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The kinematic signature of the Galactic warp with *Gaia* DR2

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Abstract

The second *Gaia* data release has published high-precision astrometric measurements for over a billion sources. In the coming years, Gaia data will make fundamental contributions to numerous open questions on the evolution of our Galaxy. We here focus on the long-standing debate on the origin and dynamical nature of the warp of our Galaxy, with particular attention to the warp-induced motions in stellar kinematics. Taking advantage of *Gaia* DR2 data, we detect the kinematic signature of the Galactic warp out to a distance of 7 kpc from the Sun. The signature manifests itself as a gradient of 5-6 km/s in the vertical velocities from 8 to 14 kpc in Galactic radius, with a signal-to-noise larger than 10. The signal is present in two samples of intrinsically young and old stellar populations, selected via a probabilistic approach. Based on our results, we argue that the warp is principally a gravitational phenomenon, thus placing an important constraint on the possible formation scenario. Finally, we observe that the old stellar populations present a smooth signal, as expected from a dynamically relaxed population, while the young sample exhibit a strongly perturbed kinematic pattern.

1 Introduction

The Galactic warp was first observed in the radio observations of neutral hydrogen more than 60 years ago (Burke, 1957); its presence was also confirmed in the dust and stars (e.g. Drimmel & Spergel, 2001; Momany *et al.*, 2006). Observations of external galaxies showed that the Milky Way is not peculiar in this respect: most spiral galaxies are warped. Notwithstanding the apparent simplicity of their stucture, the origin and dynamical nature of warps in disk galaxies continue to remain a mystery (Sellwood, 2013). Several formation mechanisms have been proposed, such as interactions with satellites, intergalactic magnetic fields, accretion of intergalactic matter, and a misaligned dark halo, amongst others. Notwithstanding the great variety of proposed warp formation mechanisms, which is actually at work for our own Galaxy remains a mystery.

Our Milky Way presents the opportunity for a unique case study of galactic warps, considering that stellar motions can be studied on a star-by-star basis. In particular, the kinematic signature of the Galactic warp is expected to manifest itself toward the Galactic anti-center as large-scale systematic velocities perpendicularto the Galactic plane (e.g. Poggio *et al.*, 2017). Using data from the second *Gaia* data release (hereafter *Gaia* DR2, Gaia Collaboration *et al.*, 2018a), we can study stellar kinematics in unprecedented detail.

2 Data

Combining Gaia DR2 and 2-Micron All Sky Survey (2MASS) photometry, we identify two samples of upper main sequence (UMS) and giant stars without the need for individual extinction estimates. The selection is based on a preliminary cut on 2MASS colours, and later refined via a probabilistic approach (see the details in Poggio *et al.*, 2018). We also apply a cut in galactic latitude $|b| < 20^{\circ}$ and apparent magnitude G <15.5, as very few fainter stars have 2MASS photometry. We obtain 599 494 UMS stars and 12 616 068 giants stars. Bayesian distance estimates (details in Poggio *et al.*, 2018) are derived for the stars of the two samples, assuming a density model for the Galactic disk, combined with the selection function of the survey, similarly to Astraatmadja & Bailer-Jones (2016). Using distances and galactic coordinates, we construct density maps (not shown here) for the two samples. The density profile of the giant sample appears as a smooth distribution, decreasing for large heliocentric distance, as expected for a magnitude limited sample, and for large Galactocentric radii, as expected from an exponential disc. In contrast, the UMS sample exhibit three observed overdensities, that correspond to sections of the nearby spiral arms (the Sagittarius-Carina arm, local arm and Perseus arm). The evident spiral structure confirms that our UMS sample is young with respect to the smooth distribution shown by the older and dynamically relaxed giant population. The comparison of the kinematic trends of the two samples, which have different typical ages, can provide important clues to the evolution of the Galaxy, as discussed in the following.

3 Results

A face-on view of the vertical kinematics is shown in Figure 1 for the two samples. Vertical velocities are calculated deriving the proper motions in galactic latitude μ_b from the *Gaia* DR2 astrometry and correcting for the solar motion $(V_{X\odot}, V_{Y\odot}, V_{Z\odot}) = (11.1, 12.24, 7.25)$ km s^{-1} (Schönrich *et al.*, 2010). For the large majority of stars in our UMS sample, line-of-sight velocities are not available, so that it is not possible to calculate directly the vertical velocity. We therefore estimate the mean vertical velocity V_Z' from the available astrometry, correcting for solar motion and differential Galactic rotation, assuming a flat rotation curve ($V_c = 240$ km/s, Reid *et al.*, 2014) (see Equation 8 of Drimmel *et al.*, 2000), as done in Gaia Collaboration *et al.* (2018b). 3 042 265 objects in our giant sample have *Gaia* DR2 line-of-sight velocities, for which we calculate directly the vertical velocity, while for the remaining we estimate the vertical velocities as done for the UMS sample. Moreover, for the subsample of stars having line-of-sight velocities, we have verified that our approximation of using V_Z' instead of V_Z produces consistent results.

The two samples present both a systematic increase of the vertical velocities of 5-6 km/s from 8 to 14 kpc in Galactocentric radius, with a signal-to-noise greater than 10. We interpret the observed gradient as the large-scale kinematic signature of the Galactic warp (Poggio *et al.*, 2018). The peak velocities in both samples appear to be not exactly toward the Galactic anti-center. This is presumably caused by the Sun not being on the line-of-nodes of the warp (Chen *et al.*, 2019); however, in the case of a lopsided warp, the line-of-nodes doesn't coincide with the maximum vertical velocities (Romero-Gómez *et al.*, 2018).

Figure 2 shows the variation of the vertical velocities in function of Galactic radius R. It is apparent from Figure 2 (right) that the vertical velocities of the giant sample increase smoothly with R, as expected from a dynamically relaxed stellar population. By contrast, the UMS sample exhibit a perturbed pattern inside 12 kpc from the Galactic center, showing a steep increase at larger Galactocentric radii.

Several tests were performed to confirm the robustness of the observed signal. Consistent results were obtained by limiting ourselves to the subsets of stars having $\varpi/\sigma_\varpi > 5$ (478 258 UMS stars and 6 373 188 giants). Moreover, we recalculated distances with the iterative approach of Schönrich & Aumer (2017) for $20^o < l < 340^o$, finding a consistent gradient. We also slightly modified the prior (e.g. assuming $L_R = 4$ kpc for the UMS sample or including a thick disc for the giant sample), always confirming the presence of the signal. We also verified that adopting as distance estimator the mode (following Bailer-Jones, 2015) or the median of the pdf produces consistent results. Finally, we explored the impact of a systematic zero-point error (exploring the range ± 0.080 mas) of *Gaia* DR2 parallaxes (Lindegren *et al.*, 2018), which only results in a contraction/expansion of the maps, but still preserves the presence of a gradient in the vertical velocities.

4 Discussion and conclusions

Taking advantage of the unprecedentedly large volume of Gaia DR2 data with exquisite astrometry, we have mapped the vertical kinematics of the Galactic disc over a larger extent than previously possible. We selected two samples of UMS and giant stars, and detected the kinematic signature of the Galactic warp in both samples. The presence of the signal in both populations, which have different typical ages, indicates that the warp is principally a gravitational phenomenon. Indeed, purely non-gravitational warp formation mechanisms (e.g. magnetic or hydrodynamical forces) would warp only the gaseous component, whose kinematics would be inherited by young stars. However, such an evidence of an initial warp kinematic signal would be erased by phase mixing in old stellar populations. The involvement of gravitational forces represents an important constraint on the possible warp formation scenario.

However, the kinematic trends observed in two samples present some differences. The giant sample exhibit a smooth gradient in vertical velocities, while the UMS sample exhibit a perturbed pattern, indicating a different response of the gas (traced by young populations) and stars to a perturbative agent. Possible candidates include the interaction with non-axisymmetric features (e.g. bar and spiral arms), external perturbers (the Sagittarius dwarf galaxy and/or the Magellanic clouds), and magnetic fields.

By depicting a general picture of the vertical motions out to approximately 7 kpc from the Sun, Gaia DR2 have already made an important contribution to the understanding of the nature of the Galactic warp, placing previous results on a wider context (Gaia Collaboration *et al.*, 2018b; Schönrich & Dehnen, 2018; Poggio *et al.*, 2017). However, numerous questions regarding the warp are still unanswered. Future work confronting this signature with self-consistent warp models and/or N-body simulations (Laporte *et al.*, 2019) will certainly reveal further details of the dynamical nature of the Galactic warp.

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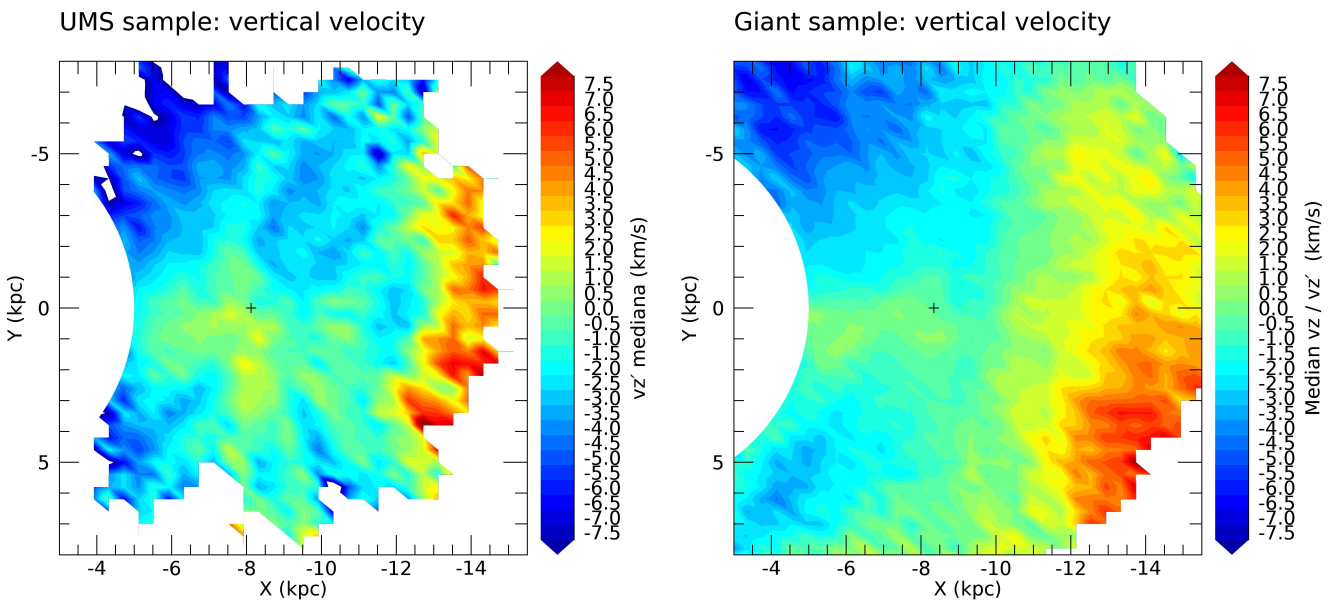

Figure 1: Maps of the vertical velocity V_Z or V_Z' (see text) for the Upper Main Sequence (UMS, left plot) and giant (right plot) sample. The Sun is represented by a black cross at X = -8.35 kpc and Y=0 kpc. The Galactic center is located at X=0 kpc and Y=0 kpc, and the Galaxy is rotating clockwise. The XY plane was divided into cells of 400 pc width, only showing the ones containing more than 50/500 stars for the UMS/giant sample.

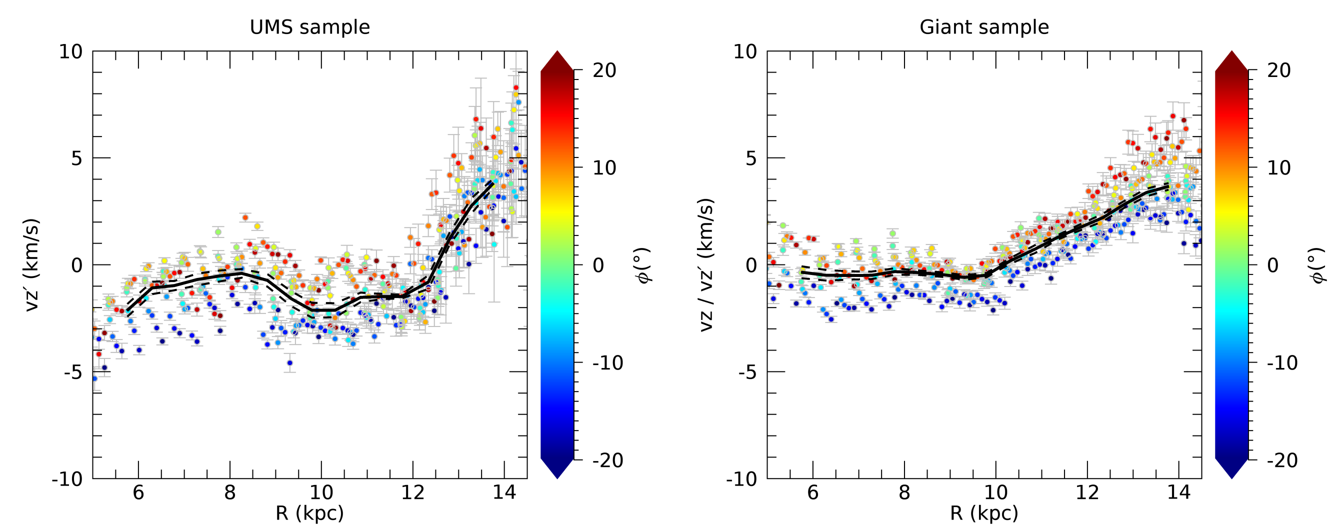

Figure 2: The variation of the vertical velocity V_Z or $V_Z\prime$ (see text) as a function of Galactocentric radius R for the UMS (left plot) and the giant (right plot) stars. Every point corresponds to a cell in the kinematic maps from Figure 1 (left and right, respectively). Gray error bars show the bootstrap error on the median for each cell. Points are color-coded by Galactic azimuth ϕ; we only show the cells with $|\phi| < 20^o$. The black solid line show the median of the points, while the dashed line shows the bootstrap error on the median.

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