Diagonal Ridge pattern of different age populations beyond 12 kpc with LAMOST Red Giant Branch Stars

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ABSTRACT

We investigate the kinemato-chemical distribution of a sample of Red Giant Branch (RGB) stars from the LAMOST survey crossed matched with Gaia DR2 proper motions, and present the time tagging for the well-known ridge structures (diagonal distributions in the \( R–V\phi \) plane) in the range of Galactocentric distance \( R = 8 \) to 18 kpc. We detect six long-lived ridge structures, including five ridges apparent in the radial velocity distribution and one ridge apparent in the vertical velocity. Based on an analysis of the evolution of the angular momentum distribution, we find that four ridges are relatively stationary, while another is evolving with time, which is confirmed by the difference analysis at different populations and supporting that there might be two kinds of dynamical origins with possible coupling mechanisms. Furthermore, ridge features are also vividly present in the chemical properties ([Fe/H], \([\alpha/Fe]\)), in particular for the mass distribution (M). The comparison between the north and south hemispheres of the Galaxy does not show a clear asymmetry in the phase space location even though the amplitude (e.g., vertical velocity) is asymmetrical. Moreover, we find that diagonal ridge structures may affect the shape of the rotation curve, which is manifested as fluctuations and undulations on top of a smooth profile.

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

1 INTRODUCTION

Galactic seismology is the inference of the Galactic potential and Galactic sub-structure from a dynamical analysis of the observed perturbations in the gas or stellar component (discs) of the Milky Way (Chakrabarti 2017; Bland-Hawthorn & Tepper-García 2021)¹, which is also characterising the Milky Way that is non-equilibrium and non-stationary in the asymmetric potential, and will undoubtedly give us a more comprehensive understanding of the dynamic origin and evolution of the Galaxy (Widrow et al. 2012; Carlin et al. 2013; Widrow et al. 2014; Liu et al. 2018; Wang et al. 2018a,b, 2019, 2020a,b,c; López-Corredoira & Sylos Labini 2019; López-Corredoira, Garzón & Wang et al. 2020; Trick et al. 2019; Yu, Wang & Cui et al. 2021; Tepper-Garcia et al. 2021; Wang et al. 2022a,b; Tepper-Garcia et al. 2022).

The cornerstone Gaia mission provides the most accurate proper motion, parallax and other parameters to date. The G-band stars in Gaia DR2 is up to 1.69 billion and among them, 1.33 billion stars have 5 parameters, 360 million stars have 2 parameters, and 7.22 million stars have radial velocity information (Gaia Collaboration et al. 2016, 2018b). With the help of Gaia data many exciting discoveries hidden in the Milky Way Galaxy are revealed recent years, as described in Antoja et al. (2018), our Galactic disc is phase mixing from the non-equilibrium state shown as the snails and ridge features.

Recently, the ridge in the outer disc of the Milky Way is unveiled in Antoja et al. (2020) using the data of Gaia EDR3 without radial velocity and age information. Khamma et al. (2019) has also revealed the ridge pattern for the vertical distance \((Z)\), vertical velocity \((V_Z)\), radial velocity \((V_R)\), metallicity \(([Fe/H])\), and abundance \(([\alpha/Fe])\) with GALAH southern sky survey. The ridge features in the rotation velocity distribution were also unravelled in Kawata et al. (2018) and they suggested that the ridge are linked to the Galactic bar and spiral arm in the range of 5 to 12 kpc.

Fragkoudi et al. (2019) used collision free N-body simulation and combined with orbital integration to find that the ridge structure is caused by the external Lindblad resonance of the Galactic bar. Barros et al. (2020) found that the stellar orbit captured by spiral resonance can also produce ridge characteristics. Laporte et al. (2020) found that Galactic bar plays important roles both in the ridge evolution and shaping the Galactic disc. In addition, Monari et al. (2019a,b)
proved that no less than 6 ridges in the local action space are related to the resonance of the bar using a slow rotating Galactic bar model with $\Omega = 39$ km s$^{-1}$ kpc$^{-1}$.

In general, for the mechanisms of the snails and ridges, the external perturbations such like the Sagittarius dwarf galaxy interaction with the Milky Way (Antoja et al. 2018; Binney & Schönrich 2018; Laporte et al. 2020; Bland-Hawthorn & Tepper-García 2021; Craig et al. 2021), the internal dynamics without external disturbance such like spiral arms, outer Lindblad Resonance of the bar (Kawata et al. 2018; Monari et al. 2019a; Khoperskov et al. 2019; Barros et al. 2020), the coupling spiral arms and Sagittarius perturbation simulations for ridges are shown in Khanna et al. (2019). To date whether or not these asymmetric patterns are from internal or external or both mechanisms is still unclear.

Using Main-Sequence-Turn-Off and OB type stars selected from the LAMOST Galactic spectroscopic surveys, Wang et al. (2020c) have reconstructed the ridge pattern in the Chemo-dynamical space. They revealed three ridges in total, two are relatively stable but one is evolving, implying there might have two kinds of ridge patterns with different dynamical origins and evolution. However, in Wang et al. (2020c), they only focus on the range within 12 kpc and are lack of information about mass, motivated by this, during this paper we will make full use of RGB stars to explore further about the ridge science mainly from the observational point of view.

The paper is structured as follows: in Section 2, we describe dataset we adopt in this work; in Section 3 we present our main results and discussion; in Section 4, we summarise the results in general.

2 DATA

The age and mass of the sample we use are mainly from the red giant branch stars of LAMOST DR4 estimated by Wu et al. (2019) with kernel principal component analysis (KPCA). Then we cross match the catalog with Xiang et al. (2019) for metallicity, abundance with Data–Driven Payne method (Ting et al. 2019), and the distance in this work is based on the bayesian estimation method from Carlin et al. (2015) for LAMOST DR5, which is also calibrated by Xu et al. (2020). In general, the catalog contains 640,986 RGB stars, which has the radial velocity, age, mass, metallicity, chemical abundance and distance we need. The radial velocity of which the uncertainty is 5 km s$^{-1}$ is estimated by using the LAMOST stellar parameter pipeline of Peking University (LSP3) (Xiang et al. 2017a), the error of mass and age determined by the KPCA is 10% and 30% respectively. Metallicity error is 0.1 dex, [α/Fe] error is about 0.05 dex (which are also wildly used in our previous work (Li et al. (2022))) and the distance uncertainty is about 15%. The proper motion is from Gaia DR2 catalog and the precision could be as high as 0.06 mas yr$^{-1}$ (for G <15 mag), 0.2 mas yr$^{-1}$ (for G = 17 mag) and 1.2 mas yr$^{-1}$ (for G = 20 mag) (Gaia Collaboration et al. 2018b).

After the cross match for LAMOST and Gaia dataset, we use the following criteria to select the final sample to present our results:

1. $8 < R < 18$ kpc and $-1.5 < Z < 1.5$ kpc;
2. SNR >10;
3. $0 < $Age $< 14$ Gyr;
4. parallax $>0$;
5. $50 < V \phi < 300$ km s$^{-1}$.

Then we have 215,122 RGB stars and the age distribution on the Teff–log g plane, star counts distribution on the R-Z plane, age distribution on the celestial coordinate are shown in Fig. 1, all of which are showing the sample properties and parameter distributions. Fig. 2 shows the 3 dimensional velocity distribution (top three) with bootstrap error (bottom three), the velocity substructure around 10-11 kpc in the left one, the asymmetric drift in the middle one and the vertical bulk motions in the right panel are clearly shown here and consistent with the results in Wang et al. (2018a, 2020a); Gaia Collaboration: Katz et al. (2018).

Notice that the position of the Sun is at 8.34 kpc (Reid et al. 2014), and its vertical distance to the disc is 0.027 kpc (Chen et al. 2001). The local standard of rest velocity in the solar neighborhood is 238 km s$^{-1}$ (Schönrich et al. 2012). The solar motions are (9.58, 10.5, 7.01) km s$^{-1}$ (Tian et al. 2015), different solar motions will not change...
our conclusion in this work. With the help of Galpy (Bovy 2015), we present the kinematics results as follows.

3 RESULTS AND DISCUSSION

3.1 Ridge distribution in kinematical and dynamical space

Fig. 3 presents the star counts (f), radial velocity (VR), and vertical velocity (VZ) on the R and Vφ plane in different age populations. The top panels is the whole sample (0-14 Gyr), the bottom four panels are ridge structures in different age populations as labelled in red. There is no obvious ridge feature in the density distribution and the reason is mainly caused by selection effect. As obviously shown in the middle column for VR, it is clearly shown that there are five ridges from the top one to the bottom one, which are matched well with the constant angular momentum dashed curved lines except the third one, it appear that there is a offset with time evolution. Moreover, we find there is another new ridge candidate in the right column for VZ and present the time stamps on it for the first time.

To investigate more about the ridge features in the north and south sphere, we divide our sample into north and south sides as shown in Fig. 4, we can still detect clear ridge signals and there is no strong asymmetry discovered in the analysis of the ridge structure location on both sides.

However, as shown in Fig. 5, the left two panels show the radial velocity and vertical velocity difference distributions of the north minus south sides, there are still three ridges in the same location as Fig. 3, but clearly the amplitude of the south and north ridges which is indicated by coloured velocity difference might be different. The right two columns show the velocity differences at different age populations for velocity (e.g., population in [3-6] Gyr minus population in [0-3] Gyr), it is showing that there is remaining one nonstable ridge. All these are consistent with the implications that the disk kinematics is asymmetrical, ridge is almost symmetrical in the phase space location but the amplitude might be different, moreover, there are two kinds of ridges which have stable or nonstable evolution with time. Notice that some dashed lines have slight difference referenced to Fig. 3 (Lx = (1570, 1750, 2160, 2320, 2650)), during this paper, all the dashed lines value (constant angular momentum) difference is at most 15% only for the mass pattern (Fig. 11), for others, almost all of them are the same or very similar, so it will not change our conclusion, we only qualitatively describe the ridge features later in order to avoid the misleading.

In order to better represent these six ridges, we named them R1, R2, R3, R4, R5 and R6 (ridges in vertical velocity diagram) from the bottom left to the upper right of each panel as we see in the Fig. 3. The R1, R2, R4, R5 and R6 ridges are relatively stable and R3 is evolving with time, which is manifesting there are two kinds of ridge with different kinds of origins. Furthermore, we then make more analysis using another way, Fig. 6 shows the ridge features in the Lx and Vφ plane coloured by the radial velocity, focusing on the five ridges on the left column we could clearly see the third ridge has fluctuations and the others keep relatively stable, this confirms that two types of ridges could possibly have two kinds of dynamical mechanisms. What’s more, the north and south distribution is also displayed in the middle and right columns, the ridge features marked by the fuchsia dashed line and conclusions are still robust as we see in the three columns. Notice that the velocity error of 2-4 kms⁻¹ and distance error of 10-15% will not change the physical conclusions about ridge in this work.

We also have analyzed the distribution of 3D angular momentum of RGB stars in the R-Vφ plane. It is shown that the Lx and Lz has increasing trend along with R, in contrast the Ly has decreasing trend in Fig. 7. There are almost no ridge features except the middle panel shown as the black dashed line.

3.2 Ridge distribution with chemistry and mass

In the previous section, we have explored the ridge kinematical or dynamical evolution. In this part we mainly present the analysis about chemistry and mass pattern for this structure. As shown in Fig. 8, the left two panels are the metallicity ([Fe/H]) and element abundance ([α/Fe]) pattern in the range of vertical height of -1.5 to 1.5 kpc, we could see two ridges indicated by the red in the second subfigure of the left diagram and one ridge indicated by the blue in the top subfigure of middle column. Here we also show the vertical velocity distribution in the narrower vertical range ([-0.2, 0.2] kpc) as Khanna et al. (2019), one ridge which is shown in the top is found during the analysis. Moreover, the south and north comparison for ridge traced by chemistry is shown in Fig. 9, the large difference is not expected for the location in the R-V φ plane at the first sight and the ridge features are still clear focusing on the red and blue diagonal distribution.

Similar to Fig. 5, Fig. 10 shows the chemical difference in the north
Figure 3. The left column shows the number density distribution ($f$), the middle column shows the radial velocity $V_R$ distribution, and the right column shows the vertical velocity $V_Z$ distribution in different age populations. The black lines in the radial velocity diagram represent the constant angular momentum $L_z = (1570, 1750, 2160, 2320, 2650)$ kpc km s$^{-1}$. The black line in the right vertical velocity diagram represents the constant angular momentum $L_z = (2920)$ kpc km s$^{-1}$. The mass distributions on the R and $V_\phi$ plane are revealed in Fig. 11 and we also find some ridge features shown as deeper red colour. The ridge signal is weaker than that in the kinematics, implying the better sampling and mass precision need to be improved in the future work.

Furthermore, Fig. 12 displays the mass and angular momentum (as complement of Fig. 6) difference in the north and south sides (left two columns), and meanwhile, the difference at different age populations (right two columns). One ridge is detected in the first and two are in the second column, meanwhile, one in the third and two are in the final column. These findings are not conflict with the previous results and implications about ridge locations, amplitude, and possible mechanisms.

3.3 Discussion

With the help of Gaia DR2 data, Antoja et al. (2018) have revealed diagonal ridge structures in the solar neighborhood and they suggested the reason for the ridge formation may be due to the phase mixing caused by the Sagittarius perturbation, but they could not rule out the influence of the internal mechanisms such like bar or spiral arm perturbation. Recently, Antoja et al. (2020) discovered the ridge structure in the outer disc of the Milky Way using the data of Gaia EDR3. However, they did not investigate more details about radial velocity, chemistry, mass and age populations of the ridge features, which are explored in this work.

Wang et al. (2020c) investigated the chemo-dynamical evolution of the ridge structure of the Galactic disc. They found three long-lived ridge structures and discovered one type is relatively stable with age, the other type changes with time. Therefore, they support that the mechanisms of these two kinds of ridges are possibly originated from phase mixing of the spiral arm of the Milky Way and the disturbance of the Sagittarius Dwarf Spheroidal Galaxy, this coupling mechanisms could also be found more details in Khanna et al. (2019). Using Gaia DR2 and GALAH DR2 Southern Sky Survey, Khanna et al. (2019) have found clear ridge features and more importantly, they also used test particle simulations and N-body simulations to explore the origins of the ridge features, they find in order to unify the ridge features and vertical motions, both the spiral arms phase mixing and the interaction between the Sagittarius dwarf galaxy with Milky Way might be better to advance our understanding for the ridges and snails. Although the spiral arm mechanism in their model could reproduce different kinds of ridges with different energy. Compared to Wang et al. (2020c), we extend the range from [8,12] kpc to [8,18] kpc with mass and also find two kinds of ridges, not only we confirm the ridges...
Figure 4. The left two columns show the radial velocity distribution on the north and south sides of the Galactic disk, and the right two columns show the vertical velocity features. The north and south sides of the Galactic disc have obvious ridge pattern but there is no clear asymmetrical ridge signals for the phase-space location (x-axis, y-axis).

Figure 5. The left two columns show the radial velocity (black dashed lines $L_z = 1750, 2160, 2650$ kpc km s$^{-1}$) and vertical velocity ($L_z$ is 2160 kpc km s$^{-1}$) difference distributions of the north minus south sides, there are still three ridges in the same location as Fig. 3, the amplitude of the south and north ridges might be different, which is showing the clear asymmetries. The right two columns show the velocity differences at different age populations for velocity ($L_z$ is 2220 kpc km s$^{-1}$ for $V_R$, 2320 kpc km s$^{-1}$, 2160 kpc km s$^{-1}$ for $V_Z$), which are showing that the there is remaining one nonstable ridge evolving with time.
Figure 6. The radial velocity distribution of RGB stars used in this paper are shown in the $L_z$ and $V_{\phi}$ plane. The five vertical fuchsia lines in the figure represent constant angular momentum $L_z = (1570, 1750, 2160, 2320, 2650)$ kpc km s$^{-1}$. We can see that third ridge (R3 in the context) changes with age and others are stationary in the left column. The middle and right columns show the distribution of sample on the north and south sides, which are similar to the left one.

Figure 7. Distribution of 3D angular momentum component in the R-$V_{\phi}$ plane in Cartesian coordinate system: angular momentum in the x direction (left), y direction (middle) and z direction (right). The only one dashed line represents the constant angular momentum curve implying there might be a ridge and possible coupling mechanisms but also we find more than three ridges.

Base on the simulation, Martinez-Medina et al. (2019, 2020) found that the ridge structure has a certain impact on the rotation curve of the Milky Way galaxy such like bumps and wiggles, which might make the rotation curve swing and fluctuate on the plane near the ridge location. Recently, focusing on the three-dimensional kinematics and age distribution of the open cluster population, Tarricq et al. (2021) found that the ridge structure can also be observed by using this tracer, and the rotation curve unveiled by the open clusters also showed a small swing and rise near the ridge. Similarly, we also present the analysis for the influence of diagonal ridge on the azimuthal/rotational velocity curve. As shown in Fig. 13, three ridges (R1, R3 and R4) shown as fuchsia dashed lines might have influence on the black rotational curve which has some fluctuations, here we admit more works might be needed for more careful analysis in the future. According to current results, we find the rotation curve conclusion is consistent with Martinez-Medina et al. (2019, 2020) and they also found a total of six ridge structures in the [8,18] kpc range through simulation focusing on the imprint of arms and bars on rotation curve.

In short, combining the ridge patterns and evolution, vertical velocity asymmetries, rotation curve signals, we think the Sgr and spiral arm should be important mechanisms for this structure formation, however we can not rule out factors such like bars effect currently, so maybe the coupling mechanisms are more favoured.

4 CONCLUSION

In this paper, we use the RGB sample obtained by cross matching LAMOST and Gaia to analyze the distribution and chemical-kinematical-dynamical properties of the ridge in the outer disc from 8 to 18 kpc. We find there are six long-lived ridges in the $R-V_{\phi}$ plane and present the time stamps onto it. Not only in the kinematical space we find or confirm the ridge features but also we have similar signals
Figure 8. The left and middle columns show the metallicity and chemical abundance distribution of the sample with the vertical height of [-1.5, 1.5] kpc respectively. The right one shows the vertical velocity distribution but with a vertical height of [-0.2, 0.2] kpc. Obviously the ridge features are detected.

Figure 9. Similar to Fig. 8 for the chemical analysis but the sample is divided into north and south sides. in the chemistry space (with gradient) and mass pattern. North-South comparisons are also shown that no clear different ridge features are detected for the location but at least for three ridges, the asymmetrical amplitude is clearly discovered. Moreover, the possible influence of ridge on the rotation curve (azimuthal velocity) are found in this work.

Furthermore, two kinds of ridges are confirmed again with more features, combining the ridge evolution, 3D velocity asymmetries and rotation curve signals related to ridges we propose that coupling
Figure 10. Similar to Fig. 5 here we show the chemical difference in the north and south sides (left two columns), and meanwhile, the difference at different age populations (right two columns). Two ridges are detected in the [Fe/H] and [$\alpha$/Fe] in the left two columns, and one or two ridges are detected in the right two columns, as shown the dashed lines, which are slightly different from the velocity analysis, but the conclusions are stable. That is, north-south has difference for ridge amplitude and two kinds of ridges are shown here.

Figure 11. The mass distribution on the R and V_ϕ plane, the left one is the whole sample and the right two are sample in the north and south sides. The constant angular momentum line is L_Z = (1400, 2020, 2340, 2580, 2790, 3050) kpc km s^{-1}. 




Figure 12. The left two columns are mass and angular momentum (as a supplement of Fig. 6) difference distribution of north minus south sides on the R/Lz and \( V_\phi \) plane, right two columns are the difference at different age populations.

Figure 13. Radial velocity distribution on the R and \( V_\phi \) plane and the rotational (azimuthal) velocity is overlapped with black curve. The vertical dashed line is the ridge and note that the rotation curve has slight wobble near the ridge region.

mechanisms consist of internal and external such like spiral arm and Sgr perturbation are more important. In future work, we will make full use of more precise data and simulated dataset to push more for the structure of diagonal ridges.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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