AGE DATING LARGE SAMPLES OF STARS: THE GAIA CONTEXT

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Abstract. The Gaia ESA mission will measure stellar parameters for 1 billion of stars in the Galaxy. We aim at dating the stars and we use a method based on their observed position in the HR diagram and the evolutionary tracks. The method is based on a Bayesian estimation. We test the precision of the program with different simulated catalogs of Gaia stars at various distances and for a different observational error on the metallicity. The goal of this study is to prepare the tools that will be used to age-date stars after the Gaia mission.

Keywords: Stars: fundamental parameters, Methods: statistical, Stars: Hertzsprung-Russell and C-M diagrams

1 Introduction

The Gaia ESA mission will observe 1 billion of stars in photometry, spectroscopy and astrometry (Perryman et al. 2001). It will be launched in 2013. The age of these stars has to be estimated to obtain information about the Galaxy such as the stellar formation history and age metallicity relation which permit to understand its formation and evolution (Freeman 1993). Also to characterize the exoplanets it is necessary to date their host stars (Havel et al. 2011).

There are several methods to determine the age of stars described by Soderblom (2010). To determine the age of stars of the Gaia ESA mission it is necessary to use a method that applies to a large sample of stars. For this purpose we use a method based on isochrones placement (Edvardsson et al. 1993). A star is plotted in the Hetzprung Russell Diagram (hereafter HRD) and the isochrone that adjusts its position is found. The most probable age corresponds to the isochrone that is closest to the star. In some regions of the HRD, the isochrones have a complex shape and stars can be adjusted by many isochrones. To select the most probable age it is useful to use a method based on the Bayesian estimation (Pont & Eyer 2004) to which we focus on the method of da Silva et al. (2006). We bring modifications on the choice of the *a priori* and on the stellar models. In the age dating we use the evolutionary tracks rather than the isochrones to reduce the number of interpolations and therefore the numerical errors.

We build a Gaia simulated catalog to evaluate the consistency between the simulated "true" age and the determined age. The catalog is constructed with the Basti evolutionary tracks and the Gaia specifications. We create several catalogs at different distances to test the precision of the determination of the ages as a function of the distance. The complementary spectroscopic observations will permit to obtain the metallicity with better observational errors. We study the effect on age determination of the observational errors on the metallicity for stars at different distances. We describe the Bayesian estimation method in Section 2 and the Gaia simulated catalogs in Section 3. We study the determination of ages as a function of the distance in Section 4 and the effect of observational error on the metallicity in the Section 5.

2 The Bayesian estimation

To date the stars we use three observables: the absolute magnitude M_{v}, the effective temperature T_{eff} and the metallicity [Fe/H]. The Bayesian estimation allows to determine the most probable age with the *a posteriori*

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probability density function $f(\tau, [\mathrm{Fe/H}], m)$ which depends on the point of the evolutionary tracks with an age τ, a metallicity [Fe/H] and a mass m. It is defined by $f(\tau, [\mathrm{Fe/H}], m) \propto f_0(\tau, [\mathrm{Fe/H}], m)L(\tau, [\mathrm{Fe/H}], m)$, where $f_0(\tau, [\mathrm{Fe/H}], m)$ is the *a priori* density function that represents the stellar and galactic properties. The likelihood $L(\tau, [\mathrm{Fe/H}], m)$ is related to the distance between the models and the star. There are several adaptations of the Bayesian estimation for the determination of the ages. Here we have chosen to use the method based on da Silva et al. (2006, hereafter DG06) who define the *a posteriori* probability density function $f(\tau_\mathrm{k})$ by:

$$f(\tau_\mathrm{k}) = \sum_\mathrm{i} p(\tau_\mathrm{k}) \frac{1}{\sigma_{[\mathrm{Fe/H}]}\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{[\mathrm{Fe/H}]_\mathrm{i} - [\mathrm{Fe/H}]^\mathrm{obs}}{\sigma_{[\mathrm{Fe/H}]}}\right)^2\right], \tag{2.1}$$

$$\text{with } p(\tau_\mathrm{k}) = \sum_\mathrm{j} \int_{m^1_\mathrm{ijk}}^{m^2_\mathrm{ijk}} \xi(m_\mathrm{ijk}) dm_\mathrm{ijk} \psi(\tau_\mathrm{k}) \exp\left[-\frac{(M_\mathrm{v,ijk} - M_\mathrm{v}^\mathrm{obs})^2}{\sigma^2_{M_\mathrm{v}}} - \frac{(\log T_\mathrm{eff,ijk} - \log T_\mathrm{eff}^\mathrm{obs})^2}{\sigma^2_{\log T_\mathrm{eff}}}\right]. \tag{2.2}$$

Where the index ijk correspond to the point of the evolutionary track with the metallicity i, the initial mass j and the age k. $\xi(m_\mathrm{ijk})$ is the initial mass function (IMF) and $\psi(\tau_\mathrm{k})$ is the stellar formation rate (SFR). σ_{M_v}, $\sigma_{\log T_\mathrm{eff}}$ and $\sigma_{[\mathrm{Fe/H}]}$ are the observational errors on the stellar parameters.
We bring several modifications to the method, in particular on the choice of the *a priori*. DG06 do not take into account any SFR. We adopt one because we have chosen not to take into account the stars that have an age greater than the Universe age. Indeed the evolutionary tracks have ages comprises between 0 and 22 Gyr for more massive stars. The SFR is defined by

$$\psi(\tau) = \begin{cases} 1 & \text{for } 0 \leq \tau \leq \text{ 14 Gyr ,} \\ 0 & \text{elsewhere.} \end{cases} \tag{2.3}$$

We have chosen to use the stellar models of Basti (Pietrinferni et al. 2004). We use the evolutionary tracks rather than the isochrones to reduce the number of interpolations. Since DG06 do not specify the IMF, we have chosen to use the one of Kroupa (2002).

3 Gaia simulated catalogs

We create a simulated catalog of 10 000 stars to compare the simulated "true" age and the determined age. The simulated catalog is based on the Gaia mission specifications (Perryman et al. 2001). For each simulated star we select three parameters in the evolutionary tracks of Basti (Pietrinferni et al. 2004): metallicity, mass and age. The metallicity is selected randomly in the MDF. We defined the MDF with the 16 882 stars of the solar neighborhood of the Geneva Copenhagen Survey (GCS) of Casagrande et al. (2011). The MDF is defined by

$$\phi([\mathrm{Fe/H}]) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{([\mathrm{Fe/H}] - \mu)^2}{2\sigma^2}\right), \tag{3.1}$$

with $\mu = -0.043$ and $\sigma = 0.19$. We take randomly the mass in the IMF of Kroupa (2002) and the age is taken randomly in the SFR (Equation 2.3). The three parameters permit to select a point of the evolutionary tracks. To fulfill the Gaia mission specifications we keep the point if the magnitude G is greater than 6, beyond this limit the star is too bright to be observable by Gaia.
To test the effect on age of the distance d of stars we create several simulated catalogs for different distances. The selection of the distance is realized thanks to the selection on the precision of the parallax. Indeed the point is kept if it has $\frac{\sigma\pi}{\pi} < 10$ %. The Gaia specification (ESA's website[i]) gives $\sigma_\pi = (9.3 + 658.1z + 4.568z^2)^{1/2} \times [0.986 + (1 - 0.986)(V - I)]$ where $z = \mathrm{MAX}[10^{0.4(12-15)}, 10^{0.4(G-15)}]$. G is determined with the transformation of Jordi et al. (2010). We create several catalogs such as 46 pc $\leq$ d $\leq$ 12 kpc. The Gaia simulated catalogs obtained for d = 46 pc, d = 1kpc and d = 10 kpc are represented in Fig. 1.
We define an observation error for each stellar parameters based on the Gaia mission (Bailer-Jones (2010) and ESA's website[i]). We assume an observational error on the effective temperature equal to 0.3% for $G \leq 15$ and increasing linearly to 4% at $G = 20$. We assume that the observational error on the metallicity is constant and equal to 0.3 dex. The error on the absolute magnitude is based on the magnitude distance relation. σ_{M_v}

[i] www.rssd.esa.int/index.php?project=GAIA&page=Science_Performance#table2

depends on the observational errors on the apparent magnitude σ_{m_v}, on the distance σ_d and on the extinction σ_{A_v}. We assume that σ_{m_V}=σ_{m_G} and the ESA's website[i] gives $\sigma_{m_G} = 10^{-3}(0.02076z^2 + 2.7224z + 0.004352)^{1/2}$. σ_{A_v} is equal to 10% of the extinction A_v (Bailer-Jones 2010).

4 Effect of the distance of the stars

We compare the simulated "true" age and the determined age for the Gaia simulated catalogs at different distances. For this purpose we define the relative difference between the two ages such as $\sigma_\tau/\tau = (\tau_{\text{simulated}} - \tau_{\text{determined}})/\tau_{\text{simulated}}$. We get the following results as a function of the distance.

1. We find 60 % of the stars with $\sigma_\tau/\tau < 20\%$ for $1 \leq$ d ≤ 8 kpc. These stars have a well-determined age. The results of the comparison are presented in Fig. 1, Panel b for d = 1kpc. The stars in red have an ill-determined age. They are located in the same problematic regions of the HRD: close to the zero age main sequence (ZAMS), regions of massive stars in the upper main sequence (MS) and red giant branch (RGB). The degeneracy in these regions is explained by the evolutionary speed of stars. In the vicinity of the ZAMS, low mass stars evolve slowly so their ages are poorly defined. On the contrary the stars on the RGB and in the upper MS evolve quickly.

2. There are 75 % of stars with $\sigma_\tau/\tau < 20\%$ for d < 1 kpc. The results for d = 46 pc are represented in Fig. 1, Panel a. The limitation on the magnitude gives a catalog with faint stars at short distances. The stars are located in the bottom of the MS which is a degeneracy region. Thus we find more stars with a poorly defined age.

3. We find 50 % of stars with $\sigma_\tau/\tau < 20\%$ for d > 8 kpc. The HRD at 10 kpc is represented in Fig. 1, Panel c. When the distance is large, observational errors on the parameters become significant. It is more difficult to determine the ages.

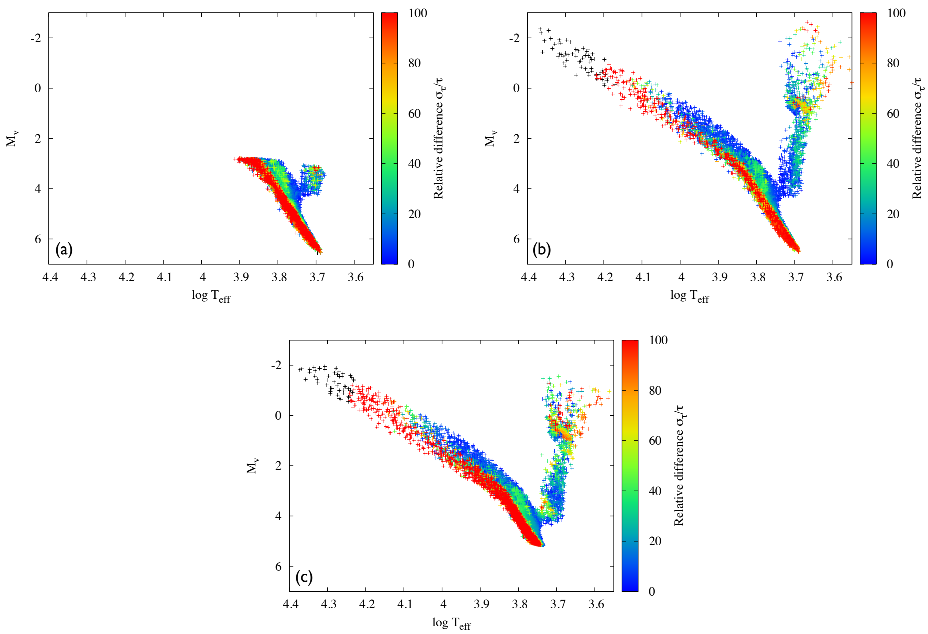

Fig. 1. Comparison of the simulated "true" age and determined age in the $\log T_{\text{eff}} - M_v$ diagram of the simulated catalogs for different distance and $\sigma_{[Fe/H]} = 0.3$ dex. **Panel a:** d = 46 pc. **Panel b:** d = 1 kpc. **Panel c:** d = 10 kpc. Colors represent the relative difference σ_τ/τ. The blue stars have a well-determined age (σ_τ/τ=0%) while the red stars have an ill-determined age (σ_τ/τ=100%). The age of black stars are undetermined.

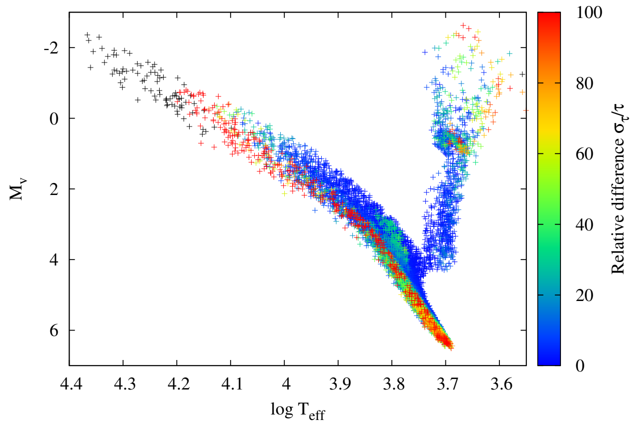

Fig. 2. Comparison of true age and estimated age in the $\log T_{\rm eff} - M_{\rm v}$ diagram of the Gaia simulated catalog with $\sigma_{[Fe/H]}$ = 0.1 dex. Colors are the same that in Fig. 1.

5 Effect of observational errors on the metallicity

The complementary spectroscopic observations of Gaia will permit to obtain the spectrum of the stars and will allow to determine the metallicity with a better observational error. We determine the ages for the same catalogs but now we take $\sigma_{[Fe/H]} = 0.1$ dex. The results of the comparison at d = 1kpc are represented in Fig. 2. We compare the determined ages and the estimated "true" ages. We find a great improvement for the stars close to the ZAMS and in the RGB. Indeed there are more than 75 % of stars with $\sigma_\tau/\tau < 20\%$ for the stars with a distance less than 10 kpc. For a distance greater than 10 kpc there are 55 % of stars with $\sigma_\tau/\tau < 20\%$. The improvement is worse for these stars because the observational errors are too important.

6 Conclusions

The Gaia ESA mission will observe 1 billion of stars. Different structures and objects will be observed depending on the distances. At less than 200 pc the Jupiter mass planets will be detected. Age of their host stars will allow to characterize these exoplanets. The open clusters, the globular clusters and the disk will also be observed by Gaia. Their dating will allow to understand the formation and evolution of the Galaxy. At these distances, there are 60 % of stars with an age well determined with our method. To promote these results we need a good accuracy on the metallicity. The complementary spectroscopic observations will allow to obtain a better accuracy, allowing a better age determination for 15 % of the stars.

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