recent works by Deupree 2000; Browning et al. 2004). The results of these simulations are very promising. They predict a prolate shape of the adiabatic cores and they show evidence for convective overshooting and differential rotation in the cores.

In the future, seismic analysis should allow to better determine the size of mixed cores. In δ Scuti stars, the low degree low frequency modes are sensitive to the composition gradient in the deep interior. As shown in Figure 8, the profile of the density inside these stars shows a discontinuity which is the signature of the boundary of the mixed core. If accurate seismic data and global parameters were available for these stars, then the inversion of seismic data should allow to infer the density profile and in turn the size of the mixed core (Roxburgh 2002).

After Hipparcos, the distances of about 10^3 A–F stars are determined with a precision better than $\sim$10%. Oscillations have been detected in very few δ Scuti but data are too partial to allow a determination of the size of the mixed core. As a result, the uncertainty of 75% on $\alpha_{\rm ov}$ quoted above, alone is responsible for an uncertainty on age ranging from 13 to 24% (Lebreton et al. 1995).

In the next decade Gaia will increase drastically the number of A–F stars with very precise distances: for instance an uncertainty $\sigma_\pi/\pi \lesssim$ 0.5% on the parallax will be reached for about 5×10^5 A stars and 3×10^6 F stars. In parallel, asteroseismic missions like COROT will measure oscillation frequencies in a few δ Scuti with very good accuracy ($\sigma_\nu/\nu \simeq 0.1\mu$Hz). This should allow to improve the precision on the overshooting parameter by a factor of $\sim$5 and to reduce the resulting uncertainty on age to a level of 3–5% (Lebreton et al. 1995). However, it is important to point out that there are other important uncertainties on age (see, Lebreton et al. 1995; Haywood 2005).

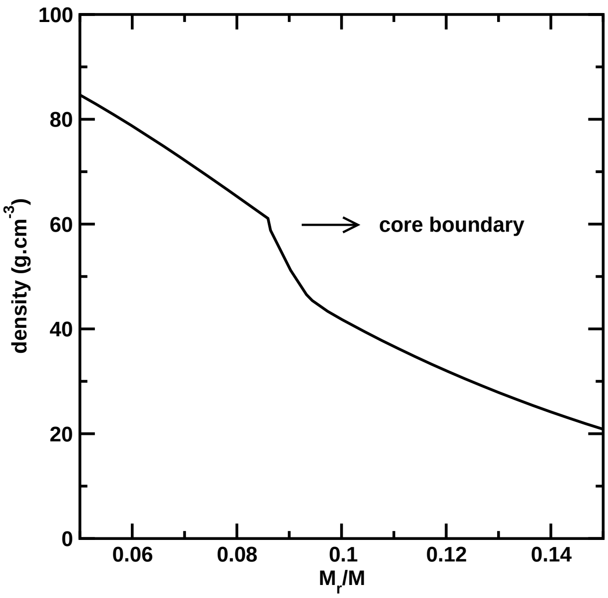

Figure 8. The density profile in the inner parts of a 1.5$M_\odot$ model.

4.2. Ages of Old Stars and Microscopic Diffusion

In low mass stars, microscopic diffusion by gravitational settling makes helium and heavy elements sink towards the interior. As time goes on, helium and heavy elements abundances decrease at the surface and increase in the core. This process acts on long time scales τ: $\tau \propto (M_{\rm CZ}/M) T_{\rm CZ}^{-3/2}$ where $M_{\rm CZ}$ and $T_{\rm CZ}$ are respectively the mass of the convection zone and the temperature at its bottom. In old low-mass metal-poor stars where its effect is maximum for $M \simeq 0.8 M_\odot$, microscopic diffusion modifies significantly the position in the HR diagram and associated age (Morel & Baglin 1999). It has therefore great implications for the determination of the ages of the oldest objects in the Galaxy which in turn provide constraints for cosmology.

Christensen-Dalsgaard et al. (1993) have shown that heliosismic constraints are better reproduced when microscopic diffusion is included in solar models. However, Richard et al. (1996) and Brun et al. (1999) have shown that it should be partially inhibited – by extra turbulent mixing in the tachocline – to reproduce the constraints on lithium and beryllium abundances. On the other hand microscopic diffusion has also been suggested to be present in old disc and halo stars (Lebreton et al. 1999).

Constraints can be brought by the observations of surface abundances of subgiants and giants in globular clusters. If microscopic diffusion has been fully active in those stars we expect that subgiants at turn-off exhibit modified surface abundances while giants having undergone the first dredge-up have recovered their initial abundances (Chaboyer et al. 2001). Observations of turn-off, subgiants and giants stars in several globular clusters performed with UVES at VLT by Gratton et al. (2001) and Carretta et al. (2004) suggest that giants and subgiants have similar metallicities. This indicates that other processes could be in competition with microscopic diffusion, the nature of which remains to be determined. However, here again, uncertainties in the analysis of observed spectra, including the NLTE corrections to abundances (Thévenin & Idiart 1999) and the uncertain $T_{\rm eff}$-scales (Gustafsson 2004) should be fixed before we definitely conclude.

After Hipparcos, direct distances are available with a precision better than 12% for only 11 subdwarfs and 2 subgiants. Gaia will provide precise direct distances for very large samples of subdwarfs and for all subgiants up to 3 kpc. It will also give access to individual distances with a precision better than 10% for stars in about 20 globular clusters. This will certainly contribute to a better determination of the age of the galactic halo.

5. CONCLUSION

On the theoretical side, the atmosphere modelling and the accuracy on the observed parameters both have a major impact on the calculation of stellar models and on their validation by confrontation with the observations. The interior models of the Sun and of a few calibrators have been much improved recently but there are remaining uncertainties in the input physics and boundary conditions that can be very large.

On the observational side, with Gaia most stellar masses and evolution stages will be unprecedently documented which will allow to improve the modelling of all kinds of stars of all populations even the rare or particular objects. However since global parameters often only provide coarse constraints, Gaia data will have to be complemented by independent information. This information is presently being obtained: accurate global data (such as direct radius measurements) and very precise abundances of a large number of chemical species are now accessible to modern instruments (for instance UVES, GIRAFFE or AMBER at VLT) and in the near future, new precise seismic data are expected from space missions MOST and COROT. Finally, parallel theoretical, numerical and experimental improvements will also be essential for the validation of the physics entering stellar models.

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