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The eye of Gaia on globular cluster kinematics: Internal rotation

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Abstract. I present the results of a survey of the kinematics of a large sample of Galactic globular clusters performed thanks to the synergy between the 2nd Gaia data release and the most extensive collection of radial velocities. This unprecedented dataset of 3D velocities of thousand of stars in 62 globular clusters has been used to investigate the rotation patterns of these stellar systems providing insight into the impact of two-body relaxation and tides on the formation and evolution of their rotation.

Keywords. methods: data analysis – methods: statistical – proper motions – technique: radial velocities – stars: kinematics and dynamics – globular clusters: general

1. Introduction

Among old (> 10 *Gyr*) stellar systems, globular clusters (GCs) are those with the largest ratio between age and half-mass relaxation time. A typical GC star completed hundreds of orbits within the cluster potential and the chance of interaction with another star, which changes its orbit, is significant. The effect of a large number of interactions is to randomize the directions of individual orbits and to lead toward an isotropic velocity distribution tending to a Maxwellian-like distribution.

Nevertheless, deviations from isotropy can be present in the velocity distribution of GC stars in the form of ordered motions (i.e. rotation) and/or preferential orientation of the velocity ellipsoid (i.e. anisotropy). In particular, the presence of rotation has deep relevance for the equilibrium of these stellar systems contributing to their kinetic energy budget and possibly leading to a flattening of their shape in the direction parallel to the rotation axis (Wilson 1975). The measure of rotation in a statistically meaningful sample of GCs is therefore crucial to study the efficiency and frequency of the above processes.

The main effect of rotation is a shift in the mean tangential motion along a preferential axis. Such a shift reflects in the velocity distribution along all the three components in proportions depending on the position angle and the inclination with respect to the line of sight of the rotation axis. Thus, a thorough analysis of rotation requires an estimate of all three velocity components. The lack of accurate proper motions has represented a major issue in the analysis of rotation of GCs till recent years.

A revolution in this field is provided by the astrometric mission Gaia which measures parallaxes and proper motions for $\sim 10^9$ stars in both hemispheres with accuracies $< 30\mu as$ (corresponding to < 1.5 km/s at a distance of 10 kpc) sampling also thousands of stars in the outer regions of all Galactic GCs (Gaia Collaboration *et al.* 2018a).

2. Observational material and Method

The analysis performed in this paper is based on two main databases: *i)* the sample of line-of-sight velocities collected by Baumgardt & Hilker (2018), and *ii)* the proper motions of the Gaia 2nd data release (Gaia Collaboration *et al.* 2018a).

The two above samples have been cross-correlated providing 3D velocities for a sub-sample of stars in each cluster. The sizes of the final samples range from 10 to ∼2500 stars according to the cluster distance and mass. Among the whole set of 109 GCs we selected only those 62 GCs with at least 50 member stars with measurements in all the three velocity components.

The effect of rotation can be detected as a modulation of the mean velocity as a function of the position angle. In particular, for a solid-body rotation with angular velocity ω the mean velocity in the three components is

$$\begin{aligned} v_Z &= \omega\ R\ sin(\theta-\theta_0) sin\ i \\ v_{\parallel} &= \omega\ R\ sin(\theta-\theta_0) cos\ i \\ v_{\perp} &= \omega\ [R\ cos(\theta-\theta_0) cos\ i + Z sin\ i] \end{aligned} \tag{2.1}$$

where R is the projected distance from the cluster centre, i is the inclination angle of the rotation axis with respect to the line of sight, θ is the position angle (defined anti-clockwise from the Y axis), θ_0 is the position angle of the rotation axis, $v_{\parallel}$ and $v_{\perp}$ are the velocity components in the directions parallel and perpendicular to the rotation axis.

For each cluster of our sample we searched for the values of θ_0, i and A ($\equiv \omega\ R$) providing the best fit of the above equations to the distribution of the three observed velocity components. We neglected the unknown distance along the line of sight (Z) in the third equation since it does not affect the mean trend of $v_{\perp}$ (since $\langle Z \rangle = 0$). The significance of rotation has been evaluated by employing a Monte Carlo technique: for each cluster, 10^4 mock observations of a non-rotating system have been simulated by randomly extracting velocities in the three components from Gaussian functions centered at $v_Z, v_{\perp}, v_{\parallel} = 0$ and with dispersion equal to the local velocity dispersion σ_i at the position of the real stars. The measurement errors have been then added as Gaussian shift with amplitude equal to the observational uncertainties of real stars (including covariances between $v_{\perp}$ and $v_{\parallel}$) and the bestfit value of the rotation amplitude has been calculated using the same technique adopted for real data. The fraction of simulations with best fit amplitudes smaller than the one obtained on real data gives the probability that the observed rotation signal is not produced by fluctuations.

A detailed description of the sample selection, reduction and data analysis process as well as the complete list of references is provided in Sollima, Baumgardt & Hilker (2019).

3. Results

We find a rotation signal at $> 3\sigma$ significance level in 24 GCs. However, the presence of systematic shifts in Gaia proper motions can produce an azimuthal variation mimicking a spurious rotation in the plane of the sky. To be conservative, we excluded the 9 GCs with rotation mainly in the plane of the sky with amplitudes below $\mu < 0.07\ mas/yr$ i.e. the typical amplitude of Gaia systematics (Lindegren *et al.* 2018).

To determine the strength of rotation in the clusters of our sample, we compare our dataset with suitable dynamical models. For this purpose, we constructed parametric models of rotating stellar systems by adopting the potential of the King (1966) model providing the best fit to the density profile and assuming the empirical relation linking the fraction of kinetic energy in rotational motion as a function of the distance to the rotation axis.

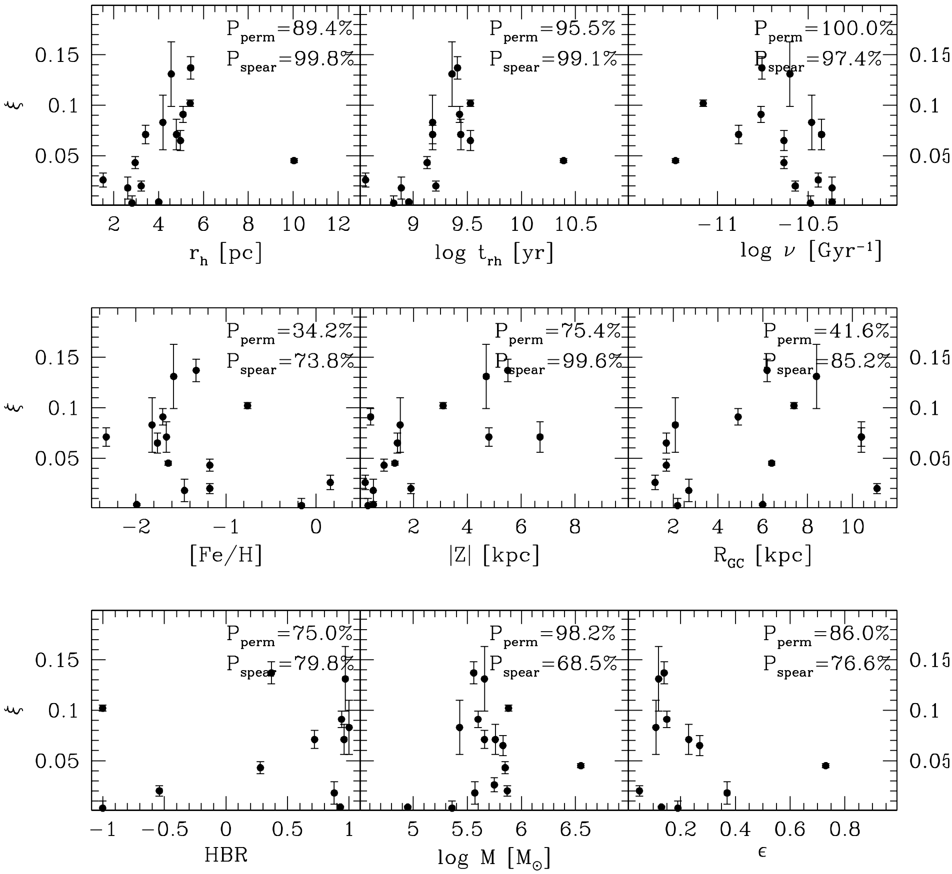

Figure 1. Correlation between the fraction of rotational kinetic energy (ξ) and various parameters. The correlation probability is indicated in each panel.

$$f = \frac{\langle v_\phi \rangle^2}{\langle v_r^2 \rangle + \langle v_\theta^2 \rangle + \langle v_\phi^2 \rangle} = \frac{b}{3} \; \frac{exp(R/R_0) - 1}{exp(R/a\ R_0) + 1} \tag{3.1}$$

where $v_r,\ v_\phi\ and\ v_\theta$ are the velocities in spherical coordinates, b governs the strength of rotation, R_0 is a scale radius at which rotation approaches its maximum contribution to the kinetic energy and a is a dampening factor at large radii. The kinematics have been then derived from the Jeans equation, assuming spherical symmetry. To assess the strength of rotation for each cluster, we calculated the fraction of kinetic energy in rotational motions $\xi \equiv \langle v_\phi^2 \rangle / \langle \sigma^2 \rangle$ of the corresponding best fit model.

The values of ξ have been used to search for correlations with other general and dynamical parameters. To evaluate the significance of such correlations we performed both the Spearman rank correlation test and a permutation test for Pearson's weighted correlation coefficient. The entire set of correlations is shown in Fig. 1 together with the corresponding correlation probabilities.

The largest correlation probabilities are those with the half-mass radius and relaxation time. Also noticeable is the anticorrelation with the destruction rate.

An interesting test for the impact of the tidal field on internal rotation has been done by calculating the angle between the rotation axes and the orbital poles of the GCs in our sample. A one-tailed Kolmogorov-Smirnov indicates a probability of 1.5% that such an angle is distributed following a constant probability per solid angle corresponding to a random orientation.

Finally, we compared the rotation period at the half-mass radius with the cluster orbital period (from Gaia Collaboration *et al.* 2018b). While these two variables are not significantly correlated when considering the entire sample (the permutation and Spearman tests give probabilities of 70.5% and 92.0%, respectively), a strong correlation of these two variables is apparent for GCs with $R_{GC} < 6$ *kpc*. Note however that the rotation period at the half-mass radius is by definition proportional to the half-mass radius itself. On the other hand, it is well known that a half-mass radius vs. Galactocentric distance relation is present among Galactic GCs (van den Bergh, Morbey & Pazder 1991), with the GCs at large distances from the Galactic centre (i.e. those which take a long time to complete their orbits) being on average more extended. So, since both the orbital and the rotational periods depend on the Galactocentric distance, the correlation between these two timescales could be spurious.

4. Conclusions

We found robust evidence of rotation in 15 out of the 62 GCs of our sample at an amplitude which cannot be explained by neither random nor systematic errors. For 9 more GCs we found a signal of rotation mainly in the plane of the sky at a level below the claimed amplitude of systematic uncertainties possibly present in the Gaia catalog. The relative strength of ordered over random motions (ξ) appear to weakly correlate with the half-mass relaxation time, with the GCs with longer relaxation times rotating faster. This suggests a primordial origin for the rotation of these stellar systems which is progressively erased by both internal and external dynamical processes.

An important improvement is expected in the near future when the next Gaia releases will be available. According to the performance prediction of the Gaia consortium, the end of mission accuracy should improve by a factor of two and the amplitude of systematics is expected to significantly decrease. In that condition, the same analysis performed here should be able to clarify the presence of rotation in the GCs with uncertain detections and to construct a much larger sample of rotating GCs which can allow to verify the correlations analysed in this work.

References

Baumgardt, H. & Hilker, M. 2018, *MNRAS*, 478, 1520
Gaia Collaboration *et al.* 2018a, *A&A*, 616, A1
Gaia Collaboration *et al.* 2018b, *A&A*, 616, A12
King, I. R. 1966, *AJ*, 71, 64
Lindegren, L. *et al.* 2018, *A&A*, 616, A2
van den Bergh, S., Morbey, C., & Pazder, J. 1991, *ApJ*, 375, 594
Sollima, A., Baumgardt, H., & Hilker, M. 2019, *MNRAS*, 485, 1460
Wilson, C. P. 1975, *AJ*, 80, 175