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Dissecting the phase space snail shell

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Abstract. The on-going phase mixing in the vertical direction of the Galactic disk has been discovered with the revolutionary Gaia DR2 data. It manifests itself as the snail shell in the $Z - V_Z$ phase space. To better understand the origin and properties of the phase mixing process, we study the phase-mixing signatures in moving groups (also known as the kinematic streams) with the Gaia DR2 data in the Galactic disk near the Solar circle. Interestingly, the phase space snail shell exists only in the main kinematic streams with $|V_R| \lesssim 50$ km/s and $|V_\phi - V_{\rm LSR}| \lesssim 30$ km/s, i.e., stars on dynamically "colder" orbits. Compared to the colder orbits, the hotter orbits may have phase-wrapped away already due to the much larger dynamical range in radial variation to facilitate faster phase mixing. These results help put tighter constraints on the vertical perturbation history of the Milky Way disk. To explain the lack of a well-defined snail shell in the hotter orbits, the disk should have been perturbed at least $\sim 400 - 500$ Myr ago. Our results offer more support to the recent satellite-disk encounter scenario than the internal bar buckling perturbation scenario as the origin of the phase space mixing.

Keywords. Galaxy: disk — Galaxy: kinematics and dynamics — Galaxy: structure — stars: kinematics and dynamics

1. Introduction

The Milky Way disk is not in a complete dynamical equilibrium. It shows prominent structure in kinematic space that is phase mixing in both horizontal and vertical directions. Using the revolutionary Gaia data, Antoja *et al.* (2018) discovered clear evidence of vertical phase mixing in the solar neighborhood for the first time. A clear snail shell can be seen in the $Z - V_Z$ phase space. This feature can be understood as the phase mixing process in a vertically perturbed disk, where the vertical oscillation frequency depends on the oscillation amplitude, generating a snail shell structure in $Z - V_Z$ space (Tremaine 1999; Binney & Tremaine 2008; Candlish *et al.* 2014; Antoja *et al.* 2018). The phase space snail shell shows up more clearly when color-coded with azimuthal velocity (V_ϕ) of stars (Fig. 1c in Antoja *et al.* 2018), which was suggested to indicate the tight correlation between the in-plane and vertical motions. The two motions are clearly entangled, but there are still important details to be clarified (Binney & Schönrich 2018; Darling & Widrow 2019). Since then, the properties of the snail shell and its dependence on the stellar parameters and spatial variation have been extensively studied (Tian *et al.* 2018; Cheng *et al.* 2019; Khanna *et al.* 2019; Wang *et al.* 2019).

It has been well known that the velocity phase space in the solar neighborhood, e.g., $V_R - V_\phi$, shows complex kinematic stream features, also known as "moving groups"

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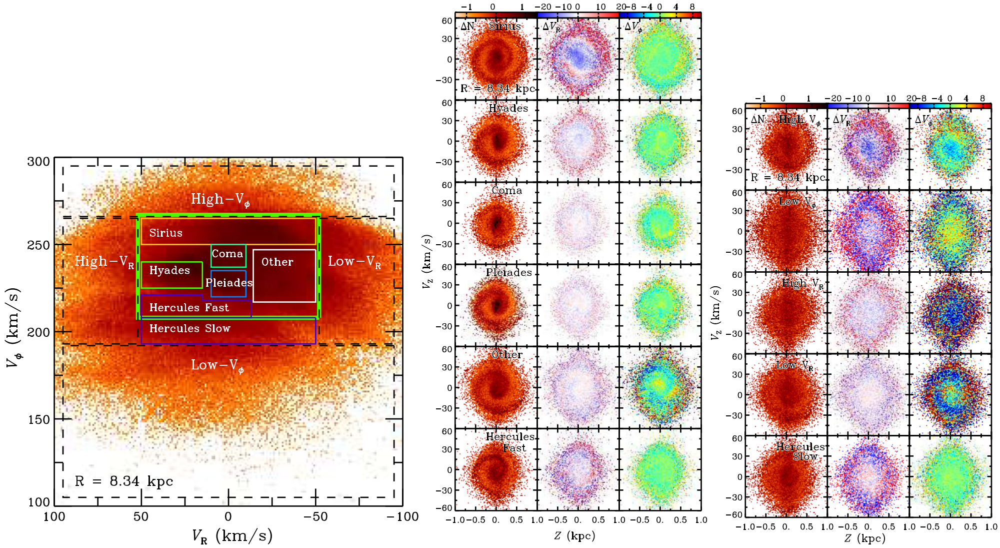

Figure 1. Left: The phase space distribution in $V_R - V_\phi$ for the sample in the Galactic disk at $R = 8.34$ kpc; Middle: The $Z - V_Z$ phase space of the main kinematic streams showing the snail shell; Right: The $Z - V_Z$ phase space of the main kinematic streams without snail shell feature.

(Dehnen 1998; Antoja *et al.* 2008). Different moving groups may have different dynamical origins. We find it physically interesting to explore the connection between the in-plane resonance-driven moving groups and the imprint of a vertical perturbation event. Here we utilize the second Gaia data release (DR2) with radial velocity, proper motions and parallax available to investigate the distributions of these moving groups in the $Z - V_Z$ phase space, which may shed light on the origin of the snail shell and the correlation between the in-plane and vertical motions.

2. Sample

From Gaia DR2, we adopted the same sample selection as Antoja *et al.* (2018), i.e., selecting stars with positive parallaxes ϖ with relative uncertainty less than 20% ($\varpi/\sigma_\varpi > 5$). In this study, we select the stars in a narrow annulus in the solar neighborhood ($R = 8.34 \pm 0.1$ kpc), which contains $\sim$ 0.93 million stars. The $V_R - V_\phi$ phase space distribution of this sample are shown in the left panel of Fig. 1, which shows a variety of streams and clumps. The main kinematic streams are selected and studied in the following analysis.

3. Results and Discussion

We further dissect the sample in the $V_R - V_\phi$ phase space into different streams, i.e., Sirius, Hyades, Coma Berenices (hereafter Coma for brevity), Pleiades, and Hercules, according to the location of these streams described in previous works (Sellwood 2010; Trick *et al.* 2019), and other regions for the purpose of comparison, i.e., the High/Low$-V_\phi$ and High/Low$-V_R$ Regions. Gaia DR2 has revealed two possible branches of the Hercules stream (Gaia Collaboration *et al.* 2018). In this work, the Hercules stream is further divided into Hercules Fast ($208 < V_\phi < 221$ km/s) and Hercules Slow streams ($193 < V_\phi < 208$ km/s). V_Z is not considered when classifying streams.

As shown in the middle panels of Fig. 1, clear snail shells can be seen in the $Z - V_Z$ phase space number density distributions of the Sirius, Hyades, Coma, Pleiades, and Hercules Fast streams, and the "Other" region. It seems that these streams show slightly

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different snail shell pattern. The radial velocity ΔV_R ($\equiv V_R - \overline{V_R}$; middle column) or azimuthal velocity ΔV_ϕ ($\equiv V_\phi - \overline{V_\phi}$; right column) color-coded phase space shows almost no snail shells, which is reasonable since the V_ϕ range of each stream is relatively narrow. The High/Low$-V_\phi$, High/Low$-V_R$ regions, and the Hercules Slow stream do not show snail shell in either the number density, V_R, or V_ϕ color-coded $Z - V_Z$ phase space, as shown in the right panels of Fig. 1.

From the $V_R - V_\phi$ phase space in the left panel of Fig. 1, it seems that the snail shell only exists in the region with $|V_R| \lesssim 50$ km/s and $210 \lesssim V_\phi \lesssim 270$ km/s (i.e., $|V_\phi - V_{\rm LSR}| \lesssim$ 30 km/s). This velocity range corresponds to the dynamically colder orbits, which are closer to circular orbits. Stars with velocities outside that region are denoted as hotter orbits.

It seems that stars on hotter orbits have sufficiently phase-mixed to show no snail shell in the $Z - V_Z$ space. The hotter orbits typically have much larger dynamical range in the disk than the colder orbits. Therefore, stars on hotter orbits make blurred elliptical rotation in the $Z - V_Z$ phase space, which leads to faster phase mixing. These results help to put tighter constraints on the vertical perturbation history of the Milky Way disk. To explain the lack of snail shell in the hotter orbits, the Milky Way disk should be perturbed at least $\sim 400 - 500$ Myr ago.

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