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Galactic Cepheids as tracers of the thin disc Initial Mass Function

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Abstract

Classical Cepheids are known to be excellent tracers of the rotation, chemical distribution and spatial density of non-axisymmetric structures of the young Galactic thin disc. Gaia is now working to measure astrometric and photometric parameters for thousands of Classical Cepheids, so these objects will be in a privileged position to define the chemo-dynamical evolution of the Milky Way young thin disc population. Our goal is to use these tracers, together with the Besançon Galaxy Model to constrain the Initial Mass Function (IMF) of the Galactic thin disc at intermediate masses. Our work, performed using data available at present, favours an IMF with a slope of $\alpha = 3.2$ for the local thin disc, thus excluding flatter values as the Salpeter IMF ($\alpha = 2.35$) for intermediate masses. This derived IMF, obtained using field stars and Galactic Classical Cepheids, is steeper than the canonical IMF. This result is consistent with the predictions of the Integrated Galactic IMF.

1 Introduction

The Initial Mass Function (IMF) plays a crucial role on galaxy evolution. Together with the Star Formation History it determines the mass distribution of the stars in the Galaxy. Although it has been deeply studied (e.g. [17],[18],[9]) the determination of its shape at intermediate and high masses is a major subject of debate for both Galactic and extragalactic science. In this context we aim to use the Besançon Galaxy Model ([15, 4]) to investigate the slope of the IMF at intermediate masses using the Galactic Classical Cepheids as tracers of the thin disc intermediate mass population. Classical Cepheids are young pulsating variables in the mass range between about $4M_{\odot}$ to $14M_{\odot}$. Their position in the Hertzprung-Russel diagram has been deeply studied (e.g. [3]) allowing us to identify them in the Besançon

Galaxy Model simulations. Moreover Classical Cepheids are bright stars and they can be well classified through observations using their light-curve. These characteristics make them an ideal tracer to study the IMF comparing observational and simulated complete samples.

2 Methodology

Our methodology is summarized in figure 1. The simulated samples are generated using the Besançon Galaxy Model (BGM) [15, 4]. In BGM the stars are generated following an IMF, a Star Formation History and adopting models for several ingredients such as chemical evolution of the Galaxy, stellar evolution, stellar atmospheres, stellar density distribution and interstellar extinction. BGM simulations are in statistical equilibrium as explained in [2].

We have tested three IMFs, described in [12], which slopes in the intermediate mass range are $\alpha = 3.2$ (Kroupa-Haywood IMF), $\alpha = 3.0$ (Haywood-Robin IMF) and $\alpha = 2.35$ (Salpeter IMF). Our simplest evaluation method consists in the comparison of the total number of simulated Cepheid with the observations. This method allows us to test which IMF is able to reproduce the total number of Classical Cepheids up to a given apparent magnitude. In addition we use the Tycho-2 data to apply a more complex evaluation method based on probabilistic theories.

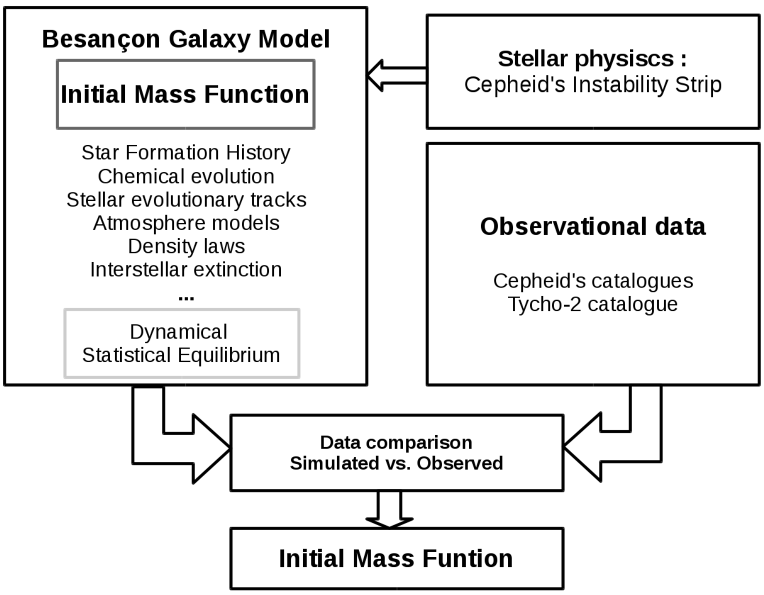

Figure 1: Scheme of the strategy used to investigate the Initial Mass Function at intermediate masses.

3 Observational Data

Our strategy requires to compare complete samples limited in apparent magnitude. The most complete Cepheid catalogues available at present are the Berdnikov catalogue ([1]) and the DDO catalogue ([6]). We have tested that 95% of Cepheids up to $V = 9$ are contained in both catalogues, thus in the present work we have used the photometric data from the Berdnikov catalogue for Cepheids up to $V = 9$. For fainter magnitudes we have used the ASAS Catalogue of Variable Stars (ACVS)([13, 14]). In figure 2 we present the Galactic distribution of the Cepheids used for the present study. Whereas the quality of the light-curves in Berdnikov catalogue ensures the stars are well classified, the classification in ACVS catalogue could contain some contaminants from other variable types. To minimize this contamination we work only with those Classical Cepheids in ACVS concentrated in the Galactic plane.

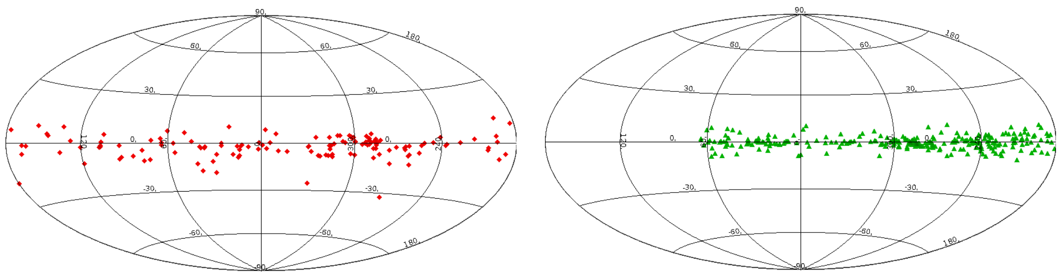

Figure 2: Sky distribution in Galactic coordinates. Left: Cepheids in the Berdnikov catalogue with $V \leq 9$. Right: Cepheids in the ACVS catalogue with $9 < V \leq 12$ and $|b| \leq 10$

4 The Hess diagram and the simulated Cepheids

The strategy for the generation of the thin disc population from [4] allows us to simulate a Hess Diagram for the thin disc population in the solar neighbourhood. In figure 3 left, we present the thin disc Hess Diagram in the solar neighbourhood that was build to be ingested in the Gaia Object Generator ([10]) as part of the Gaia Universe Model ([16]). To construct this Hess Diagram we run 400 realizations of a sphere around the Sun using the Model B described in [4] which represent a simulation of 925 Million of stars. Then we binned the data in bins of absolute visual magnitude and effective temperature. The stellar volume density shown in the Hess diagram (figure 3, left) has been computed considering both single stars and primary components of stellar systems (This diagram was published as Gaia Image of the Week at `http://www.cosmos.esa.int/web/gaia/iow_20160211`). The region of the Hertzprung-Russel diagram occupied by the pulsating variable stars is known as the Instability Strip (IS) (e.g. [3]). The hotter and cooler boundaries of the IS are called the Blue edge and the Red edge respectively. Then our simulated Cepheids are those stars which are inside the Cepheid IS (see the right side of figure 3). The binarity treatment of these objects is described in [12]. For the Cepheids up to V=9, which are situated in the

Solar neighbourhood, we have used the blue edge from [3] and the red edge from [7]. For Cepheids at larger heliocentric distances (magnitudes $9 < V < 12$) we have decided to use both boundaries from [7] which allow us to take into account the radial metallicity gradient of the Milky Way (e.g. [8]). An additional cut in luminosity is adopted to define which stars from the diagram are Cepheids (horizontal black lines, fig 3, right).

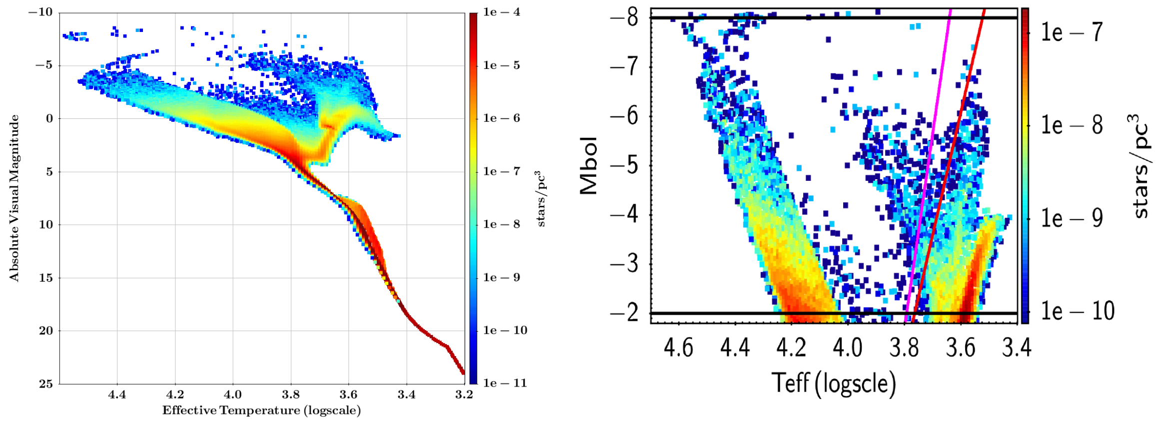

Figure 3: Left: Hess Diagram for the thin disc population in the solar neighbourhood simulated with BGM Model B from [4]. Dwarf stars are not included. Right: Zoom to the Hess Diagram where Cepheids are located. The pink and red lines show the boundaries of the Cepheid instability strip.

5 Results and Conclusions

In figure 4 we present the comparison of the absolute Cepheid counts for three different IMFs. Notice how the simulations with Kroupa-Haywood IMF ($\alpha = 3.2$) fits nicely the data while the simulations with Salpeter ($\alpha = 2.35$) and Haywood-Robin IMFs ($\alpha = 3.0$) are more than 5σ away from observational data. To add statistical robustness to the results we have applied a probabilistic method to study the Cepheid Fraction, which takes into account the number of Cepheids with respect to the total number of stars in the galactic plane (from Tycho-2 data). With this strategy we can evaluate the goodness of a given IMF to reproduce the observed Cepheid Fraction. We understand as observed Cepheid Fraction the probability to find a Cepheid each time a star is observed (see [12] for more details). In figure 5 we present the 2D posterior probability distribution function (PDF) combining the 1D PDF of both the Observed Cepheid Fraction and the simulated Cepheid Fraction. The integral of the 2D PDF over the lighted area indicates the probability that the simulation and the observation have the same Cepheid fraction. Notice that the simulation that uses Kroupa-Haywood IMF has a probability of about 80% to have the same Cepheid Fraction than the observed while Haywood-Robin has a probability of 40% and the probability for the Salpeter IMF simulation is $\approx 0\%$.

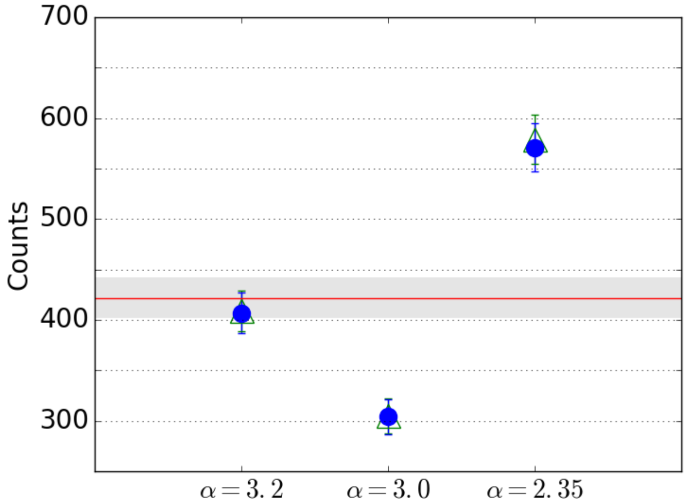

Figure 4: Testing the IMF. Cepheid counts for the complete region with visual magnitudes $V \leq 12$. The observational Cepheid catalogues are considered to be complete for the whole sky up to $V = 9$ while for the magnitude interval 9 to 12 they are supposed to be complete for $\delta \leq 29$. An additional cut ($|b| \leq 10$) is applied for the magnitude interval 9 to 12 to avoid contamination of the observational sample. The red line shows observational counts, the grey region is the region within 1σ. Filled blue dots are for the simulations with Marshall extinction model ([11]) while green triangles are for simulations with Drimmel extinction model ([5]). Error bars are due to Poisson noise. Notice here how the Kroupa-Haywood IMF with $\alpha = 3.2$ gives the best fit with the observational data while the other IMFs are more than 5σ away from the observations.

Our results favour the Kroupa-Haywood IMF with $\alpha = 3.2$ for intermediate masses. Using both field stars and Galactic Cepheids we have found an IMF steeper than the canonical stellar IMF for intermediate masses. This result is consistent with the predictions of the Integrated Galactic IMF (IGIMF). Further research is in progress to use Approximate Bayesian Computation techniques to explore a wider and continuous range of slopes of the IMF.

Acknowledgments

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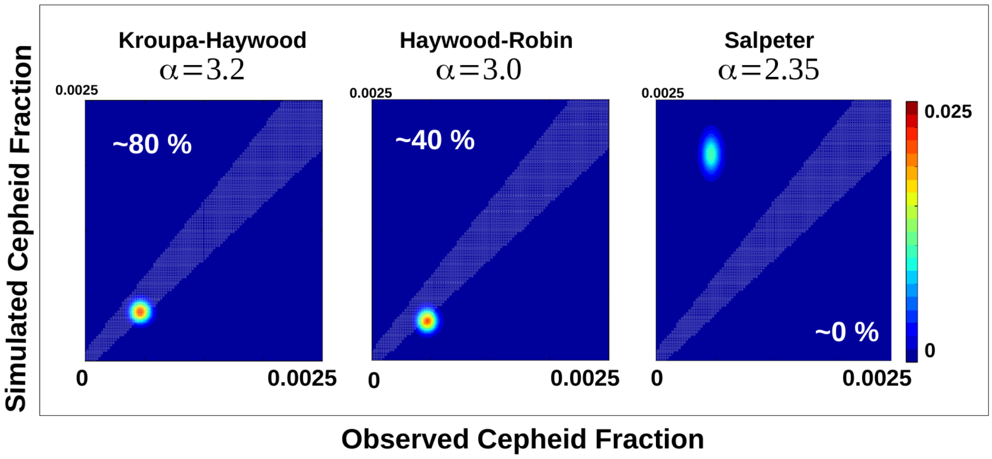

Figure 5: Full 2D posterior probability distribution function (PDF). The lighted strip is the tolerance region. The integral of the posterior PDF over the tolerance region gives the probability that observations and simulations have the same Cepheid Fraction. Left: Kroupa-Haywood IMF (α = 3.2). Middle: Haywood-Robin IMF (α = 3.0). Right: Salpeter IMF (α = 2.35)

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