X14a Origin of the two-armed vertical phase-spiral in the inner Galactic disk

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Gaia recently revealed a two-armed spiral pattern in the vertical phase-space distribution of the inner Galactic disk (guiding radius $\sim$ 6.2 kpc), indicating that some non-adiabatic perturbation symmetric about the mid-plane is driving the inner disk out of equilibrium. The non-axisymmetric structures in the disk (e.g., the bar or spiral arms) have been suspected to be the major source for such a perturbation. However, both the lifetime and the period of these internal perturbations are typically longer than the period at which stars oscillate vertically, implying that the perturbation is generally adiabatic. This issue is particularly pronounced in the inner Galaxy, where the vertical oscillation period is shorter and therefore adiabatically shielded more than the outer disk. We show that two-armed phase spirals can naturally form in the inner disk if there is a vertical resonance that breaks the adiabaticity; otherwise, their formation requires a perturber with an unrealistically short lifetime. We predict analytically and confirm with simulations that a steadily rotating (non-winding) two-armed phase spiral forms near the resonance when stars are subject to both periodic perturbations (e.g., by spiral arms) and stochastic perturbations (e.g., by giant molecular clouds). Due to the presence of multiple resonances, the vertical phase-space exhibits several local phase spirals that rotate steadily at distinct frequencies, together forming a global phase spiral that evolves over time. Our results demonstrate that, contrary to earlier predictions, the formation of the two-armed phase spiral does not require transient perturbations with lifetimes shorter than the vertical oscillation period.