Multi-scale (time and mass) dynamics of space objects
Proceedings IAU Symposium No. 364, 2022
A. Celletti, C. Galeş, C. Beaugé, A. Lemaitre, eds.
doi:10.1017/S1743921321001332

On the scattering and dynamical evolution of Oort cloud comets caused by a stellar fly-by

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Abstract. Recent GAIA observations revealed that the K-type star Gliese 710 will cross the Oort cloud in a distance between approximately 4000 and 12000 au in about 1.3 Myrs. This occurrence motivated us to study the influence of a stellar encounter on comets in the outer region of the solar system. Even if the Oort cloud extends to 100000 au from the sun, we restrict our study to the region between 30 and 25000 au where 25 million objects are distributed randomly. Comets at larger distances are not taken into account as they hardly enter the observable region after a single stellar fly-by. An overview of all objects that are scattered towards the sun for the different fly-by distances at 4000, 8000 and 12000 au shows that only a handful of objects are moving towards the sun immediately after the stellar encounter.

However, a subsequent long-term study of all objects that are moved into highly eccentric motion by the stellar fly-by shows a significant increase of comets crossing Jupiter's orbit and entering into the observable region. In addition, our study shows the first comets crossing the orbit of Earth only about 2.5 Myrs after the stellar fly-by. Thus, the impact risk for the Earth increases only some million years after the stellar fly-by.

Keywords. comets: general, Oort Cloud, solar system: general

1. Introduction

Observations of the European spacecraft GAIA predict a fly-by of a K-type star named "Gliese 710" which will pass through the Oort cloud in about 1.3 Myrs. Gliese 710 is not the first stellar visitor of the solar system. About 70000 years ago the so-called "Scholz' star" also known as WISE J072003.20-084651.2 Mamajek et al. (2015) approached the sun within approximately 52000 au which is about $4 - 12$ times the predicted distance of Gliese 710. However, the closest approach distance is quite difficult to determine as it sensitively depends on the current position and velocity of the star. Thus, various minimum distances have been announced so far, e.g. GAIA data release 2 (DR2) based integrations revealed an enounter distance of about 13900 au Bailer-Jones et al. (2018); de la Fuente Marcos (2018) suggested a distance of 10700 au and figured out that the use of additional (prior) observational data would lead to a closest approach distance of 4300 au in 1.29 Myrs.

Therefore, we decided to study the influence of a stellar fly-by for three different closest approach distances: namely 4000, 8000, and 12000 au. For these three distances of the stellar fly-by we compare the number of comets that are scattered towards the sun.

Such comet showers have been studied in former times by means of impulse approximation or numerical simulations of the N-body problem using the restricted problem (see e.g. Dybczynski (2002); Rickman et al. (2008, 2012); Fouchard et al. (2011, 2013); Berski & Dybczynski (2016) where comets are considered as mass-less bodies that influence neither each other nor the planets and the star.

This investigation also used the restricted problem where the dynamical behaviour of 25 million comets have been studied in the graviational field of the outer solar system and the passing star. The mass-less objects were placed randomly between 30 and 25000 au. Larger distances of Oort cloud comets from the sun were not taken into account as we noticed in an earlier study that these objects remain outside 20000 au after a single stellar fly-by and can hardly enter into the observable region (< 5 au) of the solar system.

In the following sections, we first describe our numerical study and provide some details about the distribution of the initial cometary reservoir. Section 3 shows the influence of the stellar fly-by on the cometary motion and the results of a long-term study of all high-eccentric cometary orbits after the stellar passage are shown in section 4. These long-term study also indicates that comets could encounter our planet Earth.

2. Method and Numerical Setup

In our numerical study we solve the equations of motion using the Bulirsch-Stoer integration method Stoer et al. (2002) which is an extrapolation method with adaptive step size. Our code has been massively parallelized on graphical processing units (GPUs) Zimmermann (2021) to allow simulations of up to 10^4 interacting massive objects. In addition, a significantly larger number of mass-less bodies can be studied with this GPU program.

Our dynamical system investigates the interaction of six massive bodies, i.e. the sun, the planets of the outer solar system (from Jupiter through Neptune), and the passing star Gliese 710. The cometary reservoir consists of 25×10^6 mass-less objects without mutual interaction. Due to the capacity of our GPUs we splitted the cometary reservoir which extends from 30 au to 25000 au into three regions (**R1-R3**):

• **R1:** a **Disk** of 5×10^6 mass-less objects with semi-major axes (a_c) from 30 to 5000 au where all objects move in nearly circular orbits (comets' eccentricities $e_c < 0.0001$) and in the same plane (inclinations $i_c < 0.0001^o$).

• **R2:** a **Flared Disk** of 5×10^6 objects with a_c from 5000 to 10000 au and e_c close to zero (< 0.0001). The inclinations of the comets increase up to 45^o with larger a_c.

• **R3:** a spherical **Cloud** of massless objects which expands from 10000 to 25000 au. The eccentricities are < 0.0001 and the inclinations vary between 0 and 180^o.

In all regions the angles of argument of pericenter ω, ascending node Ω, and mean anomaly M are randomly chosen between 0 and 360^o. Initial positions of the comets were determined using a Rayleigh distribution (where $F(x) = 1 - e^{-x^2/2\sigma^2}$ for $x \geq 0$ or $F(x) = 0$ for $(x < 0)$. The value of σ defines the location of the maximum of $F(x)$).

Since R3 is significantly larger than R1 and R2, we divided the cloud region (up to a distance of 25000 au) into shells of 5000 au containing 5×10^6 comets each. Comets at larger distances† were not taken into account as they might not be scattered into the inner region of the solar system ($a < 15$ au) by a single stellar fly-by. Because test computations showed that all objects initially outside 25000 au were scattered to semi-major axes > 20000 au. Thus, these comets need eccentricities > 0.9993 to enter $a < 15$ au. However, such objects were not found in our computations.

3. Stellar Fly-by and Cometary Scattering

Perturbations of a passing star may lead to an influx of comets from the outer solar system into the observable region. During the passage the star is considered to move on a straight line with constant velocity neglecting the gravitational pull of the Galactic tides and the sun Rickman et al. (2005).

† Note that the Oort cloud extends to a distance of 100000 au from sun.

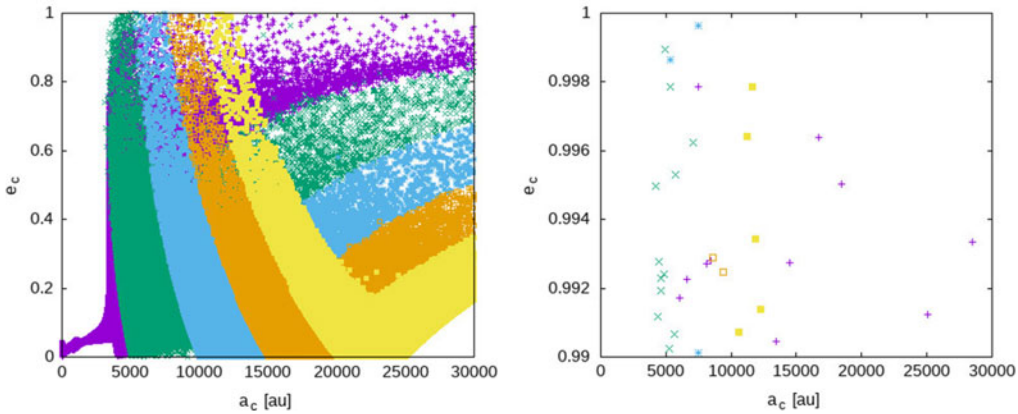

Figure 1. Scattered comets after the fly-by of Gliese 710 at 4000 au. Both panels show the scattering in the region between 30 au and 30000 au (x-axes). The upper panel shows the result for all eccentricities e_c from 0.0 to 1.0 (y-axis) and the lower panel is a zoom of the high eccentricity area between 0.99 and 1.0 (y-axis). Different colors indicate the different regions of the computations: **R1** purple, **R2** green, **R3** light blue, dark and light yellow. For details see the text.

The duration of the fly-by (i.e. the time when the star enters the Oort cloud at a distance of 100 000 au from the sun to the moment when it exits the cloud on the opposite side) depends on the encounter distance and the velocity of the passing star where the time to reach the minimum distance to the sun is given by:

$$t_d = \sqrt{\frac{b_{max}^2 - b_\star^2}{v_\star^2}}, \tag{3.1}$$

where $b_{max}(= 110000$ au) defines the maximum distance for the gravitational reach of the star; $b_\star$ is the impact parameter which defines the closest approach distance – in our study $4000, 8000$, and 12000 au, respectively, and $v_\star$ in our study is 48 km/s or 0.02772 au/day which is the velocity of a typical K-type main sequence star according to Rickman et al. (2008).

Thus, the duration of the flyby is given by $2t_d$ which is about 20 000 years in our study.

Our simulations of stellar fly-bys indicate a large influx of objects that are close to the stellar trajectory while the region that is not crossed by the star remains quasi unperturbed. This can be seen in the results of R1 and R2 in Table 1 for a fly-by distance of 12000 au. Comets close to the stellar passage were scattered either towards the sun or are ejected from the system. This is shown in the upper panel of Fig. 1 which indicates two branches forming a "V-shape" in the (a_c, e_c)-plot of the comets after a simulation time of 20000 years. The V-shape of the evolved comets is visible for each region or shell that has been studied where (i) purple "+" label the disk objects of R1, (ii) green "x" the flared disk objects of R2, (iii) light blue stars indicate objects of the innermost shell of the cloud (from 10000 to 15000 au), (iv) dark yellow open squares mark objects of the second shell (from 15000 to 20000 au), and (v) light yellow squares label objects of the shell from 20000 to 25000 au. The branch of comets pointing towards the sun is steeper than the outward going branch. Thus comets of R2 (green objects) and R3 (light blue, dark and light yellow objects) that are scattered towards the sun have higher eccentricities than those moving outwards. Only for the disk objects of R1 we also observe a stronger increase in eccentricity for outward moving objects.

The lower panel of Fig. 1 shows objects of all studied regions that are scattered into high-eccentric orbits by the passing star. Some of these objects might enter the observable

Table 1. Overview of scattered comets.

Flyby distance [au]	Region	q < 100 au	q < 15 au	q < 5 au	e > 0.9	ejected comets
	R1	56612	0	0	1004	8351
	R2	24	2	0	231	1894
4000	**R3 - Shell 1**	7	2	1	57	645
	R3 - Shell 2	4	0	0	45	451
	R3 - Shell 3	4	0	0	31	355
	R1	56599	0	0	0	0
	R2	2	0	0	91	1068
8000	**R3 - Shell 1**	4	1	0	55	665
	R3 - Shell 2	2	0	0	44	443
	R3 - Shell 3	1	0	0	26	354
	R1	56599	0	0	0	0
	R2	0	0	0	0	0
12000	**R3 - Shell 1**	2	0	0	48	609
	R3 - Shell 2	5	0	0	443	445
	R3 - Shell 3	3	0	0	28	378

Notes:
$q = a_c(1 - e_c)$ is the pericenter distance.
The values of R1 in column 3 are that high since the disk objects are distributed between 30 and 5000 au.

Table 2. Comets approaching the inner solar system.

Flyby distance [au]	Region	q < 100 au	q < 15 au	q < 5 au
	R1	214	96	75
4000	**R2**	47	11	6
	R3	10	3	3
	R1	–	–	–
8000	**R2**	26	13	6
	R3	11	4	4
	R1	–	–	–
12000	**R2**	–	–	–
	R3	15	6	2

region ($q < 5$ au). According to Table 1 only one comet of the innermost shell of R3 is on an orbit towards this region after Gliese 710 has passed the solar system at 4000 au.

4. Long-term Evolution of Comets

With a long-term study of all comets with eccentricities > 0.9 (see Table 1) we checked the possibitlity that perturbed comets might enter the observable region at a later time after the stellar fly-by. Table 2 shows the number of comets entering a region of a certain distance from the sun (either at 100 or 15 or 5 au) during the long-term computation of 10 Myrs.

The result of the long-term computations of all high-eccentric comets ($e_c > 0.9$ of Table 1) shows clearly that a closer approach of Gliese 710 (to 4000 au from the sun) scatters a significantly higher number of comets into the observable region ($q < 5$ au). However, our long-term study shows that the number of such objects is quite low: 1368 / 216 / 519 objects for a considered stellar passages at 4000 / 8000 / 12000 au, respectively. Of course we expect a higher influx rate of comets when increasing the number of objects in the long-term computations. This study is still in progress and will be compared to previous studies of Fouchard et al. (2011). First results of 10^6 comets show a good agreement with the expectations resulting from the direct injection mechanism by Fouchard et al. (2011).

Even if our study included only 25×10^6 comets, we have found a couple of comets that approach or cross the orbit of Earth which is shown in Fig. 2 where all comets are plotted that enter the observable region within the simulation of 10 Myrs. In this plot a

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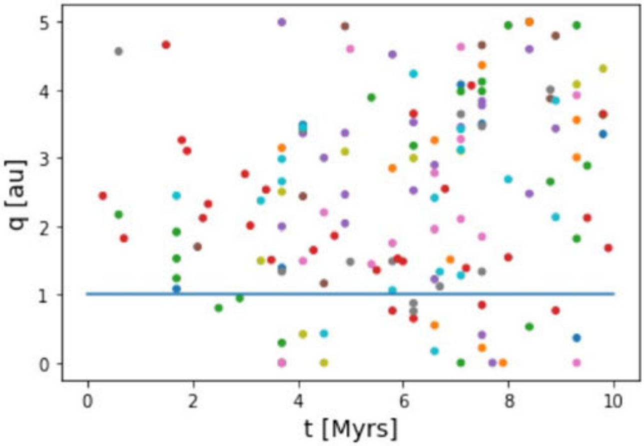

Figure 2. Perihelion distance of all comets entering in the observable region within 10 Myrs. Each color belongs to a certain comet.

certain color belongs to a certain object. Thus, we observe comets entering this region again and again. Moreover, Fig. 2 indicates that after ~ 2 Myrs the first object crosses the orbit of the Earth (i.e. the horizontal line), and the number of objects entering the region < 1 au increases visibly after 4 Myrs. Thus, a long time after the stellar fly-by the threat for planet Earth might increase.

5. Summary

Inspired by a recent observation of the European space mission GAIA, which indicates that the K-type star Gliese 710 will pass through the Oort cloud at a distance between 4000 and 12000 au from the sun, we studied the perturbations on comets moving in the outer region of the solar system and changes of their dynamical behaviour due to such stellar fly-bys .

When entering this cometary reservoir Gliese 710 perturbs the comets strongly by scattering them either towards the sun, or out of the solar system. The duration of the fly-by (to cross the whole Oort cloud) takes about 20000 years.

Our study of 25×10^6 comets randomly distributed between 30 and 25000 au shows that the strongest perturbations are close to the trajectory of Gliese 710. Moreover, cometary orbits with semi-major axes smaller than the closest approach distance of the star remain quasi unaffected.

Perturbations of the passing star create a "V-shape" of two branches with high-eccentricity orbits in the cometary reservoir. The branch pointing towards the sun is steeper and thus indicates higher eccentricities than the one directed outwards (see Fig. 1 upper panel). Only ~ 2100 of the 25×10^6 comets were scattered on high-eccentricity orbits with $e_c > 0.9$. Most of the inward moving comets showed a perihelion distance $q < 100$ au. A few comets crossed Uranus' orbit and only a single object was perturbed enough to enter the observable region ($q < 5$ au). We restricted this investigation to comets within 25000 au from the sun as a previous study by Clees (2021) indicated that a single perturbing event does not have enough impact to bring objects from distances > 20000 au into the observable region.

Our long-term study over 10 Myrs of the 2100 comets moving on high-eccentricity orbits after the stellar fly-by showed that the number of objects entering the observable region increases significantly with time, especially for the fly-by distance at 4000 au.

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Moreover, there were no close encounters of comets with the Earth right after the stellar fly-by. The first comet reached the orbit of Earth about 2 Myrs after the passage of Gliese 710, and about 4 Myrs after the stellar encounter an increase of objects crossing the orbit of Earth was found. Thus, the stellar fly-by might increase the impact risk on our planet Earth but only long time after the stellar passage.

Acknowledgements

This research was funded in whole by the Austrian Science Fund (FWF) [P33351-N].

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