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Revisit the Oort constants measurement from *Gaia DR2* observations and simulations

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1. SUMMARY

Rotation curves of disk galaxies reflect the underlying mass distribution profiles. The flat and slightly declining rotation curve of the Milky Way indicates differential rotation, since the rotation frequency varies with orbital distances. Measuring the Galactic rotation curve has remained a challenging task for astronomers. Since we are inside the Milky Way, rotation velocities can only be derived from the relative motions of special tracers, e.g., classical Cepheid, RR Lyrae stars and gas clouds (Levine et al. 2008, Metzger et al. 1998,Mróz et al. 2019, Wegg et al. 2019). The Oort constants that are measured in the solar neighborhood play important roles to bridge the local and global kinematic properties of the Milky Way disk. While multiple measurements on Oort constants have been made, an accurate estimation requires a complete catalog of precise stellar parallax, proper motions (Kerr & Lynden-Bell 1986), and radial velocities, as well as careful considerations on the effect of different sample selections, which is still lacking. We approach the question by combing the *Gaia* DR2 and test particle simulation. *Gaia* DR2 catalogs parallax and proper motion measurements of over 1.6 billion stars, giving us the most comprehensive sample to calculate the Oort constants (Gaia Collaboration et al. 2016, Gaia Collaboration et al. 2018).

Assuming a thin Milky Way disk under the cold limit and axisymmetric potential, after correcting the solar non-circular velocities about the Local Standard of Rest (LSR), (u_0, v_0, w_0), the stellar line of sight velocity, v_{los}, proper motions in the longitude and latitude directions, μ_l and μ_b, in the solar nearby region can be expressed in the Oort constants. They are usually noted by A, B, C, and K, which represent transverse shearing, vorticity, radial shearing, and gradient in the local velocity field. v_{los}, μ_l and μ_b all oscillate with a period of 180° about Galactic longitude. Furthermore, $-(A+B)$ gives the slope of rotation curve at solar orbit, $A-B$ the local rotation frequency and $K+C$ the gradient of radial velocity (Ogrodnikoff 1932, Binney & Merrifield 1998, Olling & Dehnen 2003).

Under the idealized circular orbits assumption, the longitudinal dependencies of μ_l , v_{los} and μ_b are due to the effect of rotational frequency varying at the different orbital radius. In reality, potential perturbation and non-axisymmetric Galactic potential attribute to stellar non-circular velocity components, resulting in deviations from the behaviors constrained by the Oort constants. Thus, to measure the Oort constants from a large observational database, a critical question is how to select the best subsets of stars to derive the Oort constants − to find the proper cut off ranges of the Galactic distance and latitude.

In my thesis, we first simulate a cold and thin disk treating stars as test particles to investigate the effects of different Galactic distances and latitude ranges. Stars are sampled from the Quasi Isothermal distribution function with a vertical disk scale of 0.4 kpc and velocity dispersion of 10 km/s to mimic a dynamically cold disk (Bovy 2015, Vasiliev 2019). We find the proper motion in longitude direction for stars within 1 kpc from the Sun and less than 20° in their latitude are well described by the Oort constants with small dispersion. If either the distance or the latitude cut-off range is larger, the residuals from the model become larger with systematic deviation dependent on longitude. Similarly, a smaller range of distance and latitude yields the best subset to derive the Oort constants, A, C and K from v_{los}. While μ_l and v_{los} are well described by the Oort constants when close to the MW midplane, the latitudinal proper motion, μ_b, are expected to be significant with higher latitudes. However, in a high latitude region, the stellar orbits are rather non-circular due to the large vertical oscillation. These stars tend to have larger vertical velocities, which give a more dominant contribution to μ_b than the effect from differential rotation parallel to the disk. μ_b of stars with $30^\circ \leq |b| < 50^\circ$ yield the clearest longitudinal dependency, but the dispersion and deviations are much more significant than those in μ_l and v_{los}. Thus, we conclude that it is optimal to use the μ_l and v_{los} values with stars within 1kpc and $|b| < 20^\circ$ to find the Oort constants, and estimate that $A = 15.62 \pm 0.34$, $B = -12.78 \pm 0.31$, $C = 1.31 \pm 0.40$, $K = 0.24 \pm 1.09$km/s/kpc. These values give rotational velocity at solar radius 238km/s. The values of C and K are consistent with the model set-up of symmetric Galactic potential. We also discover that the deviations

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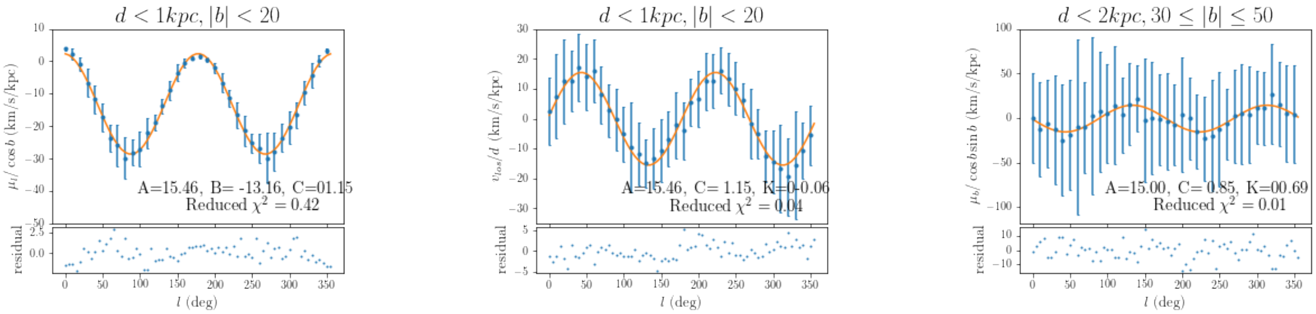
and dispersion in μ_l are due to non-zero radial velocity, while, for both v_{los} and μ_b, their scattering and deviations from the Oort constants model are attributed to non-zero vertical velocities. The results of our test particle simulation could seen in the Fig. 1.

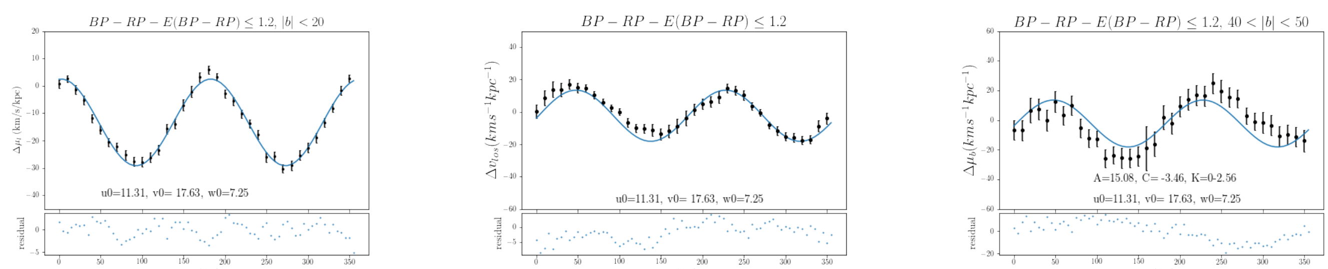


(a) (b) (c)

Figure 1: Test particle simulation result. We show the subsets that yields the best results to estimate the Oort constants from μ_l, v_{los} and μ_b. For both μ_l and v_{los} in 1a and 1b, we use stars with $d <$ 1kpc and $|b| < 20°$. And for μ_b, we use stars with $d < 2kpc$ and $30° < |b| < 50°$. The distance range is larger because there is not enough stars within 1kpc in the above latitude range from out 500,000 test particles. 1a) $\mu_l / \cos b = A \cos 2l + B \sin 2l + C$; 1b) $v_{los}/d = A \sin 2l + C \cos sl + K$; 1c) stars with $d <$ 1kpc and $|b| < 20°$ $\mu_b / \sin b \cos b = A \sin 2l + C \cos sl + K$.

For *Gaia* DR2 data, we follow the procedure laid out by the work in Bovy (2017) and Li et al. (2019), grouping the main sequence stars into six color groups after correcting color excess and derived the Oort constants from the longitudinal profiles of μ_l , v_{los} and μ_b. We discover that it is necessary to constraint the stars within 500 pc, a smaller range than that in the simulation because the non-circular deviations are more significant in the real Milky Way disk. We also find the group with the bluest stars have the smallest deviations from the models of the Oort constants, while the redder color groups have more dispersion in their μ_l and μ_b, as well as larger deviations. This is expected because redder stars are older and have been influenced by non-circular potential perturbation for a longer time, thus their motions deviate more from the circular and horizontal motions constrained in the Oort constant model. Despite that past works on using *Gaia* data to measure the Oort constants disregard radial velocity, we find the available radial velocities for the blue stars are abundant enough to estimate the Oort constants to a higher precision than μ_b. The Oort constants derived from μ_l and v_{los} of these stars within 500 kpc are $A = 15.52 \pm 0.22, B = -13.33 \pm 0.17, C = -1.88 \pm 0.08$, and $K = -1.86 \pm 0.19$ km/s/kpc, consistent with the results in Li et al. (2019), and the estimated slope of circular velocity at solar orbit is -18.26 ± 0.28 km/s/kpc. The results of analyzing *Gaia*dr2 are shown in Fig. 2

Considering the results from our simulation and *Gaia* DR2, we conclude that stellar age, galactic distance and latitude are all important factors to consider when sampling stars to derive the Oort constants. In addition, mu_l and v_{los} are more reliable tracers than μ_b. The conclusion from this work helps us understand the effect of sample selection on the Oort constants measurement, and it can provide some guidance on measuring the Oort constants from larger database (*Gaia* DR3) in the near future.



(a) (b) (c)

Figure 2: *Gaia* DR2 result for the blue main sequence stars within 500 pc from the Sun. 2a) $\Delta\mu_l = \frac{1}{\cos b}(\mu_l - \varpi(u_0 \sin(l) - v_0 \cos l) = A \cos 2l + B \sin 2l + C$; 2b) $\Delta v_{los} = \varpi(v_{los} + u_0 \cos l + v_0 \sin l) = A \sin 2l + C \cos 2l + K$; 2c) $\Delta\mu_b = -\frac{1}{\sin b \cos b}(\mu_b - \varpi[(u_0 \sin l + v_0 \cos l) \sin b - w_0 \cos b]) = A \sin 2l + C \cos 2l + K$, where (u_0, v_0, w_0) is the solar peculiar motion.