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Galactic warp kinematics: model vs. observations

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Abstract

we test the capability of several methods to identify and characterise the warping of the stellar disc of our Galaxy in the Gaia era. We have developed a first kinematic model for the galactic warp and derived the analytical expressions for the force field of a warped Miyamoto- Nagai potential. We have generated realistic mock catalogues of OB, A and red clump stars within the warped galactic disc, where a very complete model of Gaia observables and their expected errors are included. We use the family of Great Circle Cell Counts (GC3) methods and LonKin methods for detecting and characterising the galactic warp. As a complementary work, we look into one of the existing proper motion catalogue namely the UCAC4, and look for the kinematic signature of the warp. We demonstrate the necessity of correcting for a possible residual rotation of the Hipparcos celestial reference frame with respect to the extra galactic inertial one.

1 Introduction

From the time when the first 21-cm hydrogen-line observations of our Galaxy became available, the large-scale warp in the HI gas disc became apparent (Burke 1957; Oort et al. 1958; among others). The warp in stellar component of the Milky Way was detected in the NIR first from COBE data (Freudenreich et al. 1994; Drimmel et al. 2001), and later using star counts obtained from Two Micron All Sky Survey (2MASS) near infrared data (Reyle et al. 2009). While studies using the star counts can provide us with fitting the geometrical warp parameters, it is clear that stellar kinematics must also be fitted to further constraint warp models. Using Hipparcos and Tycho-2 proper motions, several authors attempt to look for kinematic signature of the Galactic warp (Miyamoto & Zhu 1998; Drimmel et al. 2000;

Bobylev 2010; among others). Discrepant results were obtained from all these works, which demonstrate the difficulty, at present, to disentangle the kinematic signature of the warp from other nearby and local perturbations as well as uncertainties in defining an inertial frame with no residual spin.

2 Simulations

We want to generate a series of test particles ensembles that represent random realisations of our various warped and twisted models of the galactic disc. Ideally, they should be built in a way that they have the imprint of the warp in their phase space coordinates. We decide to do so using a test particle simulation so that the particle coordinates are set by the potential that is being warped through a real orbit integration. For this, we start with an axisymmetric galaxy mass model with a flat disc, and create a random realisation of it. We establish the mathematical transformation that allows us to introduce the warp into an initially flat disc potential and derive the resulting force field. We then proceed to warp adiabatically the initially flat disc potential, while the test particles are integrated in this time-varying potential. Finally, we let the ensemble to relax for a few more dynamical time-scales with the potential in its fixed, final configuration. In the case of twisted warps, the warp is first applied as previously described, but then the twist is introduced as a direct geometrical transformation applied to the phase space coordinates. The kinematic distribution of our synthetic samples mimic three different tracer populations: OB, A and Red Clump (RC) stars.

In order to build a 'Gaia mock catalogue', we convert these particle ensembles into sets of simulated stars by adding stellar parameters to them. In the next step, we convert their properties into Gaia observables and apply the Gaia selection function, together with an error and a 3D extinction model (Drimmel et al. 2003), in order to produce Gaia mock catalogues that correspond to the warp models we started with.

3 Tools

We use the family of Great Circle Cell Counts (GC3) methods which are robust and powerful methods for detecting and characterising the warp. These methods can work with the Gaia observables, with samples for which full six-dimensional phase-space information is provided (mGC3 method, introduced by Mateu et al. 2011); samples for which radial velocity is lacking (nGC3 method); or samples having only positional information (GC3 method, firstly introduced by Johnston et al. 1996).

The modified Great Circle Cell Counts method (mGC3) assume stars in a fixed galactocentric ring are confined to a great circle band, with their galactocentric position and velocity vector perpendicular to the normal vector which defines this particular great circle. The peak of the distribution in the pole count map, i.e. in the map of the number of stars associated to each great circle cell, is then identified using a Bayesian fitting procedure, which results in the identification of the tilt and twist angles of the warp and their corresponding confidence intervals.

Moreover, LonKin methods have been introduced which are basically the trend of vertical motions of stars as a function of galactic longitude. Using this method, we can predict the kinematic signature of the warp in the trends of W velocity component and the μ_b proper motion.

4 Results from simulations

We use our Gaia mock catalogues to check to what extent it is that we can recover the characteristics of our warp models from them using the GC3 methods. In Figure 1, we present the results of recovering tilt, ψ, and twist angles, ϕ, using the GC3 methods on the magnitude limited samples that includes the effects of the Gaia selection function, errors and the interstellar extinction. We also find that the OB and RC stars samples are good warp tracers, whereas the A stars sample is not quite up to the task for galactocentric distances larger than ~ 12 kpc, mainly due to their fainter intrinsic luminosity. We also found that the introduction of the kinematic information in the methods (mGC3 and nGC3) improves the recovery of the tilt angle (compared to the warp model imposed) to discrepancies less than $\sim 0.75°$.

Applying the LonKin methods to the mock catalogue of RC stars, we obtain a trend in the W velocity component and the μ_b proper motion that peaks with a maximum value towards the anti-centre and grows with galactocentric radius. This maximum peak in μ_b can reach to ~ 1.3 mas yr^{-1} at galactocentric $15 < r < 16$ kpc.

5 Results from the UCAC4 catalogue

We attempt to look for the kinematic signature of the galactic warp in the available proper motion catalogues. In Figure 2 bottom panel, we present the results using the RC stars in the UCAC4 catalogue (Zacharias et al. 2013). The distances to these stars are calculated using the IR photometric data of the 2MASS catalogue. As opposed to what expected from our warp model (seen in Figure 2 top panel), using the UCAC4 data, we obtain a μ_b trend with minimum towards anti-centre. We suspect that this trend is due to the systematic errors present in this catalogue mainly caused by a residual spin of the Hipparcos celestial reference frame with respect to the extra-galactic inertial one, ω. The reason why the μ_b trend can be significantly biased by the residual spin vector is that from our warp model, we expect the warp signature to be in the order of ~ 1 mas yr^{-1} and some of the reported values from the literature for the residual spin components (Bobylev 2010; Fedorov et al. 2011) are approximately of the same order.

Using a least squares fit and under the assumption that our warp model is similar to the one of the MW (i.e. assuming that it correctly reflects the kinematics of the Milky Way warp), we determine the residual spin components for which the UCAC4 data match the warp model. As shown in Table 1, the obtained values for the spin vector component towards the galactic rotation, ω_{2g}, show a reasonable agreement with the ones reported in the literature

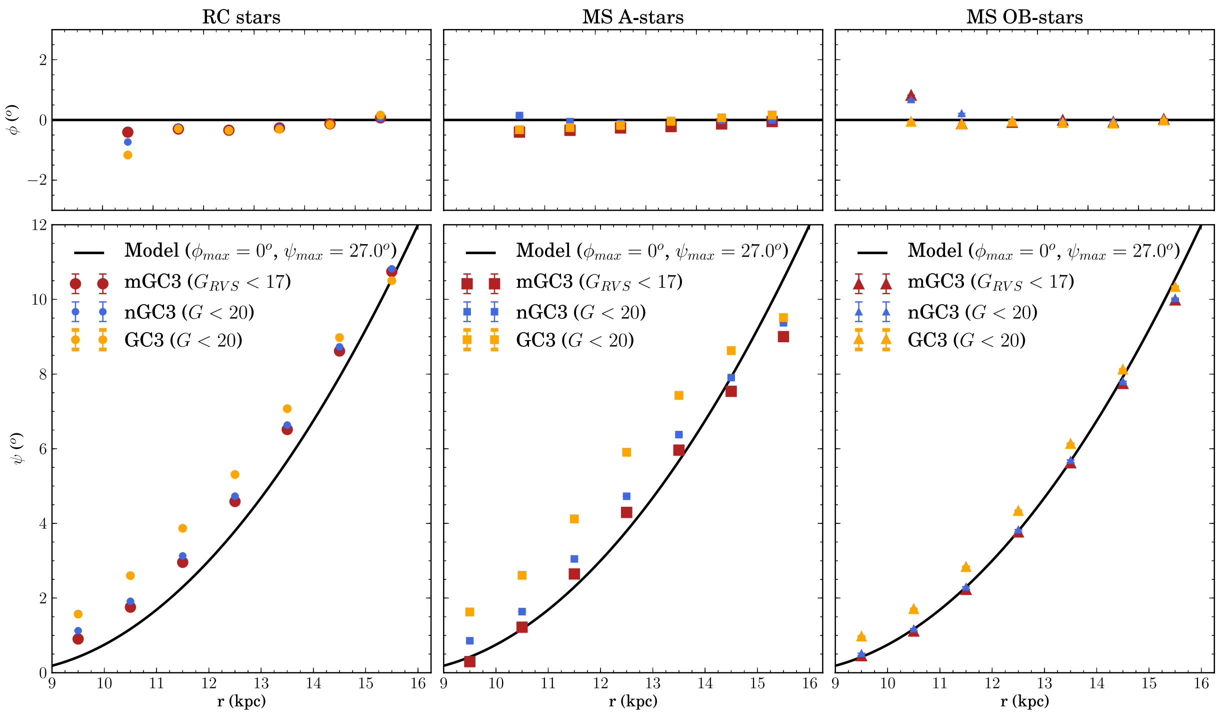

Figure 1: Tilt ψ and twist ϕ angles versus galactocentric (spherical) radius r for the magnitude limited samples (G < 20 for GC3 and nGC3, and $G_{RVS} < 17$ for mGC3) which are affected by the Gaia errors. Note that this sample initially has a null twist angle, which is recovered with a high precision for all tracers.

(Bobylev 2010; Fedorov et al. 2011). Since the UCAC4 catalogue is complete down to R∼16, we only identify a few hundreds of quasars. Due to their very large distances, these objects are supposed to have zero proper motions. We perform a least squares fit and check what should be the residual spin vector for which we obtain a zero proper motion for the identified quasars. Due to the small number of quasars in UCAC4, the resulting ω have large error bars and they agree to zero at the 2σ level.

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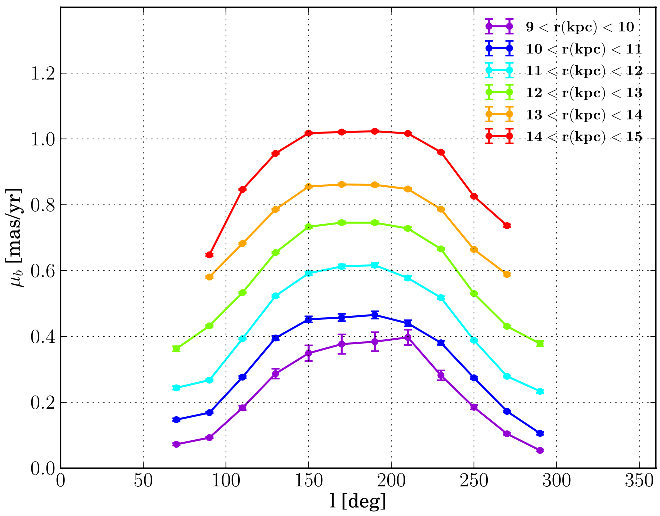

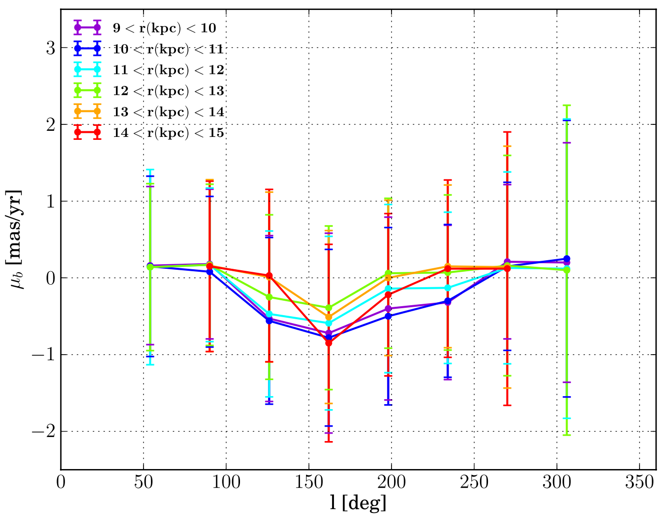

Figure 2: The median μ_b (referred to the LSR) as a function of galactic longitude for the sample of simulated RC stars with a similar magnitude limit as UCAC4 (top panel) and the sample of RC stars in UCAC4 catalogue (bottom panel). Different colours correspond to different radial bins (in kpc) as indicated in the figure. In the top panel, the error bars show the standard error of the median (the 95% confidence level). And, in the bottom panel the error bars indicate the both the error of the median and the one due to the 20% non-RC contamination in this sample.

Table 1: Components of the residual spin vector in equatorial, (ω_1, ω_2, ω_3), and galactic coordinates, (ω_{1g}, ω_{2g}, ω_{3g}), in units of $\mathrm{mas\,yr^{-1}}$. The reported values from the literature are also presented. The LSF refers to the results from our least squares fit. We also present the results from the same method after removing the outliers. Results obtained using the quasars of UCAC4 are also presented in the last row.

Method/Solution	ω_1	ω_2	ω_3	ω_{1g}	ω_{2g}	ω_{3g}
Bobylev (2010)	-0.11 ± 0.14	0.24 ± 0.10	-0.52 ± 0.16	0.05	-0.55	-0.19
Fedorov et al. (2011)	~ 0	~ 0	-1.8 ± 0.16	0.87	-1.34	-0.82
LSF	-	-	-	-0.129 ± 0.009	-1.92 ± 0.012	-
LSF, outliers removed	-	-	-	-0.09 ± 0.003	-1.55 ± 0.005	-
QSO	0.73	0.91	-1.05	-0.34 ± 0.51	-0.83 ± 0.52	-1.29 ± 0.72

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