A Search for a Globular Cluster whose Passage Through the Galactic Disk Could Induce the Formation of the Gould Belt

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Abstract—The distribution of sites where globular clusters have crossed the Galactic disk during the last 100 million years has been analyzed using the most recent kinematic data for 133 globular clusters (GCs). Three GCs (NGC 6341, NGC 7078, and ω Cen) whose distances between the positions where they crossed the Galactic disk and trajectories of the Gould Belt are less than 20% of their heliocentric distances at the crossing time (82, 98, and 96 million years ago, respectively) have been identified. For each of the clusters, this was their next to last, rather than their last, crossing of the Galactic disk. The passage of any one of these three GCs through the disk could potentially have initiated the formation of the Gould Belt.

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1 INTRODUCTION

A giant stellar–gas complex, known as the Gould Belt, is located near the Sun. This structure includes several OB and T associations, dozens of open star clusters, numerous single young stars, and molecular and dust clouds. According to modern estimates, the Gould Belt is a fairly flat system, with semi-axes of ≈ 350 × 250 × 50 pc and an inclination to the Galactic plane of about 20°. The center of the system is about 150 pc from the Sun, in the second Galactic quadrant. The stars forming the Gould Belt have ages of less than 60 million years. The total mass of the complex is approximately 1.5 × 10⁶ M☉. For a detailed description of the properties of this structure, see [1–6].

Quite a number of models have been suggested to explain the origin and evolution of the Gould Belt. According to Blaauw [7], this structure could have arisen as a result of the expansion of gas accelerated to high velocities following the explosion of a hypernova. This idea was further developed by Olano [8] in the framework of a gas-dynamical model. Lindblad [9] suggested a purely descriptive kinematic linear model for the intrinsic differential rotation and expansion of the Gould Belt that agree fairly well with observations. Bobylev [10, 11] further developed this approach for the non-linear case. Olano [12] considered an evolutionary model for a super-cluster, in which clusters such as the Hyades, the Pleiades, Coma Berenices, and the Sirius cluster were fragments of a former single complex, and the formation of the Gould Belt was a result of the contraction of the parent cloud’s central parts. None of these models are able to explain the observed inclination of the Gould Belt to the Galactic plane, while the three-dimensional model of Perrot and Grenier [13] describes...
the evolution of the inclination of the Gould Belt during a time interval about 50 million years into the past.

Another series of models consider a massive body falling onto the Galactic plane. Lépine and Duvert [14] suggested that many molecular-cloud complexes near the Sun could have been formed due to collisions between high-velocity clouds and the Galactic disk. In this model, the Gould Belt could have formed purely by chance.

Comerón and Torra [15, 16] performed numerical simulations of the passage of a high-mass \((3.3 \times 10^6 \, M_\odot)\), high-velocity cloud through the disk, and found that star formation would be most effective in the case of an oblique impact of the falling body. Levy [17] demonstrated that a shock could arise in the gas if a globular cluster (GC) crossed the Galactic disk. Finally, Bekki [18] demonstrated that the Gould Belt could have been formed some 30 million years ago as a result of a high-velocity, oblique impact between a clump of dark matter with a mass of approximately \(3 \times 10^7 \, M_\odot\) and a gas cloud with a mass of about \(10^6 \, M_\odot\). He found that the dynamical action of the falling body transformed an ellipsoidal cloud into a stellar ring structure after it has induced star formation in the cloud. His computations also showed that the resulting stellar structure should have an appreciable inclination to the Galactic disk, since the cloud becomes elongated along the orbit of the massive clump.

The masses of several GCs in the Galaxy reach a few times \(10^6 \, M_\odot\). It is quite possible that such a GC induced the formation of the Gould Belt. It is of interest to search for a particular GC capable of doing this. High-accuracy measurements of the proper motions, radial velocities, and distances are now available for many GCs, making it possible to derive their Galactic orbits over long time intervals.

The aim of this paper is to study the Galactic orbits of known GCs in order to search for a suitable candidate whose passage through the Galactic disk could have triggered the formation of the Gould Belt.

2 DATA

We based our study on the Milky Way Star Clusters catalog presented in [19], which contains the coordinates, distances, proper motions, and radial velocities for open and globular clusters in the Galaxy. Complete information is available for 133 GCs, making it possible to compute their positions and their \(U, V, W\) space velocities in order to derive their Galactic orbits.

After the appearance of the catalog [19], more accurate proper motions for a number of GCs were subsequently published. Thus, We used the data of [20] for the clusters Terzan 1, Terzan 2, Terzan 4, Terzan 9, NGC 6522, NGC 6540, NGC 6558, NGC 6652, NGC 6681, and Palomar 6, taking into account the corrections of [21]. The absolute proper motions for these GCs were derived from an analysis of ground-based observations using telescopes of the European Southern Observatory, as well as observations with the Hubble Space Telescope. Detailed studies of their individual orbits can be found in [21, 22].

We used the proper motions derived in [23] using data from the Gaia TGAS (Tycho-Gaia Astrometric Solution) catalog for NGC 104, NGC 5272, NGC 6121, NGC 6397, and NGC 6656.

We used the absolute proper-motion components and heliocentric distance for \(\omega\) Cen obtained in [24] using observations with the Hubble Space Telescope: \(\mu_\alpha \cos \delta = -3.238 \pm \)
We took the parameters of the center of the Gould Belt from [25], where they were computed from data for molecular-cloud complexes using VLBI observations of radio stars and maser sources; the position of this center is \((x_0, y_0, z_0) = (-118, 54, -12) \pm (15, 11, 8)\) pc, and its mean velocity relative to the Sun is \((u_0, v_0, w_0) = (-13.6, -15.0, -6.4) \pm (0.7, 0.7, 0.6)\) km/s.

3 METHOD

Since the method used in our study was based on analyzing the orbits of objects (GCs, the Gould Belt), we will spend some time describing our chosen model for the Galaxy. We believe that the most realistic model available is our refinement [26, 27] of the Navarro–Frenk–White model [28], based on the most recent data, supplemented with terms taking into account the influence of the central bar and spiral-density wave.

3.1 Model for the Axially Symmetric Galactic Potential

We present a model for the axially symmetric gravitational potential of the Galaxy as a sum of three components: the central spherical bulge, \(\Phi_b(r(R, Z))\), the disk \(\Phi_d(r(R, Z))\), and the massive, spherical dark-matter halo \(\Phi_h(r(R, Z))\):

\[
\Phi(R, Z) = \Phi_b(r(R, Z)) + \Phi_d(r(R, Z)) + \Phi_h(r(R, Z)).
\]

Here, we used a cylindrical coordinate system \((R, \psi, Z)\) with its origin at the Galactic center. In Cartesian coordinates \((X, Y, Z)\) with their origin at the Galactic center, the distance to a star (the spherical radius) is \(r^2 = X^2 + Y^2 + Z^2 = R^2 + Z^2\), where the \(X\) axis is directed from the Sun toward the Galactic center, the \(Y\) axis is perpendicular to the \(X\) axis and points in the direction of the Galactic rotation, and the \(Z\) axis is perpendicular to the Galactic \((XY)\) plane and points in the direction of the North Galactic pole. The gravitational potential is expressed in units of 100 km\(^2\) s\(^{-2}\), distances in kpc, masses in units of the mass of the Galaxy, \(M_{\text{gal}} = 2.325 \times 10^7 M_\odot\), and the gravitational constant is taken to be \(G = 1\).

The potentials of the bulge \(\Phi_b(r(R, Z))\) and disk \(\Phi_d(r(R, Z))\) were taken to have the form proposed by Miyamoto and Nagai [29]:

\[
\Phi_b(r) = -\frac{M_b}{(r^2 + b_b^2)^{1/2}},
\]

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

where \(M_b\) and \(M_d\) are the masses of the corresponding components and \(b_b, a_d,\) and \(b_d\) are scale parameters of the components in kpc. The halo component was taken in accordance with [28]:

\[
\Phi_h(r) = -\frac{M_h}{r} \ln \left(1 + \frac{r}{a_h}\right).
\]
Table 1: Parameters of the Galactic potential model, $M_0 = 2.325 \times 10^7 M_\odot$

| Parameter   | Value          |
|-------------|----------------|
| $M_b(M_0)$  | $443 \pm 27$  |
| $M_d(M_0)$  | $2798 \pm 84$ |
| $M_h(M_0)$  | $12474 \pm 3289$ |
| $b_b(kpc)$  | $0.2672 \pm 0.0090$ |
| $a_d(kpc)$  | $4.40 \pm 0.73$ |
| $b_d(kpc)$  | $0.3084 \pm 0.0050$ |
| $a_h(kpc)$  | $7.7 \pm 2.1$  |

Table 1 presents the parameters of the model for the Galactic potential (2)–(4) from [26, 27], computed using the rotational velocities of Galactic objects at distances $R$ out to $\sim 200$ kpc. When deriving the corresponding Galactic rotation curves, we used $R_\odot = 8.3$ kpc for the Galactocentric distance and $V_\odot = 244$ km/s for the linear velocity of the local standard of rest around the center of the Galaxy.

### 3.2 The Bar and Spiral Structure of the Galaxy

We selected a triaxial ellipsoid model in accordance with [30] for the potential of the bar:

$$\Phi_{\text{bar}} = - \frac{M_{\text{bar}}}{(q_b^2 + X^2 + [Y a_b/b_b]^2 + [Z a_b/c_b]^2)^{1/2}},$$  \(5\)

where $X = R \cos \vartheta$, $Y = R \sin \vartheta$, $a_b, b_b, c_b$ are the three semi-axes of the bar; $q_b$ is the length of the bar; $\vartheta = \theta - \Omega_{\text{bar}} t - \theta_{\text{bar}}$, $tg(\theta) = Y/X$, $\Omega_{\text{bar}}$ is the angular speed of the bar; $t$ is the integration time; and $\theta_{\text{bar}}$ is the inclination of the bar relative to the $X$ and $Y$ axes, measured from the line joining the Sun and the Galactic center (the $X$ axis) to the major axis of the bar in the direction of the Galactic rotation. We adopted the angular speed of the bar $\Omega_{\text{bar}} = 55$ km s$^{-1}$ kpc$^{-1}$, in accordance with the estimate of [31].

When the spiral-density wave is taken into account [32, 33], the right-hand side of formula (1) is supplemented with the term [34]:

$$\Phi_{\text{sp}}(R, \theta, t) = A \cos[m(\Omega_p t - \theta) + \chi(R)],$$  \(6\)

where

$$A = \frac{(R_0 \Omega_0)^2 f_{r0} \tan i}{m},$$

$$\chi(R) = - \frac{m}{\tan i} \ln \left( \frac{R}{R_0} \right) + \chi_\odot,$$

Here, $A$ is the amplitude of the spiral-wave potential, $f_{r0}$ the ratio of the radial component of the perturbation to the total gravitation of the Galaxy, $\Omega_p$ the angular velocity of the wave’s rigid-body rotation, $m$ the number of spiral arms, $i$ the pitch angle of the arms ($i < 0$ for a trailing pattern), $\chi$ the phase of the radial wave ($\chi = 0^\circ$ corresponds to the center of the arm), and $\chi_\odot$ the Sun’s radial phase in the spiral wave. We adopted the following
parameters for the spiral wave:

\begin{align*}
m &= 4, \\
i &= -13^\circ, \\
f_{r0} &= 0.05, \\
\chi_\odot &= -120^\circ, \\
\Omega_p &= 20 \text{ km s}^{-1} \text{ kpc}^{-1}.
\end{align*}

\section*{3.3 Equations of Motion}

The equations of motion of a test particle in the Galactic potential have the form

\begin{align*}
\dot{X} &= p_X, \quad \dot{Y} = p_Y, \quad \dot{Z} = p_Z, \\
\dot{p}_X &= -\partial \Phi / \partial X, \\
\dot{p}_Y &= -\partial \Phi / \partial Y, \\
\dot{p}_Z &= -\partial \Phi / \partial Z,
\end{align*}

where \(p_X, p_Y, \) and \(p_Z\) are canonical momenta, and a dot denotes a derivative with respect to time. We integrated Eqs. (8) using a fourth-order Runge–Kutta algorithm.

We took the peculiar velocity of the Sun relative to the Local Standard of Rest to be \((u_\odot, v_\odot, w_\odot) = (11.1, 12.2, 7.3) \text{ km/s},\) as was determined by Schönrich et al. [35]. Here, heliocentric velocities correspond to a set of moving Cartesian coordinates, with \(u\) directed towards the Galactic center, \(v\) in the direction of the Galactic rotation, and \(w\) perpendicular to the Galactic plane, towards the north Galactic pole.

Let the initial positions and space velocities of a test particle in the heliocentric coordinate system be \((x_0, y_0, z_0, u_0, v_0, w_0)\). The initial positions and velocities of the test particle in Galactic Cartesian coordinates are then given by

\begin{align*}
X &= R_0 - x_0, \quad Y = y_0, \quad Z = z_0 + h_\odot, \\
U &= -(u_0 + u_\odot), \\
V &= v_0 + v_\odot + V_0, \\
W &= w_0 + w_\odot,
\end{align*}

where \(h_\odot = 16 \text{ pc}\) is the height of the Sun above the Galactic plane.

\section*{3.4 Statistical Modeling}

We performed Monte Carlo statistical modeling for each GC. In these simulations, we added random errors to the object’s coordinates \((X, Y, Z)\) and space velocities \((U, V, W)\), which were computed, together with their uncertainties, taking into account the random errors in the distances, proper motions, and radial velocities.

Several methods for estimating distances to GCs are known: RR Lyrae variable stars, dynamical methods, eclipsing variables, Cepheids, fitting suitable isochrones, etc. The catalog [36] gives an extensive bibliography concerning distance-determination techniques for each GC. An analysis of the data in this catalog shows that each of the methods has a relative error of \(\sim 10\%\). Francis and Anderson [36] calculated the mean distances of each of 154 Galactic GCs and estimated the random errors of the derived distances to be in the range 1–5%.
Figure 1: Projection of the orbit of ω Cen onto (a) the Galactic plane XY and (b) the accompanying plane RZ. The orbit was computed 130 million years into the past using the axially symmetric potential model. The center of the Galaxy is at the coordinate origin, the open (light blue) squares show the position of the Sun, the x’s marked I show the times of the last Galactic-plane crossing, and the filled (blue) squares marked II show the times of the next-to-last Galactic-plane crossing. The current position of ω Cen is plotted by the large filled (red) circles.

Thus, in our simulations, we adopted a relative random error in the distance of 5% for all the GCs. The confidence intervals for the derived points where the GCs cross the Galactic plane, as well as for the model orbits in the Gould Belt, are estimated at the 99.7% (3σ) probability level.

3.5 Time Characteristics of Star Formation

It is clear that some time must elapse after the impact of a GC onto the Galactic plane before stars will be formed. Following [37], we based our study on the relation

\[ t = t_C + t_{SF} + t_A, \]  

where \( t \) is the time elapsed from the crossing of the Galactic disk by the GC to the present time, \( t_C \) the time between the crossing and the onset of star formation, \( t_{SF} \) the duration of the star formation, and \( t_A \) the age of the structure formed (in particular, the Gould Belt).

The value of the first term in Eq. (10) is known only with a large uncertainty, and is in the range 0–30 million years. For example, \( t_C = 15 \) million years according to the estimate of [14] obtained from simulations of an impact of a high-velocity cloud onto the disk. According to Wallin et al. [38], this time interval is \( t_C = 30 \) million years. In the model computations of Bekki [18], the time interval for star formation is in the range \( t_C = 7 – 15 \) million years. According to [39], the second term is \( t_{SF} = 0.2 \) million years (for a stellar mass \( M > M_\odot \)); since this is small compared to the other terms, we can neglect it in a first rough estimate. Finally, we adopted an age for the Gould Belt of \( t_A = 60 \) million years.
Figure 2: Confidence intervals for the crossing of the Galactic plane $XY$ by $\omega$ Cen (gray circles). The colored (red) curves show model trajectories for the center of the Gould Belt derived using the Monte Carlo method, (a) based on the axially symmetric potential model for an interval of 80 million years into the past and (b) taking into account the influence of the bar and spiral density wave for an interval of 96 million years into the past. The Galactic center is at the coordinate origin; the square marks the position of the Sun.

4 RESULTS AND DISCUSSION

Let us first consider Fig. 1, which shows projections of the orbit of the GC $\omega$ Cen onto the Galactic plane $XY$ and onto the accompanying plane $RZ$. The orbit was computed 130 million years into the past using an axially symmetric potential model. The times of crossing of the Galactic plane are marked in the figure. The first crossing (I) occurred 49 million years ago, when the GC passed from the southern to the northern Galactic hemisphere (a S–N transition). The second crossing (II) was 80 million years ago, when the GC passed from the northern to the southern hemisphere (a N–S transition).

Note that the direction of the passage is not the defining factor in the formation of the Gould Belt. However, since the formation process is not instantaneous, and the initial distribution of the gas is not uniform, we expect the presence of an age gradients for individual components of the Gould Belt along the trajectory of the impacting body. For example, the mean age of the main members of the Scorpius-Centaurus association (the northern part of the Gould Belt) is 10–20 million years greater than the mean age of members of the Orion association (the southern part of the Gould Belt). At the same time, the region of maximum density with the highest star-formation rate should be located at the center of the Gould Belt, as was demonstrated in [18]. By the way, the impacting body crosses the Galactic plane from the South to the North in this model.

Figure 2 displays the confidence interval for the points where $\omega$ Cen crosses the Galactic plane $XY$ and the trajectories of the center of the Gould Belt obtained using the Monte
Table 2: Parameters of the approach of the center of the Gould Belt to the site of the next-to-last Galactic-plane crossing by ω Cen

| Potential model                      | Δrt, kpc | t, million years ago | γ,° | p, % |
|--------------------------------------|----------|----------------------|-----|------|
| a) axially symmetric case            | 4.7      | 80                   | 34 ± 8 | 15   |
| b) + bar                             | 4.8      | 81                   | 35 ± 8 | 16   |
| c) + bar + spiral wave               | 2.5      | 96                   | 40 ± 8 | 20   |

Carlo method. The orbits are plotted for both the axially symmetric potential model and a model including the influence of the bar and spiral-density wave. Since the times of a GC’s crossing of the Galactic plane are somewhat different for different potentials, we integrated the model orbits of the center of the Gould Belt for different appropriate time intervals. The distribution of points where ω Cen crosses the Galactic plane corresponds to crossing II. We estimated the probability p from the number of Gould Belt trajectories that intersect the distribution of crossing points for the time t. The panels of Fig. 2 each show 100 model trajectories for the Gould Belt. Of these, 15 (Fig. 2a) and 20 (Fig. 2b) trajectories intersect the area where the crossing points are distributed; the corresponding probabilities are p = 15% and p = 20%, respectively.

Table 2 presents the nominal characteristics for the approach of the center of the Gould Belt to the site of the next-to-last crossing of the Galactic plane by ω Cen. The orbits and their characteristics were computed using three models for the potential: (a) an axially symmetric model in accordance with (2)–(4), (b) the axially symmetric model with an added contribution from the bar (5), and (c) the axially symmetric model with added contributions from the bar and spiral density wave (6). These three options for the potential are indicated in the first line of Table 2. For each crossing time t, we computed the distance between the position of the Gould Belt and the site where a GC crossed the Galactic plane, ∆rt = √(ΔX² + ΔY² + ΔZ²), where ΔX, ΔY, and ΔZ are the differences between the coordinates of the Gould Belt and the GC. The Δrt value in the second column of Table 2 was obtained by averaging all the model orbits. The crossing time t (also corresponding to an average of all the model orbits) is given in the third column, and the fourth column presents the angle γ at which the GC crosses the Galactic plane (the angle between the orbital plane of the GC and the XY plane). As was noted in the Introduction, the more acute the angle γ, the more effective the compression of the Galactic disk. The last column of Table 2 contains the probability p for the Gould Belt trajectories to intersect the distribution of the crossing points.

It follows from Fig. 2 and a comparison of the data in Table 2 that the influence of the spiral-density wave is a significant factor. Including this influence leads to a considerably lower scatter of the model orbits, and the approach parameter Δrt is smaller than in the axially symmetric case.

Figure 3 shows the model crossing points of the Galactic plane XY by GCs and model trajectories of the center of the Gould Belt plotted using the axially symmetric potential model (Fig. 3a) and the potential model taking into account the influence of the bar and spiral-density wave (Fig. 3b). We selected GCs with crossing times in the range 50–100 million years for this figure. We decided not to plot points with crossing times younger than
Table 3: Globular clusters whose crossings of the Galactic plane were near the center of the Gould Belt about 100 million years ago

| Globular cluster | $n_c$ | $\Delta r_t$, kpc | $t$, million years ago | $M/M_\odot$ | Source | Crossing | $\gamma,^\circ$ | $p, \%$ |
|------------------|-------|------------------|------------------------|-------------|--------|----------|-----------|--------|
| $\omega$ Cen     | II    | 2.5              | 96                     | $4.00 \times 10^6$ | [40]   | N–S      | 40 ± 8    | 20     |
| NGC 7078         | II    | 1.0              | 98                     | $0.65 \times 10^6$ | [41]   | S–N      | 39 ± 7    | 74     |
| NGC 6341         | II    | 1.8              | 82                     | $0.30 \times 10^6$ | [41]   | N–S      | 57 ± 9    | 72     |
| NGC 6838         | III   | 3.7              | 86                     | $0.02 \times 10^6$ | [42]   | —        | —         | —      |
| NGC 104          | I     | 7.7              | 53                     | $0.84 \times 10^6$ | [39]   | —        | —         | —      |
| NGC 6760         | II    | 8.3              | 52                     | $0.25 \times 10^6$ | [43]   | —        | —         | —      |
| NGC 6749         | III   | 9.4              | 52                     | —            | —      | —        | —         | —      |

50 million years to avoid crowding the figure, particularly as there are no points close to the Gould Belt trajectory among them. The filled (yellow) circles mark seven candidate GCs undergoing close approaches with the Gould Belt orbit; names are indicated for the three GCs closest to this orbit. We selected these seven candidates based on the proximity of their positions to the Gould Belt orbit.

Table 3 presents the parameters for these seven candidate GCs that could have undergone a close approach with the Gould Belt orbit in the past. All the data in Table 3 were obtained using the most complete model for the Galactic potential (including the bar and spiral-density wave). The columns of Table 3 give (1) the names of the GCs, (2) the ordinal number $n_c$ for a GC’s crossing of the Galactic plane in the past, (3) the distances $\Delta r_t$, (4) the time intervals $t$, (5)–(6) mass estimates for the GCs and corresponding references, (7) the type of crossing, (8) the crossing angle $\gamma$, and (9) the probabilities $p$ for the Gould Belt trajectories to intersect the distribution of crossing points.

Table 3 shows that the mass of $\omega$ Cen is an order of magnitude higher than the masses of the other GCs in this table. We could not find a mass estimate for NGC 6749 in the literature. However, it is known to have a fairly diffuse appearance, and Rosino et al. [45] remark that it could even be an open cluster. Thus, we expect the mass of NGC 6749 not to be very high.

The mass of NGC 6838 is too low for it to be the body whose impact formed the Gould Belt. We can also exclude the GCs in the last three lines of the table, namely NGC 104, NGC 6760, and NGC 6749, from the list of candidates for the following reason. All three of these GCs crossed the Galactic disk some 52 million years ago, at which time the distance between each of them and the Gould Belt orbit was too large to influence the possible formation of the Gould Belt (the distances $\Delta r_t$ exceeded 90% of the heliocentric distance to the site where each GC crossed the Galactic plane).

Figure 3 also contains a point with $(X,Y) \approx (0,-7)$ kpc that is fairly close to the Gould Belt trajectory. This is the site where the Galactic plane was crossed by Palomar 10 at time $-99$ million years. This GC is of no interest for us, as its $\Delta r_t$ was too large at that time. The situation is similar for six other objects located near the area with coordinates $(X,Y) \approx (0,-5)$ kpc: their distances to the Gould Belt orbit were too large at their crossing times ($\Delta r_t > 10$ kpc).

Figure 4a shows the confidence intervals for the points $XY$ where the Galactic plane was crossed by NGC 7078 and the model trajectories for the center of the Gould Belt plotted.
Figure 3: Model points where GCs cross the Galactic plane XY (blue circles) and model trajectories for the center of the Gould Belt. Curves are plotted 100 million years into the past (a) using the axially symmetric potential model and (b) including with the influence of the bar and the spiral-density wave. The center of the Galaxy is at the coordinate origin, the (red) squares show the position of the Sun, and the filled (yellow) circles show the positions of known clusters.

98 million years into the past, and Fig. 4b shows the same for NGC 6341, with the model Gould Belt trajectories plotted 82 million years into the past. Here, we used the full model for the potential, including the influence of the bar and spiral density wave.

Comparing Fig. 4 and Fig 2b, we can see that NGC 7078 and NGC 6341 have larger fractional intersection zones between the terminal points of the Gould Belt orbits and the distribution of the GC crossing points than does ω Cen. Thus, the probability p of a close approach to the Gould Belt orbit is higher for NGC 7078 and NGC 6341 than for ω Cen.

Note that, in the case of ω Cen, NGC 7078, and NGC 6341, the formation of the Gould Belt requires a time that is approximately double the time scale indicated by the numerical experiments of Bekki [18]. The time interval $t$ in (10) in his computations was about 45 million years, with $t_A = 30$ million years.

The Galactic orbits of ω Cen, NGC 6341, and NGC 7078 all differ considerably from circles. The orbit of ω Cen is shown in Fig. 1, while Fig. 5 shows the orbits of NGC 6341 and NGC 7078 computed 150 million years into the past using the axially symmetric potential model. It is of interest to obtain some idea of the velocity $V_{tot}$ of the GCs relative to the medium through which they were moving at the time of their crossing the Galactic plane about 100 million years ago. To address this, we first computed their cylindrical velocities $V_R, V_\theta, V_Z$ and the crossing time II, which yielded $(V_R, V_\theta, V_Z) = (-95, -68, -85)$ km/s for ω Cen, $(-130, 14, -209)$ km/s for NGC 6341, and $(121, 157, 165)$ km/s for NGC 7078.

Note that ω Cen has a retrograde orbit, and lags behind the Galactic rotation by $\Delta V_\theta \approx 68$ km/s. Gas clouds in which stars can potentially form move along essentially circular orbits, in accordance with the Galaxy’s rotation curve; their velocity at the solar distance
Figure 4: (a) Confidence intervals for the points where NGC 7078 crosses the Galactic plane XY (gray circles) and model trajectories for the center of the Gould Belt (red curves) plotted 98 million years into the past. (b) Same as (a) for NGC 6341 (gray circles), plotting the model trajectories for the center of the Gould Belt (red curves) 82 million years into the past. The center of the Galaxy is at the coordinate origin, and the (blue) squares mark the position of the Sun.

$R_0$ is $(V_\theta)_{R=R_0} = V_0 = 244$ km/s, the value we used in our potential. We see from Fig. 3 that the crossing points for all three candidates were near the solar circle about 100 million years ago, so that we can use the velocity $V_0$ as the circular velocity of the medium in rough estimates. We then obtain for the vector velocity of $\omega$ Cen relative to the gaseous medium $(V_R, V_0 - V_\theta, V_Z) = (-95, 312, -85)$ km/s, with the absolute value of the total velocity being $V_{tot} = 337$ km/s.

NGC 6341 essentially does not participate in the Galactic rotation, but has considerable radial and vertical velocities. These properties are clearly seen in Fig. 5a, where the GC moves essentially through the center of the Galaxy, as well as in Fig. 5b, where NGC 6341 ascends to $Z_{max} = 10.5$ kpc above the Galactic plane. Using the approach described above, we found $V_{tot} = 337$ km/s.

NGC 7078 rotates with $V_\theta = 157$ km/s, and also has considerable radial and vertical velocities, as is shown by Figs. 5c, d. For this cluster, $V_{tot} = 222$ km/s.

Thus, we can conclude that NGC 6341 and NGC 7078 possessed comparable energies in their collision with the medium; the small difference in their masses was compensated by the difference in their velocities. However, there is no doubt that $\omega$ Cen is leader in terms of its impact energy.
CONCLUSIONS

We have computed Galactic orbits for 133 globular clusters in our Galaxy using modern measurements of their proper motions, radial velocities, and distances. For each GC, we identified points of past crossings of the Galactic plane $XY$, considering not only the last crossing, but also several earlier crossings (to the fifth last).

Our analysis of the distribution of these points shows three of the GCs to be located very close to the trajectory of the center of the Gould Belt at times from −80 to −100 million years. These GCs are NGC 7078, NGC 6341, and ω Cen. The distance between each of these and the Gould Belt orbit at the crossing time is $\Delta r_t < 2.5$ kpc (i.e., < 20% of their heliocentric distance at the crossing time $t$), within the random uncertainties in the distances to the Galactic orbits.

We integrated the orbits of the GCs and the of center of the Gould Belt using an axially...
symmetric model for the potential, and also taking into account the contributions of the central bar and spiral-density wave. We found that the difference in the approach times when the spiral-density wave is taken into account can reach 10–15 million years.

$\omega$ Cen, whose mass, $4 \times 10^6 M_\odot$, is higher than the masses of the other candidates by an order of magnitude, is of primary interest. At the same time, the sites of past crossings of the Galactic plane by NGC 7078 and NGC 6341 are closer to the trajectory of the Gould Belt than the site for $\omega$ Cen. The time for the close approach to the Gould Belt that is closest to the present time is $t = 82$ million years ago for NGC 6341, while the time that is farthest is that for NGC 7078, $t = 98$ million years ago. In our opinion, each of these three clusters—NGC 7078, NGC 6341, and $\omega$ Cen—could be a candidate for the body whose passage through the Galactic disk may have provoked the formation of the Gould Belt.

The analysis of different sources in the literature indicates a fairly good agreement in the derived mean radial velocities and distances to the GCs studied. On the other hand, their measured proper motions have large uncertainties. It is important to use the most reliable proper motions possible for objects with large heliocentric distances. Thus, it will be important to confirm our results after the Gaia mission [46] is completed.

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