

# Discovery of rotation axis alignments in Milky Way globular clusters

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## ABSTRACT

There is an increasing number of recent observational results which show that some globular clusters exhibit internal rotation while they travel along their orbital trajectories around the Milky Way center. Based on these findings, we looked for any relationship between the inclination angles of the globular clusters' orbits with respect to the Milky Way plane and those of their rotation. We discovered that the relative inclination, in the sense rotation axis inclination – orbit axis inclination, is a function of the globular cluster's orbit inclination. Rotation and orbit axes are aligned for an inclination of  $\sim 56^\circ$ , while the rotation axis inclination is far from the orbit's one between  $\sim 20^\circ$  and  $-20^\circ$  when the latter increases from  $0^\circ$  up to  $90^\circ$ . We further investigated the origin of such a linear relationship and found no correlation with the semimajor axes and eccentricities of the globular clusters' orbits, nor with the internal rotation strength, the globular clusters' sizes, actual and tidally disrupted masses, half-mass relaxation times, among others. The uncovered relationship will impact on the development of numerical simulations of the internal rotation of globular clusters, on our understanding about the interaction of the globular clusters with the Milky Way gravitational field, and on the observational campaigns for increasing the number of studied globular clusters with detected internal rotation.

**Key words.** Galaxy: globular clusters: general – Methods: observational.

## 1. Introduction

Piatti (2019) examined the inclinations ( $I$ ) of globular clusters' orbits around the Milky Way center and found that they do not align in the same planar configuration of the dubbed Vast Polar Structure (Pawlowski & Kroupa 2014); his findings was recently confirmed by Riley & Strigari (2020). Furthermore, he found out a linear relationship between  $I$  and the eccentricity of prograde orbits (globular clusters rotating in the direction of the Milky Way's rotation), in the sense that the larger the eccentricity the higher the inclination, with a variation at most of  $\sim 10^\circ$  around the mean value at a fixed eccentricity. The unveiled correlation turned out to be also a function of the semimajor axis (or averaged Galactrocentric distance), in such a way that outermost globular clusters have orbits with the highest  $I$  values and large eccentricities. As far as globular clusters with retrograde orbits are considered, there is mostly scatter over the whole  $I$  range and eccentricities larger than  $\sim 0.4$ .

While orbiting around the Milky Way center, globular clusters are also subject of tidal forces, which cause they lose stars that can amount up to nearly half of their initial masses, depending on the shape of their orbits, peri and apogalactocentric distances, etc. Because of the redistribution of stars within the globular clusters, the internal dynamical evolution is also altered with respect to the expected one, if the globular clusters were evolved in isolation. The result is that their internal evolution is accelerated, so that globular clusters are seen at more advanced internal dynamics evolutionary stages (Piatti et al. 2019, and reference therein).

There is evidence that some globular clusters still keep some level of their primordial rotation (Sollima et al. 2019), which has long been supposed to start with a complete alignment (coplanarity) with the axis of the orbital angular velocity vector (Tiongco et al. 2018, and references therein). However, considering the long-term interaction between globular clusters and the Milky Way potential mentioned above, we wonder whether the orbit and rotation planes are somehow linked, or whether both galactic and rotation motions are independent one to each other. The topic has not received much of our attention in the available literature, possible because of the lack of a statistical significant sample of observational results on the rotation of globular clusters.

Precisely, in Section 2 we computed the rotation axis inclinations ( $i$ ) of a sample of globular clusters with respect to the Milky Way plane, in order to compare them with the  $I$  values. Section 3 deals with the analysis of such a comparison and discusses the revealed interplay between  $I$  and  $i$ . Finally, Section 4 summarizes the main conclusions of this work.

## 2. Rotation axis inclination estimates

We made use of the rotation parameters derived by Sollima et al. (2019, their Table 2) for the largest studied sample of globular clusters with detected rotation (see also their Table 3). They fitted the amplitude ( $A$ ), the inclination of the rotation axis with respect to the LOS ( $inc$ ), and the position angle  $\theta_0$  of the projected rotation axis on the sky. Thus, they provided with equations to compute the velocity components in direction parallel and perpendicular to the projected rotation axis on the sky and along the

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LOS of any point located at a small distance from the globular cluster center and at a position angle  $\theta$ . Our strategy consisted in rotating that framework around the LOS axis by an angle  $\theta_0$  in order to have the components of the rotation velocity along the R.A. and Dec. axes. In doing this, we used the following expressions:

$$4.74r_0(pmra - pmra_0) = A(\cos(\theta - \theta_0)\cos(\theta)\cos(inc) - \sin(\theta - \theta_0)\sin(\theta_0)\cos(inc)), \quad (1)$$

$$4.74r_0(pmdec - pmdec_0) = A(\sin(\theta - \theta_0)\cos(\theta_0)\cos(inc) + \cos(\theta - \theta_0)\sin(\theta_0)\cos(inc)), \quad (2)$$

$$RV - RV_0 = A\sin(\theta - \theta_0)\sin(inc); \quad (3)$$

where  $r_0$ ,  $pmra_0$ ,  $pmdec_0$ , and  $RV_0$  are the mean globular cluster heliocentric distance, R.A. and Dec. proper motions, and radial velocity, respectively (Baumgardt et al. 2019). We generated for each globular cluster a sample of points uniformly distributed along  $\theta$  from  $0^\circ$  up to  $360^\circ$  ( $\theta$  is measured from the North to the West) in steps of  $1''$  and at a distance from the globular clusters' centers equal to  $10^{-3}$  times their tidal radii (Baumgardt et al. 2019). We then computed Galactic coordinates ( $X, Y, Z$ ) and space velocities ( $V_X, V_Y, V_Z$ ) employing the *astropy*<sup>1</sup> package (Astropy Collaboration et al. 2013, 2018), which simply required the input of  $r_0$ ,  $pmra$ ,  $pmdec$ , and  $RV$  given by eqs. (1)-(3).

The components of the rotational angular momentum were calculated according to:

$$L_X = (Y - Y_0) \times (V_Z - V_{Z_0}) - (Z - Z_0) \times (V_Y - V_{Y_0}), \quad (4)$$

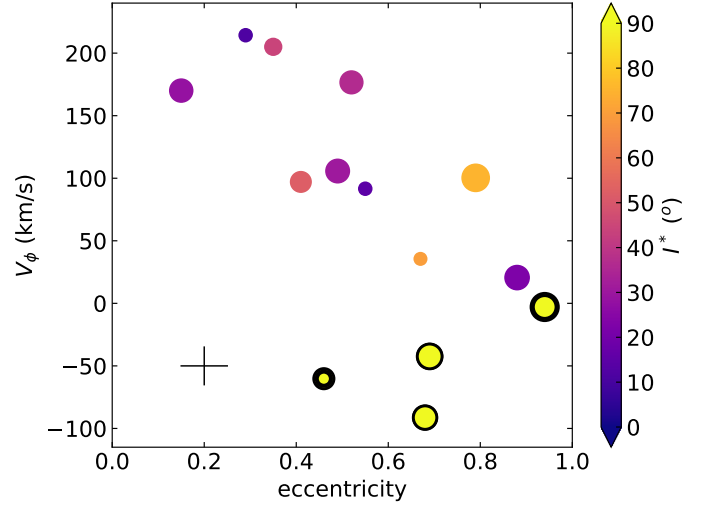
$$L_Y = (Z - Z_0) \times (V_X - V_{X_0}) - (X - X_0) \times (V_Z - V_{Z_0}), \quad (5)$$

$$L_Z = (X - X_0) \times (V_Y - V_{Y_0}) - (Y - Y_0) \times (V_X - V_{X_0}), \quad (6)$$

and the inclination of the rotation axis:

$$i = \arccos \left( \frac{L_Z}{\sqrt{L_X^2 + L_Y^2 + L_Z^2}} \right); \quad (7)$$

where the subscript 0 (zero) in eqs. (4)-(6) refers to the mean orbital position and motion of the globular cluster. We adopted as uncertainties of  $i$  the standard deviation from all the generated individual  $i$  values. Since  $I$  (see Piatti 2019) and  $i$  values range from  $0^\circ$  for fully prograde in-plane orbits (or coplanar prograde rotation) to  $90^\circ$  for polar orbits (or rotation plane perpendicular to the Galactic plane), to  $180^\circ$  for in-plane retrograde orbits or rotation planes, we defined:  $I^* = 180^\circ - I$  and  $i^* = 180^\circ - i$ , which resulted useful in the subsequent analysis.



**Fig. 1.** Relationship between globular clusters' orbital parameters. Typical error bars are included. black-edged circles represent globular clusters with retrograde motions. The size of the symbols is proportional to  $\log(a)$ ; the smallest and largest ones correspond to  $a = 1.6$  and  $13.6$  kpc, respectively.

### 3. Analysis and discussion

The orbital properties of the studied globular clusters are pictured in Figure 1, where the relationship between the Galactic velocity component  $V_\phi$  (spherical coordinates), the eccentricity, and  $I^*$  derived by Piatti (2019) is shown. As can be seen, globular clusters with prograde ( $V_\phi > 0$ ) and retrograde ( $V_\phi < 0$ ) orbits are clearly distinguished. The latter have relatively large eccentricities and nearly polar trajectories ( $I^* > 80^\circ$ ). These globular clusters have long been thought to have an accreted origin (Forbes & Bridges 2010). They have been highlighted in Figure 1 with black-edged circles. Among globular clusters with prograde orbital motions, a trend between  $V_\phi$  and the eccentricity arises, so that the higher the rotational velocity, the more circular their orbits (smaller eccentricities) and smaller  $I^*$  values. Those with more circular orbits have tightly copied the rotation of the Milky Way disk.

We also used the semimajor axes of the globular clusters' orbits ( $a$ ) defined as the average between the peri and apogalactocentric distances computed by Baumgardt et al. (2019). They better represent the distance of the globular clusters' birthplaces to the Milky Way center or the average distance where globular clusters were deposited after accretion of their host dwarf galaxy onto the Milky Way. The globular clusters in our sample span  $a$  values from 1.6 up to 13.6 kpc, i.e., they populate the Milky Way bulge (Galactocentric distance  $< 3$  kpc, Barros et al. 2016) and disk. They are represented in Figure 1 with circles whose sizes are proportional to  $\log(a)$  (kpc). Both globular clusters with prograde and retrograde orbits cover the entire range of  $a$  values. From this point of view, the studied globular clusters can be considered as representative of the whole globular cluster population in the Galactic volume considered. Therefore, if some relationship existed between  $I^*$  and  $i^*$ , this should be discovered from them.

We firstly calculated the mean and dispersion of  $i^*$  by employing a maximum likelihood approach. The relevance lies in accounting for the individual  $i^*$  measurement errors, which could artificially inflate the dispersion if ignored. We thus optimized

<sup>1</sup> <https://www.astropy.org>

the probability  $\mathcal{L}$  that a given ensemble of  $i^*$  values with errors  $\sigma(i^*)$  are drawn from a population with mean rotation axis inclination  $\langle i^* \rangle$  and intrinsic dispersion  $W$  (e.g., Pryor & Meylan 1993; Walker et al. 2006), as follows:

$$\mathcal{L} = \prod_{k=1}^N \left( 2\pi [\sigma_k^2 + W^2] \right)^{-\frac{1}{2}} \times \exp \left( -\frac{(i_k^* - \langle i^* \rangle)^2}{\sigma_k^2 + W^2} \right), \quad (8)$$

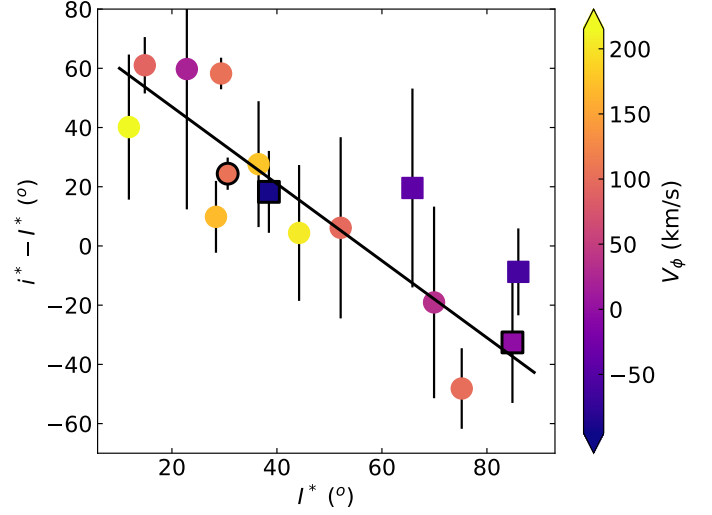
where the errors on the mean and dispersion were computed from the respective covariance matrices. We would like to note that this approach assumes that the error distribution is Gaussian, which is adopted here because of the limited number of globular clusters (cf. Frank et al. 2015). The resulting mean  $i^*$  and dispersion turned out to be  $(61.8 \pm 4.8)^\circ$  and  $(10.5 \pm 0.7)^\circ$ , respectively. This outcome reveals that the rotation axis inclinations are not randomly distributed – they do not span the whole range of values ( $[0^\circ, 90^\circ]$ ) –, and are not all aligned to the orbit axes, but span a moderately small intrinsic range. Since the mean  $i^*$  value and dispersion come from globular clusters that rotate in the same direction of their orbital motions (prograde or retrograde orbits), or in the opposite direction to their orbital motions, the above result could suggest that there should be some condition that has led the rotation axis inclinations to be more or less polarized, irrespective of the direction of the orbital motion and that of the rotation. The small globular cluster sample analyzed could jeopardize such a speculation, if a larger sample were used instead. However, this would not be the case, as judged by the subsequent results.

Figure 2 depicts the difference between the rotation and orbit axes' inclinations as a function of  $I^*$ . We have distinguished those globular clusters with prograde or retrograde orbital motions, and those with prograde or retrograde rotation. There is one globular cluster (NGC 7078) with a prograde orbit and two globular clusters (NGC 5139, 7089) with retrograde orbits that rotate in the opposite direction to their orbital motions. They have highlighted with black-edged symbols. The figure uncovers a relationship between  $i^*$  and  $I^*$  that, as far as we are aware, has not been hypothesized nor found in numerical simulations of the evolution of rotating star clusters, nor discovered observationally. As can be seen, the relative inclinations follow a linear relationship with  $I^*$  that resulted to be:

$$i^* - I^* = (-1.30 \pm 0.16)I^* + 73.00 \pm 6.53, \quad (9)$$

with a standard deviation of  $\pm 18.2^\circ$ , when we fitted the points by least square. We obtained a correlation of 0.80 and an  $F$ -test coefficient of 0.90, which undoubtedly rejects the possibility that the relative inclinations for the small sample of 15 globular clusters analyzed were dominated by a point dispersion.

This finding reveals that if the rotation axis was aligned to the orbit axis at the globular cluster's birth, such a configuration changed in the long-term evolution. Otherwise, if the rotation axis is thought of not to change along the globular cluster's lifetime, then the traditional scenario of coplanarity between the orbit and the rotation's planes as initial condition for the globular cluster evolution would no longer be supported (Tiongco et al. 2018). According to eq. (9), present-day coplanarity is observed in globular clusters with an orbit inclination  $I_0^* = i_0^* \sim 56^\circ$ . Globular clusters with orbit inclinations smaller and larger than  $I_0^*$  rotate around an axis inclined with respect to the Milky Way plane that varies up to  $\sim 20^\circ$  in excess or defect around  $i_0^*$ , respectively. Eq. (9) also allows us to predict the rotation axis



**Fig. 2.** Relative inclination versus orbital plane inclination for the studied globular clusters. Circles and squares refer to globular clusters moving around the Milky Way center or rotating in prograde and retrograde directions, respectively. Black-edged symbols represent globular clusters with opposite direction of orbital and rotational motions. Individual error bars are indicated; those for  $I^*$  are as large as the symbols' sizes. The black line represent the fitted relationship (see text).

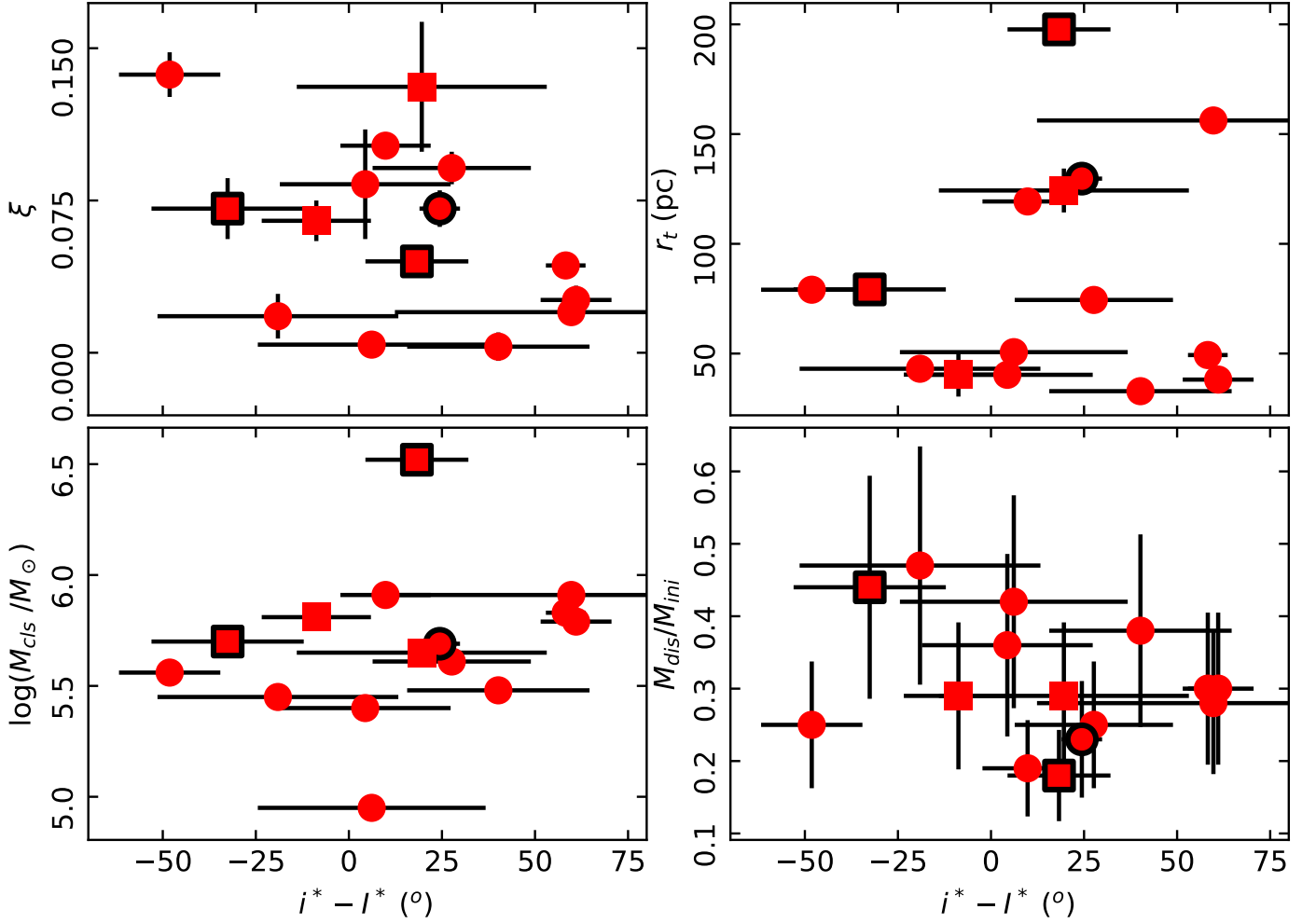
inclination of a globular cluster, provided that the inclination of its orbit is known.

We tried to find out some trail of the physical origin of eq. (9) by examining the relationships of  $i^* - I^*$  with different globular clusters' parameters taken from Piatti (2019) and Piatti et al. (2019), if another source is not mentioned. We considered  $a$  and the orbit eccentricity to link eq. (9) to orbital properties; the present mass ( $\log(M_{cls}/M_\odot)$ ), the ratio between the mass lost by tidal disruption to the total mass ( $M_{dis}/M_{ini}$ ) and the ratio of the age to the half-mass relaxation time to see whether the internal dynamical evolution has a role; the tidal radius ( $r_t$ ) and the rotation strength ( $\xi$ , Sollima et al. 2019) to connect eq. (9) to the internal rotation itself, and the status of a globular cluster according to whether it has tidal tails, extra-tidal features different to tidal tails, or simply a King (1962)'s profile (Piatti & Carballo-Bello 2020). Figure 3 shows some of these plots. As can be seen, none of them would seem to make clear that eq. (9) correlates with any of these globular cluster's astrophysical properties. For this reason, we speculate with the possibility of suggesting looking for the origin of the interplay between  $i^*$  and  $I^*$  in some large-scale effect caused by Milky Way's characteristics, such as its gravitational potential, overall magnetic field, among other.

#### 4. Concluding remarks

Motivated by some recent observational results which have presented reliable globular clusters' orbital and rotation parameters, we sought for any connection between the inclination angle of the orbital plane and that of the rotation with respect to the Milky Way plane. We analyzed 15 globular clusters, which at present is the largest sample of globular clusters with comprehensive rotation studies.

Our analysis relied on the recently published rotation parameters referred to the plane of the sky and the LOS as the natural framework. From them, we transformed the rotation velocity components to the Galactic coordinate system and computed both the inclination angle of the globular clusters' orbits



**Fig. 3.** Relative inclinations as a function of different astrophysical properties.

and those of their rotation. We found that the present-day globular clusters' rotation axis inclinations are not aligned with those of the globular clusters' orbits nor with the Galactic poles one. They resulted to be inclined with respect to the corresponding orbit axis inclination, varying from  $\sim 60^\circ$  to  $\sim -40^\circ$ , when the latter increases from  $0^\circ$  up to  $90^\circ$ . Further investigations are needed in order to find out the cause of such a behavior.

The linear relationship found between the relative inclinations and the orbits' inclinations provides new observational evidence that will impact on the future numerical simulations of the internal globular clusters' dynamics, on our understanding of the interaction of globular clusters with the Milky Way, on the increase of the number of studied globular clusters with derived rotations. From the 156 globular clusters cataloged in Harris (1996, 2010 Edition) 62 have been studied by Sollima et al. (2019), and from them 15 resulted with non-negligible internal rotation. This means that there should be nearly 22 more globular clusters in Harris (1996) with detectable internal rotation.

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