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Towards a reliable star formation history of the galactic disk in the *Gaia* era

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Abstract

A new tool is being developed to derive the star formation and chemical enrichment history of the galactic disc through comparison of future *Gaia* data with synthetic color magnitude diagrams. First steps are being conducted joining two powerful algorithms: IAC-pop/MinnIAC, a code that has widely and very successfully being applied to external galaxies, and the new version of the Besançon Galaxy Model, which allows a good control of the Initial Mass Function, the Star Formation History and the chemical enrichment. A first tuning of these algorithms to the main characteristics of the *Gaia* data is described, emphasizing the role of the accurate parallaxes, the astrometric and photometric uncertainties and the *Gaia* observational constraints of the *Gaia* data. Preliminary tests demonstrate that the methodology proposed here has huge capabilities, although ingredients such as the stellar evolutionary models are critical in the process. The strategy to incorporate higher complexity in the process is discussed.

1 Introduction

From the sixties it is well established that the basic physical processes that shape the chemical evolution of the Milky Way (MW) disk are the stellar evolution, the Initial Mass Function (IMF), the Star Formation History (SFH) and the gas in-fall and outflow in the system [17]. This scenario started changing a few years ago. The complexity has grown drastically when realizing that processes that change the orbits of stars, such as dynamical heating from perturbations like spiral structure, molecular clouds, or minor mergers, play a key role in the galactic evolution. As an example, it seems plausible that these mechanisms are able to explain how the gradient of the age-metallicity relationship in the solar neighbourhood has a shallow shape [19] or the large spread in the chemical composition of the stars belonging to moving groups [1]. The *Gaia* mission (ESA, launch 2013) and the complementary data from on-going and future ground based spectroscopic surveys (such as GES[1], [8] or WEAVE[2], ...) will undoubtedly revolutionize this research field providing, for the first time, highly accurate observational material to undertake a coherent chemo-dynamical model of the MW. *Gaia* will provide us new insights on fundamental questions of galactic astronomy such as: Which are the characteristics of the IMF and the SFH of each of the MW Galactic populations? Does the stars in the MW disk follow the inside-out star formation scenario? Is the IMF universal?

A first collaborative effort among researchers on galactic and extragalactic domains is presented here. The goal is to combine, adapt and improve tools developed up to now to be ready for the future scientific exploitation of the *Gaia* data. We plan to derive the IMF and SFH of the MW disk joining both the IAC-pop algorithm, up to now used to analyse resolved stellar populations of nearby galaxies [3] and the new version of the Besançon Galaxy Model (BGM, [6]), well focussed to the MW disk. From a general perspective, the SFH is defined as the mass transformed into stars as a function of time and metallicity, whereas the usual Star Formation Rate (SFR) is defined as the mass transformed into stars as a function of time. In this paper we present the first results of a rather simple exercise. In § 2 we describe the recent improvement of the BGM model [7]. In § 3, some generalities of the IAC-pop tool are presented. First results are reported in § 4 devoting § 5 to the description of the future steps we plan to develop. All this work is being undertaken in the context of the Red Española de Explotación Científica de *Gaia*[3].

2 The new version of the Besançon Galaxy Model

As it is well known, the derivation of the IMF from observations is not straightforward. Classical approaches depart from the observed Luminosity Function (LF) in the solar neighbourhood, that is a snapshot of the stellar population at present, and assume the SFR as known. This LF has large uncertainties at the faint end [18] and up to now we are assuming that the local LF is valid all through the galactic disk (an hypothesis that will be overcome by *Gaia*). Furthermore, the SFR has been up to now reconstructed indirectly, building models that must satisfy all the observational constraints, in a very degenerate system. With the attempt to provide new insights in this scenario, we have recently updated the BGM stellar population synthesis model. The new version [7] has been constructed and ingredients as critical as the IMF, the SFR, the binary fraction, the age-metallicity and the age-kinematic relations have been fitted to the Tycho-2 data. The optimization includes also the use of the most updated evolutionary tracks and model atmospheres. Until now, the star production process in that model was based on the drawing from the so called Hess diagrams. Each Galaxy population had one such a diagram in BGM, which was calculated once given a particular IMF and SFR. The new version of the model is able to handle different SFR, IMF,

[1]http://great.ast.cam.ac.uk/Greatwiki/GreatCds

[2]http://camd08.ast.cam.ac.uk/Greatwiki/GreatCds?action=AttachFile&do=get&target=gcds-case-v0.9.pdf

[3]REG webpage: https://gaia.am.ub.es/Twiki/bin/view/RecGaia/WebHome

evolutionary tracks and atmosphere models among others. Once the evolutionary parameters have being changed, the process of accomplishing the dynamical self-consistency of the model is run and the Galactic gravitational potential for the new evolutionary scenario is calculated (see more details in [6]).

3 The IAC-pop algorithm

IAC-star [2], IAC-pop [3] and MinnIAC [12] have been developed to derive the Star Formation History (SFH) of resolved galaxies. They have been successfully applied to several complex stellar population systems [12, 15, 16] and have proven to provide stable and accurate results. The IAC suite of codes provides the usual SFR as well as the age-metallicity relation, Z(t) and allows the analysis of the IMF as well as the stellar binarity.

The SFH is obtained in several steps: (i) computing a general synthetic color-magnitude diagram (CMD) with IAC-star; (ii) simulating realistic observational effects; (iii) parametrising and sampling of the synthetic and observed CMDs (with MinnIAC); (iv) solving the SFH for the input parametrisation (with IAC-pop); (v) averaging solutions (with MinnIAC). Usually step (iv) is repeated several times for several inputs obtained in step (iii). For this reason, step (v) is fundamental for the determination of uncertainty intervals of the solutions and final analysis of the results.

To obtain a solution, IAC-pop treats the SFH as a linear combination of simple stellar populations with positive coefficients. Simple stellar populations are sets of stars with ages and metallicities within narrow intervals and they are extracted from the common, initial, global synthetic CMD obtained in step (i), in which the observational effects have been previously simulated (step ii). The CMDs are binned (step iii) and IAC-pop works with the star counts in these bins. The star counts of the CMD corresponding to any SFH can be obtained also from a linear combination of the star counts found in the CMDs of the simple populations, with the same coefficients as those defining the SFH. IAC-pop uses a genetic algorithm to found the set of coefficients that minimizes the χ^2 resulting from the comparison of the star counts in the CMDs of the observed and of the linear combinations of simple populations.

4 First application of the IAC-pop to the Milky Way disk

The proposed approach (see Fig. 1) is based on the comparison of two CMD, the "observed" and "simulated" ones. We used the BGM to mimic the sky as seen by *Gaia* and produce the "observed" CMD. A tool has been developed to work with the observed *Gaia* data, that is, to transform to magnitudes and colours in *Gaia* passbands and to simulate the effect of Gaia. These uncertainties have been assigned to both the "observed" (BGM) and "simulated (IAC-pop) CMD. The prescription used for the estimation of the *Gaia* errors is described in the *Gaia* Science Performance webpage[4] and some colour-colour relationships extracted from

[4] http://www.rssd.esa.int/index.php?project=GAIA&page=Science_Performance

[13] have been applied.

Up to now, the IAC-pop algorithm assumes a unique distance to all stars because it has been only applied to external galaxies. In our first toy model for the MW this drawback has been overcome by using the observed stellar distances – affected by errors – provided by *Gaia* to transform apparent magnitudes to absolute ones. Therefore, "observed" and "simulated" CMD can be compared using the absolute magnitude and a color index. In the first exercise we used the (M_V, $V - I$) CMD. The next step will be to work in *Gaia* observed (M_G, $G_{\rm BP}-G_{\rm RP}$) diagram. The end-of-mission *Gaia* uncertainties have been carefully computed from uncertainties in parallaxes and magnitudes. In both chains (see Fig. 1) the IMF by [14] (with slopes equal to 0.3, 1.3 and 1.3) has been imposed.

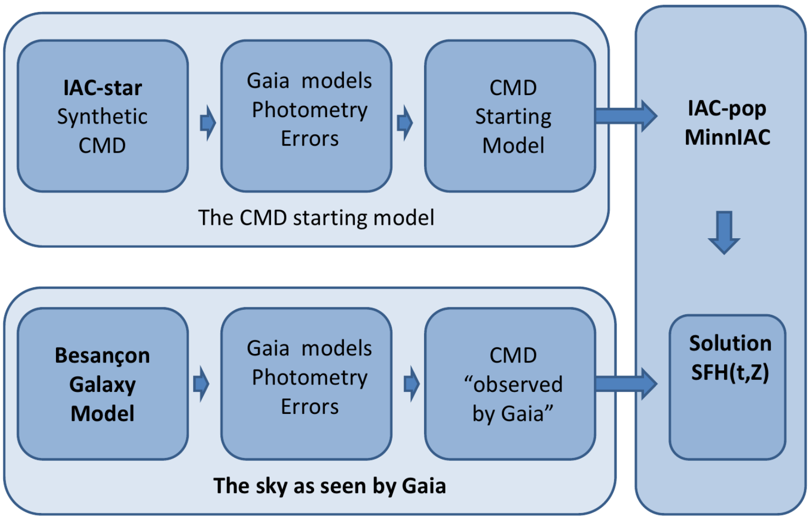

Figure 1: Scheme of the first application of the IAC-pop to the MW thin disk

The iterative process starts to look for the best fit of the SFR and Z(t) [11]. Our first working sample has been the stellar content of the thin disk component (assuming an age of 10 Gyr) in a cylinder of radius 200 pc centred on the Sun with no limitation on height above the disk. The *Gaia* simulations considered both constant and decreasing SFH. In the decreasing SFH case, the law proposed by [4] was considered with a parameter equal to 0.12. The age-metallicity relationship used was obtained from [10] and the age-velocity relationship from [9]. The solar density was extracted from [20]. The theoretical isochrones used were those of [5]. The absolute magnitude range was limited to be $3.0 < M_V < 6.5$, which includes the turn-off region to allow populations identification. The working sample has a total of $\sim 2 \cdot 10^5$ stars. No interstellar extinction has been considered.

This galactic disk sector is, and will be, the best observed system now and with *Gaia* for the derivation of the local combination of SFR, IMF and Z(t). As a result of this experiment, we state that the method demands a really good knowledge of the stellar evolutionary and atmosphere models. We found that small differences in these models when used in IAC-pop and in the BGM to generate the "simulated" and the "observed" CMD (see Fig. 1) prevents us to recover the input SFR and Z(t). This point is critical because when working with real *Gaia* data (third release, 2018) instead of BGM data, any systematic trend or error in the stellar evolutionary or atmosphere models will produce also systematic trends in the derivation of the SFR and Z(t).

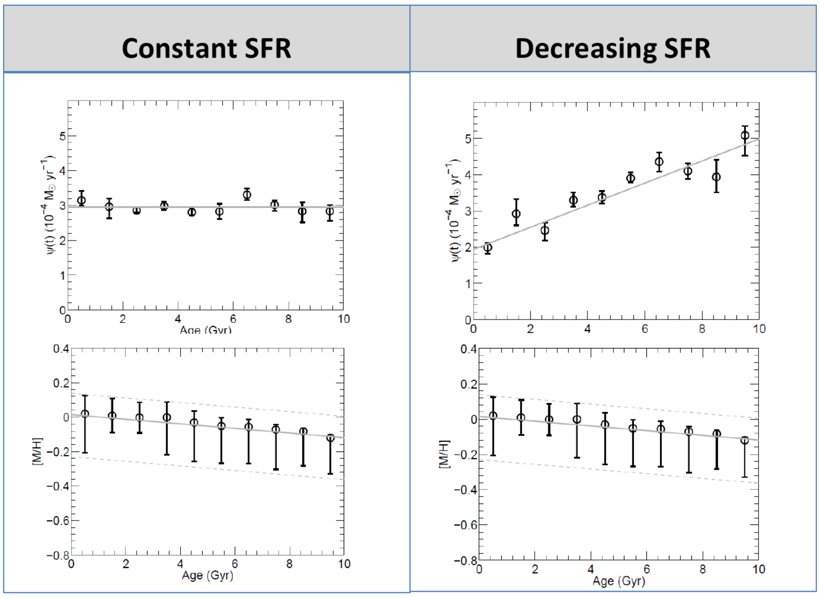

Figure 2: Comparison between true (solid line) and estimated (dots) SFH (top) and Z(t) (bottom) for constant (left) and decreasing (right) SFR. In both cases the initial Z(t) has been [10]. Error bars are one standard deviation.

To bypass this handicap we have generated the "observed" CMD in two steps. First, stars are generated using the BGM assigning to them their spatial distribution, age, mass and metallicity. This will ensure us to be using the right number of stars in agreement with the total density in the solar neighbourhood and the spatial distribution of thin disk stars. In a second step, IAC-star is used to interpolate in the stellar evolutionary model, to select which of these stars are alive and which ones are already dead in the sample and to derive $T_{\rm eff}$, $\log g$ and colours for each star. With this procedure we ensure the same stellar evolutionary and atmosphere models are used in both parts of the chain (see Fig. 1).

Figure 2 shows our first comparison between input and estimated values from IAC-pop for both the SFR and the Z(t). Results in Fig. 2 are encouraging. We succeed in this first attempt to use IAC-pop for the derivation of both the SFR and Z(t) of the solar neighbourhood thin disk.

5 Future experiments

Work is in progress to reproduce the same exercise with several cylinders at different heliocentric distances inside the *Gaia* sphere (what *Gaia* will observe) and to develop tools to take into account biases introduced when considering samples limited in apparent magnitude. One of the most critical issues will be to investigate how different IMF imposed in the "simulated" and "observed" data affects the derivation of the SFH and Z(t).

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