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UNRAVELING THE HISTORY OF STAR FORMATION IN THE GALACTIC DISK WITH GAIA *

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Abstract. In this paper we examine the star formation history inferred from the *Hipparcos* color-magnitude diagram (CMD) of field stars in the solar vicinity and check whether the whole galactic disk has formed stars in a similar fashion. We find that the properties of the CMD in question are very local and the underlying star formation history cannot hold for the whole disk. With the expected capability of *Gaia* we examine how far in space *Gaia* would be able to sample stars with the same precision of parallaxes as *Hipparcos.* We find that a minimum coverage of about 2 kpc from the Sun is easily achievable. In such a case the star formation history, derived from the *Gaia* data, is expected to represent the past star forming activity over the whole galactic disk.

Key words: Galaxy: disk – stars: formation history, HR diagram – orbiting observatories: Hipparcos, Gaia

1. INTRODUCTION

Deciphering the past history of star formation from the color-magnitude diagram (CMD) of composite stellar populations in galaxies of different morphological type is one of the main targets of modern astrophysics. For nearby galaxies, in which individual stars are

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resolved and CMDs plotted, the problem can be successfully solved, as all stars are nearly at the same distance. In contrast, in our own Galaxy the problem is much more complicated because stars are located at different distances (difficult to measure with good precision) and only integrated CMDs containing stars of any age, metallicity and distance are available. Unraveling the underlying star formation history (SFH) is a cumbersome affair. The problem is circumvented by postulating a suitable star formation law or rate (SFR) and by comparing theoretical predictions with observational data. As an illustration, let us consider the case of chemical models designed to interpret the chemical abundances and their spatial gradients in the galactic disk. In these models the SFR is assumed to be a smoothly decreasing, monotonic function of time from early epochs to the present (e.g. see model A of Chiappini et al. 1997). In contrast, other independent studies suggest that the local SFR has been quite irregular, with periods of enhancement and quiescence (see Rocha-Pinto & Maciel 1996 and references therein). They find a burst 8 Gyr ago, and a lull of activity some 2–3 Gyr ago. However, the application of their method to the data of Edvardsson et al. (1993) produces a SFR smoothly increasing till the present.

The advent of the *Hipparcos* mission has set a landmark on this topic, because for the first time it was possible to derive the CMD of field stars in the solar vicinity based on accurate distances for each individual object (Perryman et al. 1995). The *Hipparcos* CMD of field stars has been the subject of several studies aimed at testing stellar evolution theory (see Schröder 1998) and the past SFH (see Bertelli et al. 1997, 1999a) in the solar vicinity.

In this paper we address the question whether the SFH found from the *Hipparcos* data for the solar vicinity can be extended to the whole galactic disk. As the answer to this question is negative, we examine whether *Gaia*, thanks to its better capabilities as compared to *Hipparcos*, will allow us to get a sample of stars with the same distance precision but with much wider space coverage, so that the ages, metallicity and SFH in that extended region do really represent the whole galactic disk.

2. SFH IN THE SOLAR VICINITY FROM HIPPARCOS

Bertelli et al. (1997, 1999a) have analyzed the *Hipparcos* CMD for the solar vicinity published by Perryman et al. (1995) and tried to reconstruct the past SFH. To this aim, they isolated a suitable

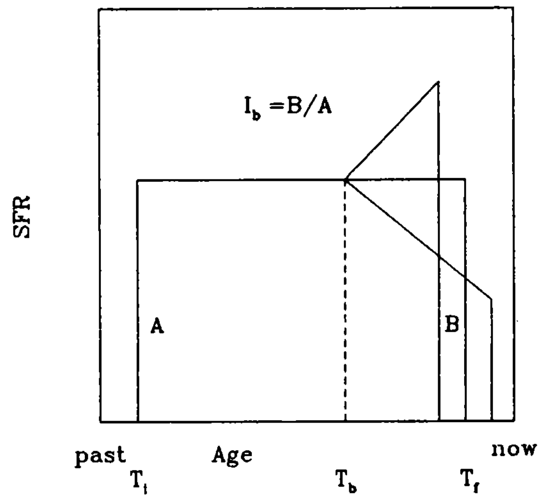

Fig. 1. Sketch of the time dependence of the star formation rate characterized by the following parameters: T_i and T_f – ages at which star formation has started and ceased, respectively; T_b – age at which star formation rate has changed with respect to the previous mean value; I_b is the amplitude ratio between the SFR at the age T_f and that in the time interval T_i–T_b.

sub-sample of the *Hipparcos* data in correspondence with a number of selection criteria and, using the synthetic HRD technique, looked for a kind of star formation responsible for the observational CMD.

2.1. Selecting the sample of stars

The sample of stars suited to the analysis has to satisfy the following conditions:

(1) All evolved stars must be included. The original *Hipparcos* CMD for stars within 50 pc from the Sun is complete for absolute magnitudes brighter than M_V = 4.5 mag, which implies that all evolved stars are taken into account.

(2) The sample must be free of cluster stars. For this reason, Bertelli et al. (1999a) removed from the Perryman et al. (1995) list all stars belonging to the Hyades.

(3) The sample must be free of multiple systems, which therefore have been eliminated.

(4) Finally, the sample must be sufficiently numerous so that statistical tests were meaningful. The sample in use contains 1431 stars.

2.2. The synthetic HRD technique

The analysis of the CMD of the selected sample rests on the synthetic HR diagrams technique which requires the following information:

(1) The initial mass function (IMF):

$$dN \propto M^{-x} dM \qquad (1)$$

for which we assume the classical Salpeter law with x considered as a free parameter to be constrained by the observations.

(2) The relative lifetime spent by stars in each elemental area of the HRD. This is derived from the Padova library of stellar models and isochrones by Bertelli et al. (1994), in which lifetimes in each elemental area are made available as a function of the star mass and chemical composition.

(3) The rate of star formation, for which different recipes are explored. The time dependence of the SFR (in arbitrary units) is sketched in Fig. 1, where T_i is the age at which star formation began, T_f is the age at which star formation ceased, T_b is the age at which star formation changed (increased or decreased) with respect to the past mean value, and finally I_b is the amplitude ratio between the SFR at the age T_f and that in the time interval T_i–T_b.

(4) The law of metal enrichment. Starting from the study of Edvardsson et al. (1993) and Ng & Bertelli (1998), in which no age–metallicity relation for field stars is found but a large scatter in metallicity is seen at each age, in each simulation the metallicity is stochastically varied from star to star within a suitable range.

Many simulations of CMDs have been generated by varying T_i, T_f, T_b, I_b and IMF slope x.

2.3. Comparing theory with observations

The comparison is separately made for main sequence (MS) and evolved red giant stars (RED). The separation in two groups is made by means of eye-drawn line as shown in the right panel of Fig. 2.

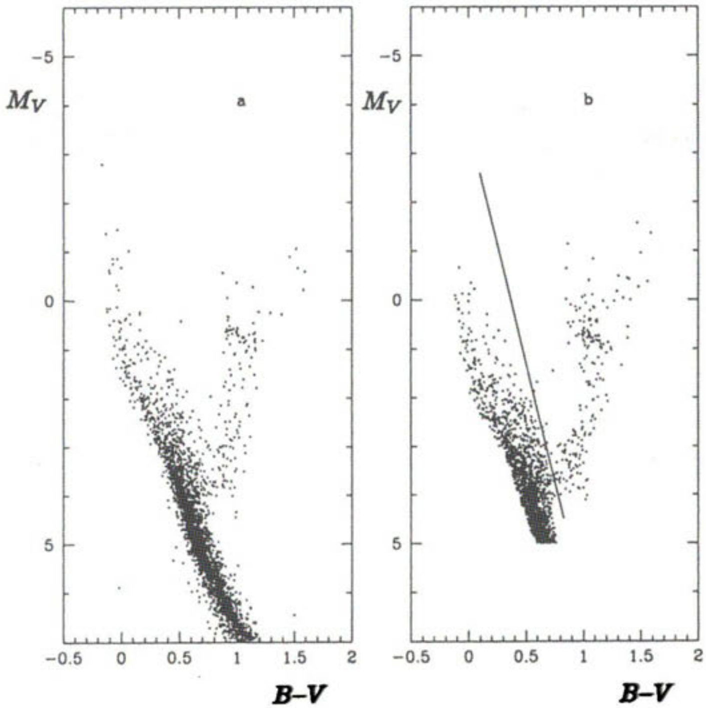

Fig. 2. Left panel: the sub-sample selected from the *Hipparcos* catalogue with the criteria described in Section 2.1. Right panel: one of the possible solutions satisfying the requirements described in Section 2.3.

The MS region. The luminosity interval spanned by the main sequence stars is divided into seven equally spaced bins except the most luminous one. For any combination of T_i, T_f, T_b, I_b and x (model), 20 simulations of the CMD have been generated using the total number of observed MS stars as the normalization parameter. Models are retained or discarded according to whether they are able to minimize the quantity

$$\chi^2 = \sum_{i=1}^{n} \left[(N_{\rm obs} - \overline{N}_{\rm model})^2 / N_{\rm obs}\right]_i. \qquad (2)$$

Finally, the Smirnov-Kolmogorof test (SK) is used to assess the degree of correspondence between the observed and simulated CMD. A tight relation is likely to exist if $SK \geq 0.6$.

The RED region. This region has been divided to three zones one of which contains all stars brighter than $M_V = 1.5$ mag. Since the majority of these stars are in the phase of central He-burning, we will refer to them using the suffix He. The same analysis as for the MS stars is made, however limited to the calculation of χ^2.

For illustration, in the left panel of Fig. 2 we show the selected sample of stars from our analysis, and in the right panel of Fig. 2 – one of the possible solutions satisfying the requirements above. The underlying SFR is constant from 10 Gyr to 4.5 Gyr and increases linearly by a factor 1.5 from 4.5 to 0.1 Gyr. The slope of the IMF is $x = 2.35$. The metallicity ranges from 0.008 to 0.03. In this simulation, the MS stars have $\chi^2 = 4.5$ and the SK parameter is ≥ 0.95. However, the ratio between the He-burning and the MS stars is by a factor of 1.5 greater than the observed one: $N_{\rm He}/N_{\rm MS} = 0.073 \pm 0.008$ compared to the observational value of 0.047.

2.4. Results of the analysis and provisional conclusions

The results of the Bertelli et al. (1999a) analysis can be shortly summarized as follows:

(1) All solutions are compatible with IMF slope $x = 2.35$ and the SFR permanently increasing (in a broad sense) from the beginning to the present.

(2) All cases, in which good solutions for the MS region are found (low χ^2 and the SK test ≥ 0.6), have values of χ^2 for the RED region which are too high and, even more important, the ratio between the He-burning and MS stars of the models is always by a factor of 1.5–2.0 greater than the observational value.

The last point is very significant. If one excludes the possibility of some unforeseen selection effects, this means that the theoretical models are probably inadequate. As reviewed by Chiosi (1999), stars whose turn-off mass is pertinent to the age range under consideration (say from 0.1 to 8–9 Gyr) may be severely affected by the problem of convective overshooting during both core H- and He-burning phases. The subject is far from being settled. Furthermore, it is also complicated by the fact that stars in the mass range 1 to 1.2 $M_\odot$ switch from radiative to convective cores during the MS phase, the convective core tends first to grow during a sizable fraction of the H-burning lifetime, and then to shrink. Whether or not in these circumstances convective overshooting from the H-burning core can grow to full efficiency is still a matter of vivid debate (see Chiosi 1999 for references). All this makes stellar models in this mass range still highly uncertain, at least as detailed predictions are concerned.

Main preliminary conclusions from Bertelli et al. (1999a) about the CMD of the solar vicinity (within 50 pc) are: (1) star formation began and ended about 10 and 0.1 Gyr ago, respectively; (2) the metallicity of the stars in this sample falls in the range $0.008 < Z < 0.03$ (see Edvardsson et al. 1993).

3. CAN THESE RESULTS HOLD FOR THE WHOLE DISK? THE ROLE OF GAIA

An obvious important question arising from the previous analysis is whether the stellar population in the solar vicinity is representative to the whole galactic disk.

To answer this question, we made use of the HRD-GST (HRD-Galactic Software Telescope) of Ng et al. (1995) and Bertelli et al. (1995). HRD-GST is a package suitably designed to study the structure of the Galaxy by deconvolving the cumulative CMD and luminosity function along any line of sight. For the purposes of the present study, we start assuming a given model of galactic structure (mass distribution, star formation, reddening etc..) along a certain line of sight and simulate the CMD that one would observe within a cone along it.

We choose two directions: towards the BW8, a field inside Baade's Window studied by Bertelli et al. (1999b) and Lynga 7, a disk cluster whose projected position falls at the outskirts of the galactic bulge.

The same stellar population shown in the right panel of Fig. 2 (which nicely simulates the 50 pc wide pool around the Sun) is distributed along the line of sight of BW8. The resulting CMD is compared with the observed one for BW8 in Fig. 3: the left panel is the CMD for BW8 and the right panel is the simulated CMD.

It is immediately evident that the disk component of the simulation (the blue vertical plume) does not correspond to the observational one. The data suggest that a much older disk component should be adopted. The age of this indicated by the CMD of BW8 is 1–2 Gyr (see also Bertelli et al. 1995) instead of 0.1 Gyr indicated by the CMD of the solar vicinity. In addition to this, one should also consider the effect of the gradient in the chemical composition

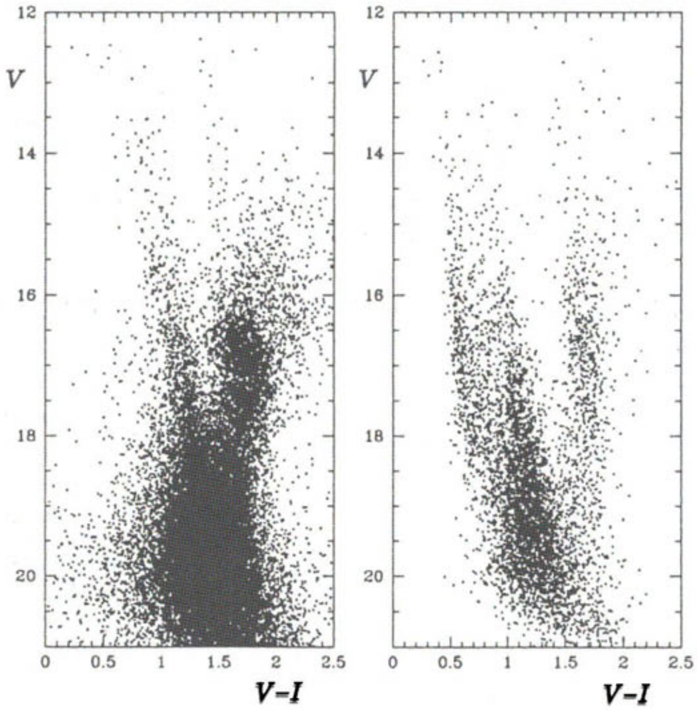

Fig. 3. Left panel: the field BW8 from Bertelli et al. (1999b) where the contribution from the galactic disk is evident (the almost vertical blue plume). Right panel: simulation of the same field using the SFR inferred from the *Hipparcos* CMD. Note the much bluer color of the blue plume, suggesting that the SFR holding for the solar vicinity cannot be extended to the whole disk.

known to exist along the galactic disk (see Simpson et al. 1995, Afflerbach et al. 1997, Rudolph et al. 1997 and references therein), which in contrast is virtually missing in the small region of 50 pc. 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.*

3.1. Using Gaia

If the *Hipparcos* data cannot be used to infer the past history of star formation in the galactic disk, would it be possible to get a sample of stars covering a large portion of the galactic disk and yet possessing the same degree of accuracy as that obtained by *Hipparcos*? Such a sample should extend far enough from the Sun in order to be really representative of the galactic disk.

Considering the future capability of *Gaia*, we would like to answer the following questions: (1) is it possible to isolate the *Gaia* volumes in the galactic disk, whose stellar content shares the same properties as the *Hipparcos* sample? (2) how far from the Sun can we go?

This ideal sample of stars should obey the following requirements:

(1) To be complete up to $M_V = 4.5$ mag, as with *Hipparcos*, so that all evolved stars 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 of *Gaia*.

(2) To possess accurate parallaxes with $\sigma_p/p \leq 0.1$.

(3) To be statistically significant.

Characterizing this sample is the subject of the coming section.

3.2. Towards Baade's Window and Lynga 7

To this aim we consider a generic volume contained in a truncated cone whose vertex is located at the Sun's position, its height is 400 pc and distance from the vertex to half-height is d. This distance d can vary thus acting as the coordinate along the line of sight. The assumed dimension of the solid angle subtended by the cone is 1 square degree (approximately the dimension of Baade's Window). With the aid of HRD-GST and the galactic model, we simulate the disk population falling into the cone as a function of d.

Supposing for *Gaia* the limiting magnitudes $V_{\mathrm{lim}} = 17$ and 18 mag and adopting its estimated parallax precision σ_p (in μas) as a function of spectral type (or color), reddening A_V and magnitude according to Table 3 of Lindegren (1998), we calculate 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};

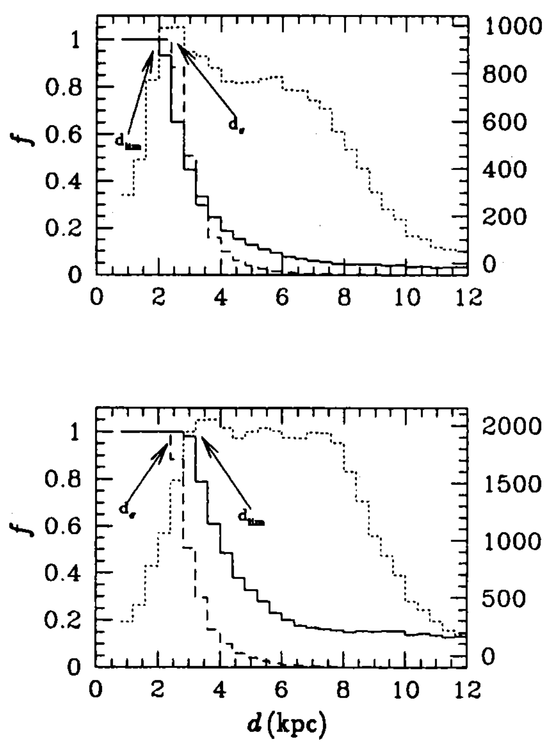

Fig. 4. Top panel: $V_{\rm lim} = 17$ mag. The dotted line represents $n_{4.5}$ (number of stars shown along the right vertical axis) as a function of distance d (in kpc) of the volume under examination. The continuous line represents the ratio $n_{\rm lim}/n_{4.5}$ whereas the long-dashed line is for the ratio $n_\sigma/n_{4.5}$. These ratios are displayed along the left vertical axis. The limit distances $d_{\rm lim}$ and d_σ are also indicated. Bottom panel: the same as in the top panel but for $V_{\rm lim} = 18$ mag. Notice that $d_\sigma < d_{\rm lim}$ in contrast with the results from the previous case.

n_{σ_p}: the number of stars more luminous than $M_V = 4.5$ mag and at the same time with $\sigma_p/p < 0.1$.

3.2.1. Towards Baade's Window

The above star counts performed along this direction are shown in the panels of Fig. 4 for $V_{\rm lim} = 17$ mag (top) and 18 mag (bottom). In both diagrams, the dotted line represents $n_{4.5}$ (vertical axis on the right). The shape of this curve is governed by the interplay between the volume increasing with d^2 and the density of

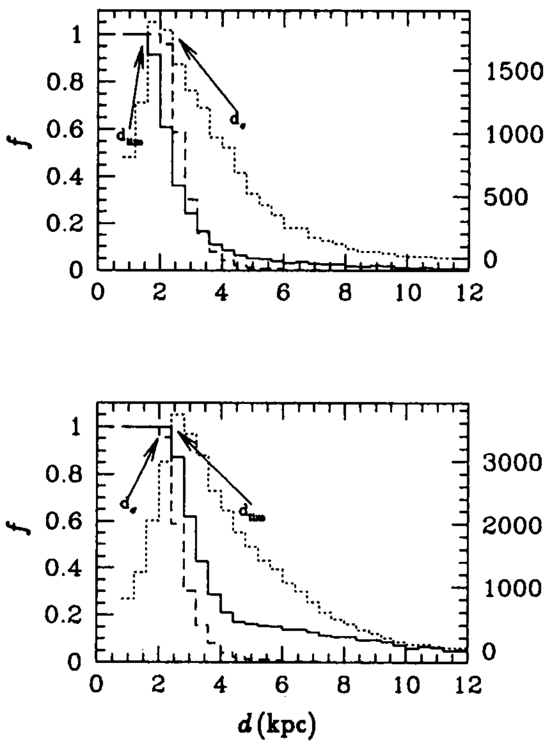

Fig. 5. The same as in Fig. 4 but for the direction towards open cluster Lynga 7.

disk stars, which beyond a certain distance starts decreasing, thus generating the peak in the distribution. The solid line represents the ratio $n_{\rm lim}/n_{4.5}$. 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 ($d_{\rm lim}$) 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 at which $n_\sigma/n_{4.5}$ falls below 1.0 corresponds to the situation in which no longer all stars more luminous than $M_V = 4.5$ have also $\sigma_p/p \leq 0.1$. 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 $\sigma_p/p \leq 0.1$. In case of $V_{\rm lim} = 17$ mag, we get $d_{\rm lim} = 2 - 2.5$ kpc while $d_\sigma = 3.5$. This means that conditions (1) and (2) are simultaneously satisfied up to (2–2.5) 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 gets too small (less than 800 objects).

Interesting enough, passing from $V_{\rm lim} = 17$ mag to 18 mag does not much improve the situation (see the bottom panel of Fig. 4). In this case $d_{\rm lim} = (3 - 3.5)$ kpc, marginally larger than in the top panel. However, much larger distances cannot be reached because d_σ rapidly degrades to the value of $d_\sigma = 2.5$ kpc.

3.2.2. Towards Lynga 7

The same analysis is repeated towards Lynga 7 with similar results (Fig. 5). In case of $V_{\rm lim} = 17$ mag (top panel), $d_{\rm lim} = 2$ kpc and $d_\sigma = 3$ kpc. In case of $V_{\rm lim} = 18$ mag (bottom panel), $d_{\rm lim} = (3 - 3.5)$ kpc and $d_\sigma = 2.5$ kpc.

4. CONCLUSIONS

The main conclusions of this study are:

(1) The SFH derived from the *Hipparcos* data for the very local solar vicinity (within 50 pc from the Sun) cannot be applied to the whole galactic disk. It seems like the solar vicinity has suffered from recent star formation activity, whereas on the average this activity has terminated at much earlier epochs approaching the galactic center.

(2) *Gaia* will be able to sample stars over much larger volumes of space and will provide the same kind of information as the *Hipparcos* CMD within 50 pc. Owing to much larger spatial coverage, the *Gaia* sample would likely be representative to the whole galactic disk.

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