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Reconstructing the star formation history of the Solar neighbourhood with *Gaia*

Edouard J. Bernard

Université Côte d'Azur, OCA, CNRS, Lagrange, France
email: ebernard@oca.eu

Abstract. Taking advantage of the *Gaia* DR1, we combined TGAS parallaxes with the *Tycho-2* and APASS photometry to calculate the star formation history (SFH) of the solar neighbourhood within 250 pc using the colour-magnitude diagram fitting technique. Our dynamically-evolved SFH is in excellent agreement with that calculated from the *Hipparcos* catalogue within 80 pc of the Sun, showing an enhanced star formation rate (SFR) in the past ∼4 Gyr. We then correct the SFR for the disc thickening with age to obtain a SFR that is representative of the whole solar cylinder, and show that even with an extreme correction our results are not consistent with an exponentially decreasing SFR as found by recent studies. Finally, we discuss how this technique can be applied out to ∼5 kpc thanks to the next *Gaia* data releases, which will allow us to quantify the SFH of the thin disc, thick disc and halo *in situ*.

Keywords. Hertzsprung-Russell diagram, Galaxy: disk, Galaxy: evolution, Galaxy: formation, solar neighbourhood

1. Introduction

Disc galaxies dominate the stellar mass density in the Universe, yet the details of their formation and evolution are still poorly understood. Even in the Milky Way for which we have access to a tremendous amount of information, the onset of star formation and the evolution of the star formation rate (SFR) of each Galactic component are still a matter of debate. However, the details of the formation of stellar systems are encoded in the distribution of the stars in deep colour-magnitude diagrams (CMDs). Their star formation history (SFH), that is, the evolution of both the SFR and the metallicity from the earliest epoch to the present time, can therefore be recovered using the robust CMD-fitting technique which has been extensively validated in studies of nearby Local Group galaxies. This technique requires the precise knowledge of the intrinsic luminosity of each star, and therefore its distance. In the coming years, *Gaia* will deliver distances and proper motions for over a billion stars out to ∼10 kpc, thus covering all the structural components of our Galaxy. For the first time, this opens the possibility of mapping the spatial and temporal variations of the SFH back to the earliest epochs. We illustrate this potential by exploiting the Gaia DR1/TGAS parallaxes for stars in the solar neighbourhood (Lindegren *et al.* 2016), and calculating the SFH of the Milky Way disc within 250 pc of the Sun. The main advantages of the CMD-fitting technique over other methods of recovering the SFH (e.g. chemical enrichment models, colour-function fitting, age/metallicity census of individual stars, ...) are the fact that determining the age of a population is much more robust than that of single stars, that one takes full advantage of the predictions of stellar evolution models, and the smaller number of assumptions. On the other hand, like other methods it is affected by the systematic effects due to uncertainties in the stellar models, as well as the poorly constrained amplitude of radial migrations in the disc.

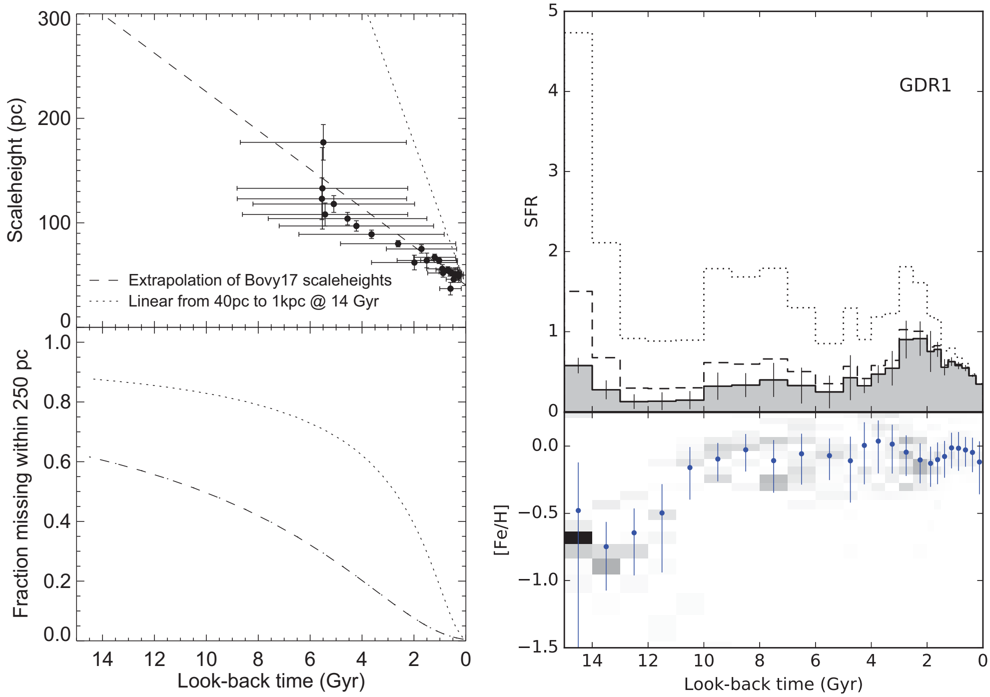

Figure 1. Left: Evolution with time of the disc scaleheight (top) and of the corresponding fraction of stars lying beyond 250 pc (bottom, see text for details). The dashed and dotted lines correspond to the mild and the extreme corrections respectively. Right: Resulting SFH, showing the evolution of the SFR (top) and metallicity (bottom) as a function of time. In the top panel, the dashed and dotted lines represent the SFR corrected for the fraction of stars that have been heated to heights >250 pc, assuming the mild and the extreme corrections respectively.

2. SFH calculation

The SFH has been calculated using the technique of synthetic CMD-fitting following the methodology presented in Bernard *et al.* (2012, 2015a, 2015b). The *Gaia* CMD of the Milky Way disc within 250 pc of the Sun was produced by cross-matching TGAS with the *Tycho-2*, *Hipparcos*, and APASS DR9 (Henden *et al.* 2012) catalogues, after transforming their photometry to the Johnson B and V filters (see Bernard 2017).

The synthetic CMD from which we extracted the simple stellar populations' CMDs is based on the BaSTI stellar evolution library (Pietrinferni *et al.* 2004). It contains 2×10^7 stars and covers wide ranges of age and metallicity: 0 to 15 Gyr old and $-2.3 \leqslant$ [Fe/H] $\leqslant 0.26$. We adopted a Kroupa (2002) IMF, and assumed a fraction of unresolved binary systems in TGAS of 10% with mass ratios between 0 and 1.

While the full photometric uncertainties due to various observational effects are typically estimated using artificial stars tests on the original images (e.g. Gallart *et al.* 1999), this approach is impossible in the case of *Gaia* for which (most of) the images are not sent back to Earth. Instead, we relied on the distributions of photometric errors as a function of colour and magnitude provided in the *Tycho-2*, *Hipparcos*, and APASS catalogues to simulate the uncertainties in the synthetic CMD. Finally, the completeness of the sample as a function of colour and magnitude was quantified by comparison with the *Tycho-2* catalogue (see Bernard 2017 for details).

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3. Results

The SFH is presented in the right panel of Figure 1: the top and bottom plots show the evolution of the *dynamically-evolved SFR* (grey histogram) and metallicity, respectively, as a function of time. However, since the SFH was reconstructed based on the stars that are located *today* within the solar neighbourhood, the effects of secular evolution of the disc have to be taken into account. While the importance of radial migrations (e.g. Sellwood & Binney 2002) has yet to be quantified, we can correct this SFR for the disc thickening with age to obtain a SFR that is representative of the whole solar cylinder.

To quantify the thickening, we used the disc scaleheight measured by Bovy (2017) for each spectral type from A0 to G3. The mean age of each type was estimated from the synthetic CMD of the solar neighbourhood from the Besançon model (Robin *et al.* 2003) by selecting all the stars with a temperature within 2% of the spectral type temperature (from Pecaut & Mamajek 2013). The solid circles in the top left panel of Figure 1 show the Bovy (2017) scaleheights plotted as a function of our estimated ages, where the horizontal errorbars represent the age standard deviation. The dashed line fitted to these points – virtually the same relation as that used by Just & Jahreiß (2010) – shows a clear change of the disc thickness as a function of age, though it could either imply that the older disc formed thicker or that it thickened with time. We then used the scaleheight fit to estimate the fraction of stars of a given age that are beyond 250 pc and therefore missing from our CMD; this is shown in the bottom left panel of Figure 1. The SFR including this correction (hereafter the *mild* correction) is shown as a dashed line in the top right panel.

Note, however, that extrapolating the Bovy (2017) scaleheights to 14 Gyr ago implies an old disc that is only ∼300 pc thick, while the Milky Way thick disc is believed to be about 1 kpc thick (e.g. Jurić *et al.* 2008). Therefore, in the top left panel of Figure 1 we also show as dotted line a scaleheight increasing linearly from 40 pc at the present day to 1 kpc 14 Gyr ago, the corresponding fraction of missing stars in the bottom panel, and the resulting SFR in the top right panel. We label it the *extreme* correction as it clearly over-estimates the scaleheight of the intermediate-age populations. The true relation is likely more complex, possibly with a break around 10 Gyr ago corresponding to the formation of the thick disc, as expected if the discontinuity in the [Fe/H]-[α/Fe] plane is due to a lull in formation between the thick and thin disk phases (Chiappini *et al.* 1997).

The dynamically-evolved SFR (i.e. uncorrected; grey histogram) shows a constant SFR for the first 10 Gyr or so, with a slight enhancement in the past 4 Gyr. This is in excellent agreement with the SFR calculated from *Hipparcos* data within a smaller volume (∼80 pc; Vergely *et al.* 2002, Cignoni *et al.* 2006). The SFR with the *mild* correction is not significantly different, except perhaps for the slightly more pronounced enhancement at early epochs corresponding to the formation of the thick disc. On the other hand, with the *extreme* correction the SFR appears roughly constant over most of the history, but with a strong enhancement at early epochs and a decreasing SFR in the past 2–3 Gyr. This shows that even with the most extreme correction our results are not consistent with an exponentially decreasing SFR as found by several recent studies (Aumer & Binney 2009; Just *et al.* 2011; Bovy 2017). Instead, it favors solutions with a roughly constant star formation over 8–10 Gyr such as found by, e.g., Snaith *et al.* (2015).

The age-metallicity relation (AMR), shown in the bottom-right panel of Figure 1, is mostly flat for the past 10 Gyr. Only the oldest stars show a lower mean metallicity ([Fe/H]~ -0.7), which may correspond to the thick disc population. This is fully consistent with the independent results from other groups using different methods and datasets (e.g. Casagrande *et al.* 2011, Haywood *et al.* 2013, Bergemann *et al.* 2014).

4. Conclusions and future prospects

We have used the *Gaia* DR1 parallaxes to produce a deep CMD that is mostly complete down to the magnitude of the oldest main-sequence turn-off within 250 pc from the Sun. We applied the CMD-fitting technique to reconstruct the dynamically-evolved SFH of the local Milky Way disc. Our results are fully consistent with those obtained previously using the *Hipparcos* data, despite the difficulty of dealing with the complex completeness function and photometric uncertainties from different catalogues. We then correct this SFR for the disc thickening with age to obtain a SFR that is representative of the whole solar cylinder, and show that even with an extreme correction our results are not consistent with an exponentially decreasing SFR. We plan to use the same technique with upcoming *Gaia* data releases. With parallaxes and homogeneous photometry in 3 bands (G, BP, RP) for $>10^9$ stars, and not limited by the poorly understood completeness function of an input catalogue like *Tycho-2* was, it will allow us to extend this analysis out to about 5 kpc, and therefore to quantify the SFH of the thin disc, thick disc and halo *in situ*, and its spatial variations. The spatial variations of the SFH within each component will also provide important constraints on the dynamical processes involved in shapping up their current stellar content.

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