Mapping the Galactic Disk with the LAMOST and Gaia Red Clump Sample. IV. The Kinematic Signature of the Galactic Warp

X.-Y. Li1, Y. Huang1,4, B.-Q. Chen1, H.-F. Wang1,3, W.-X. Sun1, H.-L. Guo1, Q.-Z. Li2, and X.-W. Liu1,4

1 South-Western Institute for Astronomy Research, Yunnan University, Kunming 650500, People’s Republic of China; yanghuang@ynu.edu.cn, x.liu@ynu.edu.cn
2 Yunnan Observatories, Chinese Academy of Sciences, Kunming, Yunnan 650011, People’s Republic of China

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Abstract

Using a sample of nearly 140,000 red clump stars selected from the LAMOST and Gaia Galactic surveys, we have mapped mean vertical velocity \( \langle V_z \rangle \) in the X–Y plane for a large volume of the Galactic disk (6 < \( R < 16 \) kpc; \(-20 < \phi < 50^\circ; |Z| < 1\) kpc). A clear signature where \( \langle V_z \rangle \) increases with \( R \) is detected for the chemically thin disk. For the signature of the thick disk, however, is not significant, in line with the hot nature of this disk component. For the thin disk, the warp signature shows significant variations in both the radial and azimuthal directions, in excellent agreement with the previous results of star counts. Fitting the two-dimensional distribution of \( \langle V_z \rangle \) with a simple long-lived static warp model yields a line-of-node angle for this kinematic warp of about 12°5, again consistent with the previous results.

Unified Astronomy Thesaurus concepts: Milky Way disk (1050); Milky Way dynamics (1051); Stellar kinematics (1608); Red giant branch (1368)

1. Introduction

Disk warping in the outer regions of spiral galaxies (>50%) is a very common phenomenon (e.g., Saha et al. 2009). In general, the inner disk of a spiral galaxy is largely flat whereas the outskirts show a significant warp signature. The warp amplitude increases strongly with radius, reaching as large as a few times the inner disk scale height. Being a typical spiral galaxy, the Milky Way (hereafter MW) also shows a clear warp in the outer disk. The Galactic warp was first detected by Kerr (1957) with H I 21 cm line observation. This was confirmed later by Weaver & Williams (1974) and Henderson (1979). Not just the neutral gas, but other components of the Galactic disk including the stars (Efremov et al. 1981; Reed 1996; López-Corredoira et al. 2002b), molecular clouds (Wouterloot et al. 1990), and interstellar dust grains (Marshall et al. 2006; Chen et al. 2019a) also show that the Galactic outer disk is strongly warped. Studies show that one part of the Galactic outer disk bends up from the Galactic plane to the north Galactic pole, whereas the other part bends down. Further studies indicate that the warp amplitude not only increases strongly with radius but also changes with azimuthal angle. The line-of-node angle with respect to the Sun–Galactic center line is estimated by different groups using different tracers to range between \(-5^\circ\) and \(26^\circ\) (e.g., López-Corredoira et al. 2002b; Momany et al. 2006; Chen et al. 2019b; Skowron et al. 2019).

Theoretically, warping of a spiral galaxy is generally interpreted as the response of the disk to perturbations. For our MW, the perturbations may come from: (i) the interactions of the Galactic disk with nearby satellite galaxies (e.g., the Large and Small Magellanic Clouds or the Sagittarius dwarf galaxy; Weinberg 1995; García-Ruiz et al. 2002; Bailin 2003); (ii) effects of the triaxial dark-matter halo (Sparke & Casertano 1988; Debattista & Sellwood 1999); or (iii) the accretion of infalling intergalactic gas (Jiang & Binney 1999; López-Corredoira et al. 2002a; Sánchez-Salcedo 2006). While many scenarios have been proposed, the exact origin of the Galactic warp remains unclear. Further information on the kinematic signature of the Galactic warp would be invaluable to clarify the situation.

Prior to the first Gaia data release (DR1), several studies (e.g., Miyaïmotó et al. 1988; López-Corredoira et al. 2014) attempted to unravel the kinematic signature of the Galactic warp, using catalogs of ground-based proper-motion measurements. The results are inconclusive due to the limited accuracy of the proper motions employed. With the release of Gaia DR1 (Gaia Collaboration et al. 2016; Lindgren et al. 2016), accurate measurements of proper motions and parallaxes for over two million stars became available. With the data, Poggio et al. (2017) have detected the signature of kinematic warp by using nearby OB stars. With Gaia DR1 and the spectroscopic information from the RAVE and Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) surveys, Schönrich & Dehnen (2018) and Huang et al. (2018) have calculated values of vertical velocity \( V_z \), azimuthal velocity \( V_\phi \), and vertical angular momentum \( L_z \) for stars in the solar neighborhood. They find that the mean vertical velocity \( \langle V_z \rangle \) increases with \( V_\phi \), \( L_z \), and the guiding center radius \( R\) (e.g., Poggio et al. 2017; hereafter Paper I) are use two samples, one of stars of the upper main sequence and another of red giant stars, and study the kinematic signature of the Galactic warp in the X–Y plane out to a distance of 7 kpc from the Sun. However, for their giant sample, only 24% of the stars have line-of-sight velocities. The distances, estimated from the Gaia parallaxes, for more distant stars may also suffer from serious systematics (e.g., Schönrich et al. 2019). Recently, Huang et al. (2020; hereafter Paper I), based on data from the LAMOST and Gaia surveys, published a sample of about 140,000 red clump (RC) stars with accurate measurements of distance, proper motions, stellar atmospheric parameters (effective temperature \( T_{\text{eff}} \), surface gravity log \( g \), and metallicity [Fe/H]), line-of-sight velocity \( V_{\text{lino}} \), and \( \alpha \)-element to iron abundance ratio \([\alpha/Fe] \). The
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Figure 1. Spatial distribution of the RC sample stars in the X-Y (left) and R-Z (right) planes. The stellar number densities (in bins of size 0.1 kpc for both axes) are represented by color bars on top, with no fewer than five stars in each bin. The Sun is represented by a black star at $X = -8.34$ kpc, $Y = 0$ kpc and $Z = 0.025$ kpc.

sample allows one to study the warp signature over a large volume for both the chemically thin and thick populations.

The paper is organized as follows. In Section 2, we define the coordinate systems and describe the data used. The results are presented and discussed in Section 3. Finally, a summary is presented in Section 4.

2. Coordinate Systems and Data

2.1. Coordinate Systems

In this paper, we use two coordinate systems. A Galactocentric cylindrical-coordinate system $(R, \phi, z)$, along with associated velocity components $(V_R, V_\phi, V_z)$, is defined with $R$ being the projected Galactocentric distance, $\phi$ the azimuthal angle increasing in the direction of Galactic rotation, and $z$ the height above the Galactic plane in the direction of the north Galactic pole. The velocity components are calculated from the sky positions, distances, line-of-sight velocities, and proper motions, using the standard transformations from Johnson & Soderblom (1987). We adopt the Galactocentric distance of the Sun $R_0$ of 8.34 kpc (Reid et al. 2014) and circular velocity at the solar radius of $V_c(R_0) = 238$ km s$^{-1}$ (Huang et al. 2016). We take solar motions with respect to the local standard of rest $(U_0, V_0, W_0) = (11.10, 12.24, 7.25)$ km s$^{-1}$ (Schönrich et al. 2010). Other values of the solar motions (e.g., Huang et al. 2015) are also tried and the results obtained are essentially the same. Also used is a right-handed Cartesian Galactocentric coordinate system $(X, Y, Z)$, with $X$ pointing toward the Galactic center, $Y$ in the direction of Galactic rotation, and $Z$ toward the north Galactic pole.

2.2. Data

LAMOST is a 4 m quasi-meridian reflecting Schmidt telescope equipped with 4000 fibers distributed in a field of view of about 20 square degrees. It can simultaneously collect spectra per exposure of up to 4000 objects, covering the wavelength range of 3800–9000 Å at a resolving power $R$ of about 1800 (Cui et al. 2012). The five-year Phase-I LAMOST Regular Surveys started in the fall of 2012 and were completed in the summer of 2017. The scientific motivations and target selections of the surveys are described in detail in Deng et al. (2012), Zhao et al. (2012), and Liu et al. (2014). Atmospheric parameters ($T_{\text{eff}}, \log g, [\text{Fe/H}]$), line-of-sight velocity $V_{\text{los}}$, and $\alpha$-element to iron abundance ratio [$\alpha$/Fe] of the targeted stars are derived with the LAMOST Stellar Parameter Pipeline at Peking University (Xiang et al. 2015, 2017). Gaia DR2 has been made available to the community since 2018 April, providing accurate parallax and proper-motion measurements for about 1.3 billion stars (Gaia Collaboration et al. 2018a). Typical uncertainties of the parallaxes are 0.04 mas for bright sources ($G < 14$ mag), 0.1 mas at $G = 17$ mag, and 0.7 mas at $G = 20$ mag. For the proper motions, typical uncertainties are 0.05, 0.2, and 1.2 mas yr$^{-1}$ at $G < 14$ mag, $G = 17$ mag, and $G = 20$ mag, respectively.

In the current work, a sample of nearly 140,000 RC stars has been used. The sample is described in Paper I, constructed with data from the LAMOST and Gaia surveys. Given the standard candle nature of RCs, distances of those stars have been measured with a typical accuracy of 5%–10%, more precise than values yielded by the Gaia parallax measurements for stars beyond 3–4 kpc. With the derived distances, line-of-sight velocities, proper motions, and [Fe/H] and [$\alpha$/Fe] values for the LAMOST and Gaia RC sample stars, we have derived 3D positions and velocities for all the sample stars, and examined the velocity field of disk stars. The current work concentrates on the vertical-velocity field of disk stars of different populations in a large disk volume. The spatial distribution of our sample stars is presented in Figure 1. The sample covers a large volume of the Galactic disk of $-16 \leq X \leq -4$ kpc, $-3 \leq Y \leq 6$ kpc and $|Z| \leq 3$ kpc.

3. Results and Discussion

The mean vertical-velocity field of the (outer) Galactic disk can be significantly perturbed in the long-lived warp model.
chemically thin and thick disk stars within the thick disk in the plane. The cuts result in 94,028 and 5212 populations, one of the chemically thin disk and another of the thick disk population. Figure 2 shows that a bimodal distribution is clearly seen. As in the previous studies (e.g., Bensby et al. 2005; Lee et al. 2011; Haywood et al. 2013), we define cuts to separate the two populations, one of the chemically thin disk and another of the thick disk in the plane. The cuts result in 94,028 and 5212 chemically thin and thick disk stars within \( |Z| < 1 \) kpc (close to the Galactic plane), respectively. The mean values of vertical velocity \( \bar{V}_z \) as a function of \( R \) for the chemically thin and thick disk stars are presented in the right panel of Figure 2. The plot shows that \( \bar{V}_z \) of the chemically thin disk stars increases with \( R \), from \(-1.5 \) km s\(^{-1}\) at \( R = 8 \) kpc to 4.5 km s\(^{-1}\) at \( R = 13 \) kpc. The trend is similar to that reported in P18 (see their Figure 3).

In addition to what found for the chemically thin disk population, we have tried to detect the warp signature for the chemically thick disk population. Figure 2 shows that \( \bar{V}_z \) of the chemically thick stars presents a very weak positive trend with \( R \), from \(-1 \) km s\(^{-1}\) at \( R = 8 \)–10 kpc to 2.5 km s\(^{-1}\) at \( R = 12 \)–13 kpc. Due to the limited number of thick-disk stars, the uncertainties of mean vertical velocities are large (the typical uncertainty is about 1.6 km s\(^{-1}\)). According to the above analysis, only 2.2\( \sigma \) detection is found for the thick-disk population on the kinematic warp. In the future, more thick-disk stars are required to random errors of mean \( \bar{V}_z \) to clarify whether there is a clear kinematic warp for the thick-disk population. On the other hand, a weak/insignificant kinematic warp signature for the thick-disk population is in line with the hot nature of orbits of the thick-disk stars (i.e., of large velocity dispersions in all directions; e.g., Chiba & Beers 2000; Bensby et al. 2003; Parker et al. 2004). Because of their hot nature, the thick-disk stars are less sensitive to the warp perturbations than the thin-disk stars and the large velocity dispersions (especially in the radial direction) of the thick-disk population can smooth the warp signature along the \( R \) direction.

To fully understand the weak/insignificant warp signature of the thick-disk population, both observational efforts (by obtaining more thick-disk stars) and theoretical dynamical modeling are required.

For the thin-disk population, we extract the kinematic warp signature shown in Figure 2 in different azimuthal slices, from \(-15^\circ\) to \(35^\circ\). The results are presented in Figure 3. The positive trend of \( \bar{V}_z \) increasing with \( R \), i.e., the kinematic warp signature, is seen in almost all the azimuthal slices. The amplitude of

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**Figure 2.** Left panel: distribution of the RC sample in the [Fe/H]–[α/Fe] plane. Thick-disk stars lie above the blue line while those of the thin disk fall below the red line. The stellar number densities in bins of size 0.014 dex in the horizontal axis and of 0.006 dex in the vertical axis are indicated by the top color bar. Right panel: the blue and orange solid lines represent mean vertical velocities of the chemically thin and thick stars, respectively. The bin size in \( R \) is 0.4 kpc for \( R < 10.2 \) kpc and 1 kpc for \( R \geq 10.2 \) kpc, comparable with the typical distance uncertainties. The shaded areas represent the \( \pm 1\sigma \) uncertainties (estimated with a bootstrapping procedure) of the mean vertical velocities.

**Figure 3.** \( R-V_z \) diagram of 94,028 thin-disk sample stars. The blue, orange, green, red, purple, and magenta solid lines represent the mean vertical velocities of stars in the azimuthal angle ranges \( \phi \in [-15.0, -5.0], [-5.0, 0.0], [0.0, 5.0], [5.0, 10.0], [10.0, 17.0] \) and [17.0, 35.0] deg, respectively, with the shaded areas representing the \( \pm 1\sigma \) uncertainties (estimated with a bootstrapping procedure) of the mean vertical velocities.
Warp signature increases with the azimuthal angle $f$ and reaches a maximum in slice $f \in [10, 17]$ deg, and then decreases slightly in the last azimuthal slice. In the scenario of a long-lived static Galactic warp model, the variations of warp amplitude with $f$ presented here indicate a line-of-node angle between $10^\circ–17^\circ$. To obtain a more precise estimate, in the next subsection we fit the distribution of $V_z$ in the $X–Y$ plane with a naive long-lived static warp model.

3.2. Fitting the $V_z$ Distribution with a Simple Model

To fit the kinematic warp with a theoretical model, the distribution of the mean vertical velocity in the Galactic plane is presented in Figure 4(a). The general trend of variations with $R$ and $\phi$ are similar to those found in P18. Theoretically, the Galactic warp can be simulated either by a transient model (e.g., Christodoulou et al. 1993; Debattista & Sellwood 1999) or a long-lived one (e.g., Smart et al. 1998; López-Corredoira et al. 2002b; Poggio et al. 2017). Observationally, the results from star counting prefer the latter (e.g., Djorgovski & Sosin 1989; López-Corredoira et al. 2002b). To fit the distribution of $V_z$ found here for the chemically thin disk population, we have adopted the long-lived static warp model proposed by Poggio et al. (2017), see their Equation (3). We have simply assumed that the mean azimuthal velocity $V_\phi$ is constant, and $R_\phi$ is zero (i.e., the warp
starts at the Galactic center; e.g., López-Corredoira et al. (2002b). We have also added a constant $c$, corresponding to the mean vertical velocity at $R = 0$ or $|\phi - \phi_0| = \pi$ to the warp equation. The final simplified model adopted here is then

$$V_\phi = aR^b \cos(\phi - \phi_0) + c,$$

where $\phi_0$ is the line-of-node angle of the warp.

To fit the observational data, values of $V_\phi$ are calculated for the individual bins of $R$ and $\phi$, and the uncertainties of the mean vertical velocities are estimated with a bootstrapping procedure. The bin size in $R$ is 0.2 kpc and that in $\phi$ is allowed to vary but no less than 1° such that there are at least 40 stars in a bin. This results in total of 776 bins. Values of $V_\phi$ of those bins are then fitted with the model described by Equation (1), using a Markov Chain Monte Carlo method. The best-fit model yields the following parameters

$$a = 3.97^{+1.77}_{-1.24},$$

$$b = 0.64^{+0.10}_{-0.09},$$

$$c = -15.31^{+2.40}_{-2.97} \text{ km s}^{-1},$$

$$\phi_0 = 12.5^{+2.0}_{-1.8} \text{ degree}.$$ (5)

The line-of-node angle obtained above agrees very well with recent estimates using pulsars (Yusifov 2004), RCs and red giants (Momany et al. 2006), and Cepheids (Chen et al. 2019b) as tracers. We note that this is the first estimate of the line-of-node angle of the Galactic warp using kinematic data. However, the other best-fit value of the warp amplitude $a$ found here is not consistent with the results reported by previous star count analysis (e.g., López-Corredoira et al. 2002b; Yusifov 2004; Momany et al. 2006; Chen et al. 2019b). This may indicate additional kinematic parameters are required to explain this kinematic warp (like a precession; e.g., Poggio et al. 2020). Also, we note that the very large negative value for the parameter $c$ is unconvincing. It is probably a consequence of assuming that the warp starts at the center of the Galaxy. In Figure 5, we show two typical examples of the best fit for constant $\phi = 0^0$ and for constant $R = 9$ kpc. Generally, the model fits the observational data quite well. The model predicted $V_\phi$ distribution, the uncertainties of the mean vertical velocities, and the fit residuals are also presented in Figure 4. The residuals are largely within 1 km s$^{-1}$.

The variations of the line-of-node angle as a function of $R$ is explored by Chen et al. (2019b). Using over 1000 classical Cepheid stars, they find that the line-of-node angle first decreases with $R$ for $R$ between 8–12 kpc and then increases with $R$ for $R$ between 12–15 kpc, and tends to twist near $R = 15.5$ kpc. They claim that the increase of the line-of-node angle between 12–15 kpc is evidence that the warp in the outer disk is predominately induced by torques associated with the massive inner disk. Our current data of mean vertical velocities do not show clear variations of the line-of-node angle with $R$. This might largely be due to (i) the relatively large uncertainties of the mean vertical velocities (see Figure 3 and Figure 4(b)); and (ii) the limited azimuthal angle coverage of the data. In the near future, this issue could be solved by adding more RC stars to the sample, selected from new LAMOST observations and the planned Sloan Digital Sky Survey (SDSS) V surveys. Moreover, the additional data could allow one to explore the dynamical evolution of the Galactic warp (Poggio et al. 2020).

4. Summary

In this paper, using a sample of nearly 140,000 RCs with accurate 3D position and velocity measurements, constructed with data from the LAMOST and Gaia surveys, we have explored the kinematic warp signature of the Galactic disk(s). With cuts in the [Fe/H]–[$\alpha$/Fe] plane, 94,028 and 5212 chemically thin and thick disk stars of $|Z| < 1$ kpc are selected from the sample. A kinematic signature of warp is clearly detected in the data for the chemically thin disk population, but the signal is not significant for the chemically thick disk population. For the thin-disk population, a clear positive gradient of mean vertical velocity as a function of $R$ is found for $R$ between 8–13 kpc. The trend agrees with the recent results from Gaia DR2 and is also consistent with the prediction of the long-lived large-scale Galactic warp model. The warp signature for the thick-disk population is much weaker, largely due to the hot nature of orbits of thick-disk stars. For the thin-disk stars, we further explore the variations of mean vertical velocity (as a function of $R$) for the different azimuthal slices and find the amplitude of warp increases with $\phi$ and reaches a maximum in slice $\phi \in [10, 17]$ deg. To quantitatively determine the line-of-node angle of the warp, we fit the distribution of mean vertical velocities of the thin-disk stars with a long-lived static warp model and find an angle around...
12°, in excellent agreement with the previous estimates from star counting.

Based on the current study alone, it is still difficult to constrain the exact origin of the Galactic warp. However, with more data expected from the ongoing and forthcoming LAMOST, SDSS and Gaia surveys, vital clues about the origin and evolution of the Galactic warp should become available in the near future.

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ORCID iDs
Y. Huang https://orcid.org/0000-0003-3250-2876

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