Age dating of old field stars. Challenges from the uncertain efficiency of atomic diffusion

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Age-dating the Milky Way stellar populations plays a major role in studies of galaxy formation and evolution. Ages of old stars that represent the fossil record of the early stages of galaxy formation are particular important. Current spectroscopic surveys provide effective temperature, surface gravity and photospheric composition of large samples of Milky Way stars, and these data can be used to determine stellar ages by employing stellar evolution models. Here it is shown how current uncertainties on the efficiency of atomic diffusion in the interiors of low-mass metal poor stars can affect the derived ages at the level of several 10%. Asteroseismic constraints on the stellar masses can reduce these errors and in the limit of high accuracy can indirectly constrain the efficiency of diffusion in the interiors of these stars.

1 Introduction

Unravelling the detailed evolutionary history of galaxies is a major goal in modern astrophysics. The Milky Way plays clearly a pivotal role in this game, given the possibility to obtain much more detailed and accurate information about its stellar content, compared to external galaxies.

To this purpose, a major effort is being devoted to large photometric surveys such as SAGA (Casagrande et al. 2014, Strömgren Survey for Asteroseismology and Galactic Archaeology), and spectroscopic surveys such as RAVE (RAdial Velocity Experiment, Steinmetz et al. 2006), LAMOST (Large sky Area Multi-Object fiber Spectroscopic Telescope, Zhao et al. 2012), SEGUE (Sloan Extension for Galactic Understanding and Exploration, Yanny et al. 2009), GAIA-ESO (Gilmore et al. 2012), APOGEE (Apache Point Observatory Galactic Evolution Experiment, Holtzman et al. 2015), GALAH (GALactic Archaeology with Hermes, De Silva et al. 2015), that derive effective temperature, surface gravity, radial velocities and photospheric abundances of several chemical elements, for large samples of Milky Way stars. At the same time, the *CoRoT* (see, e.g. Miglio et al. 2013; Mosser et al. 2010) and *Kepler* missions (Bedding et al. 2010; Chaplin et al. 2010) provide asteroseismic data for dwarfs and red giants, that lead to an estimation of stellar masses and radii.

A crucial piece of information to derive from these data are the ages of the observed stars, that provide a timeline for the development of the observed dynamical and chemical properties of the surveyed populations. Ages of old populations (older than a few Gyr) are particularly important, because these stars represent the fossil record of the early stages of galaxy formation.

Estimates of stellar ages, especially of field stars, are challenging. Age-dating is usually performed by fitting theoretical stellar evolution tracks to the observations in the log(g)-log(T_{eff}) diagram, with additional constraints given by the measured chemical abundances, and asteroseismic measurements when available (see, e.g., Serenelli et al. 2013; Valle et al. 2015, for some examples).

Slowly evolving low mass main sequence (MS) stars still close to to their Zero Age MS location are virtually impossible to age-date in the log(g)-log(T_{eff}) diagram. Ages of red giant branch (RGB) stars are also particularly challenging, because small uncertainties on T_{eff} (at fixed g) translate into large uncertainties on the star's mass, hence its age, especially when asteroseismic constraints on the mass of the object are not available.

In addition to uncertainties related to the available data and associated errors, uncertainties in stellar evolution modelling inject an additional level of incertitude in the estimated stellar ages. A relevant problem is the uncertain efficiency of atomic diffusion in the interiors of low mass stars, that can have a major impact on the estimated ages. This topic will be discussed in the following sections, with the main focus on the impact on age estimates from the log(g)-log(T_{eff}) diagram.

2 The efficiency of atomic diffusion

Basic physics considerations suggest that, in addition to convective mixing, *slow* transport processes must be efficient within the radiative regions of non-rotating stellar in-

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teriors, driven by pressure, temperature and chemical abundance gradients, and by the effect of radiation pressure on the individual ions. These processes are collectively called "diffusion processes", and their inclusion in stellar evolution computations is necessary in order to satisfy helioseismic constraints for the solar models (see, i.e., Bahcall et al. 1995).

Individual ions move under the influence of both pressure and temperature gradients, that both tend to displace heavier elements toward the centre of the star, and of concentration gradients that oppose the above processes. Radiation pushes the ions toward the surface, whenever the radiative acceleration of an individual ion species is larger than the local gravitational acceleration (this effect is negligible in the Sun). The speed of the diffusive flow depends on the collisions with the surrounding particles, and it is the extent of these collision effects that dictates the timescale of element diffusion within the star, for a given physical and chemical profile. The most general mathematical treatment for the element transport in a multicomponent fluid associated with diffusion is provided by the Burgers' equations (Burgers 1969). The most accurate determination of the diffusion coefficients within this formalism is by Schlattl & Salaris (2003), who for the first time included the effect of quantum corrections.

For a given initial mass and chemical composition, diffusion has a major effect during the MS, in hot horizontal branch stars, and during the hot white dwarf phases. The main focus here will be on the MS of low-mass stars, during which diffusion can alter also substantially the chemical stratification throughout the stellar structure. From the point of view of the surface abundances (what is measured from spectroscopy) metals and He diffuse out of the shrinking convective envelope (that maintains a uniform chemical profile due to the shorter convective timescales compared to diffusion) being replaced by hydrogen, and their abundances decrease with time, reaching a minimum around the turn off (TO). When the convective envelope starts to get increasingly deeper after the TO, most of He and metals previously diffused out of the surface convection zone are reengulfed in the convective layers, with the result that their surface abundances along the RGB are practically restored to the initial values. In general, the smaller (in mass) the convective envelope, the larger the change of surface abundances during the MS. Also in the interiors metals and He tend to sink. The resulting increase of helium in the centre at the expenses of H decreases the MS lifetime.

When convective envelopes are thin due to either low metallicity and/or increasing MS mass, radiation pressure on some ion species can overcome the local gravitational acceleration right below the convective region, and some metals are selectively pushed upwards. This will at first moderate the metal depletion from the convective envelope, then effectively reverse the trend, when metallicity goes further down (and/or mass further up). As shown by Richard et al. (2002a) calculations, a $0.77M_{\odot}$ model with initial

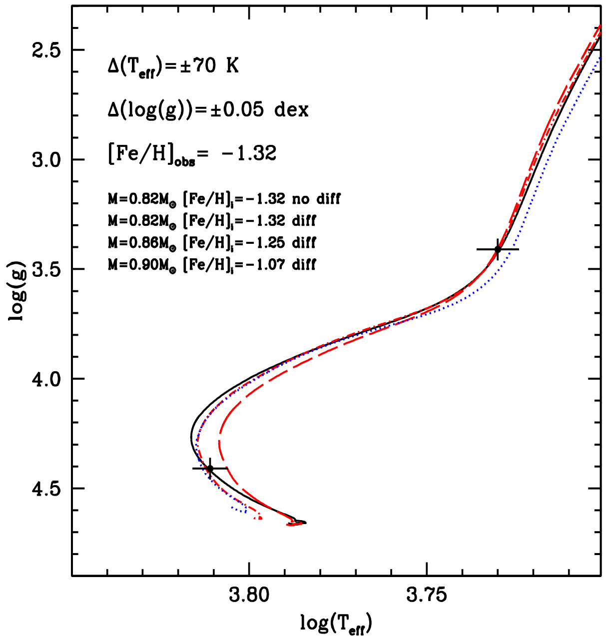

Fig. 1 The MS and RGB synthetic stars plotted in the log(g)-log(T_{eff}) diagram (filled circles) together with the associated error bars (see text for details). The following set of stellar evolution tracks is also displayed: $M=0.82M_{\odot}$, $[Fe/H]_i = -1.32$ and no diffusion (solid line), $M=0.82M_{\odot}$, $[Fe/H]_i = -1.32$ with diffusion (dashed line), $M=0.90M_{\odot}$, $[Fe/H]_i = -1.07$ with diffusion (dotted line), $M=0.86M_{\odot}$, $[Fe/H]_i = -1.25$ with diffusion (dash-dotted line). These latter two tracks do overlap almost perfectly along the MS and part of the subgiant branch evolution.

[Fe/H]=−2.31 will reach the TO (after 13.5 Gyr) with a surface Fe abundance depleted by just 0.1 dex, Ca enhanced by ∼0.2 dex, Mg depeleted by ∼0.2 dex, O depeleted by ∼0.7 dex, just to mention a few heavy elements. If radiative levitation is neglected, all metals would be depleted by similar amounts, of the order of ∼0.7 dex.

As already mentioned, constraints from helioseismology dictate the inclusion of atomic diffusion in standard stellar modelling, with perhaps just a small reduction of the diffusion efficiency by ∼10% (see, e.g., Villante et al. 2014) due to some non specified competing process. Observations of globular cluster stars however paint a different picture. Spectroscopic observations like the ones by Korn et al. (2006) and Mucciarelli et al. (2011) have shown convincingly that the variation of the abundance of Fe – amongst other elements– between the TO (where diffusion has its maximum effect) and the RGB (where the initial abundances are restored) is much smaller than what predicted by models including fully efficient diffusion.

These results point to the existence of some competing mixing mechanism that strongly inhibits diffusion at least from the convective envelopes of old metal poor MS stars in globulars (see, e.g., Richard et al. 2002a, for an ad hoc parametrization of this competing mixing process). Spectroscopy obviously cannot tell us anything about the efficiency of diffusion in the interiors. Also measurements of Li in field halo MS stars (the so-called *Spite-plateau*) is problematic for models that include fully efficient diffusion from the envelope of low-mass metal poor stars (see, e.g., Richard et al. 2002a, and references therein).

The effect of atomic diffusion –and its uncertain efficiency– on stellar ages of field stars derived from the log(g)-log(T_{eff}) diagram will be discussed in the next section, with some simple tests to derive approximate estimates of systematic age errors. Constraints on the accuracy of asteroseismic mass estimates necessary to limit these age uncertainties will be also briefly discussed. These tests are just examples, and the quantitative results cannot be extrapolated to other mass/metallicity regimes. An early analysis of the effect of diffusion on the ages of old field stars was presented by Salaris et al. (2000).

3 Atomic diffusion and age of old field stars

Let's consider one synthetic MS star with *observed* log(g)=4.41 (cgs units), log(T_{eff})=3.811 (temperature in K), and one synthetic RGB stars with log(g)=3.41, log(T_{eff})=3.736. Both stars have a *measured* [Fe/H]=−1.32. Realistic error bars of ±0.05 dex in log(g), ±70 K in T_{eff} and ±0.1 dex in [Fe/H] are attached to these *observed* values. Figure 1 shows how these two synthetic stars can be matched perfectly by a 0.82$M_{\odot}$ track with initial Fe abundance $[Fe/H]_i = -1.32$ (scaled solar metal mixture), without atomic diffusion (this track and all following models have been calculated with the BaSTI stellar evolution code, see Pietrinferni et al. 2004).

Figure 2 displays the 0.82$M_{\odot}$ evolutionary track in the t-log(T_{eff}) diagram, highlighting also the T_{eff} (and error range) of the two synthetic stars. Thick symbols along the model track denote the interval where log(g) is within the range measured for the two stars. In agreement with Fig. 1, when the theoretical track crosses the observed T_{eff} ranges, the surface gravity of the models also overlaps with the observed values. From Fig. 2 one can then derive for the MS star an age ranging between ∼7.5 and ∼9 Gyr (the size of this age interval depends on the error bars of g and T_{eff}), whilst the RGB star has an age of about 12.2 Gyr.

What if we include diffusion? In this metallicity and mass regime radiative levitation does not have any appreciable effect[1] and the surface abundances of these models are increasingly depleted when the star moves along its MS, as shown by Fig. 3. This figure displays the run of the actual surface [Fe/H] as a function of log(T_{eff}) from the Zero Age MS to the RGB for a series of models. The T_{eff} and [Fe/H] error ranges of the two synthetic stars are also marked.

[1] This has been verified by comparing the evolution of the surface abundances of Fe and other metals for a 0.8$M_{\odot}$ model with initial [Fe/H]=−1.32 and efficient atomic diffusion but without the contribution of radiative levitation, with the results for the same mass and initial composition by Richard et al. (2002b), that include also the effect of radiative levitation. The time evolution of the surface abundances in this test calculation is consistent with Richard et al. (2002b) results including also levitation.

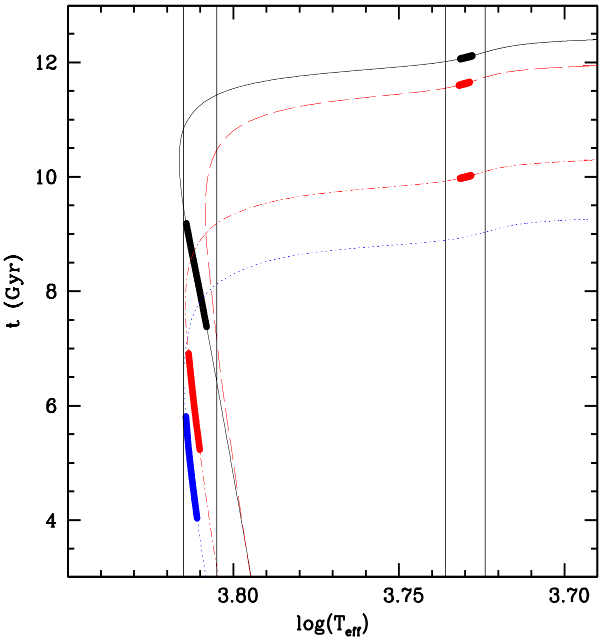

Fig. 2 The same tracks of Fig.1 but in the t-log(T_{eff}) diagram. The T_{eff} error range of the two synthetic stars is marked by pairs of vertical lines. Thick symbols along the model tracks denote the interval where log(g) is within the range measured for the two stars (see text for details).

The solid line displays the evolution of [Fe/H] for the model without diffusion discussed before, as reference. The value of [Fe/H] stays obviously constant bar a minor increase around log(T_{eff})∼3.72-3.73, that marks the first dredge-up along the early RGB. The extra He brought into the envelope by the dredge up decreases slightly H and increases [Fe/H].

The dashed line in Figs. 1 and 3 displays the results for a 0.82$M_{\odot}$ track, with initial Fe abundance $[Fe/H]_i = -1.32$, that includes diffusion. The surface [Fe/H] decreases steadily while T_{eff} increases along the MS evolution, but the track in Fig. 1 stays systematically cooler than the counterpart without diffusion, due to the increase of hydrogen in the convective envelope and the consequent increase of the opacity. These two figures show clearly that when the track crosses marginally the error box associated to the MS synthetic star, the surface [Fe/H] is too low compared to the observed value and this model cannot fit the data. On the other hand, once on the RGB the initial surface composition is basically restored and this model fits well the synthetic RGB star, for an age ∼0.5 Gyr younger than the track without diffusion, as shown by Fig. 2.

Two additional sets of models have been calculated, to highlight the degeneracy that exists between different pairs of mass and $[Fe/H]_i$, when trying to fit a MS star in the log(g)-log(T_{eff}) diagram with the inclusion of fully efficient diffusion. The dotted and dash-dotted lines in Figs. 1 and 3 display a 0.90$M_{\odot}$, $[Fe/H]_i = -1.07$, and 0.86$M_{\odot}$,

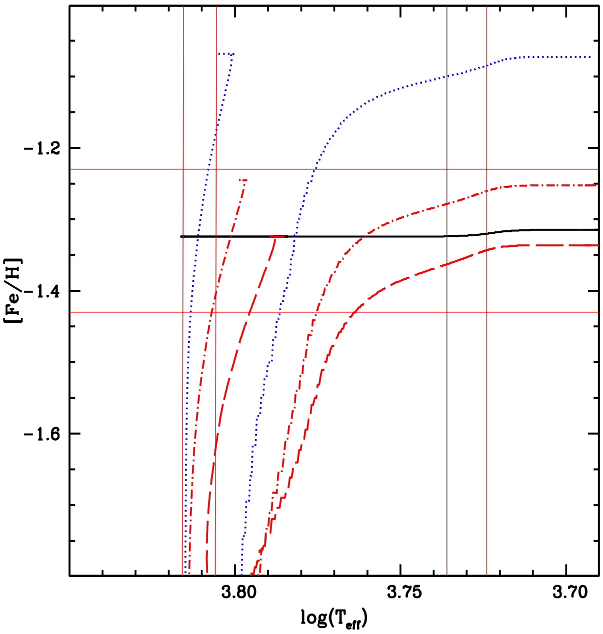

Fig. 3 Evolution with T_{eff} of the photospheric [Fe/H] for the same tracks of Fig. 1 (the same line-styles are employed). The [Fe/H] error range for the two synthetic stars is marked by a pair of horizontal lines, whilst the T_{eff} error ranges are marked by pairs of vertical lines.

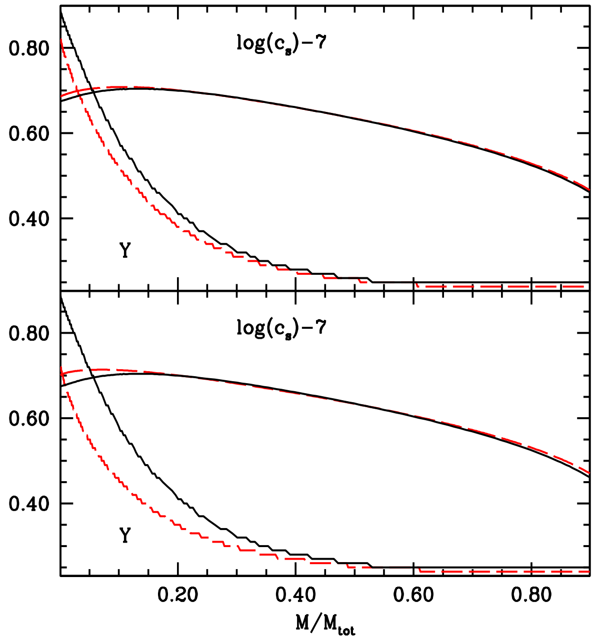

Fig. 4 Sound speed (c_s) and Y profiles within the structure of the 0.86$M_\odot$ (upper panel, dashed lines) and 0.90$M_\odot$ (lower panel, dashed lines) models with diffusion discussed in the text, that best match the MS synthetic star. Solid lines display the same profiles for the best match 0.82$M_\odot$ model without diffusion (see text for details).

$[Fe/H]_i = -1.25$ track, respectively. The two models start with different $[Fe/H]_i$, that is depleted from the envelope at different rates (due to the different mass size of the convective envelope), and they both end up matching almost perfectly the observed g and T_{eff}, and also the observed [Fe/H] within the errors. The more massive and initially more metal rich model is especially a good match also for the observed [Fe/H].

The age range estimated from the 0.90$M_\odot$ model is ~3 Gyr younger than the case without diffusion, whilst the 0.86$M_\odot$ model yields ages ~2 Gyr younger than the best fit without diffusion.

When moving to the RGB synthetic star, only the 0.86$M_\odot$ model matches well the observed g and T_{eff}, and also the observed [Fe/H] within the error bar. The estimated age is again ~2 Gyr younger than the case without diffusion (see Fig. 2). The 0.90$M_\odot$ model has a too high [Fe/H] on the RGB compared to the synthetic star, because the model photospheric Fe abundance has been almost restored to the initial value $[Fe/H]_i = -1.07$.

To summarize the results of this experiment:

– When fully efficient atomic diffusion is included in stellar evolution calculations, models with different mass and $[Fe/H]_i$ can fit a single observed MS star close to the TO, defined by a triplet of g, T_{eff}, [Fe/H] values. This degeneracy is potentially less severe for RGB stars, because if the measured [Fe/H] is very accurate, this represents very closely the star initial abundance.

– Due to this degeneracy and the effect of diffusion on evolutionary timescales at fixed mass and initial chemical composition, the age of old evolved MS stars is subject to systematic uncertainties up to ~3 Gyr if diffusion is included or neglected in the model calculations.

If asteroseismic information about the mass of the observed star are available –for example by means of scaling relations (e.g. Serenelli et al. 2013)– this systematic error on the age can be decreased. For example an accuracy of 5% on the stellar mass would exclude the 0.90$M_\odot$ model from the fit of the MS star, and reduce the systematics on the age to ~2 Gyr.

Additional constraints on mass/age can potentially come from the r_{02} ratio of small to large separations when available, that is sensitive to the derivative of the sound speed in the central regions of the star. Figure 4 displays the inner He mass fraction (Y) and sound speed profiles for the 0.90$M_\odot$ and 0.86$M_\odot$ models (dashed lines) respectively, when they match approximately g and T_{eff} of the synthetic MS star, compared to the same quantities for the no-diffusion 0.82$M_\odot$ best match model (solid lines). Notice the lower central Y in both models with diffusion, that denotes an earlier evolutionary stage along the MS compared to the model without diffusion. The resulting sound speed profiles are extremely close to the best match model without diffusion, but there are differences in the gradients within the inner ~10% of mass, that could potentially be exploited

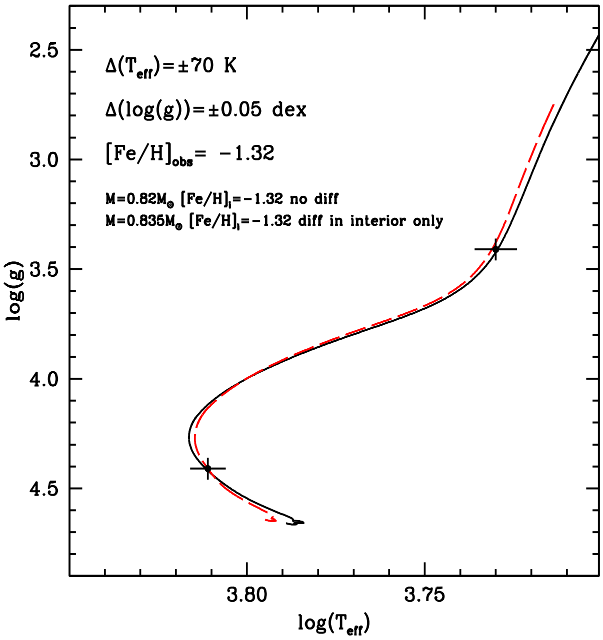

Fig. 5 As Fig. 1 but showing tracks with M=0.82M$_\odot$, $[Fe/H]_i$ = −1.32 and no diffusion (solid line), and M=0.835M$_\odot$, $[Fe/H]_i$ = −1.32 with just diffusion from the convective envelope inhibited (dashed line).

through the r_{02} ratio, to narrow down the age uncertainty discussed in these tests.

The whole analysis so far has focused on the extreme cases of fully efficient or fully inefficient diffusion. An uncertainty between these two extreme cases, without constraints from asteroseismology, can cause a systematic error up to ~3 Gyr on MS star ages, at the metallicities of these tests. As already discussed, observations point to a strong inhibition of diffusion from the convective envelopes of low-mass metal poor MS stars, but nothing can be said about the interiors. Figure 5 displays the results of a further test where models have been calculated by inhibiting the diffusion from the convective envelope, whilst keeping it fully efficient in the radiative interiors (in the calculation a transition zone of increasing diffusion efficiency is included right below the convective boundary). A track with 0.835M$_\odot$, $[Fe/H]_i$ = −1.32 (the [Fe/H] of the model stays constant during the MS) matches both the observed MS and RGB star. The age of the MS star is this time just 1.3 Gyr younger than the case without diffusion, that is still an uncertainty of ~16%. The same age difference is found for the RGB star.

4 Conclusions

The determination of accurate ages of individual field stars plays undoubtedly a major role in studies of the formation of the Milky Way, especially the case of old stars that trace the early phases of the formation of the Galaxy. A large number of spectroscopic surveys is providing databases of –among others– effective temperature, surface gravity, and photospheric chemical composition of large samples of Milky Way stars.

The derivation of stellar ages employing these data is seriously affected by the current uncertainty on the efficiency of atomic diffusion in the stellar interiors. The tests described before have shown how systematic errors up to several 10% are possible if bounds on stellar masses are lacking. Accurate asteroseismic constraints on the mass can however reduce this error, and if asteroseismic mass estimates can in the future reach extremely high accuracies – of the order of 1-2%– they could at the same time put additional indirect but strong constraints on the efficiency of diffusion in metal poor low-mass stars.

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