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Impact of the uncertainties of the ISM when studying the IMF at intermediate masses

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Abstract. We evaluate the impact of the uncertainties in the 3D structure of the Interstellar Medium (ISM) when studying the Initial Mass Function (IMF) at intermediate masses using classical Galactic Cepheids. For that we use the Besançon Galaxy Model (BGM, Robin et al. 2003 and Czekaj et al. 2014) and assume different IMFs and different interstellar structure maps to simulate magnitude limited samples of young intermediate mass stars. As our strategy to derive the IMF is based on star counts (in proceedings Mor et al. (2014) and Mor et al. 2016 in prep.), we quantify the differences in star counts by comparing the whole-sky simulations with Tycho-2 catalogue up to $V_T = 11$ and using Healpix maps. Moreover we compare simulations with different extinction models up to Gaia magnitude G=20. As expected, larger discrepancies between simulations and observations are found in the Galactic Plane, showing that the interstellar extinction in the plane is one of the major source of uncertainty in our study. We show how even with the uncertainties due to the ISM we are able to distinguish between different IMFs.

Key words. Stars: abundances – Galaxy: Initial Mass Function – Galaxy: 3D extinction maps – Galaxy: Interstellar Medium – Stars: Cepheids

1. Introduction

The IMF specifies the factorized distribution in mass of a newly formed stellar system. Together with the Star Formation History (SFH), it is one of the most important parameter for the formation and evolution of the Milky Way. Even more, it controls the evolution of the chemical composition and the luminosity of the stars and galaxies. While so important, it is often assumed to have a simple power law. Salpeter (1955) was the first to describe the IMF as a power-law $dN = \xi(m)dm = km^{-\alpha}dm$ and he estimated a power-law index of $\alpha = 2.35$ considering an age of the Milky Way of 6 Gyr. Since then, several fundamental reviews on the empirical derivation of the galactic IMF have been written, Schmidt (1959), Miller & Scalo (1979) and Kroupa (2002). Even though, the IMF is still a matter of debate. A possible way to derive the IMF is to consider the number of stars of different masses from star counts and compare with a model assuming several IMF. However the star counts in the Galactic plane, where most massive stars are present, also depends on other parameters such as the interstellar extinction.

The knowledge of ISM is very important for all the fields in astrophysics. In the last decades several efforts have been made to develop a 3D extinction map capable to reproduce the extinction in the whole Galaxy. Schlegel et al. (1998) with COBE/DIRBE and IRAS/ISSA data derived a galactic dust map to estimate galactic extinction. Drimmel & Spergel (2001) presented a 3-dimension model based on far-infrared and near-infrared from COBE/DIRBE data and Marshall et al. (2006) used the Besançon Galaxy Model (Robin et al. 2003), together with the 2MASS to derive the extinction distribution for different lines of sights. More recently Sale et al. (2014) presented a 3D extinction map based on IPHAS photometry and Green et al. (2015) from Pan-STARRS 1 and 2MASS data.

In our studies we attempt to use Cepheid counts to constrain the IMF using a population synthesis model (proceedings Mor et al. (2014) and Mor et al. 2016 in prep.). To do so we need to quantify the effects of the uncertainties of the extinction in the Cepheid counts. To quantify the mentioned uncertainties we have selected here two of these 3D extinction maps, the one from Drimmel & Spergel (2001) and the one from Marshall et al. (2006).

In section 2 we explain our methodology describing the IMFs to be tested and the selection function adopted to simulate the Cepheids. In section 3 we discuss the effects of the uncertainties in the knowledge of the ISM distribution on Tycho-2 stellar densities computed assuming different IMF. A more detailed analysis is done showing comparison between different sets of simulated data as a function of galactic longitude up to Gaia magnitude $G = 20$. Moreover we compare total Cepheid counts for simulations with different extinction models up to $G = 20$. In section 4 we discuss the expected improvements with Gaia data. Results and conclusions are presented in section 5.

2. Methodology

To quantify the impact of the 3D ISM uncertainties we compute whole sky simulations up to $V_{Tycho} = 11$ with different extinction models and we compare them with the sky distribution of stars in Tycho-2 (for $V_{Tycho} \leq 11$) catalogue. We also consider the distribution of Cepheids up to magnitude G=20, using different extinction models, in order to estimate the possibility to use Gaia to derive the IMF from these variable stars. Moreover, we compare the whole sky total Cepheid counts up to G=20, simulated with different extinction models.

2.1. The IMF's

In this paper we are focused on the study of the impact of the uncertainties on the knowledge of ISM and not on the selection of the best IMF slope. To accomplish that we have tested three IMFs representative of well covering the range of values obtained by to now: (1) Salpeter IMF (Salpeter 1955); (2) Haywood-Robin IMF (Haywood et al. 1997 + correction of Robin et al. 2003); and (3) Kroupa-Haywood IMF (Combination of Kroupa 2008 and Haywood et al. 1997). The IMFs (2) and (3) were built from Czekaj et al. (2014).

In all cases the IMF is represented by $\xi(m)$:

$$dN/dm = \xi(m) = km^{-\alpha} = km^{-(1+x)} \tag{1}$$

Where $\alpha = (1 + x)$ is the slope, and k is the normalization constant. $\xi(m)$ represents the number of stars per unit of mass. The x values for Haywood-Robin IMF are:

$$x = \begin{cases} 0.6 & 0.09 \leq M/M_{\odot} < 1.0 \\ 2.0 & 1.0 \leq M/M_{\odot} < 120 \end{cases}$$

For Kroupa-Haywood IMF:

$$x = \begin{cases} 0.3 & 0.09 \leq M/M_{\odot} < 0.5 \\ 0.8 & 0.5 \leq M/M_{\odot} < 1.53 \\ 2.2 & 1.53 \leq M/M_{\odot} < 120 \end{cases}$$

and for Salpeter IMF:

$$x = \begin{cases} 1.35 & 0.09 \leq M/M_{\odot} < 120 \end{cases}$$

If we integrate expression (1) within a mass range we obtain the number of stars (N) inside this mass range.

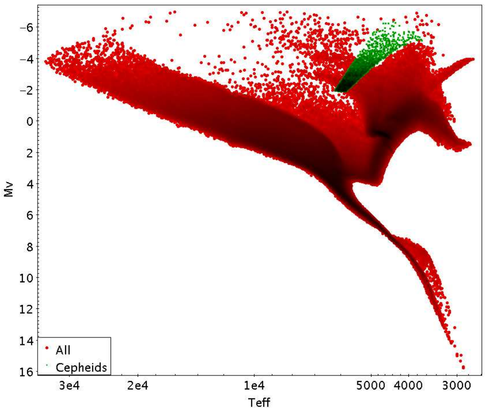

Fig. 1. Simulated H-R diagram for all stars up to $V = 12$ (red). The stars in green belong to the instability strip and are assumed to be Cepheids.

2.2. Cepheids Selection Function in BGM

The Instability Strip (IS) is the region of the HR diagram occupied by the pulsating variable stars, including Classical Cepheids. The hotter and cooler boundaries of the IS are called the blue edge and the red edge respectively. For our work in the solar neighbourhood (Mor et al. 2016 in prep.) we are using the Blue Edge from Bono et al. (2000) and the Red Edge from Fiorentino (private communication), both derived from Cepheid pulsation models at solar metallicity. In the work we present here, we also want to include the Cepheids in the outer disc. Given the radial metallicity gradient in the Milky Way (e.g., Genovali et al. (2014) for Cepheids), we also use the the Blue Edge from Fiorentino (private communication) that was derived from pulsation models at lower metallicity (z=0.008). We have also applied a Luminosity cut, imposing that the Cepheids luminosity range has to be compatible with the effective temperature range $4000 \leq T_{eff} \leq 7000K$ Bono et al. (1999) . We have also selected only the stars with (young) ages and (intermediate) masses compatible with classical Cepheids. In figure 1 we show in green the location of our IS in the HR diagram simulated using the BGM. All the stars within the IS are assumed to be Cepheids.

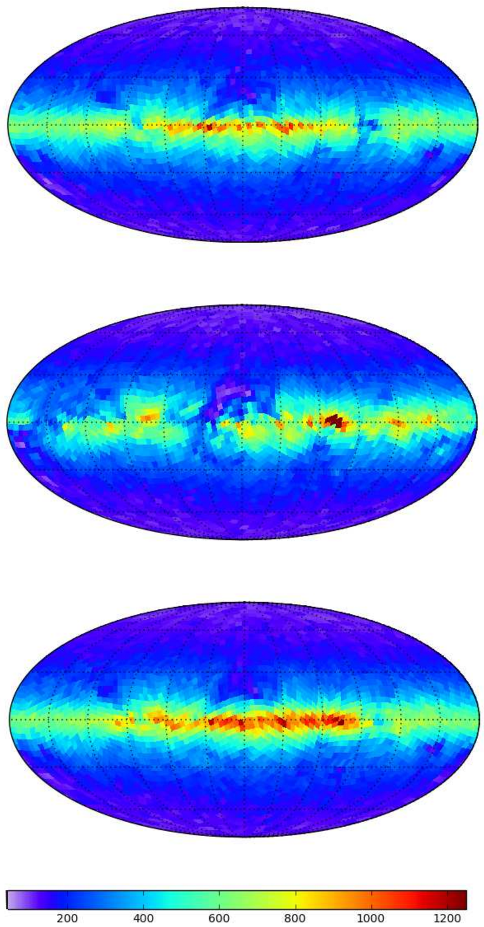

Fig. 2. Star counts per Healpix pixel up to V_{Tycho} = 11. The pixel area is 13.43 square degrees. **Top:** Sky simulation and Drimmel & Spergel (2001) extinction model for the whole sky.**Middle:** Tycho-2 catalogue up to $V_{Tycho} = 11$. **Bottom:** Sky simulation using Marshall et al. (2006) extinction for $-100 < l < 100$ and $|b| \leq 10$ and Drimmel & Spergel (2001) for the rest of the Sky.

3. The consequences of the ISM uncertainties

3.1. Tycho-2 data up to $V_T = 11$

In figure 2 we show the whole sky star counts distribution in galactic coordinates. The top map corresponds to BGM simulations of the

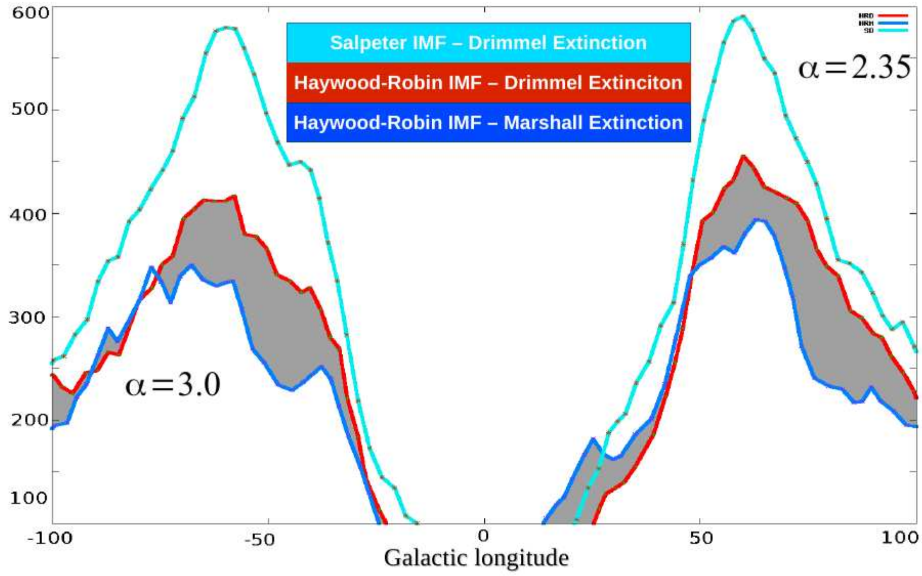

Fig. 3. Cepheid Counts as a function of galactic longitude up to Gaia magnitude $G = 20$. Light blue for the Cepheid sample simulated with Salpeter IMF and Drimmel extinction map. Red line is for Cepheids simulated with Haywood Robin IMF and Drimmel extinction map. Dark blue is for Cepheids simulated with Haywood-Robin IMF and Marshall extinction map. The grey region shows the uncertainties in the star counts, in the last two simulations, due to the uncertainty on interstellar extinction.

whole sky up to $V_{Tycho} = 11$ using the parameters of Model B (Czekaj et al. 2014) and Drimmel & Spergel (2001) extinction model. The middle map corresponds to real Tycho-2 data up to $V_{Tycho} = 11$. The bottom map corresponds to the BGM simulation using the parameters of Model B of Czekaj et al. (2014), with Marshall et al. (2006) extinction for the region $-100 < l < 100$ and $|b| \leq 10$ and using Drimmel & Spergel (2001) for the rest of the sky.

As it was demonstrated in Czekaj et al. (2014) the global star counts of the BGM simulations are in a good agreement with the Tycho-2 at $V_{Tycho} = 11$. But as can be seen in figure 2 the 3D extinction models used are not able to reproduce the local absorption structures of the ISM. Figure 2 is very illustrative to show the impact of the 3D ISM knowledge when comparing simulations with observations. In next sections we will quantify the impact of the 3D extinction map in terms of star counts for the specific case of simulated Cepheids.

3.2. The Cepheids simulated up to $G = 20$

In figure 3 we present the distribution of Galactic Cepheids as a function of longitude. It can be seen how the Salpeter IMF with the Drimmel & Spergel (2001) extinction produces more Cepheids at almost all galactic longitudes. The grey region shows the uncertainty on star counts due to the uncertainty on the extinction. Whereas some regions show very small differences due to 3D extinction models, in other regions the differences are large.

In figure 4 we show the total Cepheid counts for 6 different combinations of three IMF and two choices for the extinction model. Differences in star counts due to the different 3D extinction maps go from 7 to 10%. Haywood-Robin IMF is the IMF that produces

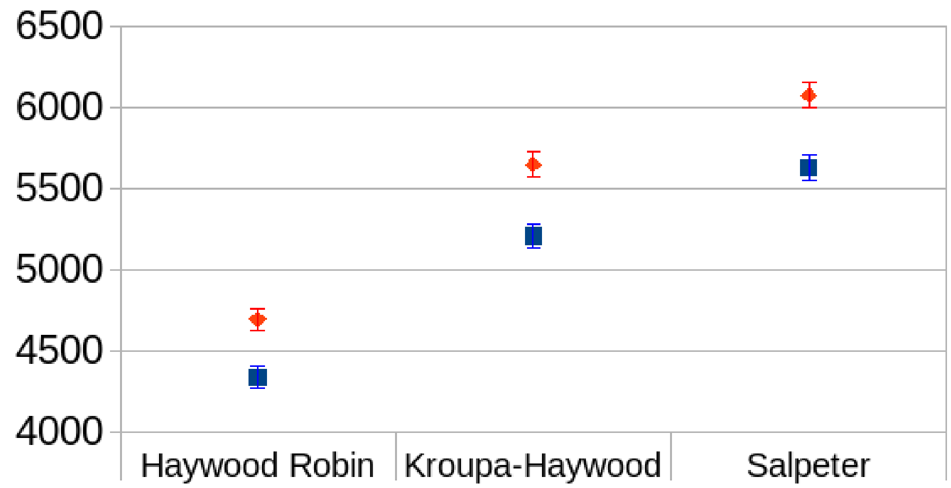

Fig. 4. Total Cepheid counts up to G=20 for 6 different combinations of three Initial Mass Function,and two choices for the extinction model. Red are for simulations with Drimmel extinction and blue are simulations with Marshall extinction. Error bars are 1σ of the Poisson noise.

less Cepheids followed by Kroupa-Haywood IMF. Salpeter IMF is the one that always produces more Cepheids.

4. Expected improvements with Gaia

It is well known that Gaia and Cepheids will play an important role when studying the ISM. Gaia will provide good distances for a large number of Cepheids, so the Cepheids P-L relation will be improved. Figure 5 shows the space distribution, integrated in z, of the simulated whole sky stars with $\frac{\sigma_\pi}{\pi} \leq 1\%$ up to V=12 with Gaia end-of-mission errors. See how we could reach 1kpc from the Sun towards the galactic centre and 1.5 Kpc in the direction of galactic rotation with very good distances.

In Figure 6 we have used BGM to estimate that about one thousand Cepheids will have good Gaia parallaxes ($\sigma\pi/\pi \leq 5\%$) reaching distances of about 6 Kpc.

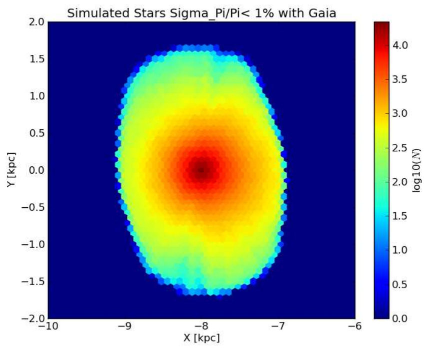

Fig. 5. Space distribution integrated in z of the simulated whole sky stars with $\frac{\sigma_\pi}{\pi} \leq 1\%$ up to V=12 assuming end-of-mission Gaia errors.

5. Results and conclusions

It has been demonstrated here that the uncertainties in the knowledge of the ISM needs to be taken into account when aiming to derive the IMF with a strategy based on star counts (i.e. see figure 2). As it is shown in figure 3 these uncertainties are highly dependent on the galactic longitude. When comparing the whole sky counts (figure 4) we have found differences from 7 to 10% depending on the IMF used. We showed that, independently of the 3D extinc-

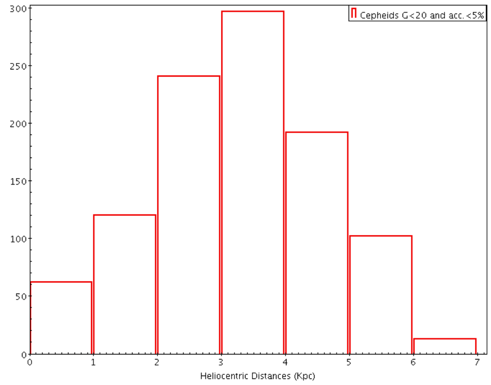

Fig. 6. Heliocentric distance distribution of Cepheids with accuracy in the parallax better than 5%

tion map used, we can constrain to a certain degree the IMF slope from Cepheid counts. Moreover Gaia will provide the tools to elaborate more accurate 3D interstellar map, this improvement will have a direct impact in the accuracy in the derivation of the IMF at intermediate masses.

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