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The effect of the passage of Gliese 710 on Oort cloud comets

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Abstract. Based on observations by Bailer-Jones *et al.* (2018) who propose a close fly-by of the K-type star Gliese 710 in approximately 1.36 Myr we investigate the immediate influence of the stellar passage on trajectories of Oort cloud objects. Using a newly developed GPU-based N-body code (Zimmermann (2021)) we study the motion of 3.6 million testparticles in the outer Solar system where the comets are distributed in three different "layers" around the Sun and the 4 giant planets. We study the immediate influence of Gliese 710 at three passage distances of 12000, 4300, and 1200 au. Additionally, different inclinations of the approaching star are considered. Depending on the passage distance a small number of comets (mainly from the disk and flared disk) is scattered into the observable region (< 5 au) around the Sun. In addition, a huge number of comets (mainly the ones directly in the path of the passing star) shows significant changes of their perihelia. But, they will enter the inner Solar system a long time after the stellar fly-by depending on their dynamical evolution.

Keywords. Comets: general; Oort cloud; Solar system: general

1. Introduction

Most stars are born in clusters and thus, gravitational interactions between the cluster members can have significant influence on the planet formation process and small body distributions (Bancelin *et al.* (2019)). Even after having left the cluster fly-bys with other stars can happen.

Recent observations show that the Sun will experience a close fly-by of another star in about 1.36 Myr when Gliese 710 will probably pass inside the Oort cloud (Bailer-Jones *et al.* (2018)). Gliese 710 is a 0.6 $M_\odot$ star which today is approximately 64 ly away from the Sun. Berski & Dybczyński (2016) state that in 1.35±0.05 Myr, Gliese 710 will be 13 366±6250 au from the Sun. De la Fuente Marcos (2018) find a slightly closer mean distance of 10 721±2114 au in 1.28±0.04 Myr in the future. Using older input data they show that the closest approach might even reach 0.021 pc or 4303 au, in 1.29 Myr. As in either case Gliese 710 will pass right through the Oort cloud it will possibly influence the orbits of the small bodies orbiting there.

As we know from e.g., Sizova et al. (2020), Torres *et al.* (2019), Vokrouhlický *et al.* (2019), Rickman et al. (2008), the influence of passing stars on Oort cloud objects is very high and in combination with galactic tides is responsible for the long period comes we are able to observe today.

All of this motivated us to investigate the influence of passing stars on the orbits of cometary objects residing in the Oort cloud.

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Table 1. Initial values for the cometary objects used in the simulations. Each region contains 600 000 objects.

inner edge (au)	outer edge (au)	eccentricity	inclination (deg)	description
50	5 000	< 0.1	$< 1\,^{\circ}$	disk – scattered disk
5 000	10 000	< 0.1	$< 45^{\circ}$	flared disk
10 000	25 000	< 0.1	$< 180^{\circ}$	Outer Oort cloud – 1^{st} shell
25 000	50 000	< 0.1	$< 180^{\circ}$	Outer Oort cloud – 2^{nd} shell
50 000	75 000	< 0.1	$< 180^{\circ}$	Outer Oort cloud – 3^{rd} shell
75 000	100 000	< 0.1	$< 180^{\circ}$	Outer Oort cloud – 4^{th} shell

2. Method and Setup

Our setup consists of the outer Solar system including the Sun and the 4 giant planets (Jupiter, Saturn, Uranus, and Neptune) with their known masses and properties, an Oort cloud (consisting of an inner disk like structure and an outer spherical structure), and a passing star. The latter initially moves on a straight line passing the Sun at a certain distance (impact parameter, d_i). The properties used for the passing star are summed up as follows:

- Mass of passing star: 0.6 $M_{\odot}$ (i.e., a K-type star as Gliese 710)
- Impact parameter d: d_1=12 000 au, d_2=4300 au, d_3=1200 au†
- Impact angle α: 0° = planar case (in the ecliptic), 30° = inclined case

The impact angle is defined as angle between the stellar orbit and the ecliptic. As there are no observational constraints we investigated the influence at the chosen angles given above. The velocity of the star is taken from Rickman et al. (2008), who give the mean relative velocity for different stellar types in the Solar neighborhood.

Cometary objects are distributed around the planetary system in the extended scattered disk (between 50 and 5000 au), the flared disk (between 5000 and 10 000 au), and the spherical Oort cloud itself (10 000 to 100 000 au). The initial positions of the objects were calculated using a Rayleigh distribution (where $F(x) = 1 - e^{-x/2\sigma}$ for $x \geq 0$ or $F(x) = 0$ for $(x < 0)$. The value of σ defines the location of the maximum of $F(x)$). For computational reasons the spherical Oort cloud was divided in 4 shells. Each shell contained 600 000 testparticles (see table 1). All simulations were conducted with the newly developed parallelized GPU-based N-body code (Zimmermann (2021)) actually designed to handle huge numbers of massive particles in interaction. Nevertheless, as the mass of the objects residing in the Oort cloud is far less than the mass of the giant planets these particles were treated as massless in our N-body computations while the Sun, the 4 giant planets, and the passing star were treated as massive. The system and the passing star are integrated for the "passing time" of approximately 20 000 yr (i.e., the time the passing star needs to cross the Oort cloud).

3. Results and Discussion

Our integrations show a significant influence of the passing star mainly on the orbits of objects close to the stellar trajectory. Fig. 2 shows a comparison between the outcome of two simulations. The left panel shows the perturbations of a planar fly-by of Gliese 710 while the right panel shows the outcome of a simulation of the inclined passage. For better visibility only the objects distributed in the disk are shown. The results indicate that a passing star in the planar case has stronger influence on the objects than a star passing at an inclined trajectory (i.e., more objects are scattered to higher eccentricities after a planar passage – see table 2). From the objects scattered due to the planar fly-by of Gliese 710 a whole of 12 objects (out of 600 000) of the inner disk are moved onto

† This distance was choosen to see if the influence is significantly stronger for such a close passage.

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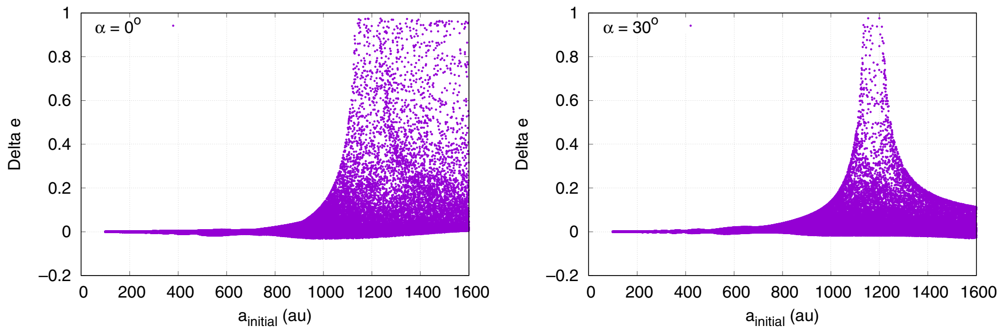

Figure 1. Comparison of different impact angles of Gliese 710 which passes at d_3=1200 au (left panel – planar case vs right panel – inclined case). The x-axis shows the initial semi-major axis of the disk objects. The y-axis shows the difference in eccentricity between the initial and final orbit.

Table 2. Comparison between the results of two integrations of Gliese 710 (planar (blue) and inclined (black) case) passing at d_3=1200 au. The table shows the absolute number of comets ending up on orbits with the eccentricity in the given ranges for the disk and the flared disk. For inclined fly-bys we observe almost no difference in the scattering process in the spherical Oort cloud.

ecc_{end}	objects D		objects FD	
$0.00 < e \leq 0.10$	573834	596177	170913	422014
$0.10 < e \leq 0.20$	12225	3092	342369	177985
$0.20 < e \leq 0.30$	5470	498	53824	1
$0.30 < e \leq 0.40$	2823	104	14457	0
$0.40 < e \leq 0.50$	1840	56	7359	0
$0.50 < e \leq 0.60$	1077	40	4243	0
$0.60 < e \leq 0.70$	864	12	2707	0
$0.70 < e \leq 0.80$	731	8	1807	0
$0.80 < e \leq 0.90$	542	10	1368	0
$0.90 < e \leq 1.00$	588	2	948	0

orbits with perihelia smaller than 5 au (observable region in the Solar system). For an inclined passage no objects were scattered into the observable area. Note that the star with d_3=1200 au passes outside of the denser part of the disk (due to the Rayleigh distribution used for the initial conditions) and inside of most of the objects residing in the flared disk. This means the dense part of the disk (i.e., most of the disk objects) is not influenced by the passage of the star which explains the huge number of objects that does not experience a big change in eccentricity (see table 2). Nevertheless, in case of an inclined passage there are some disk objects scattered to high eccentricity orbits while for the flared disk no such scattering is observed.

The long-term influence of the planets on the orbits of the scattered comets can be seen in Fig. 2 where simulations with all 4 planets show a broader distribution in the change of eccentricity (blue) than simulations where only Neptune was included (orange).

If one compares Figs. 2 (left panel) and 3 (left panel) one can see that a passing star with d_1 = 12 000 au (Fig. 3 – left panel) has almost no influence on the disk objects (note the difference in the units on the y-axis).

The influence of a passing star on the spherical Oort cloud can be seen in Fig. 3 (right panel) where the different colors depict the different shells used in the computations (see table 1). A comparison of the effects of two stellar passages at 1200 au and 4300 au can be seen in table 3 where one can observe that a closer fly-by causes stronger scattering in the disk than a fly-by with bigger impact parameter, d_i (i.e., more disk objects – even if

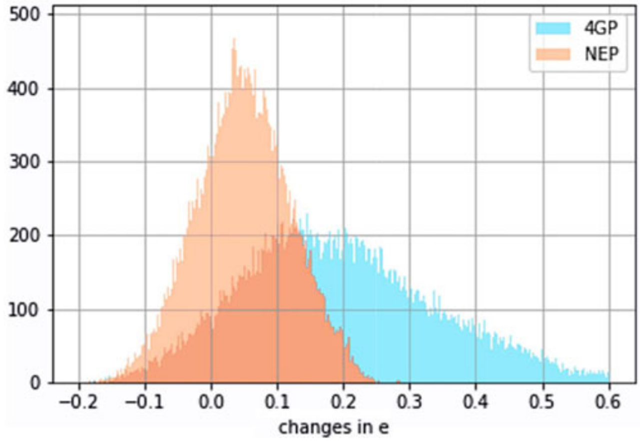

Figure 2. Influence of the giant planets on the changes in eccentricity of the comets. Blue denotes the numbers gathered from simulations with four giant planets, orange from simulations with only Neptune. Simulations in this case were run for 1 Myr showing long-term effects in the orbits of the comets. A total of 10 000 bins is used (1 bin = 100 objects) for the number of objects shown on the y-axis. Note that the negative changes in eccentricities occur due to the fact that for these long-term computations initial eccentricities for the comets were chosen to have values up to 0.2 and Δ e = $e_{\mathrm{end}} - e_{\mathrm{start}}$ (figure from Clees (2021)).

Table 3. Influence of the impact parameter, d_i, on the scattering of objects. The simulations represent the planar case for two different impact parameters: d_3 = 1200 au (blue) and d_2 = 4300 au (black).

eccentricity	objects D		objects FD		objects OC	
$0.00 < e \leq 0.10$	573834	598430	170913	429363	126014	145860
$0.10 < e \leq 0.20$	12225	1183	342369	114297	312020	322817
$0.20 < e \leq 0.30$	5470	266	53824	27471	144010	123060
$0.30 < e \leq 0.40$	2823	121	14457	12474	6675	6147
$0.40 < e \leq 0.50$	1840	0	7359	6696	6041	647
$0.50 < e \leq 0.60$	1077	0	4243	3882	3942	600
$0.60 < e \leq 0.70$	864	0	2707	2417	609	434
$0.70 < e \leq 0.80$	731	0	1807	1539	363	397
$0.80 < e \leq 0.90$	542	0	1368	1021	306	24
$0.90 < e \leq 1.00$	588	0	948	836	15	9

the numbers are really small – are scattered to higher eccentricity orbits for d_3=1200 au (blue numbers) than for d_2=4300 au (black numbers)).

4. Summary and Conclusions

In this investigation we numerically studied the immediate influence of a passing star on comets in the Oort cloud. The region feeling the strongest influence of the passing star changes with its impact parameter, d_i. If Gliese 710 passes very close to the Sun (i.e., d_3=1200 au) it influences all defined regions (see table 3) and a significant number of disk objects will experience higher changes in eccentricity. Nevertheless, the number thrown into the observable area is rather low (below 1 % – see table 3).

A passage of the star with closest approach at d_2=4300 au will strongly influence objects in the flared disk. However, for these objects it is less likely to be scattered on orbits which bring them closer than 50 au (planetary region) to the Sun.

A passage further away from the Sun (d_1=12 000 au in our simulations) shows almost no influence on the disk and the flared disk. The objects influenced in the Oort cloud in the path of the passing star are scattered to orbits with higher eccentricity but it is very

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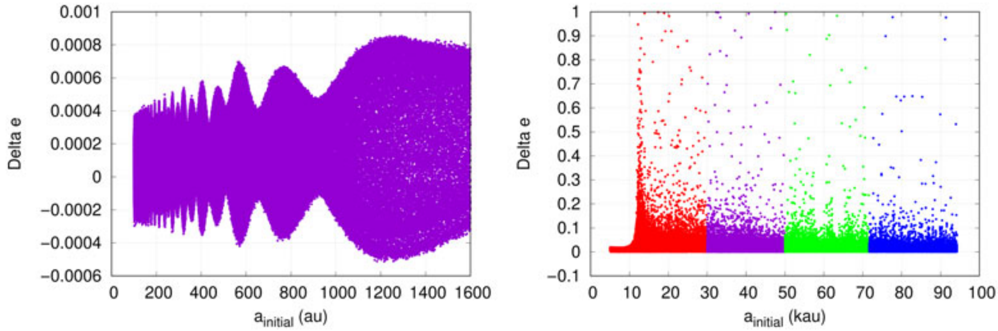

Figure 3. Same plot as Fig. 2 (left panel) but for a stellar passage at d_1=12 000 au (planar case). The left panel shows a zoom of the inner disk (note the units at the y-axis). The inner disk is not influenced by a far-away stellar fly-by. The right panel shows the different shells of the Oort cloud in different colors. Here one can see that a huge number of comets outside of the closest approach distance is scattered while the inner parts feel almost no influence.

unlikely for them to come close to the Sun. Longer computations will be needed in order to investigate the dynamical long-term influence on their orbits.

An investigation of the influence of the impact angle shows significantly different results only for the inner disk and the flared disk. A passing star penetrating the disk (flat and flared) in the ecliptic influences objects over a longer time span (the comets that are all distributed more or less in the plane where the star passes through). Thus, a high number of objects in the path of the star is scattered to orbits with high eccentricities. An inclined passing star crosses the disk at a certain distance, d_i. Thus, only objects in the vicinity of it will be influenced (see Fig. 2, right panel). Which means that only a small number of objects (with initially high inclination) is influenced by its passage. This can be seen also in table 2, where the planar and inclined passages are compared.

The influence of the passing star on the Oort cloud does not vary significantly between impact angles. This probably is due to our choice of distribution of Oort cloud objects.

Nevertheless, different masses of passing stars and longer computation times will probably yield more insight into this interesting topic.

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