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STAR FORMATION: ON GOING AND PAST

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Abstract. GAIA will be of paramount importance to understand the Galactic structure. Here we focus on the determination of the star formation history (SFH) of the Galactic disk and bulge. We discuss whether GAIA will be able to isolate a sample of stars with the same characteristics of Hipparcos data (completeness over a certain critical magnitude and high precision in the distance) which will cast light on the SFH of the whole disk. We analyze the expected results in two directions, namely the BW and the Galactic pole. Finally we discuss the contribution of GAIA to the study of the SFH of the bulge.

1 Introduction

Determining the past history of star formation from the Color-Magnitude Diagram (CMD) of composite stellar populations is one of the main targets of modern astrophysics. For nearby galaxies, in which individual stars are resolved and CMDs are derived, the problem is easier to be tackled as all stars are placed nearly at the same distance. However in our own Galaxy the problem is by far more complicated because there are differences in the distances of the stars and only CMDs containing stars of inhomogeneous age, chemical composition and distance are available. With the advent of the Hipparcos mission, for the first time it was possible to derive the CMD, in absolute magnitudes, of field stars in the solar vicinity [1] and from this CMD to study the past history of the solar neighborhood. The GAIA mission will extend significantly the performances of Hipparcos permitting the determination of the star formation histories of the disk, bulge and halo of the Milky Way.

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2 The Methods Used in the Study of the SFH

There are two main approaches to the study of the star formation histories through the analysis of the Color-Magnitude Diagrams:
– **first approach**: direct comparison of an observed stellar population with synthetic populations created from evolutionary tracks. This comparison is generally done by the utilization of a statistical estimator from which it is possible to discriminate the model better representing the observations.

In this context different techniques have been adopted:

i) The star formation rate of the models changes parametrically and the comparison with the observed CMD is made through a number of indicators sensitive to the distribution of stellar ages and metallicities. These indicators are defined conveniently each time and can be ratios between number of stars in different regions of the HR diagram, edges of populous zones, χ^2 statistics in particular zones [2–4];

ii) The first step is the creation of a grid of synthetic CMDs. Each model uses a constant star formation and is specified by the interval of age, metallicity, initial mass function (IMF). The SFH will be determined by the best linear combination of the theoretical models which match the observed data [5, 6];

iii) They express a function which represents the conditional probability density of observing the ensemble of data points given the ensemble of model points (known as the Likelihood). The ratio of the Likelihoods for two different models will correctly reflect the ratio of probabilities with which the models are a match to the data [7].

– **second approach**: direct determination of the star formation history by solving maximum likelihood problems through variational calculations.

i) The method consists in obtaining by a direct approach the best star formation rate (SFR) compatible with the stellar evolutionary models and the observations, in contrast with the statistical methods which require the construction of synthetic colour-magnitude diagrams for each possible star formation rate considered. This is because it is possible to transform the problem from one searching for a function which maximizes a product of integrals to one of solving an integro-differential equation. This methodology has been applied to a C-M diagram of a volume-limited sample of the solar neighborhood complete to $M_V \leq 3.15$. The result concerns the last 3 Gyr and shows a certain level of constant star formation superimposed on a strong, quasi-periodic component having a period close to 0.5 Gyr [8, 9].

3 The SFH of the Solar Vicinity from the Hipparcos Data

Recently Bertelli & Nasi [2] determine the SFH of the solar vicinity from Hipparcos data. The adopted method can be included in the cases labeled as "first approach" in the previous section and will be appropriate as well as for the GAIA data. With respect to the results of Hernandez *et al.* [9], where the involved time interval covers only the last 3 Gyr of the SFH, Bertelli & Nasi [2] considered the total lifetime of the disk (10 Gyr). The star sample is selected from the Hipparcos catalogue and contains all stars more luminous than $M_V = 4.5$, inside a sphere of radius $r = 50$ pc.

Two analytical SFR functions are considered:

– the **const-const** model: it is a combination of two constant SFR with a discontinuity at a time $T_{\rm b}$ ranging between the initial time (10 Gyr ago) and the final time (0.1 Gyr ago). The parameter $I_{\rm b}$, defined at time $T_{\rm b}$, is the ratio of the SFR after and before the discontinuity.
– the **var-var** model: it corresponds to an increasing rate during the first time interval and then to a variable slope (decreasing, constant or increasing).
The MS and the evolved star region (red region) are divided in a convenient number of zones. A χ^2 statistic is applied separately to the MS and to the red region. The values of the parameters $T_{\rm b}$ and $I_{\rm b}$ which minimize at the same time $\chi^2_{\rm MS}$ and $\chi^2_{\rm red}$ identify the best solution.

The main results are:

- All the solutions point in favour of an increasing star formation rate (in a broad sense) from the beginning up to the present time (with an IMF Salpeter slope);
- All the cases in which good solutions for the MS region are found, have the corresponding $\chi^2_{\rm red}$ values too high and the ratio between the He-burning and MS stars of the models is always of a factor 1.5–2.0 larger than the observed values. This fact could be due to the approximations in the treatment of the convective overshoot which render the theoretical models partly inadequate.

4 The Disk Towards the Galactic Center

An important question is whether the stellar population in the solar vicinity is representative of the whole Galactic disk. To answer to this question, we use the HRD-GST (HRD-Galactic Software Telescope) of Ng *et al.* [10] and Bertelli *et al.* [11]. HRD-GST is a package suitably designed to study the structure of the Galaxy. It requires: i) one or more stellar populations, ii) a model for the Galactic distribution of the density, iii) the reddening along the line of sight. Then the HRD-GST shoots the stars of the given stellar population in a cone along the line of sight, accordingly to the Galactic density law and the reddening. The simulated CMD obtained in this way can be compared with the corresponding Galactic field.

We analyze a field in the direction towards BW8, inside the Baade's Window [2]. In the field BW8 the contribution from the Galactic disk is given by an almost vertical blue plume which appears as an extension of the turn off of the bulge towards brighter magnitudes. In the simulation of the same field using the SFR inferred from the Hipparcos CMD, we note that the blue plume of the disk is much bluer than the observed one, suggesting that the SFR holding for the solar vicinity cannot be extended to the whole disk [12]. The immediate conclusion is that the population of the solar vicinity (within 50 pc) as seen by Hipparcos is not representative of the whole Galactic disk. **If Hipparcos data cannot be used to infer the past history of star formation in the Galactic disk, would it be possible to get a significant sample of stars confined in a definite volume, covering in distance and position a large portion of the Galaxy and possessing the same degree of accuracy as that obtained by Hipparcos?**

This ideal sample of stars should satisfy the following requirements:

1) It must be complete up to $M_V = 4.5$ mag, as with Hipparcos, so that all evolved stars will be included. This means that all stars more luminous than $M_V = 4.5$ mag must also satisfy the condition:
$m_v \leq m_{v,\mathrm{lim}}$, where $m_{v,\mathrm{lim}}$ is the limiting magnitude considered.

2) It must possess accurate parallaxes with $\sigma_\pi/\pi \leq 0.1$.

3) It must be statistically significant.

We define inside the solid angle of 1 degree completely subtending the Baade Window (BW) a volume (a truncated cone) whose height is 400 pc having a variable distance d from the vertex located at the Sun. This distance d acts as the coordinate along the line of sight. With the aid of HRD-GST and the Galactic model, we simulate the disk population falling into the volume as a function of d.

Considering for GAIA two limiting magnitudes $V_{\mathrm{lim}} = 17$ and $V_{\mathrm{lim}} = 19$ and adopting its estimated parallax precision σ_π (in μas) as a function of spectral type (or colour), reddening A_V and magnitude (according to Table 8.4 of [13]), we compute the following quantities:
$n_{4.5}$: the number of stars inside the volume at the distance d, more luminous than $M_V = 4.5$ mag.
n_{lim}: the number of stars more luminous than $M_V = 4.5$ mag and at the same time more luminous than the limiting magnitude V_{lim}.
$n_{\sigma_{\mathrm{p}}}$: the number of stars more luminous than $M_V = 4.5$ mag and at the same time with $\sigma_\pi/\pi \leq 0.1$.

The above star counts are shown in the left panel of Figure 1 for $V_{\mathrm{lim}} = 17$ mag. The dotted line represents $n_{4.5}$. The shape of this curve is governed by the interplay between the volume increasing with d^2 and the density of disk stars, which beyond a certain distance starts decreasing, thus generating the peak in the distribution.

The solid line represents the ratio $n_{\mathrm{lim}}/n_{4.5}$. It is evident that at the distance where this ratio starts decreasing below 1.0, more and more stars satisfying the condition $M_V \leq 4.5$ mag are lost because of the limiting magnitude; the distance d_{lim} is the maximum distance at which the condition (1) above is verified.

The long-dashed curve is the ratio $n_\sigma/n_{4.5}$. The distance d_σ at which $n_\sigma/n_{4.5}$ falls below 1.0 corresponds to the situation in which no longer all stars more luminous than $M_V = 4.5$ mag have also $\sigma_\pi/\pi \leq 0.1$.

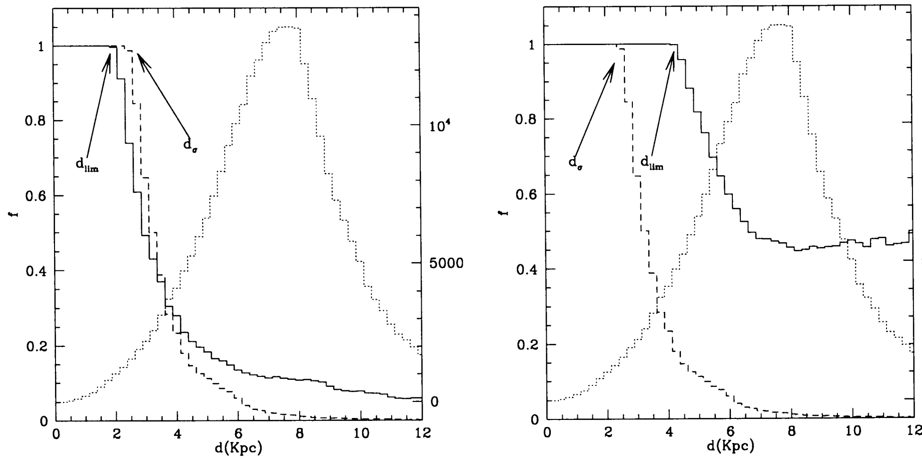

Fig. 1. The solid line represents the ratio $n_{\rm lim}/n_{4.5}$. The long-dashed curve is the ratio $n_\sigma/n_{4.5}$. The dotted line represents $n_{4.5}$. *Left panel*: case $V_{\rm lim}=17$. *Right panel*: case $V_{\rm lim}=19$.

The minimum value between $d_{\rm lim}$ and d_σ fixes the distance up to which conditions (1) and (2) are verified, *i.e.* completeness of the sample down to $M_V=4.5$ mag and parallaxes with the precision $\sigma_\pi/\pi \le 0.1$.

In the case $V_{\rm lim}=17$ mag, we get $d_{\rm lim}=2$ while $d_\sigma = 2.5$. This means that conditions (1) and (2) are simultaneously satisfied up to 2 kpc distance.

There is also a minimum distance of 1.5 kpc set by condition (3), because at closer distance the number of sampled stars get too small.

Interestingly enough, passing from $V_{\rm lim}=17$ mag to $V_{\rm lim}=19$ mag (right panel of Fig. 1) does not improve the situation. In this case $d_{\rm lim}=4$–4.5 kpc, however, these larger distances cannot be reached because of the constraint imposed by d_σ which is independent of $V_{\rm lim}$ and remains fixed at the value $d_\sigma=2.5$ kpc.

5 At Different Heights Over the Galactic Plane

The GAIA performances offer the unique opportunity of disentangling the two populations (thin and thick disk) which constitute the Galactic disk and deriving for each one the SFH at different heights over the Galactic plane. With the help of the HRD-GST we compute the CMD of a thin and thick disk population inside a square parallelepiped, centered on the sun, normal to the Galactic plane, having a side of 50 pc. In order to simulate the thin disk a synthetic stellar population is adopted having a SFR as that obtained by Hipparcos data, ages in the interval 1–10 Gyr, a Salpeter IMF slope, and stellar metallicity ranging from 0.008 to 0.03. In the case of the thick disk the synthetic stellar population has the following characteristics: ages in the range 12–8 Gyr, SFR exponentially decreasing by

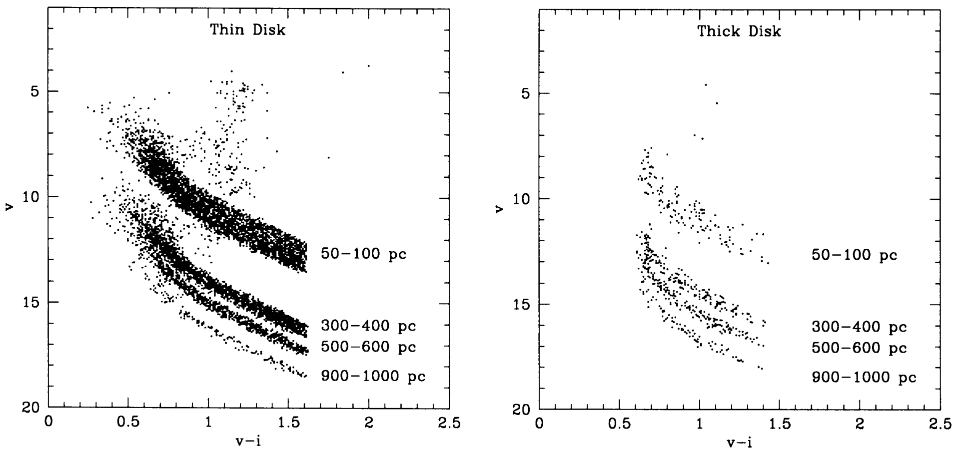

Fig. 2. *Left panel*: synthetic thin disk population at different distances from the Galactic plane (details are in the text). *Right panel*: thick disk population (see text).

a factor 2.7 from 12 to 8 Gyr, Salpeter IMF slope and metallicity going from 0.004 to 0.008. In Figures 2 (left and right panel) the stars of the synthetic thin and thick disk respectively are shown and selected at different distances from the Galactic plane up to a maximum distance of 1 kpc. The part of the CMD which is maximally sensitive to the star formation history is represented by the evolved stars brighter than the main-sequence turnoff. As it appears from the figure, the evolved stars of both the disk components closer than 1 kpc are brighter than 15–16 mag. This fact is very important because it means that up to that distance GAIA data of the evolved stars are of high quality. Since for these bright objects the radial velocities can be measured, the two disk components can be separated kinematically and chemically. As a consequence the SFH as a function of the distance from the Galactic plane can be obtained for both of them.

6 The SFH of the Galactic Bulge from GAIA

In Bertelli *et al.* [2] the SFH of the bulge from HST data of the Baade Window is studied. The HRD has been divided in strips of colour in order to derive the distribution of the stars as a function of the magnitude inside every strip. The solution is obtained by the minimization of a function which is the sum of the χ^2 in every stripe. The best solution is characterized by an age range from $t_\mathrm{i} = 12$ Gyr to $t_\mathrm{f} = 9$ Gyr, an exponentially declining star formation rate of the form $e^{-\beta\tau}$ with $\beta = 0.1$, a metal enrichment law linearly varying with time and having $0.01 \leq z \leq 0.03$, an IMF parameter $\mathbf{x} = 1.35$ (Salpeter slope: $\mathbf{x} = 2.35$). However we know that this result is weakened by the uncertainties related to the hypotheses on which this result stands. In fact the modeling of the bulge requires the following assumptions:

i) the modeling of the disk population which lays in front and inside the bulge. This imply a precise knowledge of the interstellar absorption along the line of sight up to the bulge. The uncertainty on the value of the reddening at the distance of the bulge is of the order of ± 0.15 mag. Additionally the spatial distribution of the disk stellar population is an input parameter quite uncertain. Unfortunately, from simulations with reasonable input parameters it appear that the disk population in front of the bulge presents something like a turn off point at $F_{555} = 20$ which overlaps that of the bulge.

ii) the modeling of the density distribution of the stars inside the bulge. Adopting different models of the density distribution, differences of the order of $\Delta V = 0.3$ at the magnitude of the turn off of the bulge are obtained [14].

iii) the distribution of the chemical abundance of the stars as a function of the age (the metal enrichment law).

What could be the contribution of GAIA on the above topics?

- From photometry and spectroscopy of the bright disk stars (which appear as a blue plume in the CMD of the bulge), GAIA will provide the absorption along the line of sight in the direction of bulge. Additionally disk stars and eventual young bulge objects can be disentangled on the basis of kinematic information and distance;

- Information on the age, metallicity and SFR of the stellar population belonging to the disk along the line of sight towards the BW can be obtained as discussed in the previous Section 4;

- The information given by GAIA about distances and proper motions of red luminous stars in different directions inside the bulge will provide further constraints on the mass distribution of the bulge itself. To distinguish between different spatial distributions distance determinations more precise than 10% are required. This imply that suitable targets are stars brighter than $V = 16$.

7 Conclusions

The high performances of GAIA will greatly improve our understanding of the Galaxy. This paper focus on the determination of the SFH. The main conclusions are:

1) At low Galactic latitudes GAIA will be able to measure a significant sample of stars having the same degree of accuracy as Hipparcos data up to a distance of 2–2.5 kpc.

2) GAIA will allow to disentangle the two populations (thin and thick disk) which constitute the Galactic disk. For each of them the SFH at different heights over the Galactic plane up to a distance of 1 kpc can be derived.

3) GAIA is going to contribute significantly to the determination of the SFH of the bulge giving information about metallicity range, reddening, and mass distribution.

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