

Article

Oort Cloud Comets: Perturbations Due to the Passage of Gliese 710

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Abstract

The outermost region of the Solar System is called the Oort cloud, which is the Solar System's reservoir of long-period comets that extends to distances up to 200,000 au from the Sun. Long-period comets can be injected towards the inner Solar System due to galactic tides and passing stars. While galactic tides are effective on long time scales, perturbations of stellar flybys are short-term effects that have not only occurred in the past. Gaia observations confirmed that the Solar System will experience a close flyby of the K-type star Gliese 710 in about 1.29 million years. This star will probably pass at a distance of about 10,500 au to the Sun. When crossing the Oort cloud, this 0.6 solar mass star will perturb the long-period comets, especially those objects that are close to Gliese 710's trajectory. In this numerical investigation, we use our recently developed GPU-based N-body code GANBISS and study the orbits of 100 million test-comets for the time when the star enters the Oort cloud until its closest approach to the Sun, which takes about 32,000 years. The simulations show that the stellar passage generates cometary streams, which either transport comets into the inner Solar System or scatter a huge number of comets into interstellar space. Of the 100 million comets, about one third were scattered into interstellar space, and only 63,453 comets were directed toward the Sun, of which 1662 entered the inner Solar System within 2 au. Comet streams into this region would be possible over a period of 45 million years. After Gliese 710's flyby, we investigated the influence of giant planets. This showed that the giant planets protect us from massive comet streams. The first comet with a perihelion distance close to the Earth's orbit will take about 1.505 million years to reach its perihelion after Gliese 710's flyby.

Keywords: Oort cloud; long-period comets; stellar flyby



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1. Introduction

Our Solar System is hypothetically surrounded by a cloud of comets that may extend up to 200,000 au, known as the Oort cloud, named after the Dutch astronomer J. Oort, who suggested in 1950 that there might be a reservoir of long-period comets far beyond the planets in order to explain the observations of long-period comets [1]. This idea was originally proposed by the Estonian astronomer E.J. Öpik in 1932, thus it is also called the Öpik–Oort cloud. However, this theory has not yet been confirmed but is widely accepted. In 1986, Heisler & Tremaine showed the influence of galactic tides on the cometary dynamics in this region [2]. Afterwards, many studies were dedicated either to estimating the number of comets in the Oort cloud (see e.g., [3,4]) or to investigating the origin of the

Oort cloud—see e.g., [5–8] and review articles [9–11] that provide an excellent overview of the current knowledge regarding the formation and evolution of the Oort cloud as well as additional references.

Since we cannot directly observe comets in the Oort cloud, our knowledge is based on the analysis of observed long-period comets (see e.g., [12]), which also provide clues about the structure of the Oort cloud ([13–16]). In principle, it can be distinguished between an inner and an outer Oort cloud, where the latter is the spherical Öpik–Oort cloud which extends from 10,000 to 200,000 au. For the inner Oort cloud, there are two models:

- (i) A spherical inner cloud between 2000 and 5000 au, which is called the Hills–Oort cloud [17]. It is fully thermalized and contains a larger number of comets than the Öpik–Oort cloud;
- (ii) An inner disk, which extends up to 10,000 au and is aligned with the ecliptic.

Without observation, it is not possible to determine which model reflects reality. But, if the hypothetical planet 9 is found, then the inner disk model can be ruled out [18].

However, recently, Nesvorný et al. [5] published a numerical study where they showed an interesting new feature for the inner Oort cloud: a spiral structure that formed during the first hundred million years after the formation of the Solar System and has existed for billions of years. So far, it has not been analyzed whether, or to what extent, planet 9 or a passing star might influence the spiral structure.

In the present study, we focus on the Öpik–Oort cloud, where the K-type star Gliese 710 will pass through in about 1.29 million years without entering the inner Oort cloud.

The dynamics in the outer region of the Oort cloud are characterized by the interaction of forces between galactic tides and passing stars, which together inject long-period comets into the inner Solar System [19]. Thus, the study of stellar passages is of great interest, as such events—even if they are rare—can enhance comet showers, which could increase the impact risk on Earth. Since Gliese 710 will approach within 10,500 au of the Sun, thus reaching the inner edge of the Öpik–Oort cloud, it very likely triggers comet streams in both directions—toward the Sun and into interstellar space.

This K-type star is still about 19 pc away, has a brightness of ~ 9.6 magnitudes, and can be observed with a telescope in the constellation Serpens Cauda. Its approach to the Sun was first mentioned by Garcia-Sanchez et al. in 1997 at the 23rd IAU meeting in Kyoto, where the encounter with the Solar System was found in Hipparcos data (see [20]). Observations of the European spacecraft Gaia confirmed the flyby of Gliese 710 in all data releases (DR1–DR3). In 2022, Bailer-Jones [21] showed that according to Gaia DR3, this flyby will be the closest within the next 12 million years, and there has been a similar stellar flyby in the past of the G3 star HD 7977 about 2.8 million years ago. For this stellar passage, Gaia DR2 suggested an encounter distance of about 88,487 au to the Sun, which is much smaller, applying Gaia DR3, namely 13,221 au [21]. Moreover, Dybczyński et al. in 2022 [22] published a mean flyby distance of 6600 au using Gaia EDR3.

In the case of Gliese 710, the flyby parameter also changed with the observations:

- (i) Gaia DR1 indicated an encounter distance to the Sun of 13,365 au in about 1.35 million years [23];
- (ii) Gaia DR2 suggested a flyby distance of $10,721 \pm 2114$ au from the Sun [24]. Moreover, [24] combined Hipparcos data, Gaia observations, and numerical calculations, which resulted in a flyby distance of Gliese 710 of 4300 au from the Sun.
- (iii) Using Gaia DR3, we determined the flyby distance of 10,500 au in about 1.294 million years—a similar value was published by [25].

Using the flyby parameters of Gaia DR3, we studied the motion of 100 million comets, which will be influenced by Gliese 710 when crossing the Oort cloud. For the first time, a

GPU N-body code [26] was used to compute the dynamical behavior of comets perturbed during a stellar flyby.

In this study, we first describe the dynamical model, the numerical method, and the initial configuration of the Oort cloud comets. Next, we show the perturbations caused by the stellar flyby and discuss comet streams triggered by Gliese 710, which throw comets either into interstellar space—where they are referred to as ISOs (interstellar objects)—or toward the Sun, where they could pose a threat to Earth. Finally, we present a simulation over one million years of all objects that could enter the inner Solar System after Gliese 710's flyby, where we include the gravitational influence of the gas giants, Jupiter to Neptune, and show how the planetary perturbations may change the comet streams towards the Sun.

2. Dynamical System

Gliese 710 has about 0.6 solar mass and approaches the Solar System with a velocity of 14.4 km/s, which is much slower than stars in the solar neighborhood [19]. In a heliocentric frame, the K star moves along a hyperbolic orbit, which appears as a straight line due to its high eccentricity (see Figure 1, left panel). In the right panel of Figure 1, the distance from the Sun is shown from the moment Gliese 710 enters the purple shaded region, which denotes the semi-major axis range of the Öpik–Oort cloud (10,000 to 100,000 au).

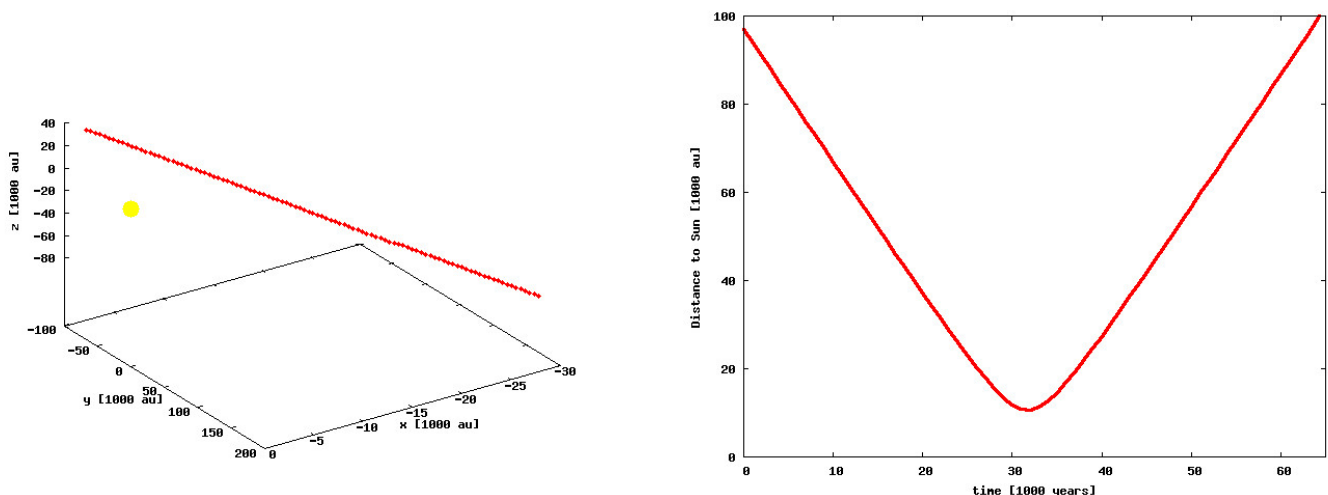


Figure 1. The left panel shows the trajectory of Gliese 710 (red line) in the heliocentric frame during the flyby with respect to the Sun (marked by the yellow dot). The right panel displays how the distance to the Sun changes during the passage through the Oort cloud.

Of course, we are aware of the fact that the Oort cloud may extend to distances from the Sun of up to 200,000 au, as cometary orbits with semi-major axes of 100,000 au might have high eccentricities (close to 1) so that these comets will also populate the region beyond the displayed area in the right panel of Figure 1. However, beyond 100,000 au, the density of objects continues to decrease, and the farther objects are from the Sun, the more effective becomes the influence of the galactic environment. Since we only want to analyze the influence of the passing star, we limited this study to the distance of 100,000 au. The right panel of Figure 1 indicates that the K star only needs 64,000 years to cross the Oort cloud when considering a flyby distance to the Sun of 10,500 au, which resulted from Gaia DR3. We used the data of Gaia DR3, as it was the latest observational data available when this study was conducted.

Since Gliese 710 is currently ~ 19 pc away from the Sun, thus, we first propagated its orbit to the distance of 100,000 au from the Sun, which led to the initial orbital data for Gliese 710 (Table 1) for our fly-by study.

Table 1. Initial heliocentric position and velocity data of Gliese 710 with respect to the Sun for the flyby study determined from Gaia DR3.

Position [au]	Velocity [au/day]
$x = -1608.0$	$v_x = -7.41509 \times 10^{-4}$
$y = -91,167.0$	$v_y = 7.71683 \times 10^{-3}$
$z = 33,121.9$	$v_z = -3.044729999 \times 10^{-3}$

As in the Oort cloud model, we usually consider an inner disk that extends up to 10,000 au followed by a spherical cloud up to 100,000 au (in semi-major axis). According to the data from Gaia DR3, it is known that the orbit of Gliese 710 is inclined with respect to the Solar System's ecliptic, which would be important if the star enters the disk of the Oort cloud.

In our numerical study, we considered a spherical cloud of comets from 10,000 to 100,000 au, where the comets were distributed according to a density profile proportional to r^α (with $\alpha = -3.5$, and r is the distance to the Sun) (see Duncan et al. [27]) and a uniform distribution in orbital energy $z = -1/a$ (where a is the semi-major axis). The initial eccentricities (e) were distributed according to $dn/de \propto e$ (n is the number of objects in the interval e and $e + de$), which corresponds to a fully thermalized distribution [17]. Initial inclinations (i) were randomly chosen between 0 and 180 degrees. All other angles (longitude of ascending node Ω , argument of peri-apsis ω and mean anomaly M) were between 0 and 360 degrees. Since studies by Francis et al. [28] and Levison et al. [29] suggest that there could be 600 billion comets larger than 1 km in the Oort cloud, a high object density is needed in the computations. As this large number of objects (even if they are massless) cannot be processed within a reasonable time in numerical simulations—even using a GPU-based N-body code—restrictions are necessary.

Thus, in addition to partitioning the Öpik–Oort cloud into 4 shells (see Table 2), we limited our study to the vicinity of the Gliese 710 trajectory, namely the region of influence (see Table 3) along its path crossing the Öpik–Oort cloud. In each shell, the region of influence around Gliese 710's trajectory was filled up with 23.5–27.5 million objects, where each shell was computed separately. To figure out the perturbations of the passing star, we considered only objects with perihelion distances $q = a(1 - e) > 70$ au.

Table 2. Shell structure of the Öpik–Oort cloud defined for our numerical simulations. The colors denote the different shells in the various Figures.

Spherical Shell	Extension [au]	No. of Objects [million]
S1 (red):	10,000–25,000	27.5
S2 (blue):	25,000–50,000	25
S3 (green):	50,000–75,000	24
S4 (purple):	75,000–100,000	23.5

Table 3. The region of influence of Gliese 710 for the encounter distance of 10,500 au to the Sun.

Method	Radius [au]
SOI	8560
Hill sphere	6140
L_1	4700
S-type stability	2310

Determination of the Region of Influence Along Gliese 710's Path

The region influenced by Gliese 710 is usually referred to as its sphere of influence (SOI), which is defined as the area around a celestial body where the gravity of this body dominates over the gravitational influence of other objects. Thus, in Gliese 710's SOI, the gravitational perturbations from the Sun are negligible, so that a two-body approximation could be used to calculate the cometary orbits.

(i) Sphere of influence (SOI):

The area of the SOI is determined by the radius

$$r_{SOI} = d \cdot (m_2/m_1)^{2/5}$$

where m_1 and m_2 are the masses of the Sun and a planet (in our case Gliese 710), and d is the distance between m_1 and m_2 .

In orbit dynamics, the SOI is mainly used to switch between reference frames, making it easier to transform trajectories relative to the Sun into trajectories relative to a planet. The application to Gliese 710 with $d = 10,500$ au yielded quite a large SOI (see Table 3), where the area is likely also influenced by the Sun.

(ii) Hill radius:

Another option to determine the area influenced by Gliese 710 is the Hill sphere, which is defined by:

$$r_{Hill} = d \cdot (m_2/3 m_1)^{1/3}$$

where m_1 , m_2 , and d are again the masses of the Sun and Gliese 710, and the distance between them. Generally, the Hill sphere defines the region where a satellite's orbit is stable against perturbation from a larger, distant body. If we apply the Hill radius to Gliese 710, Table 3 shows that the resulting area still crosses the midpoint of the distance from the Sun. Thus, the influence of the sun would not be negligible in this region.

Obviously, the simple approaches (SOI and Hill sphere) do not provide good estimates for the region which is only influenced by the passing star.

(iii) Lagrange point L_1 :

In the restricted three-body problem, the position of the Lagrange point L_1 can be used to divide the space between two celestial bodies m_1 and m_2 (i.e., the Sun and Gliese 710) into two regions, in order to determine the region of influence of these bodies.

Consider $m_1 = 1$ and $m_2 = 0.6$ solar masses, with the mass ratio $\mu = m_2/(m_1 + m_2) = 0.375$, and the distance d between m_1 and m_2 is unity. In the rotating frame, the coordinates of the masses m_1 and m_2 are $x_1 = -\mu$ and $x_2 = (1 - \mu)$, respectively, and the location $(x, 0, 0)$ of the Lagrange point L_1 is between the two masses, $x_1 < x < x_2$, and can be determined by solving the following equation numerically:

$$x - \frac{(1 - \mu)}{(x + \mu)^2} - \frac{\mu}{(x - (1 - \mu))^2} = 0$$

This leads to $x = 0.17734$ and a distance of 0.44766 from m_2 (in units of length). Taking into account the distance of 10,500 au between m_1 and m_2 , then L_1 is about 4700 au from Gliese 710 away.

(iv) S-type stability:

Another possibility is to consider the Sun and Gliese 710 as a binary star system and apply the stability limits of S-type motion ([30,31]) for the distance of 10,500 au between the two stars;

assuming zero eccentricity as a first approximation and $\mu_2 = m_1/(m_1 + m_2) = 0.625$, the stability region around Gliese 710 has a radius of 2310 au, which can be used as region of influence.

We must, of course, point out here that the S-type stability limits were determined for the bound motion of binary stars, which is not the case for Gliese 710. Nevertheless, these boundaries are suitable to define a region around Gliese 710's trajectory in which gravitational perturbations caused by the Sun can be ruled out.

Table 3 lists the region of influence of the various methods. The size of the areas in Table 3 for the various approaches make clear that the first two methods (SOI and Hill sphere) cannot be applied to two objects of similar mass, as in both cases, the defined areas extend beyond the midpoint of the Sun–Gliese 710 distance so that we cannot rule out the gravitational influence of the Sun.

Based on the various stability studies of binary stars that have been carried out in our group, we have chosen the value of the S-type stability limit to be the most reasonable solution. Since both stars have spheres of influence that do not overlap, there is also a region in between where the gravitational forces of both stars are at work, which can lead to chaotic motion of the comets. Furthermore, by using a radius of 2310 au for the region of influence, we can more easily achieve an object density that might, to some extent, be close to a realistic one.

3. Numerical Method

Even though the Oort cloud contains billions or possibly a trillion comets, the distance between neighboring objects is so large (~ 10 au and more depending on the distance from the Sun) that interactions between the comets can be ruled out. Therefore, the restricted problem can be applied for our numerical investigation, where only the Sun, Gliese 710 and the giant planets (in Section 4.2) are massive bodies and the comets are massless objects that do not interact and have no influence on the orbits of the two stars or the giant planets.

To calculate all interactions in the N-body problem and the restricted N-body problem, we use our recently developed GPU N-body code GANBISS¹ [26]. The equation of motion for a massive body m_ν under the influence of all other massive bodies is as follows:

$$\dot{\mathbf{r}}_\nu = \mathbf{v}_\nu \quad \nu = 1, \dots, N \quad (1)$$

$$\dot{\mathbf{v}}_\nu = k^2 \sum_{\mu=1, \mu \neq \nu}^N m_\mu \frac{\mathbf{r}_\mu - \mathbf{r}_\nu}{\|\mathbf{r}_\mu - \mathbf{r}_\nu\|^3}, \quad (2)$$

where $\mathbf{r}_\mu$ and $\mathbf{r}_\nu$ are the respective position vectors and $\|\mathbf{r}_\mu - \mathbf{r}_\nu\|^3$ its scalar distance, and k the Gaussian gravitational constant. The computational complexity of the N-body problem scales with N^2 , since the influence of all other objects must be calculated for each object. In case of the restricted N-body problem where the interactions between the massless objects can be neglected, the equation of motion for a massless object η under the influence of N massive objects is written as:

$$\dot{\mathbf{r}}_\eta = \mathbf{v}_\eta \quad \eta = 1, \dots, N_{ml} \quad (3)$$

$$\dot{\mathbf{v}}_\eta = k^2 \sum_{\mu=1}^N m_\mu \frac{\mathbf{r}_\mu - \mathbf{r}_\eta}{\|\mathbf{r}_\mu - \mathbf{r}_\eta\|^3}. \quad (4)$$

The computational complexity scales, therefore, to $N_{ml} \cdot N$.

To solve the equations of motion, the Bulirsch–Stoer method [32] with adaptive step size control is used. The computations were performed in the barycentric frame; and for

the error tolerance, $\epsilon = 10^{-13}$ was used. The calculations were performed on NVIDIA A100 and NVIDIA A40 and we allowed the calculation of the massless objects for the various shells (see Table 2).

Initial Set-Up of Oort Cloud Comets

As mentioned earlier, we have set the radius for Gliese 710's region of influence to 2310 au for our study, which corresponds to the stability zone of Gliese 710 when considering a binary star system (together with the Sun) with a stellar distance of 10,500 au. Figure 2 shows the initial distribution of the comets in the region of influence of Gliese 710 around its trajectory (indicated by the black line), where the different colors denote the different shells (S1–S4) as discussed in Section 2. The purple area shows the outermost shell S4, where Gliese 710 enters the Oort cloud at 100,000 au followed by the green shell S3, the blue shell S2 and the innermost shell S1 in red. The lower edge of S1 corresponds to the encounter distance of 10,500 au of Gliese 710 to the Sun. The black line after the red area of the cylinder indicates the path of Gliese 710 through the center of the cylinder.

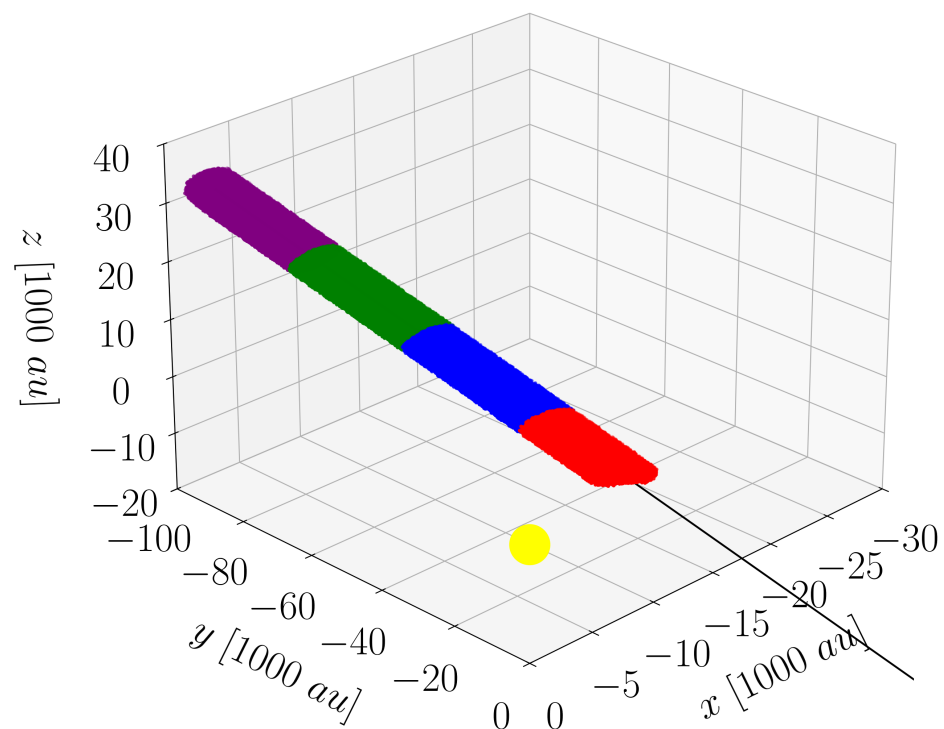


Figure 2. Initial set-up of Oort cloud comets in the region of influence along Gliese 710's path (marked by the black line). Different colors indicate the different shells: S1 red, S2 blue, S3 green and S4 purple. (x, y, z) are the heliocentric coordinates. The yellow dot denotes the location of the Sun, i.e., the center of the heliocentric frame.

4. Results

When Gliese 710 passes through the cylinder shown in Figure 2, the comets are subjected to gravitational perturbations that alter their orbits. The extent of the immediate impact caused by the stellar flyby is shown in Figure 3. As before, the different colors represent the objects of the various shells. The yellow dot marks the position of the Sun (i.e., the center of the coordinate system), and the black line indicates the path of Gliese 710 through the Öpik–Oort cloud. Figure 3 displays the positions of the comets when the K-type star is at 10,500 au, i.e., the closest distance to the Sun during the pas-

sage. An expansion of the cylinder shells due to the perturbations of Gliese 710's flyby is clearly visible.

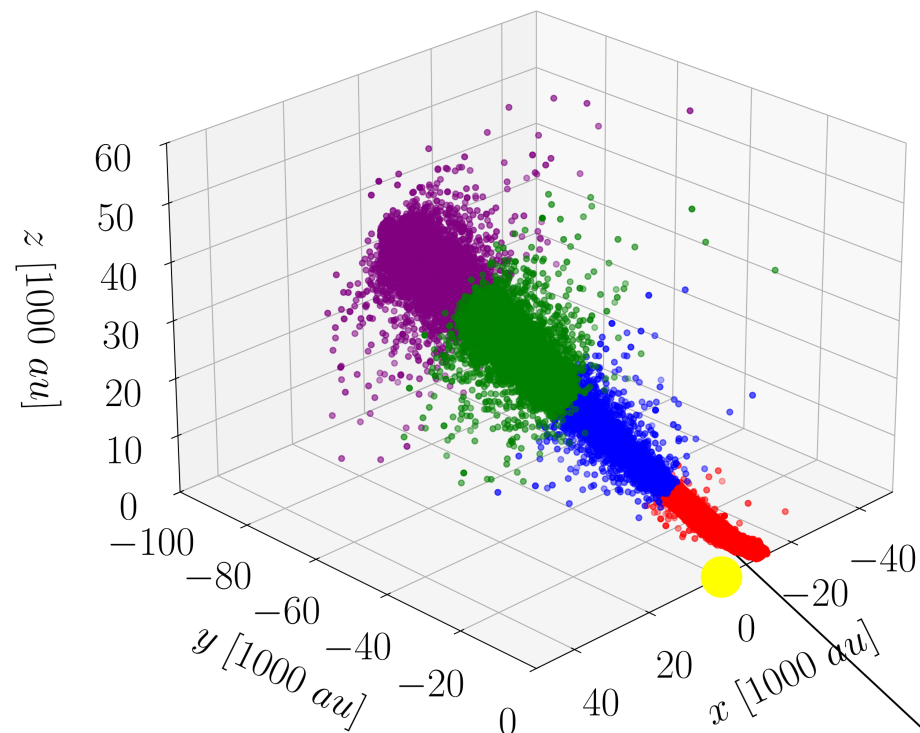


Figure 3. Oort cloud comets scattered from the region of influence due to Gliese 710's flyby where the stellar orbit is indicated by the black line. The different colors indicate the different shells and the yellow dot marks the location of the Sun (i.e., the center of the heliocentric frame).

The outermost shell (purple area) exhibits the greatest expansion, as Gliese 710 passed through this region already 32,000 years ago, and therefore the disturbance has a more pronounced effect. The green region has also expanded noticeably, whilst the two inner shells (blue and red areas)—particularly the red region, which has only just been grazed by the star—show very few scattered objects. It obviously takes several tens of thousands of years before cometary scattering becomes clearly visible. Moreover, Figure 3 indicates that the scattered objects are still in the Oort cloud when the snapshots was taken.

Another interesting feature is visible for comets closest to the Sun (red region), which seem to be shifted in the negative x-direction when Gliese 710 is at 10,500 au, which is probably caused by the combined force of the Sun and Gliese 710.

A detailed overview of the effects of Gliese 710's perturbations in the various directions of the heliocentric frame is displayed in Figure 4, where the top panel shows the perturbations in the x-y plane. In the 2D plot, the cometary streams in the y-direction towards the Sun are more visible than in the 3D Figure. The comets seem to follow the stellar trajectory with a strong expansion in both x-directions. A movement towards the y-direction against the orbital path of Gliese 710 is not visible. The middle panel of Figure 4 indicates a strong expansion of comets in the outer shells S3 and S4, where the scattering of S4 objects (purple) dominates. As in the 3D-plot, both upper panels show the shift of comets in the red area close to the Sun towards the negative x-direction when Gliese 710 is at 10,500 au.

In the bottom panel—which shows the y-z plane—the spread in both z-directions is clearly visible, although the spread is less pronounced as in the x-directions, but that could change over time.

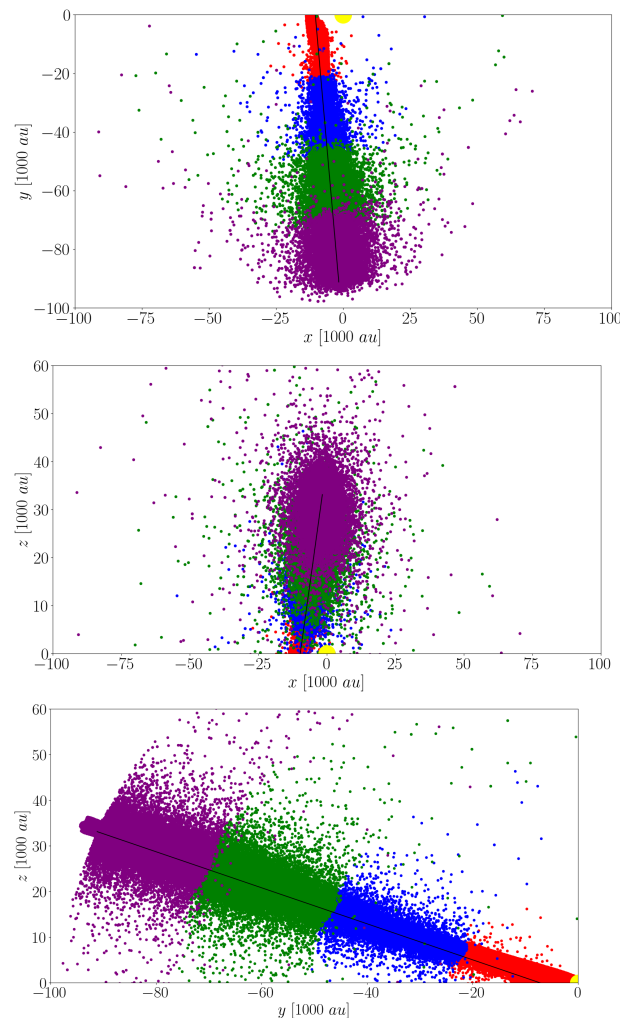


Figure 4. Perturbation of comets in the $x - y$ plane (**top panel**), $x - z$ plane (**middle panel**) and $y - z$ plane (**bottom panel**), where different colors indicate the various shells. The black line marks the path of Gliese 710 in all panels and the yellow dot indicates the location of the Sun.

Even if Figures 3 and 4 show that the scattered objects are still in the Oort cloud, the detailed data analysis of the 100 million cometary orbits after the star's passage leads to the following result:

- 30,520,212 objects escaped—thus about one third of the objects became ISOs.
- 63,453 objects indicated perihelion distances $q < 70$ au, of which
 - 4503 objects had $q < 5.2$ au;
 - 1662 objects had $q < 2$ au;
 - q of 39 objects were close to the orbit of Earth ($0.9 < q < 1.1$).

4.1. Effects of the Stellar Flyby on the Comets

Figure 5 shows all comets with perihelion distances $q < 70$ au after Gliese 710's passage. The different colors indicate objects of the different shells and the horizontal lines mark either the location of Jupiter (orange line) or that of Earth (blue line). It can clearly be seen that not all comets immediately head toward the Sun. Instead, they move outward toward the aphelion, which is shown by objects with $a > 100,000$ au in Figure 5. The 4503 objects with $q < 5.2$ au which can enter the inner Solar System are those below the orange line.

In Figure 6, the perihelion passage times² for comets with $q < 2$ au are shown. It can be seen that there is a group of 24 comets that penetrate the inner Solar System ($q < 2$ au)

within a million years after Gliese 710's flyby. These objects belong primarily to the innermost shell S1—only 4 objects are from S2 (blue dots). None of these objects has a $q \sim 1$ au, but there are 11 objects that will cross Earth's orbit, which is marked by the horizontal blue line. The first comet with q close to the orbit of Earth has a perihelion passage time of ~ 2.145 million years. According to Figure 6, there will be a huge amount of comets entering the inner Solar System starting about 1.5 million years after Gliese 710's flyby. The comet stream within 2 au persists for up to 45 million years after the stellar passage where the first additional objects from the innermost shell S1 (red dots) enter the region of terrestrial planets, followed by comets from the second shell (blue dots), and finally, the comets from the third shell (green dots). From the outermost shell (purple), only seven objects may enter the inner Solar System but not as the last ones—rather, together with objects from the second or third shell during the time from 5 to 10 million years after the stellar passage. Two of them have perihelion distances $q \sim 1$ au.

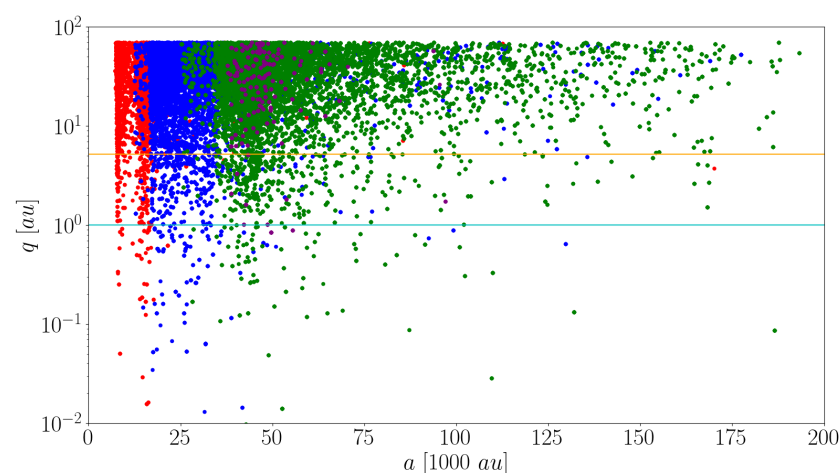


Figure 5. All Oort cloud comets with perihelion distances $q < 70$ au after Gliese 710's flyby. The x-axis denotes the semi-major axis of the comets and the y-axis shows the perihelion distance when Gliese 710 is closest to the Sun. Different colors denote objects of the various shells and the horizontal lines mark either the distance of Jupiter (orange) or that of Earth (blue) from the Sun.

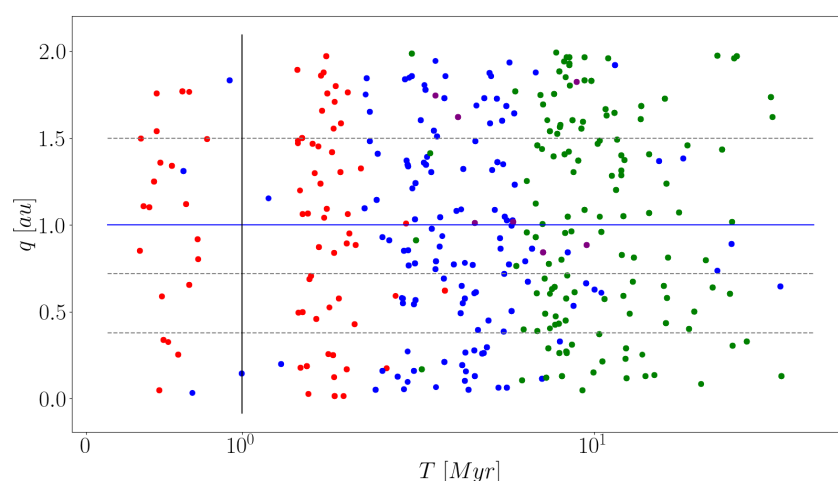


Figure 6. Perihelion passage time (x-axis) for all comets with perihelion distance < 2 au (y-axis) after the stellar flyby where the different colors indicates objects of the various shells. The horizontal blue line denotes the semi-major axis of Earth and the horizontal dashed grey lines indicate the semi-major axes of Mercury (0.48 au), Venus (0.72 au), and Mars (1.52 au). The vertical black line separates the objects that can enter the inner Solar System within the first million years after Gliese 710's flyby from the huge comet stream which begins after ~ 1.5 million years.

Since comets with $q < 70$ au enter the region where the gravitational influence of the gas giants (Jupiter to Neptune) becomes significant, these planets must be included in the calculations of the future evolution of the cometary orbits. Furthermore, it must be noted that for objects with $a > 20,000$ au, the galactic tides also play an important role in the dynamical evolution (see e.g., [3]). These facts were, of course, taken into account in our computations of comets with $q < 5.2$ au over one million years after the flyby.

4.2. Effects of Planetary Perturbations on the Comets with $q < 5.2$ au

Figure 7's top panel shows 238 comets for which the dynamical behavior has been studied in the outer Solar System. The initial orbital data was taken from the data-set after the stellar flyby. It is clearly seen that objects of only two shells—mainly of the innermost S1 (red dots) and some of S2 (blue dots)—can enter the inner Solar System within the first million years after Gliese 710's flyby. However, the result of the computations of the 238 objects shown in Figure 7 (bottom panel) indicates that only objects with initial semi-major axes $a_0 < 16,000$ au could penetrate to the region inside Jupiter during the simulation. Thus, only comets from the innermost S1 shell appear in the bottom panel. There are 12 objects that enter the area inside 2 au, and the perihelion distances of two objects are ~ 1 au. These two comets had a $q \geq 3$ au at the beginning of this study, while afterwards, they indicate an approach to Earth in about 505,000 years, and 1.366 million years, respectively.

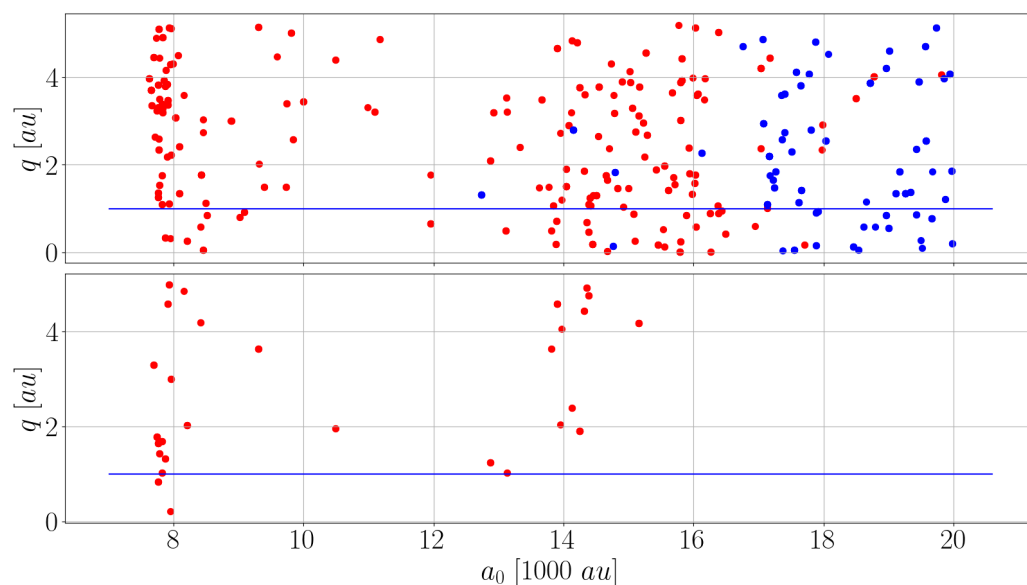


Figure 7. The top panel shows all Oort cloud comets with $q < 5.2$ au. The different colors indicate comets of two shells: red for the innermost shell and blue for the second shell. The bottom panel displays those objects with $q < 5.2$, after the orbit calculation in the outer solar system over one million years. The x-axis labeled as a_0 for both panels corresponds to the semi-major axis after the stellar flyby. The horizontal blue line marks the distance of Earth from the Sun in both panels.

Thus, the two studies of (i) stellar perturbations due to Gliese 710's flyby and (ii) planetary perturbations lead together to possible threats to Earth about 1.505 and 2.366 million years after the stellar flyby.

An analysis of the heliocentric distances of comets that enter the planetary region is presented in Figure 8, where the top panel shows that the first object appears after 450,000 years in this region. It belongs to the objects below the brown line—i.e., the location of Jupiter at 5.2 au—and is thus an object that entered the inner Solar System. We show in the bottom panel of Figure 8 the evolution of the heliocentric distance (r) of these objects with $r < 5.2$ au. It can be seen that the five entries below the brown line belong to two orbits

(note that the five dots appear in both panels). The time evolution indicates orbital changes due to perturbations of the giant planets which also lead to changes in the perihelion distance of these objects, as given by the color code displayed on the right side of the plots. According to the color scaling, it can be seen that the object, which entered the inner solar system after 450,000 years, initially had a perihelion distance of more than 3 au, which continuously decreased. After 420,000 years, the value of q was around 1.16 au for approximately 100,000 years, after which it rose again to values above 3 au. Moreover, the evolution of r suggests that there could be 13 possible encounters with Earth during the 100,000 years when q is constantly around 1.16 au. This cannot be seen in Figure 8 due to the fixed data output every 100 years.

The orbital evolution of the second comet in the bottom panel of Figure 8 shows higher values of q in the beginning and between 500,000 and 600,000 years of the one million years computation, and finally, a constant value of q around 1.53 au was achieved. Note that the green dots below the horizontal brown line are visible in both panels.

The upper panel of Figure 8 also shows two light-blue dots, which indicate orbit crossing with Earth as the perihelion of these comets is around 0.8 and 0.74, respectively. The time evolution of r for these objects shows that both objects enter the inner Solar System seven or eleven times during the simulation over one million years. Thus, these objects could cross Earth's orbit 14 to 22 times and could therefore pose a danger to Earth.

Our numerical study shows that the perturbations of Gliese 710 on comets close to the stellar path will the inner Solar System. However, when including the gravitational influence of the giant planets Jupiter to Neptune, this number will decrease significantly. Nevertheless, changes in the orbital behavior of comets caused by the planets could result in a comet posing a recurring threat over a period of, e.g., 100,000 years.

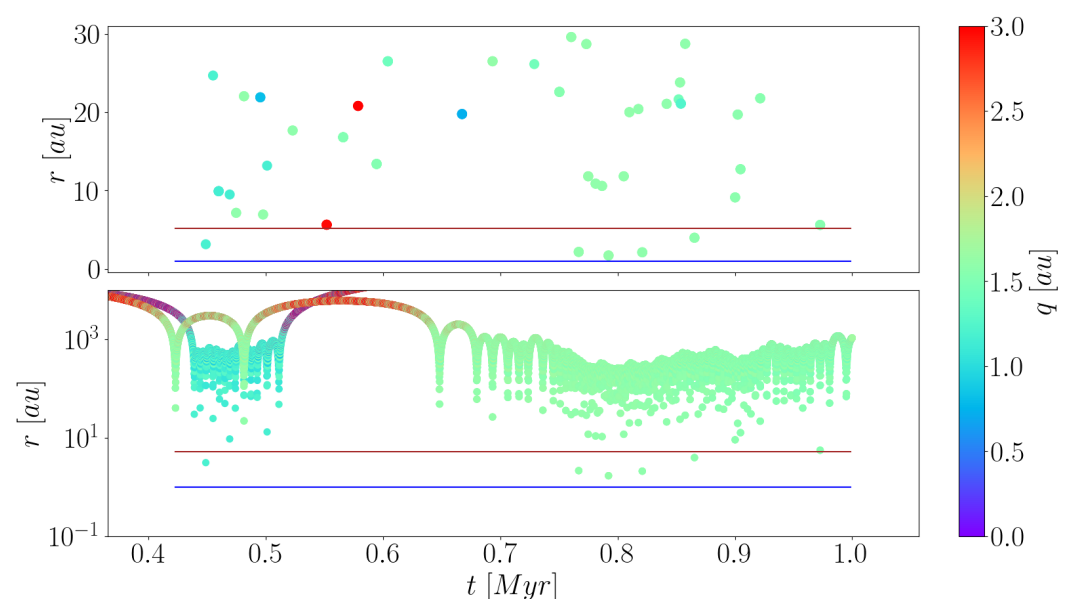


Figure 8. The top panel shows all Oort cloud comets with $q < 5.2$ au that entered the planetary system ($r \leq 30$ au) during the simulation in the outer Solar System. The bottom panel displays the $r(t)$ of objects that entered the inner Solar System—see the dots between the two horizontal lines that label the distances of Jupiter (brown) and Earth (blue) from the Sun. The colors of the dots indicate perihelion distances between 0 and 5.2 au—note that red marks $q \geq 3$ au.

5. Discussion

We performed numerical simulations of the flyby of the K-type star Gliese 710 in about 1.29 million years to analyze the stellar perturbation on the dynamics of long-period comets in the Öpik–Oort cloud, from the entry into the Oort cloud until the closest

approach to the Sun at 10,500 au. Previous studies of stellar flybys have used the impulse approximation (see, e.g., [13,19,22,33,34]), whereas in this investigation we applied the restricted N-body problem (i.e., massless comets) to examine the dynamical behavior of 100 million objects. To achieve a high object density, we did not consider the entire Öpik–Oort cloud. The comets were distributed within the region of influence—with radius 2310 au (see Table 3)—along the star’s path toward the Sun. This is only a small part of the Öpik–Oort cloud where the objects are undoubtedly the most severely affected ones, since they came closest to the star. In addition, we considered only comets with initial perihelion distances $q > 70$ au, so that the influence of the giant planets Jupiter to Neptune can be ruled out for the calculations of the stellar flyby. Thus, changes in the comets’ dynamical behavior could be attributed to perturbations caused only by the passing star.

The results of the flyby study shown in Section 4 are snapshots at the time of Gliese 710’s closest approach to the Sun—at 10,500 au. Our numerical investigation showed that the passage of Gliese 710 caused strong cometary streams into interstellar space, about one third, or more precisely 30,520,212 of the 100 million comets escaped from the Solar System. In contrast, the cometary stream heading toward the Sun—consisting of 63,453 objects—appears very small. From these objects, about 4503 comets can enter the inner Solar System ($q < 5.2$ au). In addition, 1662 objects have a perihelion distance $q < 2$ au and 39 a q close to Earth’s orbit. Moreover, the flyby simulations showed that massive comet streams into the inner Solar System can be expected for up to 45 million years after Gliese 710’s passage.

However, for comets moving toward the Sun, one must also take into account the influence of the planets, which is necessary when $q < 70$ au. Thus, we performed computations of the 4503 comets with $q < 5.2$ au to study the gravitational influence of the giant planets of the outer Solar System. The planetary perturbations reduced the number of comets entering the inner Solar System, as only comets with an initial semi-major axes of less than 16,000 au could finally enter the region inside Jupiter. These calculations covered a period of one million years and showed that, during this time, only 16 comets entered the planetary system ($r < 30$ au). They all had semi-major axes $< 11,000$ au after the stellar flyby. Figure 9 highlights the gravitational influence of the giant planets, where the red and blue areas indicate the number of objects from shells S1 and S2, respectively, (i.e., 106 in total) limited to $a_0 < 20,000$ au, which would enter the inner Solar System after the stellar flyby of Gliese 710 without considering planetary perturbations. The hatched areas show the number of objects that enter the inner Solar System after the simulation in the outer Solar System, where only 12 objects enter the region $a < 2$ au. Six of these comets have their perihelion distance close to Earth: one comet between Venus and Earth and five comets between Earth and Mars.

Although numerical calculations in the gravitational field of the outer Solar System showed that the gas giants could protect us from comet streams, an analysis of the evolution of these cometary orbits revealed that these orbits undergo changes due to planetary perturbations, which could make comets a recurring threat to Earth. In addition to the comet that repeatedly approached Earth (13 times) before being ejected from the solar system by the gas giants, our study has found two comets with perihelia within Earth’s orbit that cross Earth’s orbit probably 14 to 22 times. Additionally, two objects have been found with perihelion distances in the region of Earth and could pose a threat to Earth 1.505 and 2.366 million years, respectively, after the passage of Gliese 710.

We must emphasize that this study examined only a small region around the orbit of Gliese 710. Therefore, additional numerical studies covering a larger region—or even the entire Oort Cloud—are needed to assess the full extent of the potential risk to Earth. Moreover, long-term studies of the dynamical evolution of cometary orbits require taking

galactic tides into account, which play an important role in long-term analyses. The interplay of stellar perturbations and galactic tides has been analyzed for Oort cloud comets in a series of papers by H. Rickman, G. Valsecchi, M. Fouchard, M. Sainenfest, A. Higuchi and others (see [13–15,33,34]).

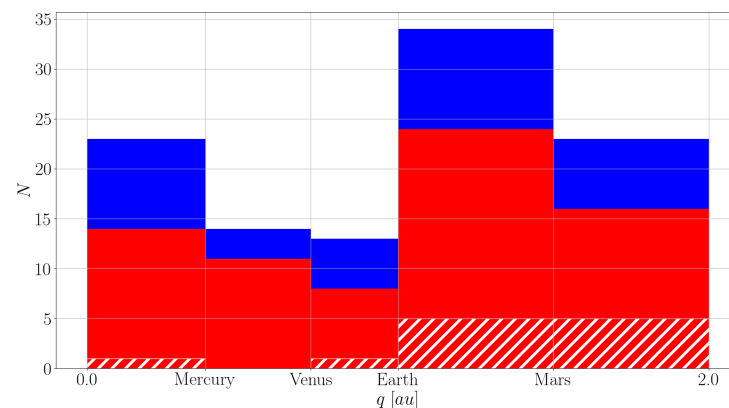


Figure 9. Number of Oort cloud comets within 2 au: Red labels the number of comets of shell S1, blue indicates the number of comets of shell S2, and the hatched area indicates the number of comets after the orbital computation in the outer Solar System.

In addition, the study of planetary perturbations should also be combined with disturbances of galactic tides, which could push the perihelion towards the Sun; both effects together trigger the Jupiter–Saturn barrier mechanism—which has been investigated by many researchers; see, e.g., [9,35,36], and revisited in detail by Kaib & Quinn [3]—and which provides a more accurate picture of the protection afforded to the inner Solar System by the gas giants. These aspects will be taken into account in future investigations.

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Notes

¹ GANBISS stands for “GPU-accelerated N-body code for binary star systems”.

² Perihelion passage time $T = t - \frac{M}{n}$ where the time t and the mean anomaly M were taken from the computations of the flyby as well as the semi-major axis a for the mean motion $n = \frac{2\pi}{a^{3/2}}$.

References

- Oort, J.H. The structure of the cloud of comets surrounding the Solar System and a hypothesis concerning its origin. *Bull. Astron. Inst. Neth.* **1950**, *11*, 91–110.
- Heisler, J.; Tremaine, S. The influence of the Galactic tidal field on the Oort comet cloud. *Icarus* **1986**, *65*, 13–26. [\[CrossRef\]](#)
- Kaib, N.A.; Quinn, T. Reassessing the Source of Long-Period Comets. *Science* **2009**, *325*, 1234. [\[CrossRef\]](#) [\[PubMed\]](#)
- Brasser, R.; Morbidelli, A. Oort cloud and Scattered Disc formation during a late dynamical instability in the Solar System. *Icarus* **2013**, *225*, 40–49. [\[CrossRef\]](#)
- Nesvorný, D.; Dones, L.; Vokrouhlický, D.; Levison, H.F.; Beaugé, C.; Faherty, J.; Emmart, C.; Parker, J.P. A Spiral Structure in the Inner Oort Cloud. *Astrophys. J.* **2025**, *983*, 74. [\[CrossRef\]](#)
- Obidowski, J.C.; Webb, J.J.; Portegies Zwart, S.; Cai, M.X. Oort Cloud Formation and Evolution in Star Clusters. *Astrophys. J.* **2025**, *987*, 29. [\[CrossRef\]](#)
- Portegies Zwart, S.; Torres, S.; Cai, M.X.; Brown, A.G.A. Oort cloud Ecology. II. the chronology of the formation of the Oort cloud. *Astron. Astrophys.* **2021**, *652*, A144. [\[CrossRef\]](#)
- Vokrouhlický, D.; Nesvorný, D.; Dones, L. Origin and Evolution of Long-period Comets. *Astron. J.* **2019**, *157*, 181. [\[CrossRef\]](#)
- Morbidelli, A. Origin and Dynamical Evolution of Comets and their Reservoirs. *arXiv* **2005**, arXiv:astro-ph/0512256. [\[CrossRef\]](#)
- Dones, L.; Brasser, R.; Kaib, N.; Rickman, H. Origin and Evolution of the Cometary Reservoirs. *Space Sci. Rev.* **2015**, *197*, 191–269. [\[CrossRef\]](#)
- Rickman, H. Cometary Dynamics—Formation and Evolution of the Oort Cloud. *Astronomy* **2026**, *5*, 8. [\[CrossRef\]](#)
- Fernández, J.A. Long-Period Comets and the Oort Cloud. *Earth Moon Planets* **2002**, *89*, 325–343. [\[CrossRef\]](#)
- Fouchard, M.; Rickman, H.; Froeschlé, C.; Valsecchi, G.B. On the present shape of the Oort cloud and the flux of new comets. *Icarus* **2017**, *292*, 218–233. [\[CrossRef\]](#)
- Fouchard, M.; Rickman, H.; Froeschlé, C.; Valsecchi, G.B. Distribution of long-period comets: Comparison between simulations and observations. *Astron. Astrophys.* **2017**, *604*, A24. [\[CrossRef\]](#)
- Fouchard, M.; Higuchi, A.; Ito, T.; Maquet, L. The “memory” of the Oort cloud. *Astron. Astrophys.* **2018**, *620*, A45. [\[CrossRef\]](#)
- Fouchard, M.; Higuchi, A.; Ito, T. What long-period comets tell us about the Oort Cloud. *Astron. Astrophys.* **2023**, *676*, A104. [\[CrossRef\]](#)
- Hills, J.G. Comet showers and the steady-state infall of comets from the Oort cloud. *Astron. J.* **1981**, *86*, 1730–1740. [\[CrossRef\]](#) [\[PubMed\]](#)
- Nesvorný, D.; Vokrouhlický, D.; Dones, L.; Levison, H.F.; Kaib, N.; Morbidelli, A. Origin and Evolution of Short-period Comets. *Astrophys. J.* **2017**, *845*, 27. [\[CrossRef\]](#)
- Rickman, H.; Fouchard, M.; Froeschlé, C.; Valsecchi, G.B. Injection of Oort Cloud comets: The fundamental role of stellar perturbations. *Celest. Mech. Dyn. Astron.* **2008**, *102*, 111–132. [\[CrossRef\]](#)
- García-Sánchez, J.; Preston, R.A.; Jones, D.L.; Weissman, P.R.; Lestrade, J.F.; Latham, D.W.; Stefanik, R.P. Stellar Encounters with the Oort Cloud Based on HIPPARCOS Data. *Astron. J.* **1999**, *117*, 1042–1055. [\[CrossRef\]](#) [\[PubMed\]](#)
- Bailer-Jones, C.A.L. Stars That Approach within One Parsec of the Sun: New and More Accurate Encounters Identified in Gaia Data Release 3. *Astrophys. J. Lett.* **2022**, *935*, L9. [\[CrossRef\]](#)
- Dybczyński, P.A.; Berski, F.; Tokarek, J.; Podlowska-Gaca, E.; Langner, K.; Bartczak, P. Important stellar perturbers found during the StePPeD database update based on Gaia EDR3 data. *Astron. Astrophys.* **2022**, *664*, A123. [\[CrossRef\]](#)
- Berski, F.; Dybczyński, P.A. Gliese 710 will pass the Sun even closer. Close approach parameters recalculated based on the first Gaia data release. *Astron. Astrophys.* **2016**, *595*, L10. [\[CrossRef\]](#)
- de la Fuente Marcos, R.; de la Fuente Marcos, C. An Independent Confirmation of the Future Flyby of Gliese 710 to the Solar System Using Gaia DR2. *Res. Notes Am. Astron. Soc.* **2018**, *2*, 30. [\[CrossRef\]](#)
- de la Fuente Marcos, R.; de la Fuente Marcos, C. An Update on the Future Flyby of Gliese 710 to the Solar System Using Gaia DR3: Flyby Parameters Reproduced, Uncertainties Reduced. *Res. Notes Am. Astron. Soc.* **2022**, *6*, 136. [\[CrossRef\]](#)
- Zimmermann, M.; Pilat-Lohinger, E. GANBISS: A new GPU accelerated N-body code for binary star systems. *Celest. Mech. Dyn. Astron.* **2023**, *135*, 33. [\[CrossRef\]](#) [\[PubMed\]](#)
- Duncan, M.; Quinn, T.; Tremaine, S. The Formation and Extent of the Solar System Comet Cloud. *Astron. J.* **1987**, *94*, 1330. [\[CrossRef\]](#) [\[PubMed\]](#)
- Francis, P.J. The Demographics of Long-Period Comets. *Astrophys. J.* **2005**, *635*, 1348–1361. [\[CrossRef\]](#)
- Levison, H.F.; Duncan, M.J.; Brasser, R.; Kaufmann, D.E. Capture of the Sun’s Oort Cloud from Stars in Its Birth Cluster. *Science* **2010**, *329*, 187–190. [\[CrossRef\]](#) [\[PubMed\]](#)
- Holman, M.J.; Wiegert, P.A. Long-Term Stability of Planets in Binary Systems. *Astron. J.* **1999**, *117*, 621–628. [\[CrossRef\]](#) [\[PubMed\]](#)
- Pilat-Lohinger, E.; Dvorak, R. Stability of S-type Orbits in Binaries. *Celest. Mech. Dyn. Astron.* **2002**, *82*, 143–153. [\[CrossRef\]](#)
- Stoer, J.; Bulirsch, R. *Introduction to Numerical Analysis*; Springer: New York, NY, USA, 1980. [\[CrossRef\]](#)

33. Fouchard, M.; Rickman, H.; Froeschlé, C.; Valsecchi, G.B. The last revolution of new comets: The role of stars and their detectability. *Astron. Astrophys.* **2011**, 535, A86. [[CrossRef](#)]
34. Higuchi, A.; Kokubo, E. Effect of Stellar Encounters on Comet Cloud Formation. *Astron. J.* **2015**, 150, 26. [[CrossRef](#)]
35. Fernandez, J.A. Dynamics of Comets: Recent Developments and New Challenges. In *Proceedings of the Asteroids, Comets, Meteors 1993*; Milani, A., di Martino, M., Cellino, A., Eds.; IAU Symposium: Rome, Italy, 1994; Volume 160, p. 223.
36. Dones, L.; Weissman, P.R.; Levison, H.F.; Duncan, M.J. Oort cloud formation and dynamics. In *Comets II*; Festou, M.C., Keller, H.U., Weaver, H.A., Eds.; University of Arizona Press: Tucson, Arizona, 2004; p. 153. [[CrossRef](#)]

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