

Ages for large samples of stars - caveats and uncertainties

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Abstract. Although a stellar age accuracy of about 10 % seems to be a reasonable requirement to draw a time line in the evolution of our Galaxy as well as in the formation and evolution of exo-planetary systems, theoretical stellar models are at present still too imperfect to really achieve this goal. Asteroseismic observations are definitely of invaluable assistance, especially if individual pulsation frequencies are available, which is still far from common. Large stellar samples are now in the spotlight with two different lines of attack, spectroscopic and photometric surveys as well as asteroseismic missions. I shall review the problems arising from stellar physics in the context of large stellar samples of main sequence and red giant stars, and I shall raise some alarm bells but also highlight some positive news for a drastic improvement in stellar age determinations below the limit of 10 % in a foreseeable future.

Keywords. methods: data analysis, surveys, stars: evolution, stars: interiors, stars: mass loss, stars: statistics, Galaxy: evolution

1. Introduction

Of all the global properties of stars, ages are the most challenging. Although they are acutely required in various fields of astrophysics, they are still affected by large uncertainties and big question marks. In this new era of large spectroscopic and photometric surveys, amply discussed in this symposium, an accurate knowledge of stellar ages is however a requisite to draw a map of the age-metallicity relation in our Galaxy and add new constraints to its chemical evolution. It is also of prime importance in the characterization of exoplanet host-stars since it obviously fixes the time frame of the formation and evolution of exo-planetary systems. It is well acknowledged that stellar modeling suffers from weaknesses and lacks in various physical aspects. With regard to ages, the most troublesome physical aspects are the extent of extra-mixing during main sequence (MS), the microscopic diffusion coupled or not with radiative accelerations during pre-main sequence (PMS) and MS and the importance of mass loss during the ascension of the red giant branch (RGB). The goal of an age uncertainty as low as 10 % would certainly be an unreachable dream without the precious help of asteroseismology and the ocean of excellent data already provided by CoRoT, *Kepler* and in a near or slightly more distant future, TESS and PLATO. For a single star with asteroseismic constraints as tight as individual frequencies, such a drastic requirement on the age is definitely at hand (e.g., Lebreton & Goupil 2014; Lebreton *et al.* 2014). However, large samples of stars often lack the beacons of individual frequencies and new problems arise.

In section 2, I shall review the age problem in the context of large samples of MS stars. Section 3 will deal with similar large samples of red giant (RG) stars in various evolutionary stages. Some additional words of caution will be given in section 4.

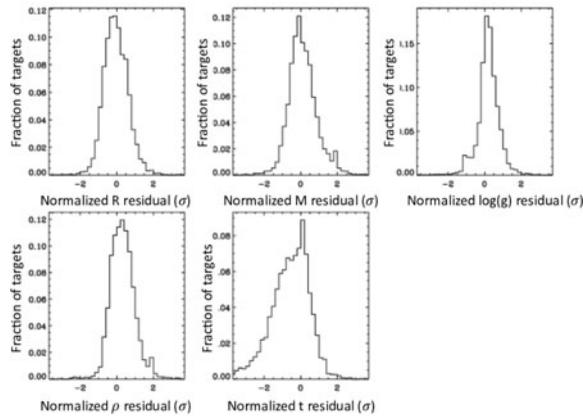


Figure 1. Histograms, for each stellar property (from top to bottom, left to right: R, M, $\log g$, ρ and age), of uncertainty-normalized residuals for all stars over all grid/pipeline combinations with respect to one of them (from Chaplin *et al.* 2014).

2. Large samples of MS stars

The lifetimes of MS stars are mostly affected by the extent of extra-mixing, which increases the amount of nuclear fuel, and by microscopic diffusion, which, on the reverse, by inducing the sinking of heavy elements towards the inner stellar layers, ages stellar cores in the process and speeds up their evolution. When asteroseismic data, *e.g.* the large separation, $\Delta\nu$, the frequency at maximum power, ν_{max} (Brown *et al.* 1991; Kjeldsen & Bedding 1995), less frequently the period spacing ΔP and in particular individual frequencies, ν_i , are added to the classical observed properties of MS stars, a drastic reduction of the age uncertainty can be reached. This was thoroughly shown by Lebreton & Goupil (2014) for HD 52265, a CoRoT main target. Similar results were obtained by *e.g.* Metcalfe *et al.* (2014) and by Silva Aguirre *et al.* (2013).

When large samples of stars are to be dealt with, new problems enter the stage. From large sets of observed data, different pipelines act as transmitters and processors to extract the best fitting solutions from various grids of theoretical stellar models (*e.g.* Stello *et al.* 2009). Those grids are computed with different physical assumptions and each combination of pipeline/grid offers its own *best model*. This range of solutions increases the uncertainty on the global stellar properties and, in particular, on the ages.

A benchmark in the complex problem of the different pipeline/grid interactions has been put forward by Chaplin *et al.* (2014). Coupling six pipeline codes to 11 evolutionary grids built with different physical assumptions, they analyzed 500 main sequence and subgiant stars observed by *Kepler*. As input data, asteroseismic $\Delta\nu$ and ν_{max} (without individual frequencies) were added to the classical observed data with metallicity, Z, whenever possible. Figure 1 shows, for each stellar property indicated in abscissa, histograms of uncertainty residuals for all stars over all grid/pipeline combinations, with respect to one of them. It is clear that, for each property except the age, the histograms show a gaussian-like appearance. This can be interpreted as an additional scatter to be introduced in the error budget. The non-gaussian feature of the age residuals conversely indicates that depending on the physics, the resulting age will be different for similar inputs. The final age uncertainty reaches 34 % with a slightly better 25 % if the metallicity is known. Similar results were obtained by Gai *et al.* (2011).

3. Large samples of RG stars

The main uncertainties affecting the ages of red giants are the amount of extra-mixing during MS and mass loss, with a variable intensity depending of the evolutionary state of the RG. Because of the presence of a huge convective envelope, diffusion is less troublesome than for MS stars.

3.1. RGs at the bottom of RGB

When leaving MS (TAMS), low mass stars have a helium core mass, m_{He} , which is isothermal and smaller than the Schönberg-Chandrasekhar mass limit, m_{is} , which is the maximum fractional mass of an isothermal core able to sustain the weight of the envelope. As the hydrogen-burning shell eats its fuel, the helium core mass grows and eventually reaches m_{is} . The stellar structure then abruptly changes and the star becomes a red giant located at the RGB bottom in the Hertzsprung-Russell diagram (HR). Adding some extra-mixing during MS leads to a larger helium core and an older age at the TAMS. Assuming that this core is still smaller than m_{is} , a growth of the isothermal core can take place. With such an extra-mixing, the MS lifetime is larger but this increase is compensated by a shorter phase of isothermal growing of the core. All in all, the ages at the RGB are very similar! Figure 2 shows the evolutionary tracks in the HR diagram with associated age tracks (on the right Y axis) as a function of T_e for a $1.3 M_{\odot}$ computed without extra-mixing (solid lines) and with a moderate extra-mixing (dotted lines)†. Although the ages at the turn-off from MS (TO) are very different, the gap is almost fully closed at the RGB bottom and the ages of RGs at the RGB bottom are thus very similar to the ages at $m_{\text{He}} = m_{\text{is}}$. This means that even though the age dispersion for MS stars is very large, it becomes extremely narrow at the RGB bottom (Miglio 2012). An additional good news is that mass loss does not play any role since the ascension of the RGB, where it could be important, has not started yet.

A TRILEGAL synthetic population of RGs (Girardi *et al.* 2012) can provide their current masses (M), radii (R) and ages, while for each star of the observed RG population, scaling relations for $\Delta\nu$ and ν_{max} (Brown *et al.* 1991; Kjeldsen & Bedding 1995) are used to derive M and R . A simple one-to-one connection serves next as an age tag for each RG of the lot (Miglio *et al.* 2013).

For reasonable extents of extra-mixing, red giants are thus quasi-free of the extra-mixing uncertainty. Moreover RGs at the bottom of the RGB are less affected by diffusion than MS stars and mass loss is still negligible. That makes RGs a *golden gift* offered by Nature to astrophysicists. This has led to a strong interaction between Milky Way physicists, stellar evolution physicists, chemical abundance physicists and asteroseismologists, which started in 2009 following the discovery of non radial oscillations in red giants (De Ridder *et al.* 2009), and is still ongoing with more and more strength. Those interested in the early steps of the saga can read “A zest of history” in Noels *et al.* (2016).

3.2. RGs at the tip of RGB

In order to start burning helium in a degenerate core, m_{He} must reach $m_{\text{flash}} \sim 0.48M_{\odot}$. Except in case of a huge amount of MS extra-mixing, m_{flash} is generally of the order of $0.1 M$ ($\sim m_{\text{is}}$) at the RGB bottom. During the ascension of the RGB, hydrogen burning takes place in a shell surrounding m_{He} , which increases accordingly up to m_{flash} at which point

† The amount of extra-mixing is imposed through the usual overshooting parameter, α_{ov} . It represents the fraction of the pressure scale height above the core, which is fully mixed. It is supposed to be the result of every possible physical processes responsible for an additional mixing, wether coming from an overshooting or a penetrative convection and/or a rotationally induced mixing.

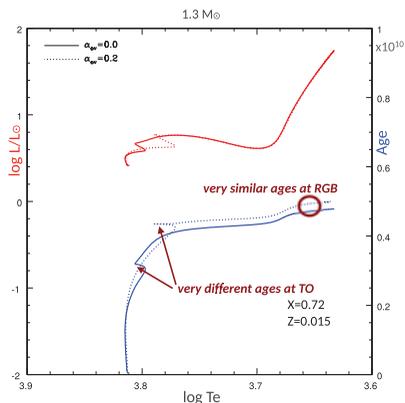


Figure 2. HR evolutionary tracks (in red) and age tracks (in blue, right Y axis) as a function of T_e for a $1.3 M_{\odot}$ computed without extra-mixing (solid lines) and with a moderate extra-mixing ($\alpha_{mv} = 0.2$, dotted lines).

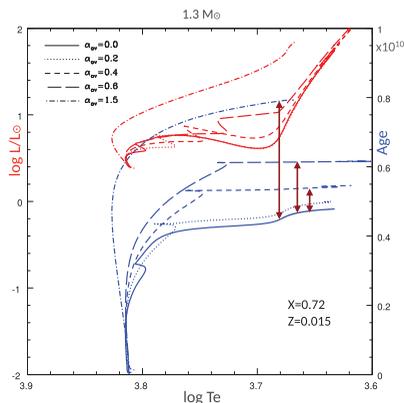


Figure 3. Same as Fig. 2 for different amounts (see legend) of extra-mixing.

a helium flash is ignited. After the flash, degeneracy is lifted and the star becomes a red clump (RC) star quietly burning helium before ascending the asymptotic giant branch. This phase is also characterized by mass loss although its quantitative importance is still unclear.

Caution! - Extra large MS extra-mixing. Since the onset of this flash requires the nuclear formation of a given mass of helium whatever the physical processes involved in the earlier phases, it could be expected that any age differences would then be erased. However, depending on the amount of MS extra-mixing, the hydrogen profile is variously affected and the physical conditions of hydrogen-shell burning are thus quite different. Although the internal structure ends up with a similar aspect with or without MS extra-mixing, the age difference remains as can be seen on Figure 3†. *The evolved RG has forgotten all that happened in its previous evolution, except its age!*

Caution! - Mass loss. During the ascension of RGB, mass loss can play an important role. The mass of a RG at the tip, derived from the scaling relations, could thus be smaller than the mass of its MS progenitor. This aspect has been well discussed as part of a SAGA (Strömgren survey for Asteroseismology and Galactic Archaeology) analysis of 989 *Kepler* mostly RG stars (Casagrande *et al.* 2016). Figure 4 shows the comparison between ages obtained with mass-loss (vertical axis, $\eta = 0.4$ - see Reimers 1975) and without mass-loss (horizontal axis). Colors identify stars with different seismic classification, as labelled in the figure. RGs are located on the diagonal, which means that mass loss does not affect their age determination as expected. RC stars conversely deviate from the diagonal. Their estimated ages with mass loss are smaller than without mass loss, which results from the fact that their MS progenitors were more massive and hence evolved more rapidly during hydrogen burning. Since the mass loss rate adopted in this analysis (Reimers 1975) is inversely proportional to the gravity, the age difference also increase with increasing age, i.e. decreasing mass.

† For more massive stars ($M \gtrsim 3M_{\odot}$, dependent on Z), the situation is worse since stars evolving without any extra-mixing already reach m_{is} at TO, which means that age differences at TO are never made up.

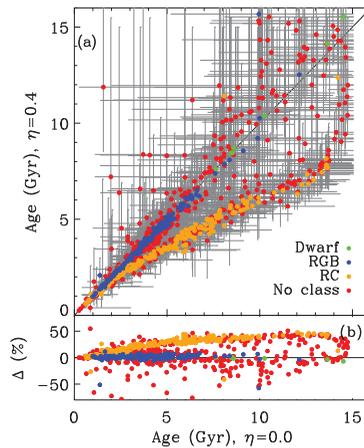


Figure 4. Comparison between ages obtained with mass-loss (Y axis, $\eta = 0.4$) and without mass-loss (X axis). Colours identify stars with different seismic classification (from Casagrande *et al.* 2016).

4. Concluding caveats - What should be done to improve age determinations?

- *Improve our understanding of diffusion*

Diffusion mostly affects the age dating of MS and subgiant stars. According to Salaris (2016) 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 %. This is confirmed by a recent analysis made by Dotter *et al.* (2017) (see also Valle *et al.* 2015; Gruyters *et al.* 2013; Silva Aguirre *et al.* 2013).

- *Improve our understanding of extra-mixing*

From the analysis of 33 double-lined eclipsing binaries, extra-mixing seems to increase linearly in the mass range 1.1 to 2.0 M_{\odot} before reaching a plateau (Claret & Torres 2016). A similar trend has been found by Deheuvels *et al.* (2016) from the seismic analysis of 24 *Kepler* low mass stars.

- *Improve our understanding of mass loss*

Comparison between asteroseismic masses of RC and RG stars in clusters seems to point out toward a rather weak mass loss, with $0.1 \lesssim \eta \lesssim 0.3$ in the case of the old open cluster NGC 6791 observed by *Kepler* (Miglio *et al.* 2012). Analysis of gas/dust ratios in 15 globular clusters observed with *Spitzer* suggest that mass loss could only be episodic along the RGB (Oraglia *et al.* 2014) while white dwarf diffusion modeling of the globular cluster 47 Tuc concludes to a negligible mass loss on RGB (Heyl *et al.* 2015). So mass loss must definitely be kept in mind but its effect could be rather weak. The age uncertainty due to mass loss mostly affect RC stars.

- *Enhance the observational efforts to obtain individual frequencies*

The importance of adding individual frequencies to the asteroseismic input data has already been stressed (see Sect. 2). Analyzing 33 *Kepler* planet candidate host stars for which the high quality asteroseismic observations can provide individual frequencies, Silva Aguirre *et al.* (2015) obtained a statistical age uncertainty of about 14 %.

The newly confirmed PLATO mission will certainly play a decisive role in this quest for precise and accurate stellar ages. Miglio *et al.* (2017) have recently shown that, provided that observations are of long enough duration (~ 150 days) to allow a robust determination of acoustic-mode frequencies, an uncertainty below 10 % on the age of a low

luminosity RG will definitely be within reach. Table 1 gives estimations of age uncertainties in MS, RG and RC stars with different constraining data, classical and asteroseismic, showing the drastic improvement when individual frequencies are at hand.

Table 1. Age uncertainties in MS, RG and RC stars.

	L, Te, Z	L, Te, Z, $\Delta\nu, \nu_{max}$	L, Te, Z, $\Delta\nu, \nu_{max}, \nu_i$
MSs	$\gtrsim 80\%$	$\gtrsim 30\%$	$\gtrsim 20\%$
RGs	$\gtrsim 80\%$	$\sim 20\%$	$\lesssim 10\%$
RCs ¹	$\gtrsim 80\%$	$\sim 20\%$	$\lesssim 10\%$

¹ Ages of red clumps stars can be affected by mass loss during the AGB ascension, with an uncertainty reaching 50 %. The values given in the tables are estimations without mass loss.

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