On the evolution of Diagonal Ridge pattern found in Gaia DR2 with LAMOST Main-Sequence-Turn-Off and OB type Stars

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ABSTRACT

We revisit the diagonal ridge feature (diagonal distributions in the $R,v_\phi$ plane) found in Gaia and present timing analysis for it between Galactocentric distances of $R = 7.5$ and 12 kpc, using Main-Sequence-Turn-Off and OB stars selected from the LAMOST Galactic spectroscopic surveys. We recover the ridge pattern in the $R-v_\phi$ plane color coded by stellar number density and mean radial velocity and find this feature is presented from very young (OB stars, few hundred Myr) to very old populations ($\tau > 9$ Gyr), accompanying with the north-south asymmetrical ridges. One of the ridge patterns, with constant angular momentum per unit mass, shows clear variations with different age populations compared. However, the remaining two ones are very stable, clearly implying there might have two kinds of ridge patterns with different dynamical origins and evolution. For the vertical velocity and height, there are no ridge features corresponding to the in-plane Galactoseismogy features, but the metallicity and [$\alpha$/Fe] have some weak signals. This first temporal chemo-kinematical analysis for ridge strongly supports that the ridge pattern might be originated from the phase mixing of disrupting spiral arms implying different ridges have different physical processes and no coupling phenomenon, although other possible scenarios such as Sgr perturbations could not be ruled out.

Keywords: Milky Way disk (1050); Milky Way dynamics (1051); Milky Way evolution (1052); Milky Way formation (1053) Milky Way Galaxy (1054)

1. INTRODUCTION

Galactic modeling requires considering evolution and an asymmetric potential, as pointed out by Antoja et al. (2018), who have revealed in our Galaxy many intriguing signals such as snail shells, arches and ridges, etc. The so called Galactoseismology (Widrow et al. 2012, 2014) concludes the non-equilibrium and non-stationary potential of the Milky Way, observed in many density or velocity asymmetries in Liu et al. (2017); Wang et al. (2018a,b,c, 2019, 2020a,b,c); Xu et al. (2015); Gaia Collaboration: Katz et al. (2018); Carrillo et al. (2019); Trick et al. (2019); López-Corredoira et al. (2019a); López-Corredoira et al. (2020) and reference therein, which are significant for us to understand the dynamical history of the Milky Way. There is no doubt we are entering into a golden era of the Galactoseismology by embracing Gaia (Gaia Collaboration et al. 2018) parallax and proper motions.

The inspiring snails and ridges imply that the disk is phase mixing from an out of equilibrium state (Antoja et al. 2018). Hence, quadrupole patterns and phase spirals at different Galactic positions have been revealed by Wang et al. (2019), showing that external perturbations by the Sagittarius dwarf galaxy might be the dynamical origin for it. Time stamps on it suggested the snails happened between 0.5 and 6 Gyr ago, thus leading to the consideration that young stars may have memory of
the interstellar medium (Tian et al. 2018). Phase space snail shells in different cold and hot orbits distributions are also dissected in Li & Shen (2020). Unfortunately, these works using LAMOST survey (Deng et al. 2012; Liu et al. 2014; Cui et al. 2012; Zhao et al. 2012) did not investigate more details for the intriguing ridges.

For the phase mixing patterns and structures, scenarios are mainly classified in two types: one is the external perturbations (Antoja et al. 2018; Binney & Schönrich 2018; Bland-Hawthorn et al. 2019; Laporte et al. 2019; Minchev et al. 2009; Craig et al. 2019), e.g. Sagittarius dwarf galaxy perturbation; the other one is the internal dynamics (Khoperskov et al. 2019; Barros et al. 2020; Quillen et al. 2018; Monari et al. 2019), e.g. buckling of the stellar bar accompanied by bending waves without an external intruder.

Both the spiral arms and Sagittarius perturbation simulations for ridges are shown in Khanna et al. (2019). Outer Lindblad Resonance of the bar could create the prominent ridges (Fragkoudi et al. 2019) and it could be used to compare with ridge map in Kawata et al. (2018). Multiple ridges were also found in Hunt et al. (2018) with 2D transient spiral arms. Arches might be the projection of ridges in the $V_R, V_\phi$ plane (Antoja et al. 2018) and both are connected together (Ramos et al. 2018). Some recent works are also showing that the ridges could be produced by only internal mechanisms such as spirals without external contributors (Barros et al. 2020; Michtchenko et al. 2019). So far, it is still very ambiguous for us to have a clear picture for the ridges, arches, vertical waves, either the origins or relations. And whether they are from internal or external or both mechanisms is very unclear. In this work, we focus on the ridge pattern, tracing it in time stamps in a multiple-dimensional parameter space, trying to get more details of its features and better constraining its origin. There are other recent works discussing the snails, but relatively fewer works focused on ridge and without time evolution analysis as we pretend here.

The cornerstone Gaia-DR2 mission (Gaia Collaboration et al. 2018) has already measured precise proper motions and distances for more than 1.3 billion stars. Gaia data in combination with statistical distribution of stellar ages of millions of stars from LAMOST (Deng et al. 2012; Liu et al. 2014; Cui et al. 2012; Zhao et al. 2012) provide a good sample to study the ridge pattern, by which we can track the temporal evolution of the feature from multiple perspectives and thus push the understanding of that without precedent in history.

This paper is organized as follows. In section 2, we introduce how we select the Main-Sequence-Turn-Off (MSTO) and OB stars sample and describe its properties concisely. The results and discussions are presented in Section 3. Finally, we conclude this work in Section 4.

2. THE SAMPLE SELECTION

A sample of around 0.93 million Main-Sequence-Turn-Off stars with subgiant stars contribution from the LAMOST Galactic spectroscopic surveys including disk region, Galactic–Anticenter region, etc., is selected based on their positions in their locus in the $T_{\text{eff}} - M_V$ plane. With the help of LAMOST DR4 spectra and the Kernel Principal Component Analysis (KPCA) method, accuracies of radial velocities reach 5 km s$^{-1}$. The ages are determined by matching with stellar isochrones using the Yonsei-Yale (Y2) isochrones and Bayesian algorithm. Overall, the sample stars have a median error of 34% for the age estimates (Xiang et al. 2017a,b,c). The OB stars selection is easily selected by spectral line indices space in LAMOST and the distance here is from Gaia (Huang et al. 2020), more details could also be found in Liu et al. (2019).

The second data release of the Gaia mission with unprecedented high-precision proper motions with typical uncertainties of 0.05, 0.2 and 1.2 mas yr$^{-1}$ for stars with G-band magnitudes $\leq$ 14, 17 and 20 mag respectively, has made possible to map the Galaxy’s kinematics and Galacto-seismology with hitherto the largest spatial extent (Gaia Collaboration: Prusti et al. 2016; Gaia Collaboration et al. 2018).

We show the MSTO sample in Fig. 1. It shows the $T_{\text{eff}}$ vs. $\log g$ distributions colored by age, we can see most of stars have surface gravity larger than 3, and younger stars have higher effective temperature than the old ones. In order to build the reliable sample containing stellar astrophysical parameters and precise kinematical information, we use criteria from LAMOST spectroscopic survey and Gaia catalogs as follows:

1) $|Z| < 1.5$ kpc and $7.5 < R < 12$ kpc;
2) SNR $> 20$;
3) age less than 14 Gyr and larger than 0;
4) $v_\phi = [50, 350]$ km s$^{-1}$;
5) parallax $> 0$ and the relative error $< 0.20$.

3. RESULTS AND DISCUSSIONS

3.1. Ridge patterns investigation for MSTO stars

For this part, we investigate the ridge pattern in the different parameter space plots. We show in Fig. 2 density ($f$), radial velocity ($v_R$) and vertical velocity ($v_z$) distributions in the plane of the rotational velocity in the $y$ axis and radial distance in the $x$ axis; the white dotted curves represent constant angular momentum of $L_Z = (1800, 2200, 2550)$ kpc km s$^{-1}$ including the con-
The pattern is top to the bottom. For the ridge A in the top, we could see three strips as ridge A, ridge B, ridge C from the top to the bottom. Here we define these three strips well and has no variation, but it is weaker and weaker when the age is larger than 6 Gyr, possibly due to the age precision. We suggest the variable ridge A ($\tau > 3$ vs. $\tau < 3$ Gyr) and invariable ridge B, C are showing two kinds of ridges possibly originated from different physical scenarios, which is helpful for us to unveil the origins of the ridge.

When we keep going with the $v_R$ pattern in the same plane, an intriguing phenomenon is discovered. Just as shown in the right panel of Fig. 2, what we could see is that no clear and significant ridge features are observed, which is different from the results of Khanna et al. (2019) showing clear pattern in the vertical velocity distribution. The ridge stars in Khanna et al. (2019) are mainly consisting of mid-plane stars less than 0.2 kpc, which is different from our results here using stars less than 1.5 kpc (in order to get more stars and see the ridge pattern in $v_R$ clearly). When we use similar but more stringent selection conditions, the sample is too small to see very clear pattern like Fig. 2 due to the increasing poisson noise and observational errors, etc.

All stars with all heights contribute to the ridge but in this case, the vertical information, e.g., $z$, might be completely washed out (Khanna et al. 2019). We could test whether there is a possibility that these factors mentioned here and last paragraph also might affect the distribution of $[Fe/H]$, $[\alpha/Fe]$, $v_z$. It means not only the effects wash out the vertical information, but also they smear the chemical patterns. As shown in Fig. 3, the $[Fe/H]$, $[\alpha/Fe]$ ($z=\pm[1.5]$ kpc), and $v_z$ ($z=\pm[0.2]$ kpc) distributions are displayed that there are still weak ridge features in the metallicity and abundance, especially for the top panels in the right and middle figure. We have plotted there red and blue strips in the range of $8$–$10$ kpc and around $230$ km s$^{-1}$. Other features are not so clear, but we could still detect some signals, e.g., the third row of the left panel and the second row of the middle figure. Although we use a narrow range of stars, we still could not detect ridge features in the vertical velocity distribution in the right figure. The rotational

![Figure 1](image)

**Figure 1.** The figure shows the MSTO stars age distribution in the $T_{eff}$ and $\log g$ plane adopted in this work; younger stars are hotter than older stars for effective temperature.
velocity of y axis, bin size and the minimum number of each pixel we adopt here are different from the Fig. 2 but it can not change our conclusion at all.

Meanwhile, we investigate more features about the vertical information, as displayed in Fig. 4, where the vertical velocity features belong to $z = [-1.5, 1.5]$ kpc are showed; vertical height distributions belong to $z = [-0.2, 0.2]$ kpc; and height distributions belong to $z = [-1.5, 1.5]$ kpc in the $(R, v_\phi)$ plane. What we could see here is that there is no any clear ridge features in all figures so that we could say the in-plane and vertical asymmetry is decoupling for this work. Moreover, the right two figures have a clear gradient for rotational velocity with radial distance in all sub-figures, and there is clear dip around 8.4 kpc shown as blue histograms for the middle sub-figures. It might imply there are vertical oscillations here.

Summing up, in the $v_\phi, R$ plane for our sample, we see the well-known ridge pattern in density and radial velocity or in star-counts and in-plane space accompanied by the weak signals in the $[Fe/H]$, $[\alpha/Fe]$ distributions, with the time tagging analysis not shown in previous works yet. They are displaying observational evidence that the different ridges have different angular momentum that is variable or not with time, which shows for the first time there are two types of ridges with different properties and origins. However, it was not found by us in the vertical velocity and heights distributions. Our current results support the decoupling of the in-plane asymmetry and vertical motions, thus then we agree the viewpoint that the spiral arm could contribute to the ridge features that will be shown in the discussion. So far, we could not rule out the vertical information might be washed out due to the broad height and sample precision or other underlying systematics to make it featureless, thus we can not rule out the possibility that the in-plane asymmetry and vertical motions, including chemical pattern, might be coupled together but we could not clearly reveal it currently.

### 3.2. Ridge patterns investigation by OB stars

As mentioned in the last section, the ridge pattern has existed for at least 9 Gyr. In order to know more about its evolution, we make full use of LAMOST different samples. We use OB stars (Huang et al. 2020; Liu et al. 2019) to chart the distributions of density and radial velocity in the $(R, v_\phi)$ plane, which is displayed in Fig. 5. It clearly denotes that there are obvious ridge strips colored with green and blue in the left and right, especially for the radial velocity in the range of R from 9–11 kpc and $v_\phi$ from 0 to $-40$ km s$^{-1}$. OB stars typical age are relatively younger, about tens to few hundred Myr, so it implies the ridge started at least few hundred Myr ago. The OB stars selection of this work is similar to Liu et al. (2019) with spectral line indices space and sample criteria during this work is similar to the MSTO stars.

Again, by combing the MSTO and OB stars patterns, we conclude that the ridge feature is extended between less than few hundred Myr and more than 9 Gyr. The stars with $\tau > 9.0$ Gyr could not be dissected into more bins due to the no clear ridge patterns caused by the old stars are kinematically hot so that they are not as sensitive as young stars for the response to the possible perturbations, and sampling rate is also an important factor in our work.

### 3.3. Discussions

As manifested and implied in Wang et al. (2020b) and references therein, we suggest many mechanisms might be coupled together to cause the complexed and abundant vertical asymmetries with bending and breathing modes accompanied with mean non zero radial motions and asymmetrical rotations for the disk regions. All of these might be under a same comprehensive dynamical distribution function. In-plane asymmetries and vertical motions are coupled together as shown clearly in Antoja et al. (2018): Khamma et al. (2019), but whether other different locations and populations are still coupling together is not clear. Antoja et al. (2018) used a relatively narrow range in the solar neighborhood to discover the snails in $z, v_z$ plane and arches, shells, box in $v_R, v_\phi, v_z$ plane, thus then draw the coupling conclusion, but it is not clear for ridges coupling phenomenon in $R, v_\phi$ plane corresponding to the larger distance range during that work. We might examine the details of the chemistry for ridges alone.

A relatively clear picture was proposed by Khamma et al. (2019), they made use all stars of GALAH southern sky survey, test particle simulation and N-body simulation to explore the relations of ridges, arches and vertical waves, which have differences for the sky coverage and tracers with us. Here we provide the ridge sensitive time, starting time and suggest the angular momentum of ridge variation in different age populations and ridge asymmetries, etc. by using LAMOST northern sky survey and only MSTO and OB stars.

Khamma et al. (2019) suggested the ridges, arches and vertical waves are coupled together, and if all stars above the plane contribute to the ridge then the vertical information might be erased, $|Z|$ distribution as an example is emphasized in that work. Moreover, they implied the $v_R$ and density are strongly correlated each other and some signals are also detected in $[Fe/H]$, $[\alpha/Fe]$, which are consistent with our main results. Meanwhile, they
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Figure 2. Stars distribution in the \((R,v_\phi)\) plane with LAMOST MSTO stars and Gaia DR2 proper motion in different age populations. Heat maps of various quantities are shown; Left panel is the density \(f\) distribution, middle one is the radial motion \(v_R\), the right panel is the vertical velocity \(v_z\). The white dotted curves represent constant angular momentum of \(L_Z = (1800, 2200, 2550)\) kpc km s\(^{-1}\) with contribution of the \(V_{LSR}\). The radial distance range is from 7.5 to 12 kpc.

also pointed out clearly that phase mixing of disrupting spiral arms can generate both the ridges and arches accompanied with the points of no coupling phenomenon and different ridges could be originated from different scenarios in theoretical view, but if they want to unify the coupling planar and vertical motions, an intermediate satellites like Sagittarius perturbation is favored. We actually find two kinds of ridge patterns in different age populations and it does not exist in \(v_z\) so that we currently inclined to support the former scenario according to our current understanding.

If the error or precision of the sample or other systematics could wash out ridge pattern colored by \(v_z\) and \(z\), then the latter one of Sgr perturbation should be possible in this work. More importantly, in addition to the vertical signals not detected, we firstly detect the angular momentum of one ridge pattern is variable with age but other two are stable, implying the two kinds of ridges might have different origins, which is more similar to the results shown in phase mixing model without perturbation displayed in previous works. On the other hand, so far whether the spiral arm could contribute to the vertical motions is not clear so that we could not rule out the possibility spiral arm might play a role to the vertical motions, in this case, phase mixing models of spiral arms can not be ignored at any time. In other words, even if we detect vertical signals here with high precision data in the future, the internal mechanisms such as spiral arms could also be an important contributor, thus then our conclusions for this work are still robust.

We also have finished a test in Fig. 6. The heat maps of various quantities show the stars radial velocity distribution in the \((R,v_\phi)\) plane in different age populations for all sample (left), southern stars of the ridge (middle), northern stars of the ridge (right). There are north-south asymmetries implying that north ridges are higher than the south ridges when we compare the blue
strips of the middle and right panels. For example, there is a about 10 km s$^{-1}$ difference for the blue strips located at similar location both in the second and third row of the two figures. These evidence suggest us that the there are asymmetrical ridge features. Unfortunately we could not discriminate the phase mixing model of spiral arms and Sgr like perturbations only from this figure.

By investigating the origin of moving groups and diagonal ridges with the help of simulations of stellar orbits and birthplaces, Barros et al. (2020) pointed out that the diagonal ridges could be originated from the spiral resonances. There is no evidence of incomplete phase mixing in the vertical direction of the disk found in Michtchenko et al. (2019) and their results could be explained by internal mechanisms without external perturbations. Recently, Kushmiruk et al. (2020) investigated the HR 1614 moving groups and proposed that several different mechanisms such as resonances of the bar, spiral structure, phase-mixing of dissolving spiral structure, phase-mixing due to an external perturbation should be combined to explain this feature. All these works are supporting our viewpoints here, that is to say, the ridge features shown by our observational results can be definitely contributed by the internal scenario but there are other possibilities.

In short and again, after considering the precision of the LAMOST phase-I is not as accurate as GALAH, we could not rule out the Sgr like perturbations scenarios or both the internal and external mechanisms are coupled together with different levels. However, our current results robustly support the internal mechanisms such as spirals could be the important contributor to the ridges. The vertical velocity distribution might not appear due to factors such as the broad height and sample precision, etc. Recent ridge patterns results with LAMOST is also not clear at all except the radial velocity (Wheeler et al. 2020). We suggest these factors possibly simultaneously affect the $v_z$, $z$, [Fe/H], [$\alpha$/Fe]. Whatever, our work provides a new clue for us to push the understanding of the evolution and origin of the ridge by a novel angle and LAMOST-II medium resolution with more accurate radial velocity and abundance data will help us to investigate more.

4. CONCLUSION

In this work, using LAMOST–Gaia combined stars, we corroborate the existences of the ridge structure in the density and radial velocity distribution in $v_\phi, R$ plane, but not clearly displayed in the $v_z$ and $z$ distributions. More importantly, with the help of three ridges detailed analysis, the evidence of the two kinds of ridge
patterns with possibly different dynamical origins are firstly revealed, shown as the ridge angular momentum is variable or not variable in different age populations for this paper. All these evidences strongly support one of the viewpoints of Khanna et al. (2019), that is to say, the toy model of phase mixing model with initial distribution of particles confined to four thin spiral arms could produce the ridge patterns and different ridges might have different physical scenarios, but there is no coupling phenomenon of vertical and planar motions for this model. Moreover, the weak ridge patterns are shown in $[\mathrm{Fe/H}]$, $[\alpha/\mathrm{Fe}]$ distributions and the north-south asym-
Figure 6. Stars distribution in the $(R,v_φ)$ plane colored by radial velocity. Heat maps of various quantities are shown; Left panel is radial velocity distribution of all sample, middle one is the southern sample, the right panel is the northern sample. There are asymmetries showing that north ridges are larger than the south ridges. The rotational velocity of y axis, bin size and the minimum number of each pixel here are different from the Fig. 2.

metrics of the ridges are also clearly displayed in this work.

We further investigate the temporal evolution of the ridge pattern with different stellar ages, and find that it is sensitive to the perturbations for at least 9 Gyr. With the help of younger populations of OB stars, we discover it reaches until at least few hundred Myr ago. This is the first time stamps work on the ridge. Different levels of sensitivity of different stellar populations for the response to the possible dynamical perturbation are unveiled again in this work. We also speculate that the vertical kinematics ($v_z$) might be affected by the mentioned broad heights, sample selection and errors of sample or other systematics, making them no featureless. If we agree the vertical motions is washed artificially, then the Sgr like perturbation might be the cause. But again, we believe our new results strongly support the internal mechanisms could produce ridges. There is also a possibility that different mechanisms are coupled together with different contributions. These features are non-trivial to be investigated in more details by us, e.g., we will go farther distance beyond 12 kpc to characterize it in more dimensions, which is not the target of the current work.

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