Kinematic characteristics of the Milky Way globular clusters based on *Gaia* DR2 data

I. V. Chemerynska¹,²*, M. V. Ishchenko³,⁴, M. O. Sobolenko³, S. A. Khoperskov⁵,⁶, P. P. Berczik⁷,⁴,⁸,³

¹Taras Shevchenko National University of Kyiv, Glushkova ave., 4, 03127 Kyiv, Ukraine
²Institut d’Astrophysique de Paris, CNRS – Sorbonne Université, 98bis boulevard Arago, 75014 Paris, France
³Main Astronomical Observatory, National Academy of Sciences of Ukraine, 27 Akademika Zabolotnoho St., 03143 Kyiv, Ukraine
⁴Fesenkov Astrophysical Institute, Observatory 23, 050020 Almaty, Kazakhstan
⁵Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany
⁶GEPI, Observatoire de Paris, Université PSL, CNRS, 5 Place Jules Janssen, 92190 Meudon, France
⁷Astrophysikalisches Rechen-Institut, Zentrum für Astronomie, University of Heidelberg, Mönchhofstrasse 12-14, 69120 Heidelberg, Germany
⁸Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Eötvös Loránd Research Network (ELKH), MTA Centre of Excellence, Konkoly Thege Miklós út 15-17, 1121 Budapest, Hungary

Using the data from *Gaia* (ESA) Data Release 2 we performed the orbital calculations of globular clusters (GCs) of the Milky Way. To explore possible close encounters (or collisions) between the GCs, using our own developed high-order $\varphi$-GRAPE code, we integrated backward and forward orbits of 119 objects with reliable positions and proper motions. In the calculations, we adopted a realistic axisymmetric Galactic potential (*bulge* + *disk* + *halo*).

Using different impact conditions, we found four pairs of six GCs that may have experienced an encounter within twice the sum of the half-mass radii (**collisions**) over the last 5 Gyr: Terzan 3 – NGC 6553, Terzan 3 – NGC 6218, Liller 1 – NGC 6522 and Djorg 2 – NGC 6553.

**Key words:** Galaxy: globular clusters: general - Galaxy: kinematics and dynamics - methods: numerical

INTRODUCTION

It is believed that GCs in the Milky Way (MW) are old gravitationally bound systems of stars with typical ages $\gtrsim 10$ Gyr and masses $\gtrsim 10^4 M_\odot$ [13]. These objects are a powerful tool to examine the Galactic structure and assembly history at different scales from the star clusters formation to hierarchical merger events [14]. The recent precise astrometric measurements from *Gaia* Data Release 2 (DR2) [8] provide a possibility to measure the mean proper motions for $\sim 150$ GCs as a system in the MW which makes it possible to study the orbital evolution of the GC systems as a whole.

In this work, we aim to explore the close encounters between different GCs and find the pairs of the GCs which have an encounter within twice the sum of the half-mass radii (**collisions**). In order to do that, using two GCs catalogues [5, 23], we study the dynamics of the GCs as the test-particles in the axisymmetric MW-like potential over the last 5 Gyr [1, 2, 10, 17, 19–21].

GLOBULAR CLUSTER SAMPLE

Prior to the orbital integration, we prepared a complete catalogue of the GCs. We combined two recent catalogues [5, 23] to get a full list of the 152 GCs sample with the orbital parameters and their masses (see Table 3). The resulting catalogue contains the complete phase-space information required to set the initial conditions in our simulations: right ascension (RA), declination (DEC) and distance (D), proper motions $\mu_{\varphi} = \mu_\alpha \cos \delta$, $\mu_\delta$ and radial velocity $v_r$.

To avoid the calculation of the GCs orbits with large initial conditions uncertainties we first performed an analysis of the errors of the *Gaia* measurements required for our simulations. In Fig. 1 we show the relative errors for the radial velocity and proper motions of CGs, where for convenience each GC was assigned an identification number (ID, see Table 3). The obtained uncertainties for the radial velocity ($v_r$) lie in the range of $[-10\%, +15\%]$ for all studied GCs. The analysis of the uncertainties for

*chemerynskaira@gmail.com

© I. V. Chemerynska et al, 2022
proper motions \((\mu_\alpha^*, \mu_\delta)\) showed that its value can exceed 30\% for some individual GCs in our sample. Therefore, the GCs with a relative error larger than 30\% for radial velocity and proper motions were removed from our catalogue and further analysis, and these 8 GCs were marked as ‘me’ (i.e. measurement error) in Table 3.

For calculation of positions and velocities in the Galactocentric rest-frame (for the basic coordinate transformation see [12]), we accepted an in-plane distance of the Sun from the Galactic center and the plane as \(X_\odot = 8.178\) kpc [9] and \(Z_\odot = 20.8\) pc [6], a velocity of the Local Standard of Rest (LSR) as \(V_{\text{LSR}} = 234.737\) km\(\text{s}^{-1}\) [15], and a peculiar velocity of the Sun with respect to the LSR as \(U_\odot = 11.1\) km\(\text{s}^{-1}\), \(V_\odot = 12.24\) km\(\text{s}^{-1}\), \(W_\odot = 7.25\) km\(\text{s}^{-1}\) [22].

We adopt the initial positions and velocities of the GCs in the heliocentric coordinate system as \((X, Y, Z)\) and \((U, V, W)\) as follows:

\[
\begin{align*}
x &= X + X_\odot + X_{\text{LSR}}, \\
y &= Y + Y_\odot + Y_{\text{LSR}}, \\
z &= Z + Z_\odot + Z_{\text{LSR}}, \\
u &= U + U_\odot + U_{\text{LSR}}, \\
v &= V + V_\odot + V_{\text{LSR}}, \\
w &= W + W_\odot + W_{\text{LSR}},
\end{align*}
\]

where we adopt \(U_{\text{LSR}} = W_{\text{LSR}} = 0\) and \(Y_\odot = 0\).

**ORBITS INTEGRATION**

For the GCs orbit integration we adopted the MW-like gravitational potential based on the superposition of bulge+disk+halo models. In particular, the total potential consisting of a spherical bulge \(\Phi_b(R, z)\), an axisymmetric disk \(\Phi_d(R, z)\) and a spherical dark-matter halo \(\Phi_h(R, z)\) can be written as follows:

\[
\Phi(R, z) = \Phi_b(R, z) + \Phi_d(R, z) + \Phi_h(R, z),
\]

where \(R^2 = x^2 + y^2\) is the Galactocentric distance in polar coordinates and \(z\) is the vertical coordinate perpendicular to the disk plane.

Potentials of the bulge and the disk were taken in the form of Miyamoto-Nagai [16], while the dark matter potential is in the form of Navarro-Frenk-White (NFW) profile [18]:

\[
\Phi_b(R, z) = - \frac{M_b}{(r^2 + b^2_b)^{1/2}},
\]

\[
\Phi_d(R, z) = - \frac{M_d}{\left[\left(R^2 + (a_d + \sqrt{z^2 + b^2_d})^2\right)\right]^{1/2}},
\]

\[
\Phi_h(R, z) = - \frac{M_h}{r} \ln \left(1 + \frac{r}{b_h}\right),
\]

where \(r = \sqrt{R^2 + z^2}\) is the spherical galactocentric distance, while masses and the scale-lengths of the components are shown in Table 1 [3, 4].
For the GCs orbital integration, we used a high-order parallel dynamical N-body code $\varphi$-GRAPE which is based on the fourth-order Hermite integration scheme with hierarchical individual block time steps scheme [7]. More details about the code architecture and special GRAPE hardware can be found in [11].

Table 1: Galactic potential parameters.

| Parameter       | Value      | Unit |
|-----------------|------------|------|
| Bulge mass $M_b$| $1.03 \times 10^{10}$ | $M_\odot$ |
| Disk mass $M_d$ | $6.51 \times 10^{10}$ | $M_\odot$ |
| Halo mass $M_h$ | $29.00 \times 10^{10}$ | $M_\odot$ |
| Bulge scale param. $b_b$ | 0.2672 | kpc |
| Disk scale param. $a_d$  | 4.4 | kpc |
| Disk scale param. $b_d$  | 0.3084 | kpc |
| Halo scale param. $b_h$  | 7.7 | kpc |

Before moving forward in the analysis of the collisions of the GCs population we have tested our numerical setup in order to keep tracking the GCs whose orbits are the same during backward and forward integration. First, we integrated all 152 GCs backward for 5 Gyr then we use the positions of velocities of all the GCs at the end of the simulations and integrate them forward for 5 Gyr. One could expect that the resulting positions and velocities should be identical to the observed ones. However, we have found that the orbits of 25 GCs are not invertible. These GCs usually pass very close to the galactic center and most likely even an adaptive time-step is not able to capture their motions in close proximity to the center. Another possibility is a non-integrability of the potential (i.e. it is hard to quantify) and thus we leave this issue for further studies. These GCs are marked as ‘to’ (i.e. type of orbit) in Table 3 and they were removed from further analysis. As a result, our final sample consists of 119 objects.

GC COLLISION PAIRS

In order to count the possible maximum number of collisions between all the pairs of GCs, we first checked all the close encounters during the simulation time with the maximum separation up to 100 pc resulting in 2019 and 1973 close encounters in our sample during the backward and forward orbits integrations, respectively.

We defined a close encounter as a ‘collision’ if (i) the minimum distance between the GCs is less than half the sum of their half-mass radii ($dR_{\text{coll}} < 2(R_{\text{hm},1}+R_{\text{hm},2})$) and (ii) the relative velocity between these objects at the same time $dV_{\text{coll}}$ is $< 200$ km s$^{-1}$. The first collision condition (i) reduced the number of close encounters to only 18 events, while applying the second (ii) condition we obtained only four reliable collision events.

Figure 2 shows the separation parameter as a function of time for backward (left panel) and forward (right panel) integration where four reliable collisions (Terzan 3 – NGC 6553, Terzan 3 – NGC 6218, Liller 1 – NGC 6522, Djorg 2 – NGC 6553) are marked by red asterisks. It is worth mentioning, that all the colliding GCs were likely originally formed in the MW disk [14].

In order to estimate the global collision rate, in Fig. 3 we present the cumulative collision number as a function of GCs minimum impact parameter $dR_{\text{coll}}$ (left panel) or relative velocity $dV_{\text{coll}}$ (right panel) at the moment of collision. Based on these plots we can estimate that in each ten million years there is at least one collision with the impact parameter less than 50 pc and less than 300 km s$^{-1}$. From these cumulative distributions of collision number we found that the minimum values of impact parameter and relative velocity are $dR_{\text{coll}} \approx 5$ pc and $dV_{\text{coll}} \approx 85$ km s$^{-1}$, respectively.

The distribution with the impact parameter was fitted by a simple power-law function:

$$\frac{dN_{\text{coll}}}{dt}(dR_{\text{coll}}) = 10^{a \cdot \log(dR_{\text{coll}}) + b},$$

where the best-fit slope parameters are $a = 2.06$ and $b = -4.51$. On the contrary, the velocity distribution was fitted by the cumulative normal distribution function:

$$\frac{dN_{\text{coll}}}{dt}(dV_{\text{coll}}) = \frac{1}{\sqrt{2\pi}} \int_{dV_{\text{coll}}}^{\infty} \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{(dV_{\text{coll}} - \mu)^2}{2\sigma^2} \right) \, dt,$$

where the best-fit mean and variance values are $\mu = 472$ and $\sigma = 209$, respectively.

In Fig. 4 we present the orbits of colliding GCs which are colour-coded by time. The time range is about ten million years around the moment of collisions. A more detailed orbital structure is shown on the right side of each figure. The solid line corresponds to the first GC in a pair, while the dashed line shows the second one. The intersection of the orbits (‘collision’) is marked as a red circle. Note that our study presents the simplified scenario and the more proper study of the GCs ‘collisions’ orbits requires consideration of the gravity interaction between the GCs.

In Table 2 we summarise the exact time of ‘collisions’ together with the minimum separations and relative velocities at the exact moment of collision.

To check the possible uncertainties introduced by the velocity errors of Gaia measurements (see Fig. 1), we performed additional 10 thousand runs of the backward integration with the $\pm \sigma$ randomly initialised and normally distributed velocities. The $\sigma$ velocity errors ($eV_\varphi$, ePMRA and ePMDEC) were taken from the catalogue presented in [23]. Following this way, we can approximately estimate the probability value for our four GSs to collide during the last 5 Gyr of the evolution of our Galaxy. From this
set of 10 thousand individual runs, we obtained that our selected clusters ‘collide’ in $\approx 11.21\%$ of studied cases. Taking advantage of the randomisation in the initial conditions, for each individual GCs pair, we also estimated the lower limit of the collision probability (see the last column in Table 2).

Table 2: Characteristics of collision GC pairs.

| GC1   | GC2   | $dR_{\text{coll}}$ (pc) | $dV_{\text{coll}}$ (km s$^{-1}$) | Time (Myr) | Prob. (%) |
|-------|-------|-------------------------|---------------------------------|-------------|-----------|
| Terzan 3 - NGC 6553 | 25.58 | 148.18 | 237 | 22.09 |
| Terzan 3 - NGC 6218 | 10.75 | 183.12 | 580 | 24.32 |
| Liller 1 - NGC 6522 | 9.38 | 185.04 | 2625 | 25.14 |
| Djorg 2 - NGC 6553 | 20.22 | 153.14 | 2889 | 20.23 |

CONCLUSIONS

Using the present-day Gaia DR2-based catalogues [5, 23] we have analysed the orbits for the sample of the Milky Way globular clusters. From 152 GCs we rejected 8 objects with large values of velocity error and 25 GCs were removed from the analysis due to the unstable orbit during backward/forward integrations. For the remaining 119 GCs, we analysed both backward and forward orbits calculated in the MW-like external potential using our own developed high order $\phi$-GRAPE code. Using a complex criteria for the collision detection we identified four candidates of colliding GC pairs: Terzan 3 – NGC 6553, Terzan 3 – NGC 6218, Liller 1 – NGC 6522 and Djorg 2 – NGC 6553. We also estimated the overall collision rate as about one collision per 10 Myr. Our experimental overall close encounter (‘collision’) number ($N_{\text{coll}} = 4$) is in good agreement with the simple estimation from the collision rate statistical approximations (see Fig. 3).

ACKNOWLEDGMENTS

The authors thank the anonymous referee for a very constructive report and suggestions that helped significantly improve the quality of the manuscript. PB and MI acknowledge the support within grant № AP14869395 of the Science Committee of the Ministry of Science and Higher Education of Kazakhstan (“Triune model of Galactic center dynamical evolution on cosmological time scale”). The works of MI and MS were supported by the National Academy of Sciences of Ukraine under the research project of young scientists № 0121U117799. The work of PB, MI and MS was also supported by the Volkswagen Foundation under grant № 97778. The work of PB was also supported by the Volkswagen Foundation under a special stipend № 9B870. PB and MI acknowledge the support by the Ministry of Education and Science of Ukraine under the collaborative grant № M/32-23.05.2022.

This work has made use of data from the European Space Agency (ESA) mission GAIA,1 processed by the GAIA Data Processing and Analysis Consortium (DPAC)2. Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the GAIA Multilateral Agreement.

REFERENCES

[1] Allen C., Moreno E. & Pichardo B. 2006, ApJ, 652, 1150
[2] Allen C., Moreno E. & Pichardo B. 2008, ApJ, 674, 237
[3] Bajkova A.T. & Bobylev V.V. 2021, Astron. and Astrophys. Transactions, 32, 177
[4] Bajkova A.T. & Bobylev V.V. 2021, Research in Astronomy and Astrophysics, 21, 7, id.173
[5] Baumgardt H., Hilker M., Solitama A. & Bellini A. 2019, MNRAS, 482, 5138
[6] Bennett M. & Bovy J. 2019, MNRAS, 482, 1417
[7] Berezkin P., Nitadori K., Zhong S. et al. 2011, in ‘International conference on High Performance Computing’, Kyiv, Ukraine
[8] Gaia Collaboration: Helmi I., van Leeuwen F., McMillan P. J. et al. 2018, A&A, 616, id.A12
[9] Gravity Collaboration: Abuter R., Amorim A., Bauböck M. et al. 2019, A&A, 625, id.L10
[10] Gnedin O.Y. & Ostriker J.P. 1997, ApJ, 474, 223
[11] Harfst S., Guandalris A., Merritt D. et al. 2007, New Astron., 12, 357
[12] Johnson D.R.H. & Soderblom D.R. 1987, AJ, 93, 864
[13] Kharchenko N.V., Piskunov A.E., Schilbach E., Röser S. & Scholz R.D. 2013, A&A, 558, id.A53
[14] Krujssen J.M.D., Pfeffer J.L., Chevance M. et al. 2020, MNRAS, 498, 2472
[15] Mardini M.K., Placco V.M., Meiron Y. et al. 2020, ApJ, 903, id.88
[16] Miyamoto M. & Nagai R. 1975, Publ. Astron. Soc. Japan, 27, 533
[17] Moreno E., Pichardo B. & Velázquez H 2014, ApJ, 793, id.110
[18] Navarro J.F., Frenk C.S., White S.D.M. et al. 1997, ApJ, 490, 493
[19] Pichardo B., Martos M. & Moreno E. 2004, ApJ, 609, 144
[20] Pérez-Villegas A., Rossi L., Ortolani S. et al. 2018, Publ. Astron. Soc. Australia, 35, id.e021
[21] Pérez-Villegas A., Barbuy B., Kerber L.O. et al. 2020, MNRAS, 491, 3251
[22] Schönhich R., Binney J. & Dehnen W. 2010, MNRAS, 403, 1829
[23] Vasiliev E. 2019, MNRAS, 484, 2832

1https://www.cosmos.esa.int/gaia
2https://www.cosmos.esa.int/web/gaia/dpac/consortium
Fig. 2: Relative separation of the GC collision pairs (black dots) in backward (left) and forward (right) integrations. Open squares indicate collisions with $dR_{\text{coll}} < 2(R_{\text{hm,i}} + R_{\text{hm,j}})$, while asterisks present collisions with $dV_{\text{coll}} < 200 \text{ km s}^{-1}$.

Fig. 3: GCs collision rate as a function of the relative distance (left) and relative velocity (right). Black dashed line (left) is a power-law fit $f(x)$ for relative distance distribution in Eq. (4) and dash-dotted line (right) is the cumulative distribution function fit $g(x)$ for relative velocity in Eq. (5).
Table 3: The list of GCs in our sample compiled from two catalogues of [5, 23].

| ID | Name       | Flag | ID | Name       | Flag | ID | Name       | Flag | ID | Name       | Flag |
|----|------------|------|----|------------|------|----|------------|------|----|------------|------|
| 1  | NGC 104    |      | 32 | NGC 5634   |      | 63 | NGC 6273   |      | 94 | Terzan 5   | to   |
| 2  | NGC 288    |      | 33 | NGC 5694   |      | 64 | NGC 6284   |      | 95 | NGC 6440   | to   |
| 3  | NGC 362    |      | 34 | IC 4499    |      | 65 | NGC 6287   |      | 96 | NGC 6441   |      |
| 4  | Whiting 1  |      | 35 | NGC 5824   |      | 66 | NGC 6293   | to   | 97 | Terzan 6   | to   |
| 5  | NGC 1261   |      | 36 | Pal 5      |      | 67 | NGC 6304   |      | 98 | NGC 6453   |      |
| 6  | Pal 1      | me  | 37 | NGC 5897   |      | 68 | NGC 6316   |      | 99 | NGC 6496   |      |
| 7  | E 1        | me  | 38 | NGC 5904   |      | 69 | NGC 6341   |      | 100| Terzan 9   | to   |
| 8  | Eridanus   |      | 39 | NGC 5927   |      | 70 | NGC 6325   |      | 101| Djorg 2    | cc   |
| 9  | Pal 2      |      | 40 | NGC 5946   |      | 71 | NGC 6333   |      | 102| NGC 6517   | to   |
| 10 | NGC 1851   |      | 41 | BH 176     | me  | 72 | NGC 6342   |      | 103| Terzan 10  |      |
| 11 | NGC 1904   |      | 42 | NGC 5986   |      | 73 | NGC 6356   |      | 104| NGC 6522   | cc   |
| 12 | NGC 2298   |      | 43 | FSR 1716   |      | 74 | NGC 6355   |      | 105| NGC 6535   |      |
| 13 | NGC 2419   |      | 44 | Pal 14     |      | 75 | NGC 6352   |      | 106| NGC 6528   |      |
| 14 | Pyxis      |      | 45 | BH 184     |      | 76 | IC 1257    |      | 107| NGC 6539   |      |
| 15 | NGC 2808   |      | 46 | NGC 6093   |      | 77 | Terzan 2   |      | 108| NGC 6540   |      |
| 16 | E 3        |      | 47 | NGC 6121   | to  | 78 | NGC 6366   |      | 109| NGC 6544   | to   |
| 17 | Pal 3      | me  | 48 | NGC 6101   |      | 79 | Terzan 4   |      | 110| NGC 6541   |      |
| 18 | NGC 3201   |      | 49 | NGC 6144   |      | 80 | BH 229     |      | 111| ESO 280-6  |      |
| 19 | Pal 4      | me  | 50 | NGC 6139   |      | 81 | FSR 1758   |      | 112| NGC 6553   | cc   |
| 20 | Crater     |      | 51 | Terzan 3   | cc  | 82 | NGC 6362   |      | 113| NGC 6558   | to   |
| 21 | NGC 4147   |      | 52 | NGC 6171   |      | 83 | Liller 1   | cc  | 114| Pal 7      |      |
| 22 | NGC 4372   |      | 53 | ESO 452-11 | to  | 84 | NGC 6380   | to  | 115| Terzan 12  |      |
| 23 | Rup 106    |      | 54 | NGC 6205   |      | 85 | Terzan 1   | to  | 116| NGC 6569   |      |
| 24 | NGC 4590   |      | 55 | NGC 6229   |      | 86 | Ton 2      |      | 117| BH 261     |      |
| 25 | NGC 4833   | to  | 56 | NGC 6218   | cc  | 87 | NGC 6388   |      | 118| NGC 6584   |      |
| 26 | NGC 5024   |      | 57 | FSR 1735   | me  | 88 | NGC 6402   | to  | 119| NGC 6624   | to   |
| 27 | NGC 5053   |      | 58 | NGC 6235   |      | 89 | NGC 6401   |      | 120| NGC 6626   | to   |
| 28 | NGC 5139   |      | 59 | NGC 6254   |      | 90 | NGC 6397   |      | 121| NGC 6638   |      |
| 29 | NGC 5272   |      | 60 | NGC 6256   | to  | 91 | Pal 6      |      | 122| NGC 6637   |      |
| 30 | NGC 5286   | me  | 61 | Pal 15     |      | 92 | NGC 6426   |      | 123| NGC 6642   |      |
| 31 | NGC 5466   |      | 62 | NGC 6266   |      | 93 | Djorg 1    | to  | 124| NGC 6652   | to   |

NOTE: Parameters for all GCs was taken from [23] with exception for GCs marked * with data from [5]. Column Flag contain additional information: me – GC was excluded from the integration due to their significant measurement errors, to – GC was excluded from the integration due to their type of orbit, cc – GC what satisfied ‘collision’ conditions.
Fig. 4: 3D orbits of GC ‘collision’ pairs in $\sim 20$ Myr (left) and $\sim 1$ Myr (right) around collision moment (from top to bottom): (Terzan 3, NGC 6553), (Terzan 3, NGC 6218), (Liller 1, NGC 6522) and (Djorg 2, NGC 6553). Trajectories are colour coded by time, arrows indicate the motion direction, and open circles show the time moment of collision.