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Search for Galactic warp signal in Gaia DR1 proper motions

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Abstract. The nature and origin of the Galactic warp represent one of the open questions posed by Galactic evolution. Thanks to Gaia high precision absolute astrometry, steps towards the understanding of the warp's dynamical nature can be made. Indeed, proper motions for long-lived stable warp are expected to show measurable trends in the component vertical to the galactic plane. Within this context, we search for the kinematic warp signal in the first *Gaia* data release (DR1). By analyzing distant spectroscopically-identified OB stars in the Hipparcos subset in *Gaia* DR1, we find that the kinematic trends cannot be explained by a simple model of a long-lived warp. We therefore discuss possible scenarios for the interpretation of the obtained results. We also present current work in progress to select a larger sample of OB star candidates from the *Tycho-Gaia* Astrometric Solution (TGAS) subsample in DR1, and delineate the points that we will be addressing in the near future.

Keywords. Warp, Milky Way, Kinematics, Galactic evolution

1. Introduction

The warp of the Milky Way is a well known feature of the outer disk, whose presence has been detected in the gas, dust and stars. However, its dynamical nature - as well as the formation mechanism - continues to remain an unsolved mystery. In the case of a long-lived static warp, systematic vertical motions would result in measurable trends in the stellar proper motions (Smart & Lattanzi 1996), which become most significant toward the Galactic anti-center. We select OB stars since they can be seen to large distances and are expected to trace the gaseous disk, in which the warp was originally detected. Given the unprecedented astrometric precision, we first search for the warp kinematic signal the Hipparcos subset in the first *Gaia* data release (DR1, Gaia Collaboration 2016) (see Poggio *et al.* 2017, hereafter Paper I). Section 2 gives a brief overview of the obtained results and discusses possible interpretations. Section 3 is dedicated to the selection of OB stars candidates in the *Tycho-Gaia* Astrometric Solution (TGAS) sample in DR1.

2. Hipparcos subset in Gaia DR1

Data selection. From the Hipparcos catalog (van Leeuwen 2008), we spectroscopically select the OB3 stars with apparent magnitude $m_V < 8.5$ and parallax $\varpi < 2$ mas, in order to remove local structures. The resulting selection contains 989 stars, among which 758 are present in the Hipparcos subsample in *Gaia* DR1. In the following, we present and discuss the results obtained with the smaller sample having *Gaia* superior astrometry.

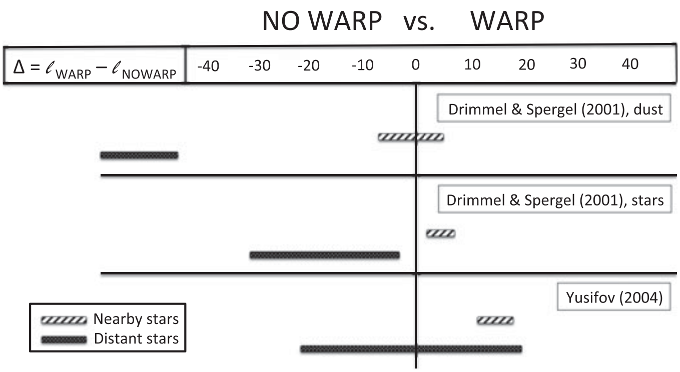

Figure 1. The difference of the loglikelihoods $\Delta = \ell_{WARP} - \ell_{NOWARP}$ (i.e. the likelihood ratio) for three different warp models according to the nearby ($1 < \varpi < 2$ mas) and distant ($\varpi < 1$ mas) stars of the sample. Positive (negative) values of Δ favour the warp (nowarp) model. The length of each bar is proportional to the uncertainty in Δ, calculated using bootstrap resamples.

The model. The modelled spatial distribution consists of four major spiral arms (Georgelin & Georgelin 1976, Taylor & Cordes 1993) and one local arm, with a gaussian density profile in the Galactic plane and an exponential vertical profile. Some spatial parameters are taken from the literature, while others are tuned to reproduce the longitude, latitude and apparent magnitude distribution observed in the data (see Paper I for the details). The kinematics is described by a simple model which includes solar motion from Schönrich *et al.* (2010), Galactic rotation from Bland-Hawthorn & Gerhard (2016) and velocity dispersions from Dehnen & Binney (1998). Astrometric errors are included in the model, together with the selection function of both Hipparcos catalogue and Hipparcos subset in *Gaia* DR1. Finally, the warp can be incorporated as a vertical displacement $z_W(R, \phi)$ in the z spatial coordinate, while its kinematic signal has a systematic offset $v_{z,W}(R, \phi)$ in the vertical velocities v_z.

Results. Depending on the warp spatial parameters, different kinematic signals are expected. Here we consider the three different sets of warp parameters, from Drimmel & Spergel (2001) (both dust and stars) and Yusifov (2004). The kinematic signal predicted by each of them is compared to the alternative model – the *nowarp* model, i.e. the absence of warp signal –, by constructing the expected probability distribution function in the proper motions μ_b as a function of galactic longitude l. Figure 1 summarizes our results, showing the likelihood of the various warp models with respect to the no warp model for our TGAS-Hipparcos dataset, divided into nearby ($1 < \varpi < 2$ mas) and distant ($\varpi < 1$ mas) stars. Our model for a long-lived warp predicts that the kinematic signal becomes stronger for larger distances, while the data do not show any evidence of warp signal for the most distant stars, consistent with the previous works of Smart *et al.* (1998) and Drimmel *et al.* (2000).

Interpretations. The absence of the warp kinematic signal in our dataset can be explained by several different scenarios. The first possible explanation is that our sample of OB stars in the Hipparcos subset of *Gaia* DR1 (approximately 0.5-3 kpc from the Sun) is not sufficiently sampling the Galactic warp. Indeed, there is no consensus about where the warp starts, although most studies find that the warp starts inside or close to the Solar circle (Momany *et al.* 2006; Reylé *et al.* 2009). Another possible interpretation is that the warp signal is overwhelmed by other perturbations, such as vertical waves in the disk (Gómez *et al.* 2013). Finally, it might be that our model of a long-lived stable warp is not appropriate, and additional effects should be taken into account, like precession

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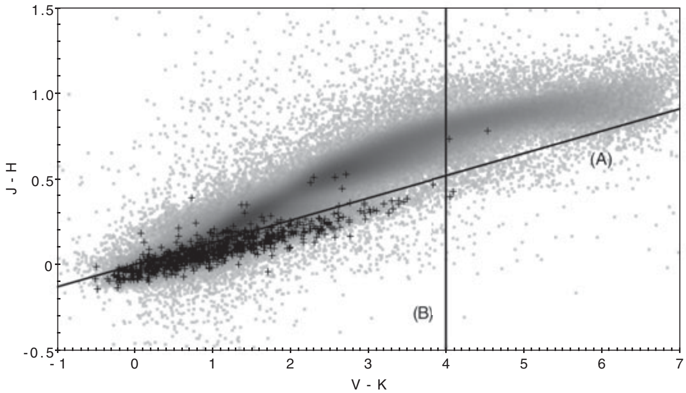

Figure 2. The TGAS stars with 2MASS and APASS photometry are represented by the grey dots, with the grey scale showing their density. Known O-B3 stars from the Tycho-2 Spectral Type Catalogue (black crosses) are located in the bottom-left part of the plot. Lines (A) and (B) are used for the selection process (see text).

or an amplitude varying with time. To shed further light on the nature of the Galactic warp it will be necessary to consider a larger dataset that samples a larger volumn of the Galactic disk.

3. TGAS in Gaia DR1

The selection of OB stars from the TGAS catalog is not trivial. Indeed, spectral classifications or parameter estimates such as $\log(g)$ and $T_{\rm eff}$ are available in literature only for a small fraction of TGAS stars, and not for the all sky. We therefore developed a selection criterium which combines astrometric with photometric measurements from the 2MASS (Skrutskie *et al.* 2006) and APASS (Henden *et al.* 2016) surveys, available for 1 824 237 TGAS stars. The first step of the method takes advantage of the fact that different stellar populations lie in different regions of the color-color plot shown in Figure 2. Known O-B3 stars from the Tycho-2 Spectral Type Catalogue (Wright *et al.* 2003, black crosses) are overplotted with the TGAS stars (grey density map). Extinction moves the OB stars to the right, but separated from the majority of giants and stars on the main-sequence. We begin by selecting all the TGAS stars below line (A) and bluer than line (B).

In order to reduce the fraction of contaminants that remain in our selected region of color-color space (mostly early A stars), we perform a second selection based on estimating the absolute magnitude of the stars using ϖ, σ_ϖ and G magnitude, assuming an exponentially decreasing prior for the heliocentric distance (similar to Bailer-Jones (2015)) and for the height from the Galactic plane. Taking extinction into account via the $(V - K)$ colors, we select as candidates those objects that have at least 75% probability of being brighter than B3 stars on the main sequence, resulting in ≈ 37000 candidate OB stars. Figure 3 shows the distribution on the sky of our selected sample. Applying our selection criterium to the Tycho-2 Spectral Type Catalogue, we estimate the amount of contamination from non-OB stars being about 40% for stars with $\varpi < 2$ mas and 30% for $\varpi < 1$ mas. However, the presence of late OB stars (i.e. with spectral type later than B3) is relevant ($\approx 40\%$ of the selected stars). The relatively high fraction of contaminants is expected to be reduced with better parallax measurements in future Gaia releases.

<u>*Future works*</u>. We are developing a tool aimed at determining the likelihood of a model, given an observed sample selected as above. The objective is to perform a parameter

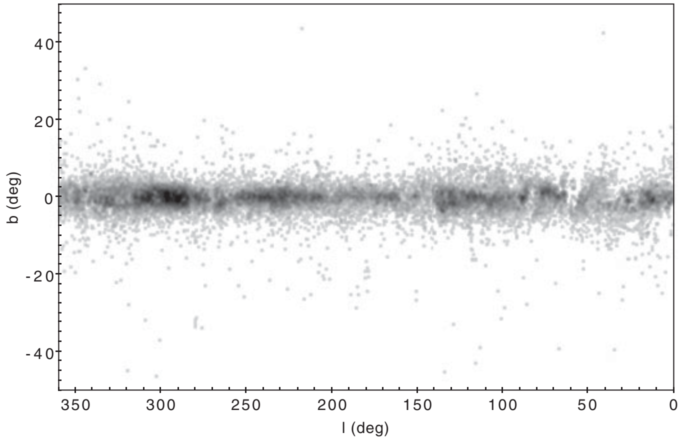

Figure 3. Location of the selected OB star candidates in the sky. The grey scale indicates stellar density.

adjustment for relevant kinematic warp parameters, such as the warp precession or possible amplitude variations.

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