The Galactic Disk Phase Spirals at Different Galactic Positions Revealed by Gaia and LAMOST Data

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Abstract

We have investigated the distributions of stellar azimuthal and radial velocity components $V_{\phi}$ and $V_{R}$ in the vertical position–velocity plane $Z-V_{\phi}$ across the Galactic disk of $6.34 \lesssim R \lesssim 12.34$ kpc and $|\theta| \lesssim 7.5^\circ$ using a Gaia and Gaia-LAMOST sample of stars. As found in previous works, the distributions exhibit significant spiral patterns. The $V_{\phi}$ distributions also show clear quadrupole patterns, which are the consequence of the well-known tilt of the velocity ellipsoid. The observed spiral and quadrupole patterns in the phase space plane vary strongly with radial and azimuthal positions. The phase spirals of $V_{\phi}$ become more and more relaxed as $R$ increases. The spiral patterns of $V_{\phi}$ and $V_{R}$ and the quadrupole patterns of $V_{R}$ are strongest at $-2^\circ < \Phi < 2^\circ$ but negligible at $4^\circ < \Phi < 6^\circ$ and $-6^\circ < \Phi < -4^\circ$. Our results suggest an external origin of the phase spirals. In this scenario, the intruder, most likely the previously well-known Sagittarius dwarf galaxy, passed through the Galactic plane in the direction toward either Galactic center or anti-center. The azimuthal variations of the phase spirals also help us constrain the passage duration of the intruder. A detailed model is required to reproduce the observed radial and azimuthal variations of the phase spirals of $V_{\phi}$ and $V_{R}$.

Key words: Galaxy: disk – Galaxy: kinematics and dynamics – Galaxy: structure

1. Introduction

It is recognized that the Milky Way is not steady and axisymmetric. The stellar populations of the Milky Way disk are perturbed by non-axisymmetric structures, including the Bar, the Spiral arms, the halo substructures, and the satellite dwarf galaxies (Siebert et al. 2012; Gómez et al. 2013; Bovy et al. 2015), and therefore show significant phase spirals (Antoja et al. 2018; Bland-Hawthorn et al. 2019; Tian et al. 2018), as well as radial motions and vertical bulk motions (Siebert et al. 2011; Carlin et al. 2013; Williams et al. 2013; Sun et al. 2015; Huang et al. 2016; Carrillo et al. 2018; Wang et al. 2018). Studying those phase spirals and bulk motions can help us understand the perturbation history of the Milky Way (disk).

Antoja et al. (2018) first detected the remarkable phase spirals in the local stellar disk. They found that the distributions of stellar radial and azimuthal velocity components $V_{R}$ and $V_{\phi}$ show significant spiral patterns in the vertical position–velocity plane $Z-V_{\phi}$. Further works have studied the variations of the phase spirals with stellar age, action, chemistry, and disk position using the Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST)-Gaia (Tian et al. 2018) and the Galactic Archaeology with HERMES (GALAH)-Gaia (Bland-Hawthorn et al. 2019) data. Their results not only confirm the original remarkable discovery of Antoja et al. (2018), but also resolve significant variations of the phase spirals with aforementioned parameters. Tian et al. (2018) found that the spirals are gradually apparent from $\tau < 0.5$ Gyr, and then slowly disappear until $\tau > 6.0$ Gyr. Bland-Hawthorn et al. (2019) showed that the phase spirals are more easily discerned in the distributions of $\alpha$-poor stars than those of $\alpha$-rich stars. They also find that the spiral is clearest in stars with smaller action $J_\alpha$, and tighter in stars with smaller angular momentum $L_\alpha$. The radial and azimuthal variations of phase spirals were also found by Bland-Hawthorn et al. (2019) and Laporte et al. (2019). It is worth noting that the sample of Bland-Hawthorn et al. (2019) only covers a small distance range of 1 kpc from the Sun and Laporte et al. (2019) does not study the azimuthal variations of phase spirals; the spatial variations of the phase spirals need to be explored in a larger volume of the Galactic disk.

In the theoretical view, several works have attempted to explain the observed phase space spiral patterns by either external (Antoja et al. 2018; Binney & Schönrich 2018; Bland-Hawthorn et al. 2019; Laporte et al. 2019) or internal (Khoperskov et al. 2018) perturbations. Both scenarios can reproduce the phase spirals of $V_{\phi}$ and $V_{R}$ in the Solar neighborhood. Antoja et al. (2018), Binney & Schönrich (2018), Bland-Hawthorn et al. (2019), and Laporte et al. (2019) suggested that the phase spirals are probably the consequence of the Sagittarius dwarf galaxy perturbation. Independent to the external perturbation scenario, Khoperskov et al. (2018) suggested that the observed phase space spirals can be produced naturally by vertical oscillations driven by the buckling of the stellar bar—there is no need for an external perturber (a massive satellite or a sub-halo), whereas simulations considering external or internal perturbations predict different spatial variations of the phase spirals. In the external

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scenario, Bland-Hawthorn et al. (2019) implied tighter phase space spirals in the inner disk due to faster vertical oscillations led by a stronger disk gravity in the inner disk. Khoperskov et al. (2018) have also predicted the properties of phase space spirals in different $R$ and $\Phi$ bins considering internal perturbations, but did not find a tighter phase space spirals in the inner disk. Thus, studying the phase space spirals at different disk positions in a larger volume of the disk can no doubt distinguish the origins of the phase spirals. Unfortunately, the radial and azimuthal variations of the phase spirals are not well studied yet.

In the current work, we study the phase space spirals at different disk positions ($R$ and $\Phi$), in particular its radial variations, to see whether the phase space spirals in the inner disk are tighter as predicted by the scenario of Bland-Hawthorn et al. (2019). Our work is based on the recently released Gaia second data release (DR2), which provides precise proper motions and distances for more than 1.3 billion stars, and precise line-of-sight velocities for more than 7 million stars. In addition, the LAMOST surveys have yielded precise line-of-sight velocities and metallicities for millions of stars. These data enable us to derive accurate 3D velocities for large samples of stars across the Galactic disk ranging from 6 to 12 kpc, thus allowing us to examine the spatial variations of the phase space spirals across a wide range of the disk.

This Letter is organized as follows. In Section 2, we briefly introduce the samples used. In Section 3, we present the main results. The discussions are presented in Section 4. Finally, we summarize our work in Section 5.

2. Data

2.1. Coordinate Systems

We use the Galactocentric cylindrical system ($R$, $\Phi$, $Z$) with $R$, the projected Galactocentric distance, increasing radially outward, $\Phi$ in the direction of the Galactic rotation, and $Z$ toward the North Galactic Pole. The Sun is assumed to be at the Galactic midplane (i.e., $Z_0 = 0$ pc) and has a value of $R_0$ of 8.34 kpc (Reid et al. 2014). We adopt a local circular speed of rotation curve of $V_R(R_0) =$ 240 km s$^{-1}$, and solar motions ($U_0$, $V_0$, $W_0$) = (11.1, 12.24, 7.25) km s$^{-1}$ relative to the local standard of rest (Schönrich et al. 2010). The results presented in the current work are stable if we choose $Z_0 = 27$ pc and other solar motions relative to the local standard of rest (Huang et al. 2015).

2.2. The Stellar Samples

By 2016 June, $\sim$6.5 million stellar spectra of signal-to-noise ratios higher than 10 for 4.4 million unique stars have been obtained with LAMOST (Xiang et al. 2017a) during the Pilot Surveys and the first four years of the five-year Phase I Regular Surveys of the LAMOST Galactic spectroscopic surveys (Deng et al. 2012; Zhao et al. 2012; Liu et al. 2014; Yuan et al. 2015). Stellar atmospheric parameters (effective temperature $T_{\text{eff}}$, surface gravity log $g$, metallicity [Fe/H]) and line-of-sight velocities $V_\lambda$ with random error of 5 km s$^{-1}$ derived from the spectra using LSP3 (Xiang et al. 2015, 2017b) are available.

Precise parallaxes and proper motions of 1.3 billion stars in the Milky Way are now provided by the Gaia DR2 (Gaia Collaboration et al. 2018). Distances and asymmetric uncertainties are also available for those 1.3 billion stars in Gaia DR2 provided by Baier-Jones et al. (2018), who derived the distances and uncertainties with a Bayesian method. In the current work, we adopt their distances. Line-of-sight velocities $V_\lambda$ for 7 million stars are also provided with an accuracy of $\sim$1 km s$^{-1}$. Combining the distances, proper motions, and the line-of-sight velocities $V_\lambda$ of millions of stars provided by the Gaia DR2, we derive accurate 3D velocities of 7,224,631 (hereafter named the “Gaia sample”) stars. 3D velocities of 3,600,275 (hereafter named the “Gaia-LAMOST sample”) stars are also derived using the distances, proper motions from Gaia DR2 and $V_\lambda$ from the LAMOST surveys.

We estimate 3D velocities ($U$, $V$, $W$) and associated uncertainties of the individual stars using the method of Johnson et al. (1987). When we derive the errors of ($U$, $V$, $W$), the errors of distances, proper motions, and line-of-sight velocities are considered based on the principle of uncertainty propagation. Then we transform $(U, V, W)$ to $(V_R$, $V_\Phi$, $V_Z)$. Errors of $(V_R$, $V_\Phi$, $V_Z)$ are also estimated based on the principle of uncertainty propagation.

In order to obtain reliable results, we have removed stars with $V_R$, $V_\Phi$, and $V_Z$ uncertainties larger than 50 km$^{-1}$, stars of distance uncertainties larger than 25%, and stars of $|V_R| > 400$ km s$^{-1}$, or $|V_\Phi - 240| > 400$ km s$^{-1}$ or $|V_Z| > 400$ km s$^{-1}$. Finally, the Gaia sample contains 6,150,394 stars, and the Gaia-LAMOST sample contains 3,344,860 stars.

3. Results

In this section, we examine the spatial variations of the phase spirals of $V_\Phi$ and $V_R$ using the two samples. First, we divide the Gaia sample into six radial bins of $R$ from 6.34 to 11.34 kpc and six azimuthal bins of $\Phi$ from $-6^\circ$ to $6^\circ$ to investigate the phase spirals of $V_\Phi$ and $V_R$ in the different bins of $R$ and $\Phi$. Stars in the Gaia-LAMOST sample are also divided into six radial bins of $R$ from 7.34 to 12.34 kpc to investigate the phase spirals of $V_\Phi$ and $V_R$ at different $R$. The distribution of the Gaia-LAMOST sample stars in the $Z$–$\Phi$ plane is not symmetric, which is the consequence of the LAMOST sampling strategy, limiting magnitudes, and so on. Above the Galactic plane, most of the stars have negative values of $\Phi$, whereas below the Galactic plane, most of the stars have positive $\Phi$. Thus, we do not study the azimuthal variations of the phase spirals with the Gaia-LAMOST sample. When we explore the radial and azimuthal variations of the phase spirals, we adopt an azimuthal range $\Phi$ of $[-7.5^\circ, 7.5^\circ]$ and a radial range $R$ of [7.84, 8.84] kpc, respectively. Likewise, when we examine the distributions of $V_\Phi$ and $V_R$ in the $Z$–$V_R$ plane, we adopt bin sizes of $\Delta Z = 0.01$ kpc and $\Delta V_R = 1.0$ km s$^{-1}$.

3.1. The Phase Spirals at Different Galactic Positions as Revealed by the Gaia Sample

3.1.1. Slicing by R

We first investigate the radial variations of the phase space spirals using the Gaia sample. Figure 1 shows the distributions of $V_\Phi$ = 228 km s$^{-1}$ (left panels) and $V_R$ (right panels) of the Gaia sample stars in the $Z$–$V_R$ plane and in the different radial bins. The radial range and number of stars in each bin are labeled in the figure.

The distributions of $V_\Phi$ show significant phase spirals. Our results confirm the previous finding of Antoja et al. (2018), Bland-Hawthorn et al. (2019), and Tian et al. (2018) for the Solar neighborhood. The phase spirals are apparent in all the
Galactic radii. The radial range and number of stars of each bin are labeled in VR radial bins, especially in the bin of $6.34 \text{ kpc} < R < 10.34 \text{ kpc}$. The results strongly support the idea that the phase spirals are a disk-wide phenomenon (Bland-Hawthorn et al. 2019).

The phase spirals of $V_R$ vary strongly with Galactic radius $R$ as Figure 1 shows. The larger the $R$, the more relaxed the phase spirals. In Figure 1, the inner spirals become more and more relaxed as $R$ increases, and essentially disappear at $R > 9.34 \text{ kpc}$. The outer spirals are stronger in the outer disk than in the inner disk. One can find three spirals at $R < 9.34 \text{ kpc}$, two spirals at $9.34 \text{ kpc} < R < 10.34 \text{ kpc}$, and only one spiral at $10.34 \text{ kpc} < R < 11.34 \text{ kpc}$ in the phase space plane of $-1 < \Phi < 1 \text{ km s}^{-1}$ and $-50 < V_R < 50 \text{ km s}^{-1}$, which is consistent with the results of Laporte et al. (2019), see their Figure 14). The observed results presented here are consistent with the N-body simulation predictions of Bland-Hawthorn et al. (2019; see their Figure 22), who suggest that the stronger disk gravity in the inner disk leads to faster vertical oscillations and tighter phase spirals. In this scenario, one can see more spirals in the inner disk than in the outer disk in the same phase space region, which is indeed what one sees in Figure 1.

The distributions of $V_R$ in the phase space plane at different Galactic radii are also presented in Figure 1. They show clear quadrupole patterns at all Galactic radii except that of $R > 10.34 \text{ kpc}$; values of $V_R$ are relatively small in the top-left and bottom-right parts of each right panel compared to those in the top-right and bottom-left corners. The quadrupole patterns, first mentioned by Bland-Hawthorn et al. (2019; see their Figure 16), are the consequence of the well-known tilt of the velocity ellipsoid (Siebert et al. 2008; Binney et al. 2014; Bland-Hawthorn et al. 2019). The quadrupole patterns are the clearest at $8.34 \text{ kpc} < R < 9.34 \text{ kpc}$, with the smallest $V_R$ in the top-left and the bottom-right region, which is consistent with the previously observed radial velocity dip in the Solar neighborhood (Siebert et al. 2011; Huang et al. 2016; Carrillo et al. 2018; Tian et al. 2017).

At $7.34 < R < 10.34 \text{ kpc}$, the phase spirals are also found in the distributions of $V_R$, which are broadly similar to those of $V_R$. However, the phase spirals are less tightly wound compared to those of $V_R$, which is again consistent with the numerical simulation results of Bland-Hawthorn et al. (2019). In the innermost ($R < 7.34 \text{ kpc}$) and the outermost ($R > 10.34 \text{ kpc}$) parts of the disk, the phase spirals are barely visible.

### 3.1.2. Slicing by $\Phi$

We now investigate the distributions of $V_\phi$ and $V_R$ of the Gaia sample stars in phase space plane in different azimuthal bins. Figure 2 shows the main results. The azimuthal range and the number of stars in each bin are labeled in the figure.

The phase spirals of $V_\phi$ are apparent in all azimuthal bins. Three spirals are clearly seen, with shapes that are quite similar. The phase spirals become stronger as $\Phi$ increases, are the strongest at $-2^\circ < \Phi < 2^\circ$, and then fade away as $\Phi$ further increases. Interestingly, the mean values of $V_{\phi}$ at $-2^\circ < \Phi < 2^\circ$ are the smallest.

The distributions of $V_R$ in the phase space plane in the different $\Phi$ bins are also presented in Figure 1. Similarly, the phase spirals are found in all the $\Phi$ bins, and are the strongest at $-2^\circ < \Phi < 2^\circ$. Quadrupole patterns are found in all the bins, and are also the strongest at $-2^\circ < \Phi < 2^\circ$.

### 3.2. The Phase Spirals at Different Galactic Positions as Revealed by the Gaia-LAMOST Sample

In order to verify the robustness of our detections of the phase spirals at different Galactic positions, we show in Figure 3 the $V_\phi$ and $V_R$ distributions of the Gaia-LAMOST sample in the $Z$-$V_Z$ plane at different Galactic radii. What Figure 3 reveals is broadly similar to that seen in Figure 1.

Compared to Figure 1, the spiral patterns of $V_\phi$ are less well resolved by the Gaia-LAMOST sample stars, especially for the inner spirals in the inner disk ($7.34 < R < 9.34 \text{ kpc}$). As mentioned in Section 2, line-of-sight velocities of the Gaia-LAMOST sample stars are much less accurate than those of the Gaia sample. This is responsible for the aforementioned difference. In Figure 3, the phase spirals in outer disk ($R > 9.34 \text{ kpc}$) are much stronger than those seen in Figure 1. This may be partly due to the fact that stars in the Gaia-LAMOST sample have smaller mean values of the absolute azimuthal angle compared to those of the Gaia sample stars at $R > 9.34 \text{ kpc}$, which is consistent with the results of Section 3.1.2.

In Figure 3, the distributions of $V_R$ in the phase space plane are broadly consistent with that seen in Figure 1, but less...
clearly. The quadrupole patterns are also similar to those uncovered by the Gaia sample. In Figure 3, the quadrupole patterns are seen even at $R > 10.34$ kpc. This is not the case when using the Gaia sample. The reason is that stars in the Gaia-LAMOST sample have smaller mean values of $F |\Phi|$ than those of the Gaia sample, considering that the spiral and quadrupole patterns of stars of smaller $F |\Phi|$ are stronger than those of larger $F |\Phi|$. Moreover, there is a clear break of $V_R$ from south side ($Z < 0$ kpc) to north ($Z > 0$ kpc), especially in the range of $7.84 < R < 9.84$ kpc. We suggest that it might be caused by the quadrupole patterns of the spirals, the bright limiting magnitudes, and very low sampling rates of the LAMOST surveys in the solar neighborhood after a careful check.

4. Discussion

4.1. The Effects of 3D Velocity Errors on the Phase Spirals

As discussed in Section 3.1.1, there are three phase spirals of $V_\phi$ in the inner disk ($R < 9.34$ kpc), but only one or two phase spirals in the outer disk ($R > 9.34$ kpc). Meanwhile, the errors of the 3D velocities of stars at $R > 9.34$ kpc are larger than those of stars at $R < 9.34$ kpc. In order to check the relationship between spiral numbers and velocity errors, we use the Monte Carlo method to check if the spirals in the range of $[7.84, 8.84]$ kpc are still robust. We first increase the errors of 3D velocities of each star at $7.84 < R < 8.84$ kpc by scaling with a factor, which is estimated as the ratio of the mean random velocity errors of stars at $9.34 < R < 10.34$ kpc and those of stars at $7.84 < R < 8.84$ kpc. The final velocities of the stars are derived by adding the errors, which are randomly generated assuming Gaussian distributions, with the increased errors as the dispersions. We then examine the resultant $V_\phi$ and $V_R$ distributions in the phase plane. The process is repeated 1000 times, and the resultant 1000 distributions of $V_\phi$ and $V_R$ are quite similar one to the other.

Figure 4 shows one of the resultant $V_\phi$ and $V_R$ distributions in the phase space plane before and after increasing the velocity errors for stars at $7.84 < R < 8.84$ kpc. The phase spirals of $V_\phi$ and $V_R$ seen show negligible differences before and after increasing the velocity errors. We therefore conclude that the results of more relaxed phase spirals of $V_\phi$ in the outer disk are authentic.
Our results as revealed by both the Gaia and the Gaia-LAMOST samples suggest that the phase space spirals of $V_\phi$ become more relaxed as $R$ increases. The phenomenon is exactly predicted by the $N$-body simulations of Bland-Hawthorn et al. (2019) and Laporte et al. (2019), who suggested that the passage of the Sagittarius through the Galactic plane, a scenario of an external origin, produces the vertical phase-mixing and phase spirals. The predicted radial variations of the phase spirals of $V_\phi$ as driven by buckling of the stellar bar (internal origin; Khoperskov et al. 2018) are on the other hand not so consistent with the conclusion of Laporte et al. (2019). Our results suggest instead an origin of the phase spirals that are developed from an external perturbation.

If this scenario of an external origin is true, the location of the intruder passing through the Galactic plane and the mass and passage duration of the intruder become important issues. An intruder will attract stars to it, changing their 3D velocities as the intruder passes through the Galaxy (Binney & Schönrich 2018, see their Figures 1 and 2). Meanwhile, the phase spirals at different Galactic positions, especially its radial and azimuthal variations, are no doubt strongly affected by the aforementioned parameters of the intruder. In other words, one can study the intruding passage location and duration through the radial and azimuthal variations of the phase spirals of $V_\phi$ and $V_R$.

When an intruder passes through the Galactic plane, the effect of the intruder on the star in the line of the Galactic center and the intruder is largest, and the phase spiral in this direction is clearest. In Figure 2, we find that the phase spirals of $V_\phi$ and $V_R$ are clearest at $-2^\circ < \Phi < 2^\circ$, and become weaker as $|\Phi| > 2^\circ$. It suggests that the external intruder passes through the Galactic plane in the direction of either the Galactic center or the anti-center. The azimuthal variations of the phase spirals of $V_\phi$ and $V_R$ also tell us something about the mass and the passage duration of the intruder. A detailed model is required to reproduce the results presented here.

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5. Summary

In this Letter, we study the phase space spirals of $V_\phi$ and $V_R$ using the Gaia and LAMOST data, and investigate the radial and azimuthal variations of the spiral and quadrupole patterns in the phase space plane. The main results are as follows.

1. The distributions of $V_\phi$ in the $Z-V_Z$ plane show strong spiral patterns at $6.34 < R < 12.34$ kpc.
2. The phase spirals of $V_\phi$ become more relaxed as $R$ increases.
3. The distributions of $V_R$ in the $Z-V_Z$ plane show strong quadrupole patterns in all $R$ and $\Phi$ bins. They also show spiral patterns but not so tightly wound as those of $V_\phi$. In the innermost ($R < 7.34$ kpc) and outermost disk ($R > 10.34$ kpc), the spiral patterns are barely visible.
4. The spiral patterns of $V_\phi$ and the quadrupole and spiral patterns of $V_R$ in the $Z-V_Z$ plane are the strongest at $-2^\circ < \Phi < 2^\circ$, but almost invisible at $4^\circ < \Phi < 6^\circ$ and $-6^\circ < \Phi < -4^\circ$.

The radial variations of the phase spirals of $V_\phi$ are consistent with the predictions of perturbation by an external intruder as suggested by Bland-Hawthorn et al. (2019) and Laporte et al. (2019), but are inconsistent with an internal origin as suggested by Khoperskov et al. (2018). The azimuthal variations of the phase spirals of $V_\phi$ and $V_R$ suggest that the intruder passes through the Galactic plane in the direction of either the Galactic center or the anti-center. The azimuthal variations of the phase spirals of $V_\phi$ and $V_R$ also tell us something about the mass and the passage duration of the intruder. A detailed model is required to reproduce the results presented here.

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Figure 4. Distributions of $V_\phi = 228$ km s$^{-1}$ (left panels) and $V_R$ (right panels) in the $Z-V_Z$ plane for stars at $7.84 < R < 8.84$ kpc, before (bottom panels) and after (top panels) increasing the velocity errors.
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