The Local Spiral Arm in the LAMOST-Gaia Common Stars?

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Abstract

Using the LAMOST-Gaia common stars, we demonstrate that the in-plane velocity fields for the nearby young stars are significantly different from those for the old ones. For the young stars, the probably perturbed velocities that are similar to the old population are mostly removed from the velocity maps in the X–Y plane. The residual velocity field shows that the young stars consistently move along Y with faster $v_\phi$, at the trailing side of the local arm, while at the leading side, they move slower in the azimuth direction. At both sides, on average the young stars move inward with a $v_R$ of $-5 \sim -3$ km s$^{-1}$. The divergence of the velocity in the Y direction implies that the young stars are associated with a density wave near the local arm. We therefore suggest that the young stars may reflect the formation of the local spiral arm by correlating themselves with a density wave. The range of the age for the young stars is around 2 Gyr, which is sensible since the transient spiral arm can persist for that long. We also point out that alternative explanations of the peculiar velocity field for the young population cannot be ruled out if solely using this observed data.

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

1. Introduction

Spiral arms are very common features in disk galaxies and are also found in our Galaxy (Kerr 1957; Benjamin et al. 2005). However, the origin of these complicated structures is not conclusively known, although many theories have been proposed (see Binney & Tremaine 2008; Shu 2016). Lin & Shu (1964) suggested that the spiral structures are long-lived density waves. However, this was challenged by observations of external galaxies (Foyle et al. 2011). Toomre & Toomre (1972) found that dynamical tidal interaction can induce spiral structures in a galaxy. But then it is hard to explain why galaxies that have not experienced major mergers, such as the Milky Way, also have spiral arms. Sellwood & Carlberg (1984) argued that the spiral structures are short-lived and are formed from the instability. Sellwood & Carlberg (2014) further explained that the nature of the recurrent spiral arms is an overlapping of multiple spiral modes. Kawata et al. (2014), on the other hand, claimed that the spiral arms are corotating, i.e., their pattern speeds are equal to the circular speeds.

Because the dynamical properties of the spiral structures in the Milky Way are so hard to detect, most observational works turn toward understanding spiral structure through perturbed stellar velocity distributions (Quillen et al. 2011; Siebert et al. 2012; Faure et al. 2014). In recent years, many observations have revealed that the nearby stars display complicated peculiar motions, which may be the result of perturbations, in radial and vertical directions (Siebert et al. 2011; Carlin et al. 2013; Williams et al. 2013; Sun et al. 2015, etc.). However, the perturbed velocities (also called bulk motion, asymmetric motion, streaming velocity, or peculiar velocity in different studies) may either be induced by the spiral structures or by other non-axisymmetric features, e.g., the Galactic bar or merging dwarf galaxies (Gómez et al. 2013; Bovy et al. 2015; Grand et al. 2015). There are also some works constraining the formations mechanisms of the spiral structures with comparisons of the locations of the gaseous and stellar arms (Hou & Han 2015).

Recently, Tian et al. (2015) showed that the young stars have different asymmetric motions with the old stars in U and W. Tian et al. (2016) further compared the radial variation of $v_R$ and $v_\phi$ between the young and relatively old red clump stars from the LAMOST survey and found that the radial oscillations of the velocities for the two populations show similar long-wave modes but different short-wave modes. These observational facts hint that the young stars may contain different types of peculiar velocities. They may either retain some memory of the kinematical features of their birthplaces, or directly reflect the kinematics of the spiral arms, or they are more sensitive to the perturbations than older populations due to their more circular stellar orbits. In order to investigate the role played by the spiral arms in the peculiar velocities, a two-dimensional in-plane velocity field, rather than a one-dimensional radial variation of the velocities, is required. Subsequently, accurate astrometric data, combined with line-of-sight velocities measured from stellar spectra, are needed.

As of 2016 September 14, the Gaia survey (Gaia Collaboration et al. 2016b) has published its first data release (Gaia Collaboration et al. 2016a), including new proper motion estimates with an accuracy of $\sim 1$ mas yr$^{-1}$ for 2 million bright stars (Lindegren et al. 2016). The Gaia DR1, combined with the spectroscopic data from the LAMOST DR3 data, allows us to map the three-dimensional velocities of the stars within $\sim 1$ kpc around the Sun with high accuracy. In this Letter, we study the in-plane peculiar motions for young stars in the solar neighborhood using the latest astrometric data from Gaia. The data selection and processing are described in Section 2. The result and discussions are illustrated in Section 3. In the last section we present a brief conclusion.
2. Data

The data used in this work are from two surveys, the stellar parameters and the line-of-sight velocities are from the LAMOST DR3 data (Cui et al. 2012; Deng et al. 2012; Zhao et al. 2012), and the parallaxes and proper motions are from the Gaia DR1 (Gaia Collaboration et al. 2016a). We adopt the distance estimated by Astraatmadja & Bailer-Jones (2016), who applied a Bayesian model to derive the distance from the parallax, taking into account the Milky Way prior and systematic uncertainties in the Gaia catalog. There are totally more than 190,000 common stars in the two catalogs. From the LAMOST derived stellar parameters (Wu et al. 2014), we select about 15,000 young F-type stars with $6500 < T_{\text{eff}} < 7500$ K, an error of distance from Astraatmadja & Bailer-Jones (2016) smaller than 30% (including the systematic error of the Gaia parallaxes), and an absolute magnitude in the $K_s$ band between $-1$ and $3$ mag. Because in this work we focus on the disk, we cut the range of vertical distance to the Galactic mid-plane with $|Z| < 0.3$ kpc. Meanwhile, we cut the distance with $D < 0.6$ kpc to ensure the completeness of the data. Then we obtain 6822 F-type stars as the tracers of the young population. In order to characterize the velocities for the young population, we also select 5088 K-type sub-giant branch (SGB) stars with $3800 < T_{\text{eff}} < 5700$ K and $-0.5 < M_K < 3$ as the control sample. Figure 1 shows the HR diagram of the LAMOST-Gaia common stars, overlapped with the PARSEC isochrones (Bressan et al. 2012) with ages of 1, 3, 6, and 10 Gyr at solar metallicity (magenta lines). It is seen that most of the selected F-type stars (solid white box) are around 1–3 Gyr, while the K-type stars in the SGB control sample (dashed white box) are concentrated around ages of 3–6 Gyr.

The absolute magnitude in the $K_s$ band is derived from the distance provided by Astraatmadja & Bailer-Jones (2016), the apparent $K_s$ magnitude is from 2MASS, and the derived interstellar extinction in the $K_s$ band is from Majewski et al. (2011).

There are some stars with supersolar metallicities in both the young and old populations. According to Kordopatis et al. (2015) and Liu et al. (2015), these very metal-rich stars were likely formed from the inner disk. In order to make sure that the sample is local, we remove the stars with [Fe/H] $> -0.05$ dex. We also cut out a few stars with [Fe/H] $< -0.6$ to exclude most of the contaminations, e.g., the blue straggler stars, from the thick disk and stellar halo populations. After the cut in metallicity, the number of remaining F-type young stars is 3692 and the number of the rest K-type SGB stars is 2011.

We adopt a solar motion w.r.t. the local standard of rest as $(U_0, V_0, W_0) = (9.58, 10.52, 7.01)$ km s$^{-1}$ (Tian et al. 2015), the distance from the Sun to the Galactic center is $R_0 = 8.34$ kpc (Reid et al. 2014), and the local circular speed is 238 km s$^{-1}$ (Schönrich 2012). Figure 2 shows the spatial distribution of the young (left panel) and old (right panel) stars in the $X$–$Y$ plane, in which $X$ points from the Galactic center to the outskirts of the disk through the Sun and $Y$ points to the direction of the rotation of the disk. Note that these coordinates do not fit the usual direction to look at the Milky Way, i.e., looking it from the north Galactic pole. Hence, in the remaining figures in this Letter we flip the direction of the $X$-axis so that the Milky Way is looked at from the north Galactic pole and the direction of the rotation is upward. The samples are located within 0.6 kpc around the Sun. Thus, $Y$ is approximately equivalent with the azimuth angle.

3. Result and Discussions

Figure 3 shows maps of the median azimuthal ($v_{\varphi}$) and radial ($v_{\parallel}$) velocities in the $X$–$Y$ plane for the young and old stars, respectively. The median velocity values are provided only for the bins containing more than 20 stars to ensure good statistics. The bin size is 0.125 × 0.125 kpc. No smoothing technique is applied to these maps. The local spiral arm derived from the astrometry of the masers (Reid et al. 2014; Xu et al. 2016) is superposed to the figure (the center of the arm is represented by the solid lines and the width of it is represented by dotted lines).

From panel (a) it is seen that the map of the median $v_{\varphi}$ for the young population displays a clear declining trend with increasing $X$. As a comparison, panel (b) shows the map of $v_{\varphi}$ for the old K-type SGB stars. It shows a ridge located from $(8.9, -0.2)$ to $(8.2, +0.4)$ kpc with a lower $v_{\parallel}$ of about 220 km s$^{-1}$. Outside the ridge, $v_{\varphi}$ increases to around 225 km s$^{-1}$. This is substantially different from the velocity gradient for the young stars that is shown in panel (a). The pattern of $v_{\varphi}$ for the old stars seems to be correlated with the direction of the local arm. This hints that the
Figure 3. The top row shows maps of the median $v_R$ in the $X$-$Y$ plane for the F-type stars (young) and K-type SGB stars (old) in panels (a) and (b), respectively. The location of the Sun is at the black crosses. The black solid line and the two black dotted lines crossing from top to bottom in each panel indicate the local spiral arm and its width, respectively. Panel (c) shows the residual map of the subtraction of panel (b) from panel (a). The bottom row shows the maps of the median $v_R$ in the $X$-$Y$ plane for the F-type stars (young) and K-type SGB stars (old) in panels (d) and (e), respectively. Panel (f) shows the residual map of panel (d) subtracted by panel (c).

The velocity pattern may reflect the perturbation induced by the spiral arm.

We then look at the map of $v_R$ for the young population in Figure 3 (d). It shows that the young stars move inward with $v_R \sim -3$ km s$^{-1}$ at $R < 8.5$ kpc, while their $v_R$ is around zero at $R > 8.5$ kpc. Looking at the map of $v_R$ for the old population in panel (e), we find that $v_R$ is roughly around +5 km s$^{-1}$ at $R > 8.5$ kpc and about zero or even less than zero at $R < 8.5$ kpc. The trends for the gradients of $v_R$ for the young and old populations are similar. However, the values of $v_R$ for our sample are about 5 km s$^{-1}$, which leads to the order of $\sim 1$ km s$^{-1}$ in each $X$-$Y$ bin since each bin contains at least 20 stars. Because the uncertainty of $v_R$ in each bin is comparable with the local variations in the $v_R$ map, these variations between neighboring bins in panels (d) and (e) are likely dominated by statistical fluctuation. However, the global radial trend displayed in both the young and old populations may not be due to the velocity uncertainties, but is likely a true feature since lots of bins demonstrate this trend together.

The old stars should be completely relaxed. Hence, the peculiar velocity shown in the old stars is most likely due to the perturbations induced by the spiral arm or the bar. In principle, if the kinematics for the old stars suffers from the perturbations, the young population should be affected in a similar way with similar or even more intensive amplitudes because they are more kinematically cold and thus more easily perturbed.

Therefore, the significant difference in the maps of the velocities between the young and old populations in panels (a), (d), (b), and (e) of Figure 3 implies that the young stars may be driven by two different mechanisms: (1) perturbations that are the same as those also affecting the old stars and (2) a special mechanism that does not affect the old populations, but only influences the young stars. Then we can remove most of the perturbed velocities due to the first driver by subtracting the maps of velocities for the old stars from those for the young stars in the $X$-$Y$ plane.

The residual velocity maps are shown in Figures 3 (c) and (f). In most parts of the $X$-$Y$ plane, the residual $v_R$ in panel (c) is positive from about 10 to 30 km s$^{-1}$. The positive residual values can be naturally explained by the different asymmetric drift, which is smaller for the young populations than for the old ones. The residual $v_R$, also displays a clear gradient from the bottom right to the top left. The direction of the gradient is approximately parallel with the normal direction of the local arm. It shows that the young stars move along the azimuthal direction faster on the trailing side of the local arm, while they move slower by 20 km s$^{-1}$ on the leading side.

The residual $v_R$ in panel (f) displays negative values around $-5 \sim -3$ km s$^{-1}$ with some local variations. Considering that the uncertainty of $v_R$ in each bin is around 1 km s$^{-1}$, the local features with variations of $\sim 2$ km s$^{-1}$ may be due to the arbitrary fluctuation. However, even taking into account the uncertainties, panel (f) still shows that on average the $v_R$ of the young population is about 3 $\sim 5$ km s$^{-1}$ smaller than that of the old one.

To better quantify the kinematical features, we display the two components of the divergence of the in-plane velocity in Figure 4. The top panel shows the map of $\partial v_Y / \partial Y$ and the bottom panel shows the map of $\partial v_X / \partial X$. First, the largest values of divergence occur in $\partial v_Y / \partial Y$, which varies from +30 to $-15$ km s$^{-1}$ kpc$^{-1}$ from the bottom right to the top left in the $X$-$Y$ plane. Second, the direction of the variation of $\partial v_Y / \partial Y$ is roughly along the normal direction of the gas-identified local arm. Finally, $\partial v_X / \partial X$ is quite flat around zero, implying that almost no gradient of velocity occurs along $X$.

Now consider the continuity equation of fluid mechanics,

$$ \frac{dp}{dt} = -\rho \left( \frac{\partial v_X}{\partial X} + \frac{\partial v_Y}{\partial Y} \right) - \left( v_X \frac{\partial p}{\partial X} + v_Y \frac{\partial p}{\partial Y} \right). $$ (1)
if the stellar density does not rapidly change with time, then the left side of Equation (1) essentially equals zero. Because Figure 4 shows that the divergence of velocity is dominated by $\partial v_Y / \partial Y$ and the divergence along the $Y$ ($X$) direction would only affect the variation of the density along $Y$ ($X$) direction, the variation of the stellar density $\rho$ should also be dominated by $\partial \rho / \partial Y$.

$\partial v_Y / \partial Y$ declines from $+30$ km s$^{-1}$ kpc$^{-1}$ to about $-15$ km s$^{-1}$ kpc$^{-1}$, passing through the zero-point at the line from $(X, Y) \sim (8.2, +0.3)$ to $\sim (8.7, -0.1)$ kpc. Hence, $\partial \rho / \partial Y$ increases from negative values behind the line (w.r.t. the rotation direction) to positive values in front of the line according to Equation (1). Consequently, the stellar density $\rho$ must increase, with $Y$ starting from the line. In other words, the young stars are associated with a density wave near the gas-identified local arm. Therefore, we suggest that the motion of the young stars probably reflects the local arm by kinematically associating themselves with a density wave.

This scenario is not in conflict with the mean age for the young tracers, which is only $\sim$2 Gyr. Such a timescale is within the expected lifetime of the transient spiral structures (Sellwood & Carlberg 2014).

Moreover, the distributions of the in-plane velocities displayed in Figure 5 show that, for the young stars (panel (a)), the velocity distribution forms a tight arc shape. By contrast, the old stars (panel (b)) show an extended and roughly featureless distribution with a moderate bump at around $v_R \sim 30$ km s$^{-1}$ and $v_\phi \sim 180$ km s$^{-1}$, which should be the Hercules stream (Dehnen 2000; Xia et al. 2015). The velocity distribution shown in panel (a) can be qualitatively compared with simulations from Quillen et al. (2011). We find that an orientation of the arc that is similar to our sample is located at the inter-arm regime (see the panels in the 3rd row and the 2nd, 5th, and 6th columns in their Figure 8), not on the arm, which is consistent with the locations of the majority of our samples.

Besides the transient spiral mode (Sellwood & Carlberg 2014), quite a few works have discussed alternative channels for the formation of the spiral structures and some theoretical works have given observational predictions in velocity distributions. Particularly, regarding the local arm, Xu et al. (2016) thought that it might have been formed from the perturbation of the giant molecular clouds (D’Onghia et al. 2013), according to their latest maser observations. Li et al. (2016) found that the local arm, which can persist over a short time, may not be due to the density wave, but may be naturally induced in a scenario in which the disk contains two pairs of prominent spiral structures based on their numerical simulations. We also note that, recently, Hunt et al. (2016) claimed that the fast rotating stars found at radii a few hundred parsecs beyond the Sun may be driven by the Perseus arm rather than the local arm.

Different spiral theories may give different explanations for the peculiar motion of the young stellar populations unveiled in this work. Using the observed data, we cannot rule out other explanations. Further investigations, including more observations in larger volumes and with well-defined N-body simulations, are required to clarify the nature of the peculiar velocity fields for the young stars.

4. Conclusions

In this Letter we study in-plane peculiar motions using more than 3000 young stars combined with line-of-sight velocities from LAMOST DR3, with parallax and proper motions from the Gaia DR1. The latter provides accurate proper motions with uncertainties of about 1 mas yr$^{-1}$ up to 1 kpc in distance, which are the best astrometric measurements so far.

We select F-type stars as tracers for the young population and the old K-type SGB stars as the control sample. After removing the peculiar motions due to perturbations, the residual velocity field for the young stars correlates with the gas-identified local spiral arm. The $\partial v_Y / \partial Y$ map for the young stars implies that the stellar density may increase with $Y$, starting from the line from $(X, Y) \sim (8.2, +0.3)$ to $(8.7, -0.1)$ kpc. This hints that the young stars are associated with a density wave located around the local spiral arm. We then suggest that the young stars are involved in the formation of the local arm by inducing the density wave, which hence directly reflects the kinematical features of the arm. We also note that a few alternative mechanisms to explain such a peculiar velocity field cannot be ruled out.

In the future it will be worthwhile to directly compare the peculiar velocity field unveiled by the young stars in this work with various simulations so that observational evidence can help to determine the origin of the spiral structures.
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