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Milky Way globular cluster dynamics: are they preferentially co-rotating?

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Abstract The motion of baryonic components of the Milky Way is governed by both luminous and dark matter content of the Galaxy. Thus, the dynamics of Milky Way globular clusters (GCs) can be used as tracers to infer the mass model of the Galaxy up to a large radius. In this work, we apply the directly observable line-of-sight velocities to test if the dynamics of the GC population are consistent with an assumed axisymmetric gravitational potential of the Milky Way. For this, we numerically compute the phase space distribution of the GC population where the orbits are either oriented randomly or co-/counter- rotating with respect to the stellar disk. Then we compare the observed position and line-of-sight velocity distribution of ~150 GCs with those of the models. We found that, for the adopted mass model, the co-rotating scenario is the favored model based on various statistical tests. We do the analysis with and without the GCs associated with the progenitors of early merger events. This analysis can be extended in the near future to include precise and copious data to better constrain the Galactic potential up to a large radius.

Key words: Galaxy: kinematics and dynamics — globular clusters: general — galaxies: dwarf — Galaxy: halo — methods: statistical

1 INTRODUCTION

The nearly flat rotation curve of the Milky Way (MW) in the outer Galaxy, inferred from stellar motion as well as spectroscopic observation of a variety of tracers of the interstellar medium (ISM, e.g., $H\alpha$, HI and CO emission lines), is explained by invoking the existence of a massive dark matter (DM) halo (e.g., Rubin et al. 1980; Begeman et al. 1991). Although there are a few galaxies for which the rotation curve falls off according to a Keplerian prediction (Honma & Sofue 1997), the majority of spiral galaxies exhibit a similar flat rotation curve. The nature and properties of this dominant component of the mass in our Galaxy, at present, remain mostly uncertain. The mass and density distribution of various components of the MW have been studied earlier in detail through mass models (e.g., Caldwell & Ostriker 1981; Dehnen & Binney 1998; Klypin et al. 2002), kinematic models (e.g., Sharma et al. 2011) and dynamical models (e.g., Widrow et al. 2008; Bovy & Rix 2013). The most notable one among these is the mass model put forward by Dehnen & Binney (1998), which considers an axisymmetric potential and three principal components of the MW, viz. the disk, bulge, and halo. The disk consists of the ISM, and the thin and thick stellar disks. The bulge and halo are each described by a spheroidal density distribution. The HI 21-cm line, in particular, is one of the most powerful tools to study the kinematics of our Galaxy, as the radial extent of the HI gas is greater than that of the visible component. However, the dynamics of the Galaxy and, in turn, the properties of the DM halo can also be studied from the structure and kinematics of other baryonic components, such as globular clusters (GCs) and satellite galaxies (SGs). In this work, we use the phase space distribution of GCs based on direct observables (position and line-of-sight component of their velocity) to check the consistency of the current MW mass model.

Hierarchical structure formation predicts that the merging of smaller subhalos leads to the formation of a DM halo (Springel et al. 2008; Frenk & White 2012). The residual subhalos are observed today as SGs. The MW has about 59 SGs within 0.5 Mpc from the Galactic center that are gravitationally bound to the MW, but not all are necessarily in orbit (Kallivayalil et al. 2006; Besla et al. 2007; Pardy et al. 2020). The MW also has nearly 200 GCs with a roughly spheroidal distribution around the Galaxy. They constitute the halo population of our Galaxy. The majority of these GCs lie at low latitudes in the inner Galaxy, i.e., within \sim 20 kpc from the Galactic center (Koposov et al. 2007; Dotter et al. 2011; Gaia Collaboration et al. 2018).

The SGs are more DM dominated than the GCs in their small-sized halos. In the outermost regions of the Galaxy, beyond the luminous disk, the gravitational potential of the DM halo can be constrained from observed velocities of GCs and SGs (Sofue 2013).

Depending on the nature of a DM candidate, the number of subhalos predicted from cosmological simulations can be as much as a few orders of magnitude more than the number of dwarf galaxies observed as satellites (Strigari et al. 2008; McConnachie et al. 2009; Strigari 2018). The general consensus in the Λ -CDM model is that the stellar halos of MW type galaxies are formed from continuous accretion, merger events or tidal disruption of many smaller DM subhalos at high redshifts (Bullock et al. 2001). The outer- and inner-halo of the MW with overlapping structural components can thus be assumed to be composed of two kinds of stellar populations: one that originated in other galaxies and was accreted by MW in merger events, and another which originated in situ from the evolution of MW itself. They exhibit different spatial density profiles, stellar orbits and stellar metallicities (Carollo et al. 2007). Chemodynamical studies of the latest data from Gaia (Gaia Collaboration et al. 2016) and SDSS (Abolfathi et al. 2018) provide definitive evidence of the presence of tidal debris from a major merger event around 8-10 Gyr ago, during the early stages of halo assembly, leaving its imprint on the 'sausage' like structure formed in velocity-space (Helmi et al. 2018; Belokurov et al. 2018; Myeong et al. 2018). Apart from the Gaia Sausage, there are predictions of accretion due to other less-massive merging dwarfs (Myeong et al. 2019; Piatti 2019).

In this paper, we investigate whether these accretion events could have contributed significantly to the resulting dynamics of the GC population. With limited information about the orbits, studying the exact dynamics of individual GCs or SGs is an intricate problem. Instead, we address here the consistency of the GC phase space distribution for an assumed gravitational potential. We consider the dataset of GCs (Harris 1996, 2010; Sohn et al. 2018) with known Galactic coordinates (l, b), distance to the clusters from the Sun, D_{\odot} and observed line-of-sight velocity $v_{\rm los}$. From this, we construct the distribution of GCs around the Galactic center. We then use the public licensed code GALPOT to simulate, for a given mass model of the MW, the position-velocity (l vs. v_{los}) distribution for a sample of GCs with the same Galactocentric distribution. A comparison between the simulated and observed phase space distribution will allow one to check if the assumed mass model is consistent with the GC dynamics. We also check how the phase space distribution changes because of the GCs associated with the progenitor galaxies of the merger events - Gaia-Enceladus, Sequoia or Sagittarius d-



Fig. 1 Hammer projection of the Galactocentric distribution of GCs.

Sph. Please note that the same analysis can be done for the SGs as well. However, the line-of-sight velocity data are available for a lesser number of SGs (Newton et al. 2018), and hence, here we restrict our analysis mostly to GCs.

We discuss the observed statistics for GCs and the mass model utilized for this analysis in Section 2. The methodology of our analysis and the results are presented in Section 3. We discuss the implications of our results in Section 4 and draw our conclusions in Section 5.

2 DATA AND MASS MODEL

The catalog of the GCs (Harris 1996, 2010) provides coordinates (l, b), line-of-sight velocity v_{los} , metallicity, photometry and other structural parameters. In the following, we discuss the observed statistics of the GCs and their spatial distribution in Section 2.1, and present the potential model employed to calculate the circular velocity from Galactocentric distance $\mathbf{R}_{\mathbf{G}}$ and the setup for GALPOT code in Section 2.2.

2.1 Observed Statistics

For each GC, we calculate the Galactocentric distance R_G , vertical distance z from the Galactic plane and Galactocentric angular coordinates θ and ϕ from l, b and D_{\odot} data on the GCs. For this, we took the distance to the Sun from the Galactic center to be $R_0 = 8.2 \,\mathrm{kpc}$, the best fit value found in McMillan (2017). By matching the best dynamical model obtained in Chatzopoulos et al. (2015) to the proper motion and line-of-sight velocity dispersion data of nuclear star clusters, they ascertained the value of R_0 to be $8.27 \pm 0.09|_{\text{stat}} \pm 0.4|_{\text{syst}}$, where systematic errors account for uncertainties in the dynamical modeling. The number of GCs falls off sharply beyond $R_G = 20$ kpc. The Galactocentric angular distribution of GCs is depicted using the Hammer projection in Figure 1. As expected, the distribution is consistent with a uniform spherical distribution. We plot the observed line-of-sight velocities $v_{\rm los}$ against Galactic longitude l in Figure 2, where the color



Fig. 2 Distribution of the line-of-sight velocity (v_{los}) as a function of Galactic longitude (l) for GCs with color bar indicating the Galactic latitude (b).

bar indicates the value of Galactic latitude *b* for the GCs. The overplotted sinusoidal curve in the figure illustrates the component of $v_{\rm los} \propto \sin(l)$, reminiscent of a similar boundary for tracers from the Galactic disk. Note that the mentioned catalog lists 157 sources, of which the velocity information is available for 143 GCs, and only those are included in the analyses.

2.2 The Gravitational Potential

The observed distribution of (l, v_{los}) for GCs is compared with the predicted distribution for the model axisymmetric potential of the MW. For this, we have implemented the public licensed code GALPOT. It was originally written in C++ by Walter Dehnen and later developed by Paul J. McMillan (McMillan 2017), which is an extension of a previous model by McMillan (2011). In addition to other components, the new model incorporates gas discs that account for the MW's cold gas. The MW mass is decomposed into six axisymmetric components – bulge; DM halo; thin and thick stellar discs; and HI and molecular gas discs. With an axisymmetric approximation to the Bissantz & Gerhard (2002) model, the bulge density profile is expressed by

$$\rho_{\rm b} = \frac{\rho_{0,\rm b}}{(1+r'/r_0)^{\alpha}} \, \exp[-(r'/r_{\rm cut})^2]\,,\tag{1}$$

where $r' = \sqrt{R^2 + (z/q)^2}$ is in cylindrical coordinates, with $\alpha = 1.8$, $r_0 = 0.075 \,\mathrm{kpc}$, $r_{\mathrm{cut}} = 2.1 \,\mathrm{kpc}$ and axis ratio q = 0.5. The total bulge mass considered is $M_{\mathrm{b}} = 8.9 \times 10^9 \,M_{\odot}$ with an uncertainty of $\pm 10\%$. The scale density $\rho_{0,\mathrm{b}} = 9.93 \times 10^{10} \,M_{\odot} \,\mathrm{kpc}^{-3} \pm 10\%$. The thin and thick stellar disc of MW are modeled as exponential according to the Gilmore & Reid (1983) model

$$\rho_{\rm d}(r,z) = \frac{\Sigma_0}{2z_{\rm d}} \, \exp\left(-\frac{|z|}{z_{\rm d}} - \frac{R}{R_{\rm d}}\right),\tag{2}$$

with scale height z_d , scale length R_d and central surface density Σ_0 . The total disc mass is $M_d = 2\pi\Sigma_0 R_d^2$. The scale heights of the discs are fixed at $z_{d,thin} = 300 \,\text{kpc}$ and $z_{d,thick} = 900 \,\text{kpc}$. The HI and molecular gas discs are defined by the functional form mentioned in Dehnen & Binney (1998) as written below

$$\rho_{\rm d}(R,z) = \frac{\Sigma_0}{4z_{\rm d}} \exp\left(-\frac{R_{\rm m}}{R} - \frac{R}{R_{\rm d}}\right) \operatorname{sech}^2(z/2z_{\rm d}) \,. \tag{3}$$

Similar to the stellar disc, the gas disc also exhibits an exponential decline with R, but has a hole in the center with an associated scale length R_d . The maximum surface density is found at $R = \sqrt{R_d R_m}$, and the total disc mass is given by $M_d = 2\pi \Sigma_0 R_d R_m K_2 (2\sqrt{R_m/R_d})$ where K_2 is a modified Bessel function. Also, the disc model posses an isothermal *sech*-squared profile. The HI disc model resembles the distribution found in Kalberla & Dedes (2008). The presence of the gas discs significantly deepens the potential well near the Sun, and hence affects the dynamics near the solar neighborhood. The surface density is set to be $10 M_{\odot} \text{ pc}^{-2}$ at a fiducial value of $R_0 = 8.33 \text{ kpc}$, the distance of the Sun from the Galactic center. The DM halo density is described by

$$\rho_{\rm h} = \frac{\rho_{0,\rm h}}{x^{\gamma} (1+x)^{3-\gamma}} \,, \tag{4}$$

where $x = r/r_{\rm h}$, with $r_{\rm h}$ the scale radius. They have considered $\gamma = 1$, for the best-fit potential model, which is the NFW profile (Navarro et al. 1996). GALPOT provides the gravitational potential associated with axisymmetric density distributions. It includes the potential models from Piffl et al. (2014), McMillan (2011), Dehnen & Binney (1998), McMillan (2017) and their variants. Here, we use the best-fit potential model of McMillan (2017), which contains four disk components and two spheroidal components. The values of various parameters for this bestfitting potential model are provided in table 3 of McMillan (2017). The mass of the MW within 300 kpc, calculated by Watkins et al. (2010), is found to be between 1.2 and $2.7 \times 10^{12} M_{\odot}$. The estimate yielded by GALPOT is $(1.6 \pm 0.3) \times 10^{12} M_{\odot}$, which is well within the plausible range. Thus, the potential model is representative and well-suited while also considering the dynamics of GCs.

As the Galactocentric distance to a source can be written as $R_G = \sqrt{R_p^2 + z^2}$, for non-coplanar orbits of the GCs we express the approximate circular velocity as

$$v_R = \left(\frac{d\Phi}{dR_G} R_G\right)^{1/2},\tag{5}$$

$$\frac{d\Phi}{dR_G} = \frac{d\Phi}{dR_p} \frac{R_p}{R_G} + \frac{d\Phi}{dz} \frac{z}{R_G}, \qquad (6)$$

where $R_p = R_G \sin \theta$ is the component of galactocentric distance in the plane of the disk and z is the vertical height



Fig.3 l vs. v_{los} plot for (*left*) mixed rotation, (*middle*) co-rotation and (*right*) counter-rotation; obtained from the simulated data points constrained by observed distribution. The color bar indicates the values of Galactic latitude b.



Fig. 4 The top panel displays the median value of v_{los} in each bin with error bars representing the velocity range covered by the first and third quartile values. The bottom panel depicts the p value for a 1D K-S test between observation and models, in each l bin with $\Delta l = 30^{\circ}$.

to the source. $\Phi = \Phi(R, z, d\Phi/dR, d\Phi/dz)$ is the potential of the system. GALPOT takes as input the values of R_p and z, and produces output v_R . As described in Section 3, this is then utilized to compute the expected $v_{\rm los}$ for a given distance and direction.

3 ANALYSIS AND RESULTS

For this assumed mass model, as described in Section 2.2, we next investigate the expected l vs. v_{los} distribution numerically by transforming the velocity in the Galactocentric frame to that in the observer frame. For this, we consider GCs as test particles, their angular positions (θ , ϕ) distributed uniformly on the surface of a sphere and the Galactocentric distances R_G having the same distribution as the observed one. For better statistics, we have implemented 200 times the number of data points in each $\Delta R_G = 2 \,\mathrm{kpc}$ bin, so that the relative number of test particles in the l vs. v_{los} distribution represents the probability density of observing a GC at that (l, v_{los}) . The angle ψ , between the rotation axis of the disk and the unit vector perpendicular to the GC's orbital plane, is taken as a random variable. From the circular velocity v_R obtained using GALPOT, we then compute l, b and v_{los} for the test particles. Note that the value of $n_z = \cos \psi$ determines whether the GC is co-rotating ($\cos \psi > 0$), counter-rotating ($\cos \psi < 0$) or mixed (no constraint on ψ). These simulated l vs. v_{los} distributions are displayed in Figure 3, in the left, middle and right panels for mixed, corotating and counter-rotating scenarios, respectively. The color bars in the figures indicate the values of Galactic latitude b in these plots. As expected, these distributions quantitatively deviate significantly from that of neutral hydrogen and CO in the Galactic disk (Kalberla & Dedes 2008; Dame & Thaddeus 2011) due to the non-coplanar distribution of GCs.

We bin the $v_{\rm los}$ data into 30° intervals over l, and find the median value of $v_{\rm los}$ in each $l-{\rm bin}$ for the various rotation models, as well as the observed data. We show this in the upper panel of Figure 4 along with error bars that represent the velocity range covered by the first and third quartile values, thus encompassing 50% of the data points. For the observed values, the shaded region indicates the region about the median for extrapolated values of the first and third quartiles. In the bin for the l range between $90^{\circ} - 120^{\circ}$, no data for $v_{\rm los}$ are present from observation. It can be seen that the median values in each bin for the co-rotation model are closer to those for observed data. To compare the observed distribution with the expected distributions from these three models, we applied the Kolmogorov-Smirnov (K-S) test (Fasano & Franceschini 1987). The test returns the K-S test statistic d and the significance level p. Smaller p values indicate that the data are significantly different from the model. The onedimensional K-S statistics for the $v_{\rm los}$ distributions, considering the entire l range, suggest that the observed distribution is more likely to match the co-rotation of GCs than counter or mixed rotation. We also perform a onedimensional (1D) K-S test for the $v_{\rm los}$ distribution in each l-bin of 30° interval. The results are depicted in the lower panel of Figure 4. The obtained p value from the 1D K-S test is higher for the co-rotational model than for counter or mixed rotation.

The K-S test is also well-suited to compare two samples of two-dimensional (2D) distributions obtained from the data and model. Here we consider the 2D dataset corresponding to l and v_{los} values. The obtained d and p values for comparison between the various modes of rotation with the observed data are listed in Table 1. We find that the pvalue is highest for the co-rotation model. Thus, the null hypothesis that the two samples are drawn from the same distribution cannot be rejected for the co-rotation model. However, with the significance level being lower, the null hypothesis can be rejected for counter or mixed rotation. These results are consistent with that from 1D K-S tests. This clearly implies that, for the assumed mass model, the observed phase space distribution $(l - v_{los})$ of the GCs is consistent with a sample preferentially co-rotating with the Galactic disk.

We repeat our calculation of K-S statistic d and significance level p after excluding the GCs from the dataset that may have originated from merging dwarf galax-

Table 1 2D K-S test for Data vs. Model

Dynamics	K-S statistic d	p value
Mixed-rotation	0.119441	0.100220
Co-rotation	0.112045	0.148733
Counter-rotation	0.221819	0.000062

ies. Even after removing the GCs associated with Gaia-Enceladus (Myeong et al. 2019), the progenitor galaxy of the 'sausage', and GCs from less massive progenitors like Sagittarius, Canis Major and Kraken (Kruijssen et al. 2019), the co-rotation model is still found to be the preferred model in explaining the observed l vs. v_{los} distribution. In fact, removing only the 'sausage' population yields p = 0.49994 for co-rotation, the highest among all the scenarios considered. On further excluding the other GCs from less massive parent dwarfs (Sagittarius, Canis Major and Kraken), the p value is found to be 0.255308. This agrees with the observation that the Sequoia stars exhibit a strong retrograde motion, whereas the Sausage stars have no net rotation and move on predominantly radial orbits (Myeong et al. 2019).

4 DISCUSSIONS

We applied a standard Galactic mass distribution model from GALPOT to understand the phase space distribution of GCs in the MW Galaxy. For modeling, we restrict ourselves to simplified circular orbits of GCs and an axisymmetric gravitational potential of the MW. Note that the eccentricity of the GC orbits cannot be constrained at present from available observations alone in a model-independent manner. The uncertainties in the observed parameters depend on the inherent assumptions in modeling the underlying potential (Simpson 2019). With better data, when the eccentricity distribution is more constrained, this analysis can be further improved. Here, instead of considering a non-circular orbit for individual GCs, we have done an order of magnitude consistency check using the distribution of observed proper motion. The observed trend is found to be in broad agreement with the Gaia measurements (Eadie & Jurić 2019; Vasiliev 2019). Currently, reliable proper motion data are available for only 34 GCs from Gaia (Watkins et al. 2019). We plan to carry out an extended but similar analysis with position (l, v), line-of-sight velocity and proper motion of the entire sample (expected to be soon available for the full sample) in the near future. Mass estimates of the MW found in these studies and also in Watkins et al. (2010) and Posti & Helmi (2019) are al-1 consistent with each other within a factor of two. They have utilized a potential model which is similar to that implemented in the best-fit potential model of GALPOT.

Please note, our analysis is a simple but complementary method to the Jeans analysis of radial velocities for kinematic tracers like stars or star clusters to model the gravitational field of galaxies. However, the Jeans analysis requires measurement of the radial velocity, which is difficult, and its dispersion, which, in turn, depends on the functional form of the circular velocity of the underlying potential. Also, with the details of the orbits being unknown, these measurements have uncertainties from velocity anisotropy, stellar halo density profile at large distances (Battaglia et al. 2005; Bílek et al. 2019), etc. The radial distribution can be extrapolated for an incomplete GC survey, but the radial velocity dispersion, which is not a directly observable quantity, has to be deduced from the lineof-sight velocity measurements (Binney & Mamon 1982), and will suffer from the same uncertainties as in our analysis. It is worth mentioning that the conclusion drawn here is based on a static potential. Indeed, this is a simplification for the purpose of this study. The mass of the different components of the Galaxy changes through a significant amount of merging during the Galaxy evolution over Gyr timescale. A complete analysis including the full orbital evolution of the Galactic GCs is, unfortunately, beyond the scope of the current analysis. However, based on the current observations, we expect that the main result of this analysis, that the GCs are preferentially co-rotating, will not significantly alter even when the time variation is included in the modeling.

The recent discovery of tidal debris from what appears to be an ancient major merger event ${\sim}10\,{
m Gyr}$ ago (Helmi et al. 2018; Myeong et al. 2018), referred to as 'Gaia Sausage', is predicted to dominate the Galactic stellar halo at distances ranging from the MW bulge region to the MW halo's break radius at around 20-30 kpc (Simion et al. 2019; Deason et al. 2018; Vincenzo et al. 2019; Lancaster et al. 2019). Belokurov et al. (2018) have estimated the virial mass of Gaia-Enceladus, the progenitor galaxy, to be $M_{\rm vir} > 10^{10} M_{\odot}$. Other such studies in the past have provided evidence of similar such accretion episodes like the Sequoia event and merger of less massive progenitors like Canis Major, Kraken and Sagittarius (Ibata et al. 1995; de Boer et al. 2015; Kruijssen et al. 2019; Myeong et al. 2019; Barbá et al. 2019). Many of the GCs in our sample are associated with these merger events. Hence, we repeat the analysis by excluding those GCs that are associated with earlier merger events, to check whether the preferentially co-rotating GC population is mostly due to the mergers. However, our analysis, after excluding these GCs, still shows (somewhat improved) accordance with the co-rotation model, considering the observed dynamics. This is indicative that the preferentially co-rotating model is not entirely due to known accretion events.

Finally, a similar analysis can also be done with the SGs. A similar preliminary analysis shows a marginally better match with the co-rotation model; however, the

data are sparse. Out of 59 SGs of the MW with known distance (within 0.5 Mpc), velocity information is available for only 28 (Drlica-Wagner et al. 2015; Bechtol et al. 2015; Koposov et al. 2015). Only recently, the data for SGs and dwarf spheroidals are reaching unprecedented refinement in the era of ongoing observational surveys (e.g., Abbott et al. 2018). We plan to employ the improved data set, including the recent proper motion measurements, with the complete sample of GCs and SGs for a detailed study in the future.

5 CONCLUSIONS

In this study, we have compared the observed (l, v_{los}) phase space distribution of the MW GCs with a simple scenario based on the standard mass model of the Galaxy. We use the best-fit potential model in GALPOT for this, and compare the direct observables, position and line-of-sight velocity, to check if the GC dynamics are consistent with the adopted mass model. Multiple statistical measures show that the model with a co-rotating GC population is favored over a counter-rotating or randomly rotating sample of GCs. We also find that even when the GCs associated with various progenitors of early merger events are excluded from the dataset, co-rotation is still found to be the preferred model. The recent compelling evidence of major merger events, along with the identification of GCs associated with these events, has significantly changed our perception of MW halo formation. The signatures of massive impacts during the evolutionary stage of Galaxy formation are retained in the substructures through their kinematical and chemical composition data. Extending such analysis with precise data of GC dynamics, including the reliable proper motion of the complete sample, may be able to explain the overall co-rotation of the GC population fully and also put better constraints on the MW mass model.

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