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Dynamics of the Oort cloud and formation of interstellar comets

Torres Rodriguez, S.

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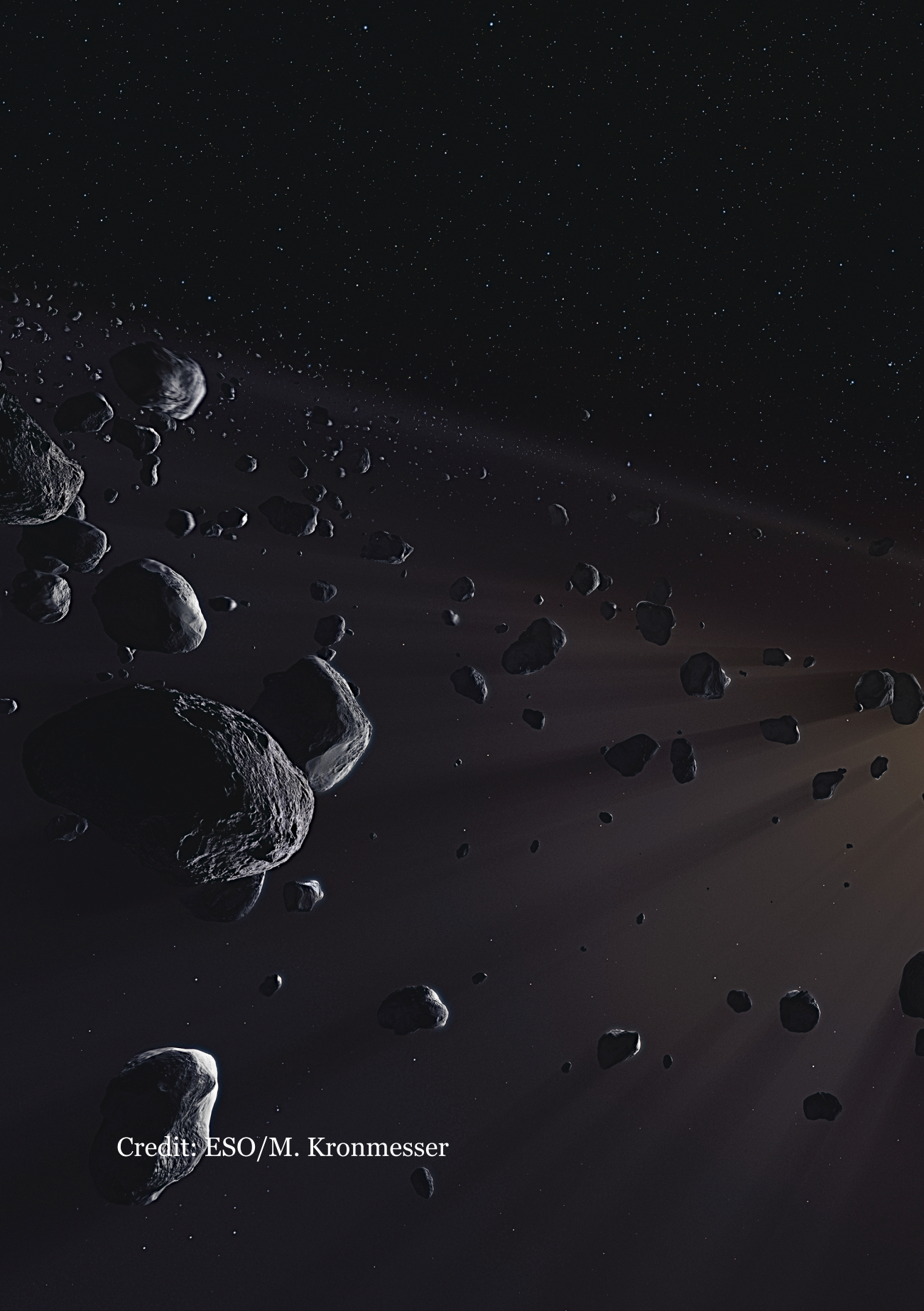


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Author: Torres Rodriguez, S.

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Chapter 4

Dynamical evolution of the solar system debris disk in its birth cluster

S. Torres, M. X. Cai, D. Mukherjee,
S. Portegies Zwart, and A. G. A. Brown
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Abstract

The Sun, like many other stars in the Milky Way galaxy, probably formed in a star cluster. Due to the relatively high stellar density in such a cluster, encounters are expected to affect the early stage of the dynamical evolution of the solar system. In particular, the outer parts of the solar system are vulnerable to such perturbations. Here, we investigate the role of stellar flybys on the formation of the Oort cloud. This is done using the LonelyPlanets module in the AMUSE framework. In LonelyPlanet the effect of a star cluster on individual planetary systems is resolved in two steps: first, we simulate the star cluster without planets to subsequently evolve each planetary system while taking the perturbations of nearby stars into account. In our calculations, each star receives a debris disk and a population of planets. Calculations are performed with small disks (of 16-35 au) and large disks (of 40-1000 au). The calculations are carried out with two arrangements of planets. One configuration that mimics the current solar system and one case in which we adopt a compact configuration with planets closer together than they are today. Objects in the outer edge of the debris disk are scattered by passing stars and in the inner edge by the interaction with the planets. The planets cause asteroids to be ejected and park them in resonant orbits. Stellar encounters play an important role in heating the debris disks, resulting in eccentric and inclined orbits with respect to the initial conditions. Up to $\sim 36\%$ of the original disk material is ejected from the planetary systems to become *sōlī lapidēs* such as 'Oumuamua. These objects are ejected with a typical velocity of 1-3 km/s.

Introduction

Oort (1950) proposed the existence of a cloud of comets that surrounds the solar system which was subsequently named after him. The Oort cloud is thought to contain about 10^{11} – 10^{12} comets (Brasser & Morbidelli 2013), with a total mass of around 2–3 (e.g., Francis 2005; Morbidelli 2005). Its shape is conjectured to be nearly spherical, with the cloud extending up to 0.5 pc from the Sun, limited by the Hill sphere of the solar system (Oort 1950; Chebotarev 1965). Because these estimates of the Oort cloud properties are highly uncertain (mainly because of the lack of observations of the long-period comets), the creation, evolution and even the existence of the Oort cloud remain a puzzle today. One of the main questions related to the origin of the Oort cloud is related to the moment of its formation. Sev-

eral works have explored the origin and evolution of the Oort cloud, mainly by performing numerical simulations. These studies follow two main ideas of formation: a *primordial* or a *late* formation of the Oort cloud. The *primordial* model occurs in the early stages of the solar system when the Sun was still in its birth cluster (see e.g., Oort 1950; Hills 1981; Heisler & Tremaine 1986; Duncan et al. 1987; Weissman 1996; Wiegert & Tremaine 1999; Dones et al. 2004; Levison et al. 2010). In this scenario the planetesimals were scattered due to the interaction with the growing giant planets and started populating the Oort cloud. The *late* model assumes that the Sun already left its birth cluster. In this alternative scenario the Oort cloud was created in the later stages of the solar system formation possibly due to gravitational instabilities when the giant planets experienced an orbital resonance, which caused the minor bodies to be ejected onto almost unbound orbits (see e.g., Levison et al. 2004; Brasser et al. 2006; Fouchard et al. 2006; Kaib & Quinn 2008; Morbidelli 2005; Duncan 2008; Brasser & Morbidelli 2013; Shannon et al. 2014; Dones et al. 2015; Nesvorný 2018; Shannon et al. 2019; Vokrouhlický et al. 2019).

Nowadays the model is adopted that the solar system was born in a star cluster (Portegies Zwart 2009; Adams 2010) and that it was still a cluster member when the planets formed (Pichardo et al. 2012; Portegies Zwart & Jílková 2015; Martínez-Barbosa et al. 2016). Considering that the lifetime of an open cluster is around 100 Myr and stellar clusters are dense environments, the probability of close encounters is higher than in the case the

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Sun would be isolated (Portegies Zwart & Jílková 2015). Therefore the Oort cloud most probably faced interactions with the siblings of the Sun.

Nordlander et al. (2017) discussed the evolution of a primordial Oort cloud for different models of the birth cluster of the Sun (low, intermediate, and high mass). They considered the evolution of the cloud in a long-lived cluster starting at 100 Myr and finishing with the late heavy bombardment (~ 500 Myr). They found that a primordial Oort cloud will likely not survive for any of the cluster models, with the low-mass cluster having the best chance for the solar system to survive. This result thus favours a delayed formation of the Oort cloud (e.g., Brasser & Morbidelli 2013). Other authors suggested (see e.g., Levison et al. 2010; Jílková et al. 2016; Pfalzner et al. 2018; Hands et al. 2019) that part of the Oort cloud was captured through the interactions with passing stars while the Sun was in its birth cluster, and that also objects like Sedna are the consequence of a dynamical interaction with closely passing stars. Overall, the formation of the Oort cloud while the Sun was still in its birth cluster is constrained by two scenarios. One which is in favour of a dynamical instability of a protoplanetary disk due to the migration of the giant planets and random passing stars (see e.g. Fernández & Brunini 2000; Brasser et al. 2012); and the other propose that a fraction of the Oort cloud was capture due to the interaction with the stars in the cluster (see e.g. Levison et al. 2010; Hands et al. 2019).

Motivated by the idea that the formation of the Oort cloud occurred while the Sun was in its birth cluster, we aim to study the formation and evolution of the Oort cloud in such an environment. Direct N-body simulations were used, where specifically we performed a set of simulations modelling the evolution of the solar system debris disk while the Sun is still in its birth cluster. We studied the dynamical evolution of the debris disk under the influence of a single and multiple random stellar encounters and the giant planets. We explore two models of the solar system, *extended* and *compact*. The *extended* model is based on the present-day orbits of the giant planets (i.e., Jupiter at 5.2 au, Saturn at 9.5 au, Uranus at 19.2 au and Neptune at 30.1 au) and an extended debris disk ($40 < a < 1000$ au). The *compact* model is a Nice-based model (Gomes et al. 2005; Tsiganis et al. 2005; Morbidelli et al. 2005) with giant planets in compact orbits (Jupiter at 5.5 au, Saturn at 8.1 au, Neptune at 11.5 au, and Uranus at 14.2 au) and a compact disk ($16 < a < 35$ au). In Section 5.2 we describe our numerical implementation. In Section 5.3 we present the results for our N-body simulations for the evolution of the solar system in a birth cluster environment for the two models mentioned before. In Section 5.4 we discuss the effect

of a dense environment on the creation of *transitional interstellar comets* (Torres et al. 2019a) and hyperbolic objects like 'Oumuamua (Meech et al. 2017; Williams 2017). Finally in Section 4.5 we present our summary and conclusions.

Section 4.2

Numerical implementation

To study the dynamical evolution of the solar system in a dense environment, we considered two alternative models, which we refer to as *extended* and *compact*. For each model we performed two sets of simulations, one in which only one close encounter between the solar system and another star (*Extended 1* and *Compact 1* models) is considered and the other in which multiple random encounters are considered (*Extended N* and *Compact N* models). The initial conditions of the four models are listed in Table 4.1 and a schematic representation is provided in Fig. 4.1.

For the simulations and the generation of the initial conditions for the *Extended 1* and *Compact 1* models we used REBOUND (Rein & Liu 2012) with the WH-Fast integrator (Rein & Liu 2012). We ran 32 simulations in which we assumed a Sun-like star approaching the solar system at distance ranging from 225 au to 400 au, at inclinations i of 0, 30, 60, and 90 degrees, and with a velocity relative to the Sun of $\sim 1 \text{ km s}^{-1}$, typical for an open cluster environment (Binney & Tremaine 2008). The planetesimals in the disk are approximated as massless test particles (1000 per simulation), and the evolution time is set to 20 000 yr, with the encounter happening 10 000 yr after the start of the simulation.

For the models *Extended N* and *Compact N* we simulated the solar system in an open cluster-like environment. We first used the code *LonelyPlanets* (Cai et al. 2015, 2017, 2018). *LonelyPlanets* combines NBODY6++GPU (Wang et al. 2015) and REBOUND (Rein & Liu 2012) through the framework of the Astrophysical Multi-purpose Software Environment – AMUSE (Portegies Zwart et al. 2009; Pelupessy et al. 2013; Portegies Zwart et al. 2013b; Portegies Zwart & McMillan 2018). We used NBODY6++GPU and a Plummer sphere model (Plummer 1911) to simulate the open cluster, with an initial mass function ranging from 0.08 to 100 (Kroupa 2001), 2000 stars, and a virial radius of 1 pc. A Sun-like star is then chosen randomly by the *LonelyPlanets* module and the solar system is placed around it and is evolved for 100 Myr. The code then uses a KD

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Table 4.1: Initial conditions for the extended and compact models. The first column indicates the type of model. The second column shows the size of the disk. The third column represents the positions of the giant planets (Jupiter (J), Saturn (S), Uranus (U), and Neptune (N)), followed by the integration time, the number of encounters and the perturber distance.

Model	disk [au]	Position of the Planets [au]	Time [Myr]	Encounters	Perturber distance [au]
<i>Compact 1</i>	16–35	J:5.5, S:8.1, N:11.5, U:14.2	0.02	one	225 – 400
<i>Extended 1</i>	40–200	J:5.2, S:9.5, U:19.2, N:30.1	0.02	one	225 – 400
<i>Compact N</i>	16–35	J:5.5, S:8.1, N:11.5, U:14.2	100	multiple	$10^2 - 10^4$
<i>Extended N</i>	40–1000	J:5.2, S:9.5, U:19.2, N:30.1	100	multiple	$10^2 - 10^4$

4.2 Numerical implementation

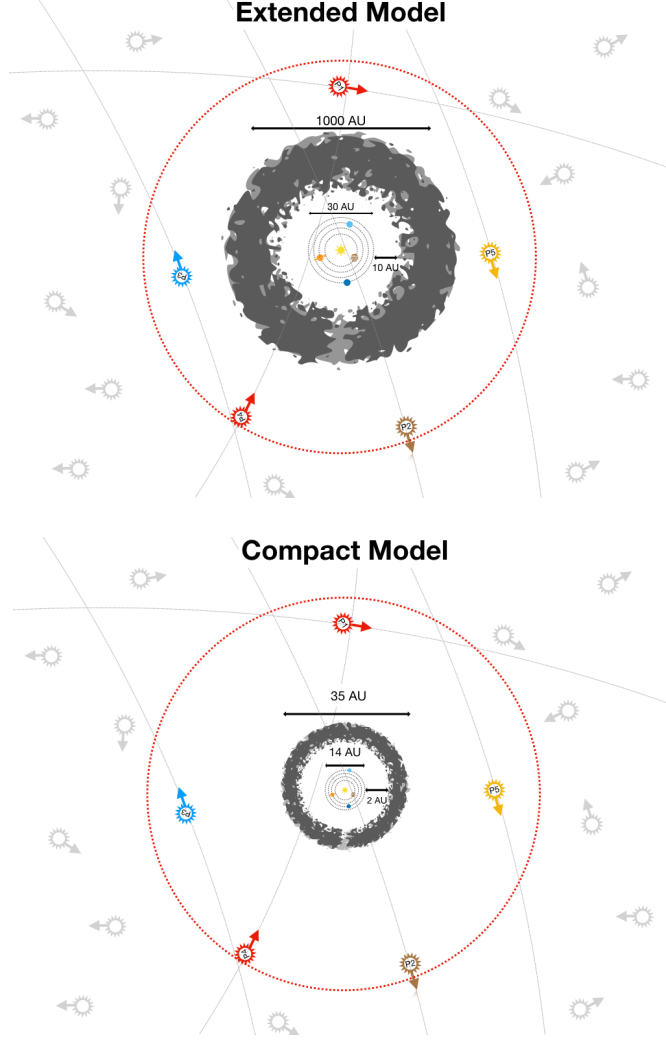


Figure 4.1: Illustration of the solar system for the extended (top panel) and compact (bottom panel) models. The planetary region for the extended model uses the present day positions of the planets. In the compact model the giant planets are in compact orbits (Jupiter at 5.5 au, Saturn at 8.1 au, Neptune at 11.5 au, and Uranus at 14.2 au). The grey disk represents the debris disk of which the size is set to 1000 au for the extended model (top panel) and 30 au for the compact model (bottom panel). The dotted red circle indicates the boundary of the neighbour sphere, beyond which we ignore the influence of any perturbations by passing stars (distance not to scale). Grey stars represent the stars in the cluster that are ignored. The coloured star symbols (P1, P2, P3, P4, and P5) represent the five nearest stars that perturb the solar system at a given time. The arrows indicate the direction of motion of the perturbers.

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tree to find the five closest stars to the Sun at any given time. These stars and the solar system are then evolved together using the IAS15 (Rein & Spiegel 2014) integrator, thus simulating the effect of encounters between the solar system and stars in the cluster. IAS15 was chosen as it is a high order, adaptive time step integrator which attains relative energy errors of $\sim 10^{-14}$ for timescales of the order of 100 Myr. Even though this integrator is non-symplectic, it preserves energy better than symplectic integrators. Its adaptive time step scheme helps resolve collisions with more precision. We first made a rough study with a grid of low-resolution simulations (200 simulations with 200 test particles in the debris disk). We then selected 24 systems and used these to initialize high-resolution simulations including 2000 test particles in the disk. In each of those simulations the Sun is born in a different position in the cluster.

Section 4.3

Effect of stellar encounters on the early solar system

Debris disks are the remnants of planet formation. Several observations suggest that the disk sizes range from the inner part of the planetary systems (~ 10 au) to ~ 1000 au (Stark et al. 2009; Hughes et al. 2018). The architecture, structure and dynamics of these disks depend on several factors, but primarily on the type of star and the cluster environment, considering that most of the stars are born in the stellar clusters (Lada & Lada 2003). Several studies suggested that the Sun was born in a stellar cluster (e.g., Portegies Zwart 2009; Adams 2010; Pichardo et al. 2012). However, it is still unclear if the current configuration of the solar system was reached when the Sun was still in the cluster, or after the Sun left the cluster. In this section we present the results of the simulations described above and focus on the evolution of the particles in the solar system debris disk.

4.3.1 Extended models

We first explore the dynamical evolution of a medium sized (40–200 au) debris disk suffering only one encounter with another stars (Sect. 4.3.1) and of a large debris disk (40–1000 au) which experiences multiple encounters with other stars (Sect. 4.3.1).

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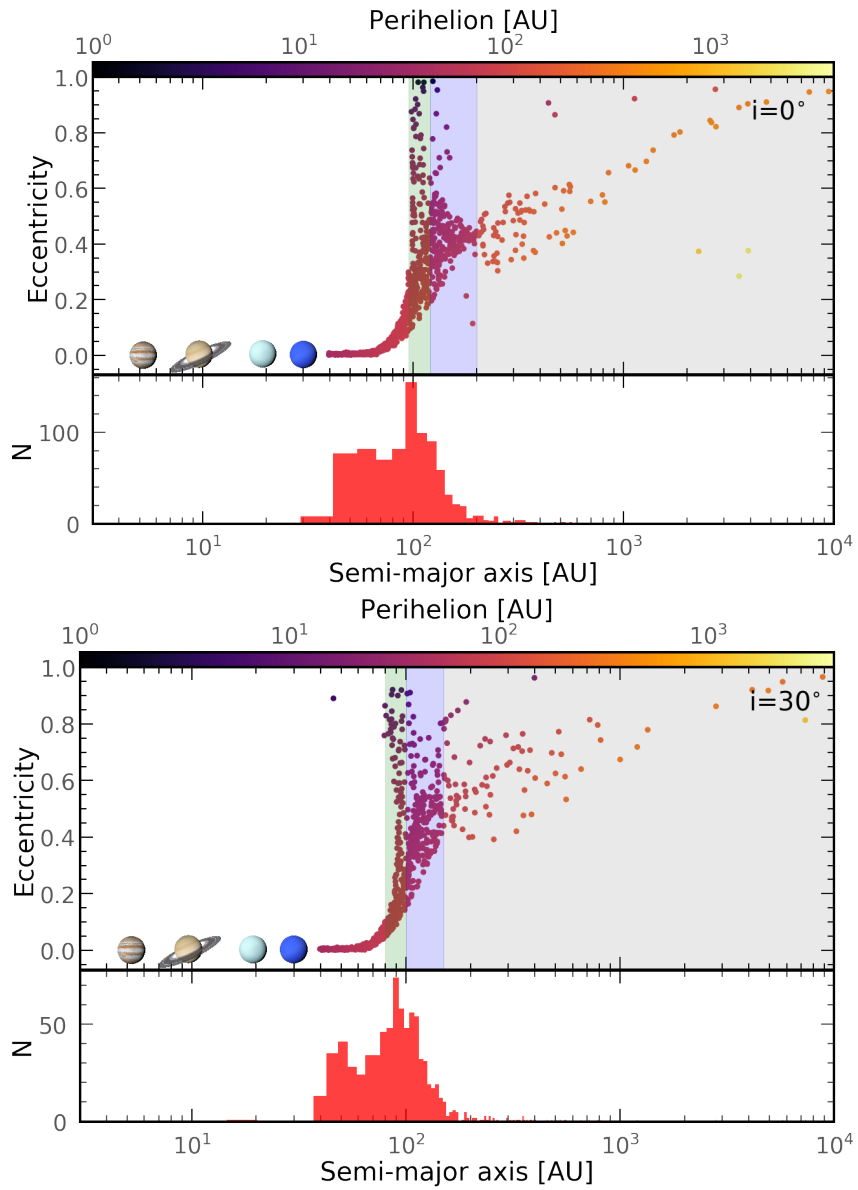


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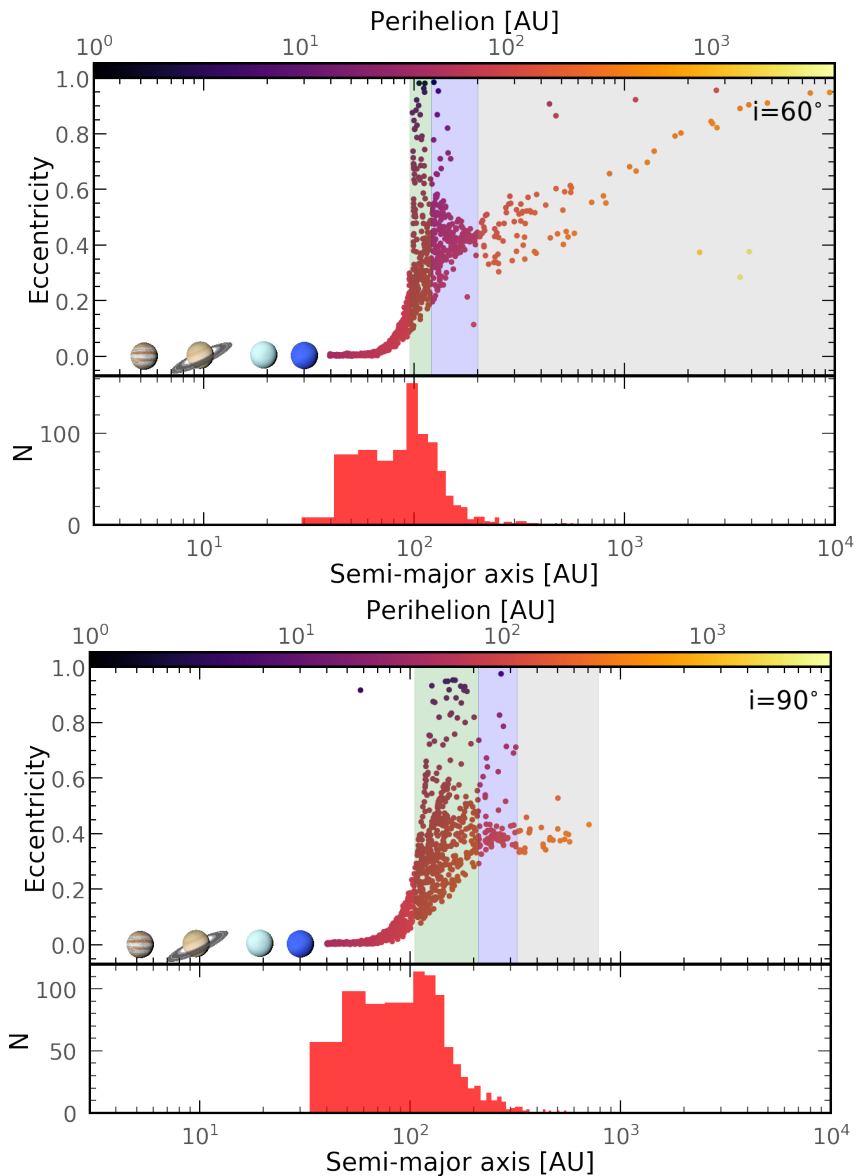


Figure 4.2: Extended 1 model. The top panel in each plot shows the semi-major axis a as a function of eccentricity, while the distribution of the particles over a is shown in the bottom panel. The different rows represent the inclination angle i of the encounter (0, 30, 60, and 90 degrees). The impact parameter is set to 300 au and the mass of the perturber is 1 . The positions of the four giant planets are shown with symbols in the bottom left of the top panel in each plot.

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Table 4.2: Extended 1 model. Semi-major axis distribution of the particles in the disk after a close encounter with a Solar-like star. The impact parameter is set to 300 au, for an encounter angle of 0, 30, 60 and 90 degrees. The first column represents the different regions of the solar system, divided into four. The first row represents the original disk over which the particles were initially distributed ($40 < a < 200$ au), in which the transneptunian region ranges from 40 - 50 au. Followed by the planetary region ($0 < a < 30$ au), the inner Oort cloud ($200 < a < 10\,000$ au), and finally the unbound particles (hyperbolic comets).

Inclination angle	0°	30°	60°	90°
Original disk	73%	76.4%	81.2%	88%
Planetary region	0.4%	0%	0%	0%
Inner Oort cloud	6.4%	5.2%	9.4%	12%
Unbound	20.2%	18.4%	9.4%	0%

Extended 1

Following the method described in Sect. 5.2 and using the initial conditions listed in Table 4.1 second row, we performed 32 simulations for the *Extended 1* model. In Fig. 4.2 and Fig. 4.3 we show the most interesting case, when the perturber passes to within 300 au from the Sun (Table 4.2). When the inclination angle of the encounter is set to 0°, most particles ($\sim 73\%$) remain in the original disk despite the close encounter. The particles with semi-major axes between 40 and 60 au retain eccentricities near zero. The eccentricities for the rest of the particles range from 0.1 to 0.9 (the same holds for the 30° inclination angle). The transneptunian region ($30 < a < 100$ au) gains $\sim 8.5\%$ more particles as compared to the original distribution, and the inner Oort cloud region ($200 < a < 10\,000$ au) acquires $\sim 6.4\%$ of the initial particles. Additionally 20.2% of the particles become unbound (Fig. 4.3). When the inclination angle is set to 30°, the perturbation is very similar to the previous case (see Table 4.2) but less strong. The transneptunian region gains 1.7% more particles than the case for 0° and the inner Oort cloud region is less populated (5.2% of the initial particles gets semi-major axis between 200 and 10 000 au). The effect of a close encounter decreases further for the 60 and 90 degree inclination angle cases (see also, Punzo et al. 2014; Pfalzner et al. 2018). For a 60 degree inclination angle, the population in the inner Oort cloud increases 3% and 4.2% with respect to the 0 and 30 degrees cases, respectively. When the angle is set to 90 degrees around 12% of the original particles acquire a semi-major

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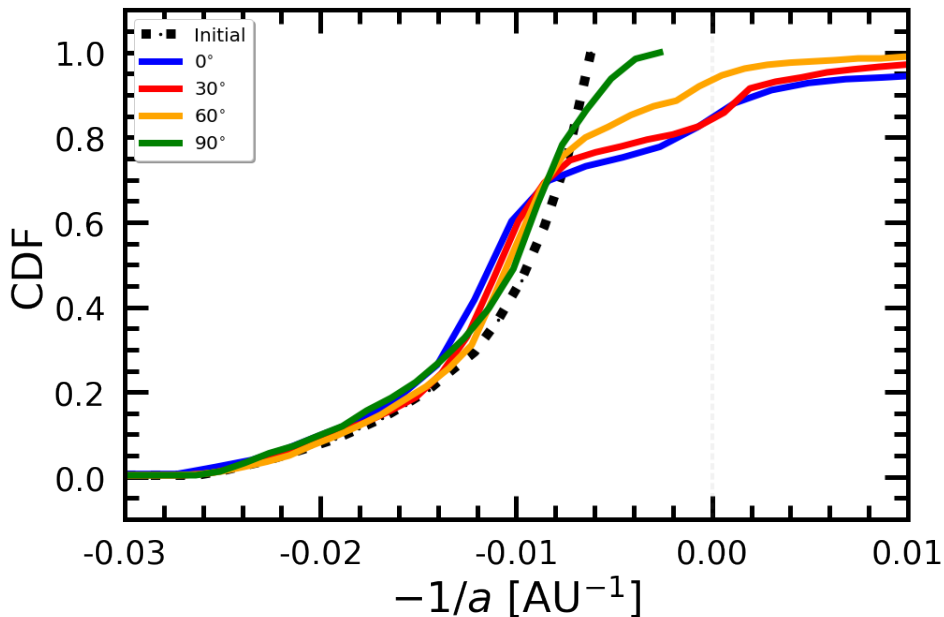


Figure 4.3: Extended 1 model. Cumulative distribution of the final energy of particles in the disk. Coloured lines represents the different inclination angles of the encounter (0, 30, 60, 90 degrees). While the black dotted line shows the initial distribution. The impact parameter is set to 300 au and the mass of the perturber is 1 . Negative values represent the bound particles, while the positive ones the unbound. The distributions have KS-probability of $\sim 0.90\%$ for 0° , $\sim 0.19\%$ for 30° , $\sim 0.07\%$ for 60° , and $\sim 0.05\%$ for 90° , respect to the initial one

axis in the Oort cloud region. The transneptunian region increases its population similarly for 60 (6.8%) and 90 (5.2%) degrees inclination angles.

The geometry of an encounter will define the fate of the debris disk. Even if the impact parameter is rather small (300 au for the cases presented here) the inclination angle of the encounter strongly affects the resulting structure and dynamics of the particles in the system. The differences are reflected in the properties of the particles in the different regions of the solar system after the encounter. For $i = 0^\circ$ about 0.4% of the initial particles end up with their semi-major axes in the planetary region ($0 < a < 30$ au), while for $i = 30^\circ$, 60° or 90° no particles end up in this region. In the transneptunian region, an increase of planetesimals occurs for $i = 30^\circ$, while the most efficient inclination angle to populate the inner Oort cloud region is 90 degrees, with the encounter lifting the semi-major axis of 12% particles to the regions between 200 and 10 000 au. The structure of the

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initial disk however is similar for all the inclination angles. Particles with semi-major axes between 40 and 65 au remain unperturbed, while particles at 65–200 au reach eccentricities up to 1 (Fig. 4.2). Additionally, as shown by the shaded areas in Fig. 4.2, after the encounter the disk is divided into three main populations for all the interaction angles (Fig. 4.2):

Green shading: Eccentricities are ranging from ~ 0.1 to 1, and perihelion distance from 0 to 50 au.

Blue shading: Eccentricities are ranging from ~ 0.2 to 0.6, and perihelion distance from 50 to 100 au.

Grey shading: Eccentricities are ranging from ~ 0.4 to 1, and perihelion distance from 100 to 1000 au.

Even though the encounters at different inclination angles produce a different structure in the disk, the three populations are discernible in all cases.

Finally, it is well known that a very close encounter between a star and a planetary system, can lead to the capture (see e.g., Jílková et al. 2015; Pfalzner et al. 2018) and ejection of a considerable fraction of its debris disk, creating a large population of unbound objects (see e.g., Cai et al. 2017; Pfalzner et al. 2018; Torres et al. 2018, 2019a, and references therein). However, it is worth mentioning that even for a very close encounter like the one described in this section (300 au), the angle of the interaction will determine the rate of ejection. When the angle of the interaction is around 90 degrees all the particles remain in the system. On the other hand if the angle is between 0 and 30 degrees around 20.2% of the initial disk gets unbound from the system (positive values in Fig. 4.3), creating a considerable fraction of interstellar comets such as 'Oumuamua.

Extended N

Following the method described in Sect. 5.2 and the initial conditions listed in Table 4.1 (fourth row), we performed a set of 200 simulations. For each simulation, we focused on the effect of the five closest stars in the cluster to the Sun at any given time. In Fig. 4.4 we show the final distribution of the orbital elements of all the particles in the 200 systems. The particles in mean-motion resonance with Neptune (2:3, 3:5, 4:7, 1:2, 2:5) between 50 and 100 au, resembles the Kuiper belt objects in the solar system.

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Most of the particles have eccentricities between 0 and 0.4 ($\sim 82\%$), and orbital inclinations between 0 and 20 degrees ($\sim 88\%$). The inner part of the disk in all our experiments is perturbed enough to create sub-structure within the disk (see Fig. 4.7). In the outer part of the disk approximately 7.5% of the planetesimals are ejected and start populating the inner Oort cloud ($1000 < a < 20\,000$ au). Just a tiny fraction ($\sim 0.02\%$) reaches the outer part of the current outer Oort cloud ($a > 20\,000$ au). Overall, in these simulations, the effectiveness of close encounters with other stars injecting energy into the orbits of the planetesimals is high. A notable number of planetesimals have already started populating the Oort cloud, and a considerable number of planetesimals acquired eccentric orbits ($\sim 18\%$). Some of the objects in eccentric orbits have planet-crossing perihelia which can lead to further scattering them to even wider orbits with a higher eccentricity. The combined effects of planet scattering (internal) and stellar encounters (external) appears to be very effective in populating the bound Oort cloud. It should also be noted that a considerable fraction of planetesimals ($\sim 36\%$) were ejected from the systems after the encounter with the stars (to panel Fig. 4.14). These would be essential in creating the unbound comets and can explain the existence of objects like 'Oumuamua in other planetary systems (see e.g., Portegies Zwart et al. 2018; Torres et al. 2019a).

Fig. 4.4 shows the final distribution of the orbital elements of the particles over all 200 simulated systems. We now take a closer look at the selected individual systems. Figures 4.5, 4.6, and 4.7 show the results for the selected cases. We selected two systems that undergo a series of weak to moderate encounters, but no strong encounters (systems 128 and 14), the majority of asteroids in this system remain bound to the body star. A further system was selected that experienced some stronger encounters as well as a series of weak encounters (system 100). Two systems that undergo a series of moderate to strong encounters (system 86 and 157) complete the selected set. In Fig. 4.5 we show the orbital evolution of the particles in the disk after 100 Myr. Additionally the distance of the encounter is shown in the top panel of each plot. After 100 Myr in all of our five selected experiments, the giant planets remained in stable orbits. This result implies that in a dense environment such as stellar clusters, the planets in our solar systems could have survived a series of encounters without changing their orbits. If the planetesimal disk was more compact and closer to Neptune, the planet-disk interaction could have triggered the migration of the planets and the ejection of the particles as we show in Sect. 4.3.2.

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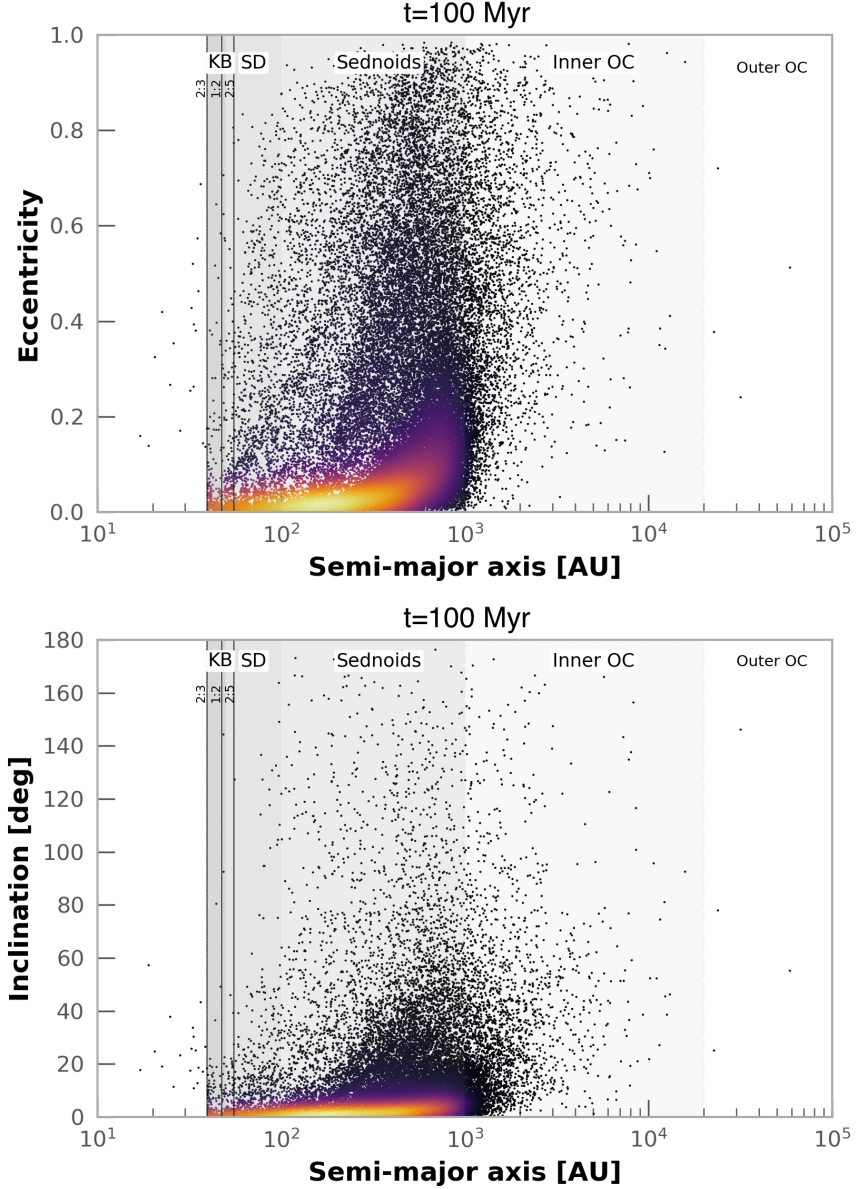


Figure 4.4: Extended N model. Semi-major axis as a function of eccentricity (top panel) and orbital inclination (bottom panel) for all the particles in the 200 simulated systems. The grey areas represent the different regions of the solar system (Kuiper belt (KB), scatter disk (SD), Sednoids, inner and outer Oort cloud (OC)), while the dash lines show the 2:3, 1:2, and 2:5 resonances with Neptune. The integration time is set to 100 Myr. An animation can be found online.

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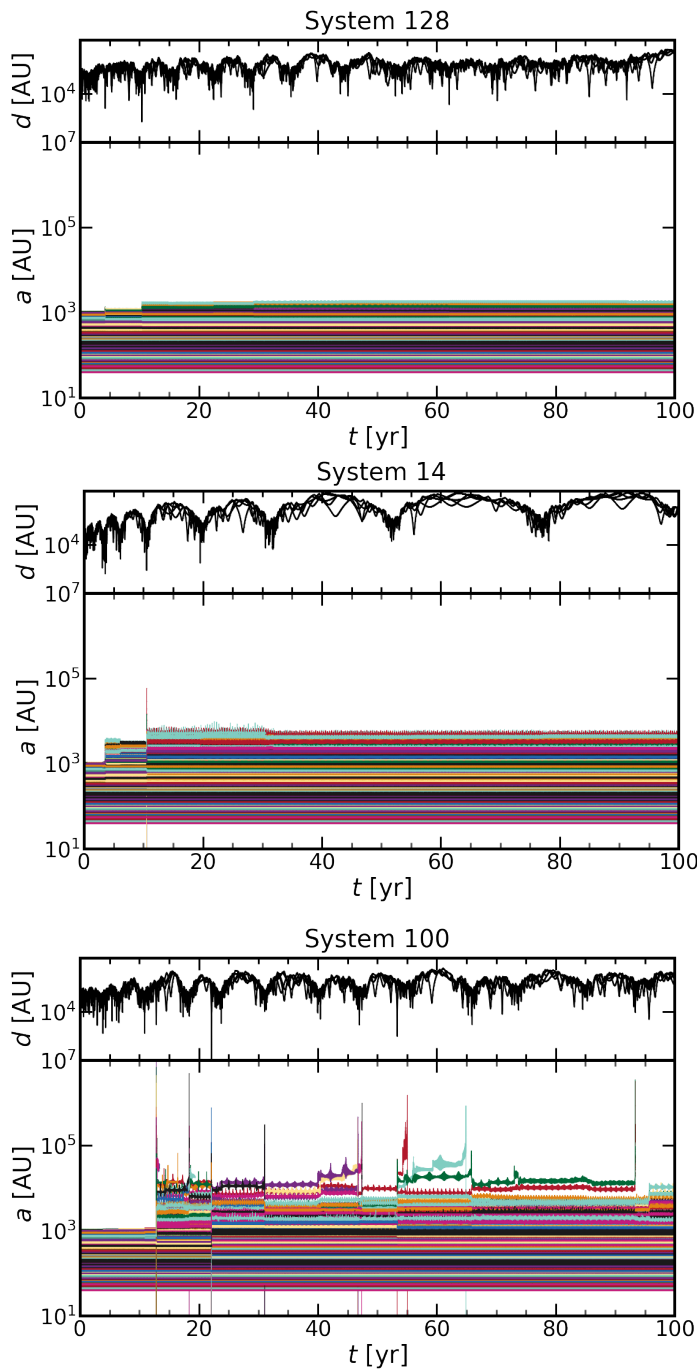


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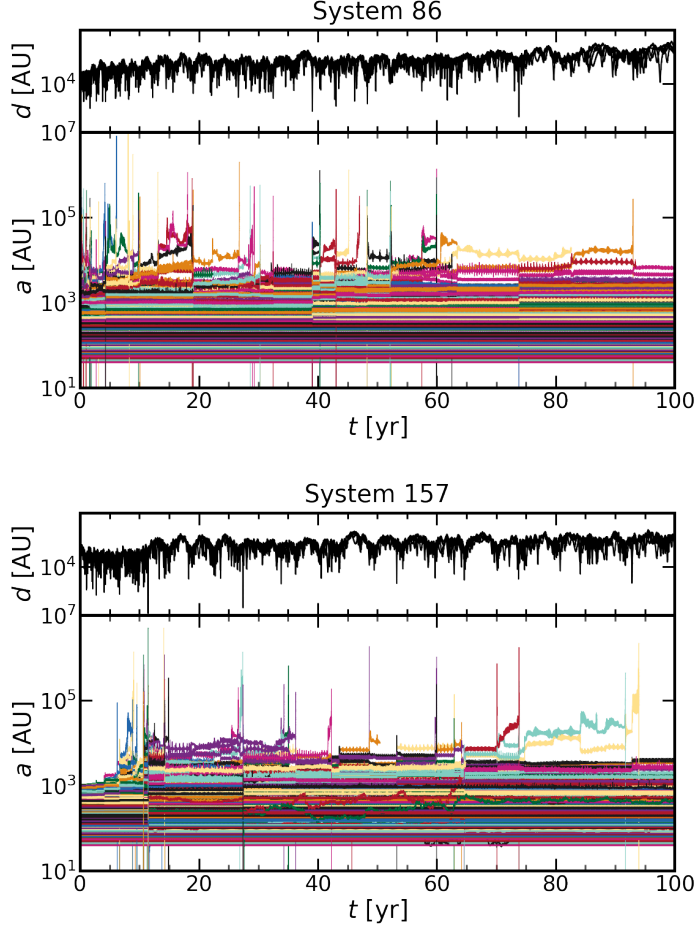


Figure 4.5: Extended N model. Orbital evolution of the particles in the disk after 100 Myr. The bottom panels in each plot shows the semi-major axis as a function of time, while the top panels show the distance of the perturber as a function of time. The different panels represents the systems numbered 128, 14, 100, 86, 157. Coloured lines correspond to each particle in the system.

The most stable system is no. 128 (first row in Fig. 4.6). All the particles remain in the disk after multiple encounters. The five closest encounters over 100 Myr range from 1000 to 5000 au (first panel, Fig. 4.5) are not close enough to inflict a considerable perturbation. However, the disk is heated somewhat in its outer parts, with a small fraction of particles reaching semi-major axes up to 2000 au. System 14 (second row in Fig. 4.6) retains 99.5% of the initial particles, but an early close encounter (second panel, Fig. 4.5)

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leads to 2.1% of the particles reaching eccentricities between 0.4 and 1 and 7.1% reaching semi-major axes larger than 1000 au. In system 100 17% of the particles are ejected from the disk due to the closest encounters (with impact parameter ~ 300 au) with a very low mass star (~ 0.2). Approximately 71% of the particles remain with semi-major axes between 40 and 1000 au, while 9.6% attain semi-major axes between 1000 and 5000 au with eccentricities ranging from 0.1 to 1. Most of the particles have orbital inclinations between 0 and 50 degrees (78.4%), and the rest of the inclinations are distributed between 50 and 150 degrees (third row in Fig. 4.6). The most perturbed systems are no. 86 (fourth row in Fig. 4.6) and no. 157 (fifth row in Fig. 4.6). System 86 experienced two close encounters, the first one with a red dwarf star with a mass of 0.5 at 488 au and later on with a brown dwarf (0.08) at 899 au. This causes the ejection of 13.4% of the initial particles and the creation of three main populations of objects. The first one, planetesimals in the disk, acquired semi-major axes around 200 au, and eccentricities from 0.2 to 1 (green shaded region, fourth-row Fig. 4.6). The second population has semi-major axes ranging from 100 to 1000 au (blue shaded region, fourth-row Fig. 4.6), and orbital inclinations between 0 and 20 degrees. About 23% of the particles gained eccentricities between 0.4 and 1, while the rest has eccentricities ranging from 0.2 to 1. The third and final population contains about 2.1% of the initial planetesimals with semi-major axes from ~ 500 to 6000 au (grey shaded region, fourth-row Fig. 4.6) and eccentricities from 0.2 to 1 and orbital inclinations up to 80 degrees.

The most strongly perturbed system is no. 157 which loses 57.5% of the initial planetesimals. As in the previous cases, this is due to two very close encounters at impact parameters of 336 au and 507 au (Fig. 4.5) with stars with masses of 0.5 and 0.1, respectively. As a consequence of the close encounters a tail is created. The tail contains three main populations and several branches produced by subsequent (weak) stellar encounters, as is shown in the fifth panel of Fig. 4.6). The first population has semi-major axes between 40 and 100 au (green shaded region, fifth-row Fig. 4.6), with eccentricities within 0 and 1 and orbital inclinations from 5 to 50 degrees. The second population (blue shaded region, fifth-row Fig. 4.6) has semi-major axes from 100 to 300 au, with eccentricities from 0.3 to 1 and inclinations up to 20 degrees. The final population (grey shaded region, fifth-row Fig. 4.6) has orbital inclinations distributed between 20 and 180 degrees, while eccentricities range from 0 to 1. About 2.2% of the particles reaches semi-major axes between 1000 and 4000 au (Oort Cloud region). Despite the close encounters experienced by this system, only a small fraction of

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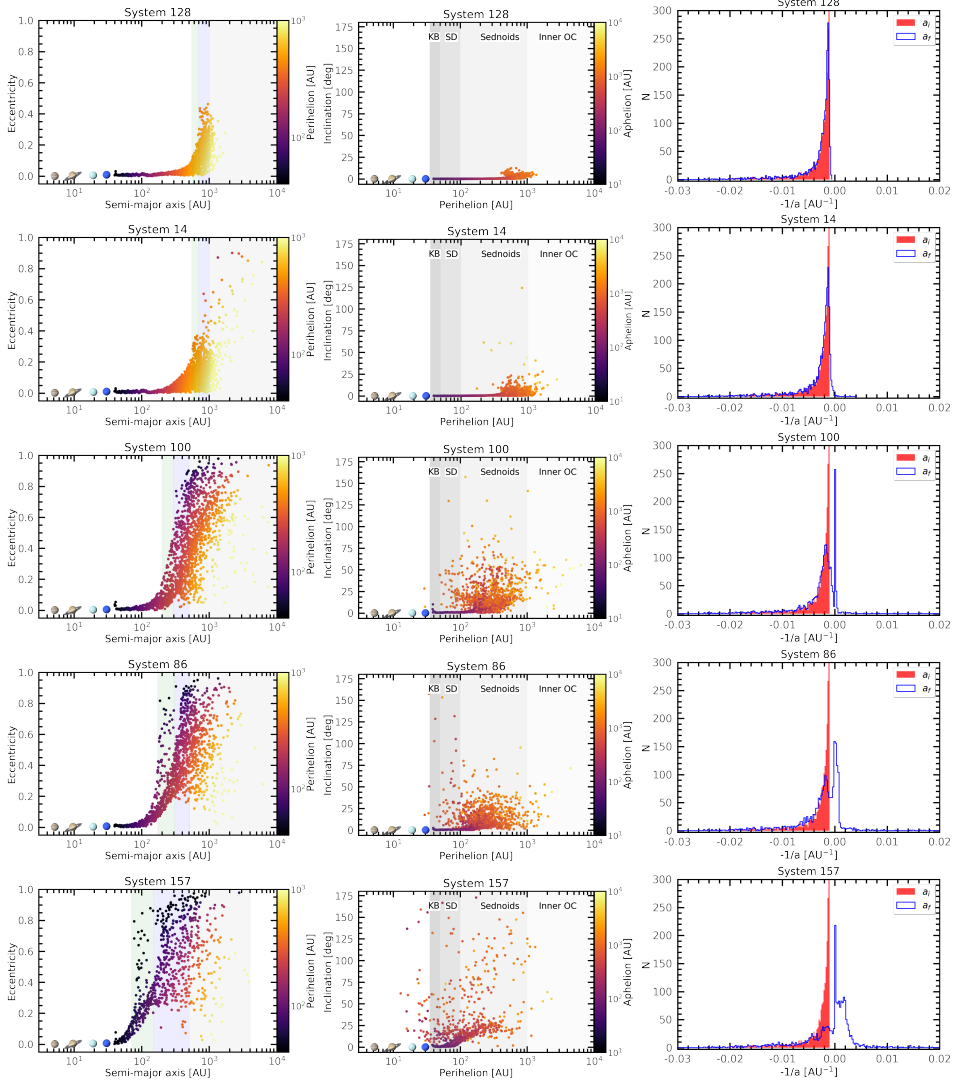


Figure 4.6: Extended N model. Orbital elements of the particles in the disk after 100 Myr and multiple stellar encounters. The leftmost column shows the semi-major axis as a function of the eccentricity, with the dots colour coded by perihelion. The green, blue and grey shaded regions show the different populations created after the encounters in each system. The middle column shows the perihelion as a function of orbital inclination, with the dots colour coded by aphelion. The grey shaded areas show the different regions of the solar system (Kuiper belt (KB), scatter disk (SD), Sednoids, and inner Oort cloud (OC)). The rightmost column shows the distribution of the orbital energy of the particles in the disk, the red histograms corresponding to the initial energy and the blue curve to the final energy. Each row corresponds to the systems numbered 128, 14, 100, 86, and 157, respectively.

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particles populates the outer Oort cloud. This is mainly because the encounter happened in the inner part of the disk, creating a considerable fraction of hyperbolic objects (57.5%). On the other hand, the planets remain in a stable orbit, the objects within $\sim 40 - 50$ au entered in mean motion resonance with Neptune.

In all of the systems presented here a tail in $a-e$ space is created due to strong encounters. In some cases (system 100, 86, and 157) multiple branches are visible which are produced by weak stellar encounters. Additionally three populations of objects are created (green, blue, grey shaded regions in the first column of Sect. 4.6). The multiple stellar encounters trigger the ejection of the particles up to the edge of the current inner Oort cloud (20 000 au). Subsequent perturbations due to the Galactic tidal field will circularise the orbits of particles with large semi-major axes (see Brasser et al. 2012), thus turning them into Oort cloud particles. The particles with small semi-major axes where the Galactic tidal field is not efficient remain in (highly) eccentric orbits which will become unstable on a secular timescale. As such the tail in $a-e$ will disappear in due time. The overall structure of the systems strongly depends on the geometry of the encounter, as we discussed in Sect. 4.3.1 and as illustrated in Fig. 4.7.

Overall, the experiments presented here illustrate different scenarios of how the solar system could have been perturbed in its early stages. A condition for a stable system is that the disk of planetesimals is far enough from the planets, otherwise the planet instability due to the interaction with the disk will heat the disk and most of the particles will be ejected to large distances. In the scenarios explored here, the formation of the Oort cloud could have been Initiated by a close encounter between one or more stars and the solar system without considering orbital instabilities for the planets (Morbidelli 2005), assuming that the planets reached their current positions while the solar system still was in its birth cluster and the gas in the protoplanetary disk disappeared from the disk (see also Brasser et al. 2012). Further dynamical evolution of the planetesimals in the inner Oort cloud induced by the Galactic tidal field, and occasional close encounters will start populating the outer Oort cloud. During interactions with passing stars the Sun can also capture material from the other stars. Sedna was argued to present an example thereof (Jílková et al. 2016).

4.3 Effect of stellar encounters on the early solar system

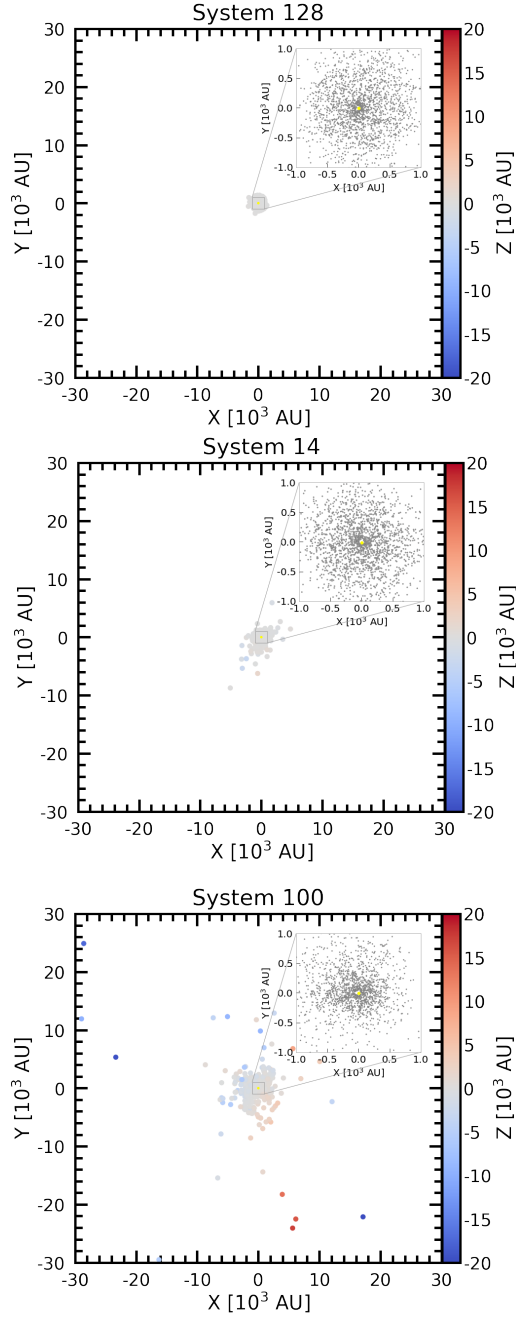


Figure 4.7: Continue...

4 Formation and Evolution of the Oort cloud

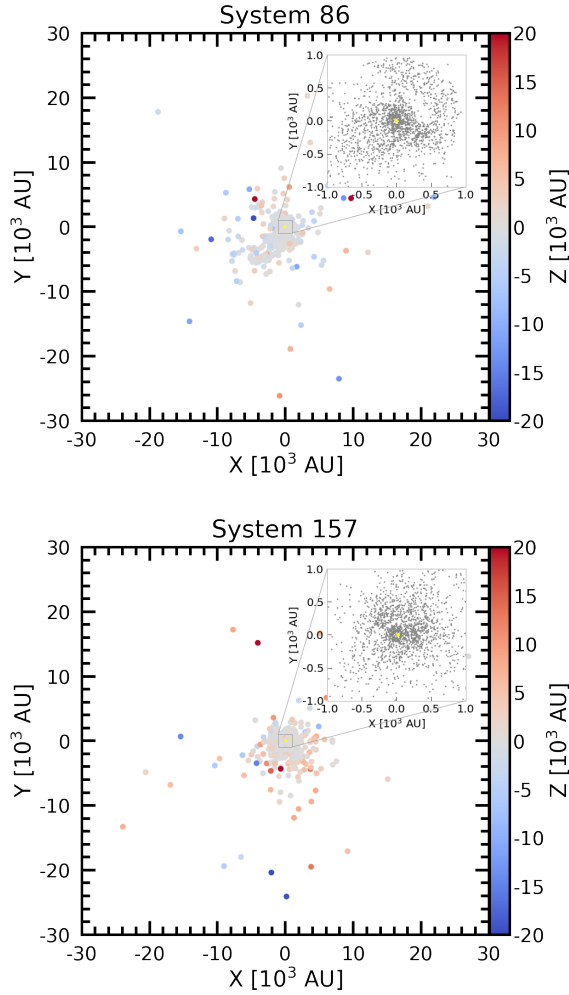


Figure 4.7: Extended N model. Final positions of the particles in the disk, represented with Cartesian coordinates Y vs. X , with the dots colour coded by Z . The panels correspond to the systems numbered 128, 14, 100, 86, and 157.

4.3 Effect of stellar encounters on the early solar system

4.3.2 Compact models

For the construction of the compact models we followed the classical Nice model (Gomes et al. 2005; Tsiganis et al. 2005; Morbidelli et al. 2005) for the early solar system. Although new versions of the model were presented (Morbidelli et al. 2007; Nesvorný & Morbidelli 2012; Morbidelli & Nesvorný 2019), Morbidelli et al. (2007) point out that the orbit evolution of planets was similar to the original version. The classical Nice model thus fulfills our propose and provides us with the tools to understand the dynamical instability of the giant planets and the scattering of planetesimals which attain Oort cloud orbits. In Sect. 4.3.2 we present our results for one encounter between the solar system and another star, while in Sect. 4.3.2 the results for multiples encounters are presented.

Compact 1

For the *Compact 1* model we performed 32 simulations considering the parameters describe in the Sect. 5.2 and Table 4.1. We find that the velocity of the Sun after the encounter with the perturber ranged from $\sim 0.06 \text{ km s}^{-1}$ to 0.08 km s^{-1} when the inclination of the perturber was 0 degrees. However, when the inclination of the perturber was increased to 30 degrees, the velocity of the Sun (after impact) ranged from $\sim 0.07 \text{ km s}^{-1}$ to 0.5 km s^{-1} . This velocity is lower than the mean velocity of stars in a cluster ($\sim 2 \text{ km s}^{-1}$). This indicates that an impact with a GO star even at a very close distances between 225 and 400 au would not be strong enough to eject the Sun from the cluster, but it will strip a considerable fraction of the particles in the disk. The particle ejection efficiency for a close encounter is maximum when the perturber is inclined at an angle of 30 degrees. The perturber does not produce any noticeable effects on the disk when it is inclined at an angle of 90 degrees. Although the perturber with an impact parameter of 275 au does not produce a lot of unbound particles, it produces the highest number of bound particles with a semi-major axis greater than 150 au. Encounters at close distances, especially at 250, 275, and 300 au resulted in the migration of planets.

For an impact parameter of 300 au and an angle of 60 degrees, Uranus and Neptune swap positions and their final semi-major axis resembles the present day positions of the giant planets in the solar system (third row Fig. 4.8). At 10 000 yr after the impact Jupiter is at 5.12 au, Saturn at 10.69 au, Uranus at 18.42 au and Neptune at 29.83 au. For all the simulations performed, we also investigate the effect of a retrograde approach by

4 Formation and Evolution of the Oort cloud

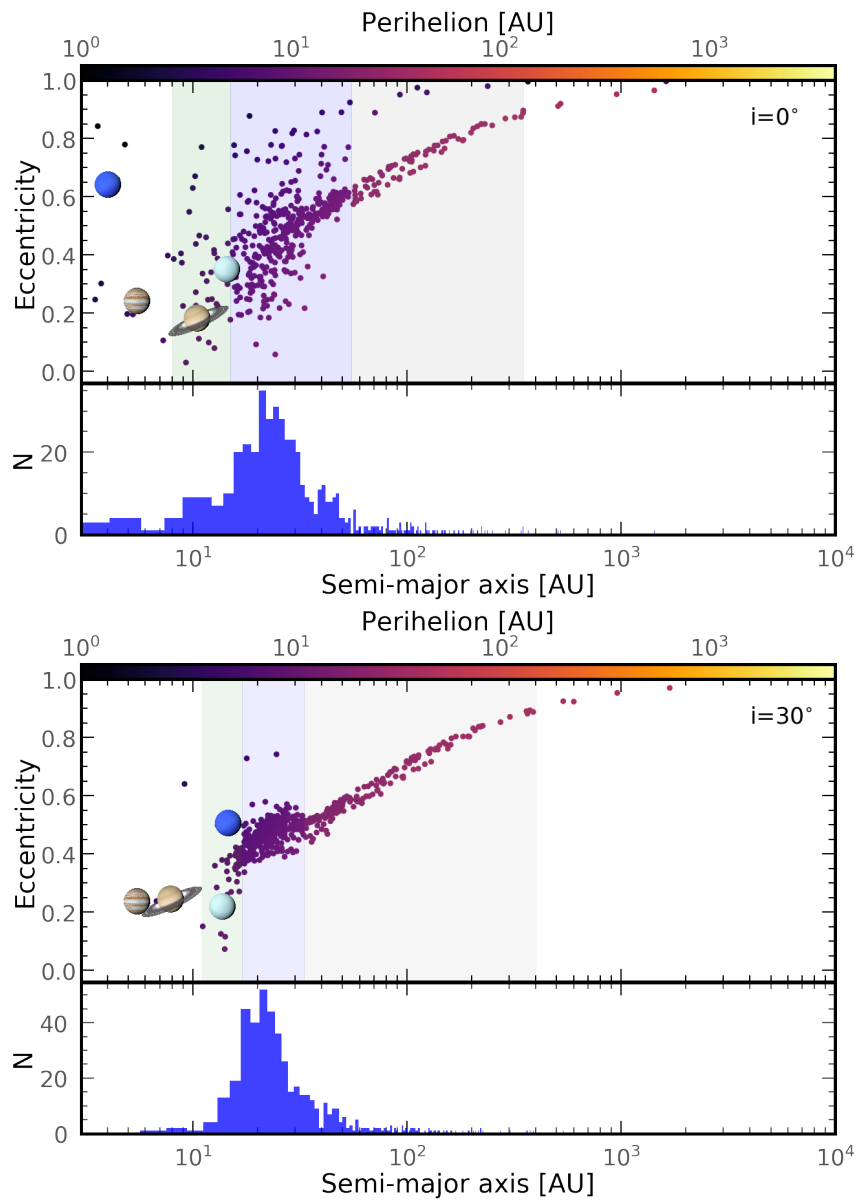


Figure 4.8: Continue...

4.3 Effect of stellar encounters on the early solar system

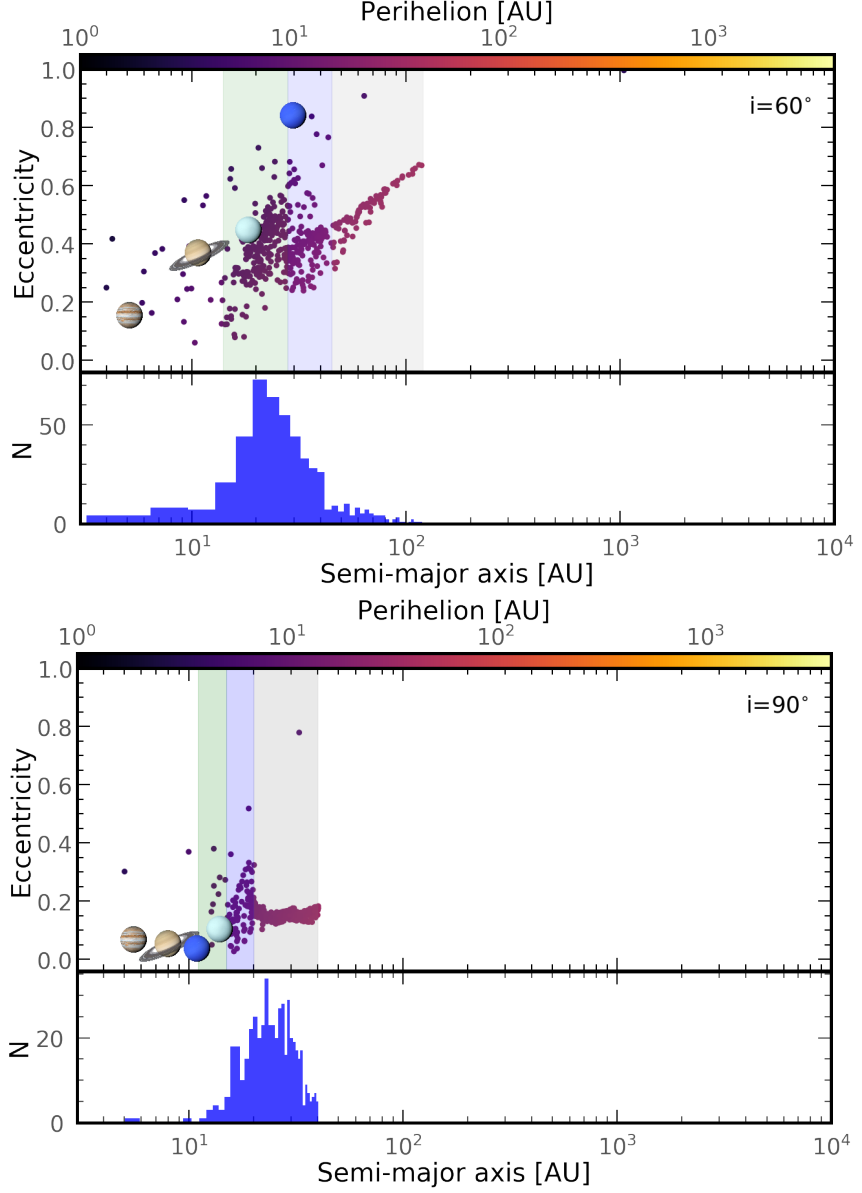


Figure 4.8: Compact 1 model. The top panel in each plot shows the semi-major axis of the debris disk particles as a function of eccentricity, while the distribution of the particles over semi-major axis is shown in the bottom panel. The different rows represent the different inclination angles of the encounter (0, 30, 60, 90 degrees). The impact parameter is set to 300 au and the mass of the perturber is 1 . The positions of the four giant planets are shown with symbols in the bottom left of the top panel in each plot.

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Table 4.3: Compact 1 model. Semi-major axis distribution of the particles in the disk after a close encounter with a Solar-like star. The impact parameter is set to 300 au, for an encounter inclination angle of 0, 30, 60 and 90 degrees. The first column represents the different regions of the solar system, divided into five. The first represent the original disk over which the particles were distribute ($16 < a < 35$ au), followed by the planetary region ($0 < a < 16$ au) , the transneptunian region ($35 < a < 100$ au), the inner Oort cloud ($200 < a < 10\,000$ au), and finally the unbound particles (hyperbolic comets).

Inclination angle	0°	30°	60°	90°
Original disk	52.4%	63%	62.4%	87.6%
Planetary region	11.8%	6%	8.2%	6%
TNOs region	25.2%	22%	27.8%	6.4%
Inner Oort cloud	9.4%	9%	1.3%	0%
Unbound	1.2%	0%	0.3%	0%

the perturber (with respect to the debris disk). We found that a retrograde approach is more efficient at disrupting material from the protoplanetary disk. In general, the migration of the planets and therefore the evolution of a protoplanetary disk is dictated by the geometry of the encounter. Inclinations within 0–60 degrees can lead to migration of the giant planets and the ejection of transneptunian objects to very wide and highly eccentric orbits (Fig. 4.9).

In Fig. 4.9 the energy distribution of the particles in the disk is shown for an impact parameter of 300 au. As previously discussed the strongest disruption occurs for angles between 0 and 60 degrees. For an angle of zero degrees about 11.8% of the particles enter into the inner planetary region ($a < 5$ au) and 25.2% reach the present day transneptunian region (35 to 100 au). Only a small fraction (9.4%) reach the inner Oort cloud regions ($100 < a < 3000$ au) and 1.2% become hyperbolic objects (Table 4.3). The weakest perturbation occurs when the angle is set at 90 degrees. Considering that 300 au is a very close encounter the perturbation is ruled by the planet-disk interaction, but the stellar encounter triggers the ejection of the particles, with a considerable fraction ($\sim 25\%$) penetrating the transneptunian region Table 4.3.

4.3 Effect of stellar encounters on the early solar system

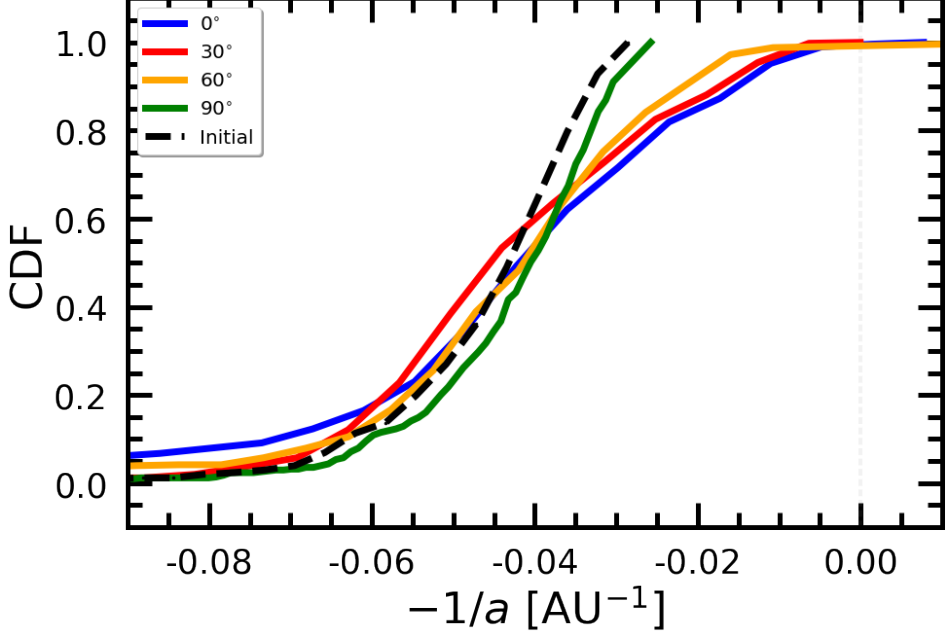


Figure 4.9: Compact 1 model. Cumulative distribution of the final energy of the particles in the disk. Coloured lines represent the different inclination angles at which the perturber approaches the solar system (0, 30, 60, and 90 degrees). The black dotted line shows the initial distribution. The impact parameter is set to 300 au and the mass of the perturber 1 . Negative values represent the bound particles, while the positive ones the unbound. The distributions have KS-probability of $\sim 0.08\%$ for 0° , $\sim 0.12\%$ for 30° , $\sim 0.08\%$ for 60° , and $\sim 0.03\%$ for 90° , respect to the initial one.

4 Formation and Evolution of the Oort cloud

Compact N

As described in Sect. 5.2 we performed a set of 200 simulations for the *Compact N* model which were set up similar to the *Extended N* models. We evolved the systems for 100 Myr, accounting for multiple stellar encounters during the evolution. In Fig. 4.10 we show the final distribution of all the particles. The particles with semi-major axes between 15 and 20 au are in mean-motion resonance with Uranus (resembling the objects in Kuiper belt in our solar systems). The external part of the disk is only slightly perturbed by the stellar encounters. Approximately 0.8% of the planetesimals are ejected into Kuiper belt region, 0.45% to the scattered disk range and 0.40% into the Sednoids range. None of the particles reaches the Oort cloud region. Overall, the strongest perturbation that the planetesimals experience is due to the interaction with the giant planets, particularly Uranus. The orbital evolution of the giant planets after 100 Myr is stable. The planets did not migrate in any of our simulations, mainly because the encounters are distant and the disk massless. Around 12.5% of the particles acquired eccentricities between 0.1 and 0.7 and $\sim 7\%$ are ejected from the system, creating interstellar comets.

In Sect. 4.3.1 we studied the five most interesting cases in our *Extended N* simulations. In this section for comparison we analyze the same systems, i.e. numbers 128, 14, 100, 86, and 157. In Figs. 4.11, 4.12 and 4.13 we show the evolution of the orbital elements of the disk particles, the final orbital elements and the energy distribution, and the position of the particles after 100 Myr, respectively. System 128 (first row in Fig. 4.12) has an early close encounter (1000 au), which in combination with the interaction between the giant planets and the disk and the following encounters leads to the ejection of 6.5% of the initial planetesimals. The remaining planetesimals concentrate in the original disk (95%) with eccentricities near zero, while the rest reaches the scattered disk region with eccentricities between 0.2 and 0.6. System 14 (second-row in Fig. 4.12) does not suffer an important change in the orbital parameters and remains mostly stable during 100 Myr. A small fraction (1.5%) of particles reach high eccentricities ($0.1 < e < 0.6$) and approximately 6% are ejected mainly because of the interaction with Uranus. The particles between 16 and 20 au enter in mean-motion resonance with Uranus. Systems 100 (third-row in Fig. 4.12) and 86 (fourth row in Fig. 4.12) retain 94.5% of the initial particles.

4.3 Effect of stellar encounters on the early solar system

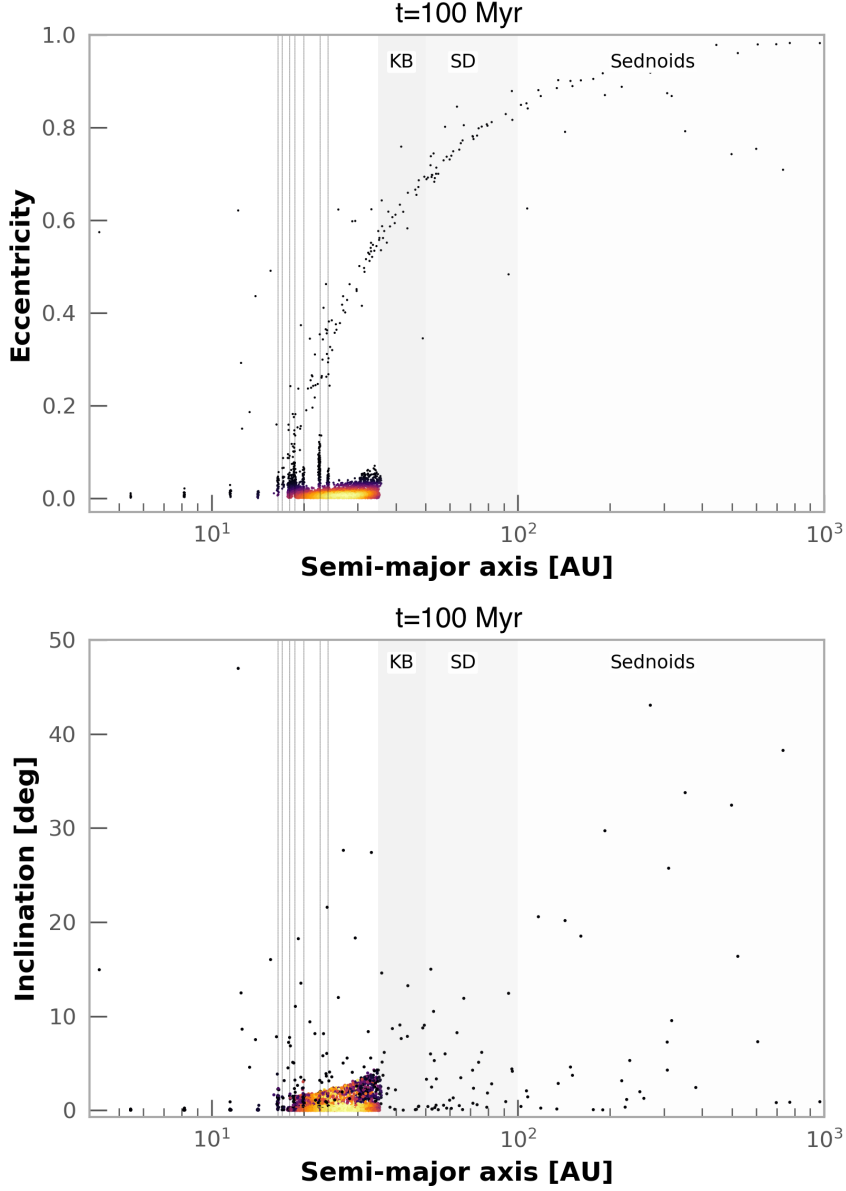


Figure 4.10: Compact N model. The semi-major axis as a function of eccentricity (top panel) and inclination (bottom panel) for all the disk particles in the 200 simulated systems. The grey shaded areas represent the different regions of the solar system (Kuiper belt (KB), scatter disk (SD), Sednoids), while the dashed lines indicate the mean motion resonance of the particles with Neptune. The integration time is set to 100 Myr. An animation can be found online.

4 Formation and Evolution of the Oort cloud

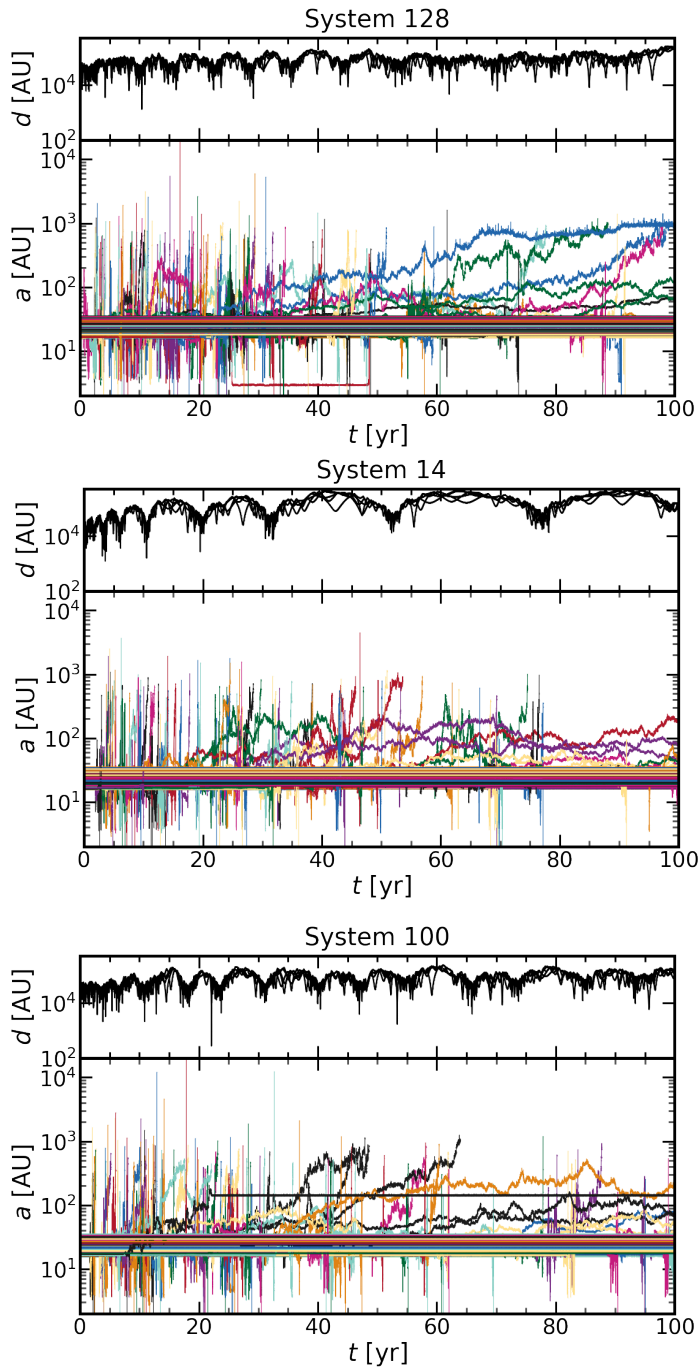


Figure 4.11: Continue...

4.3 Effect of stellar encounters on the early solar system

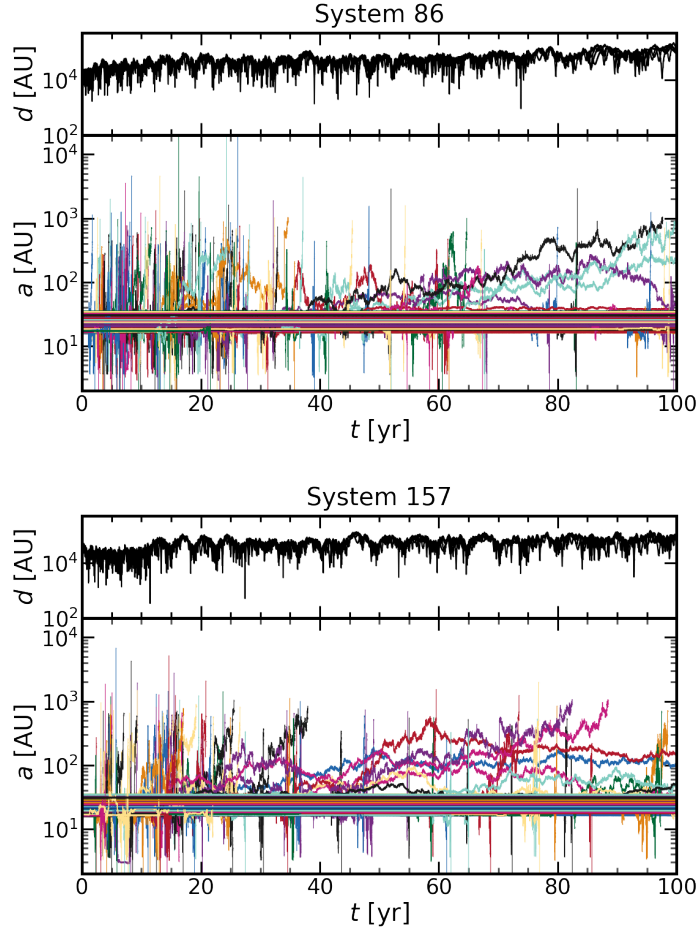


Figure 4.11: Compact N model. Orbital evolution of the particles in the disk over the 100 Myr simulation. The bottom panels in each plot show the semi-major axis as a function of time, while the top panels show the distance of the perturber. The different panels represents the systems 128, 14, 100, 86, and 157. Coloured lines corresponds to each particle in the system.

4 Formation and Evolution of the Oort cloud

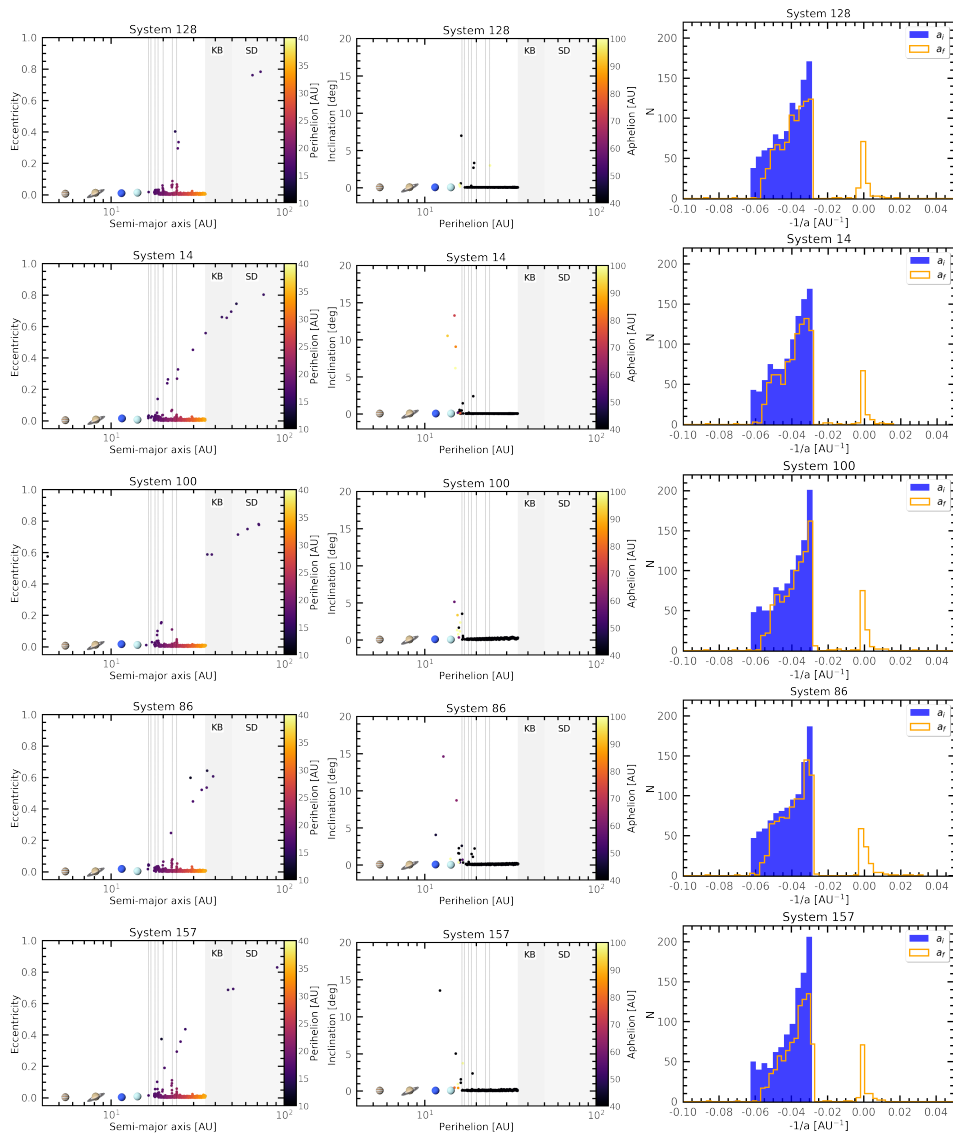


Figure 4.12: Compact N model. Orbital elements of the particles in the disk after 100 Myr and multiple stellar encounters. The leftmost column shows the semi-major axis as a function of the eccentricity, with the dots colour coded by perihelion. The middle column shows the perihelion as a function of inclination, with the dots colour coded by aphelion. Dashed line represent the regions where the particles are in mean motion resonance. The grey shaded areas represent the different regions of the solar system (Kuiper belt (KB), and scatter disk (SD)). The rightmost column represents the orbital energy of the particles in the disk after 100 Myr. The red histogram corresponds to the initial energy, and the blue curve to the final energy. The rows correspond to the systems 128, 14, 100, 86, and 157, respectively.

4.3 Effect of stellar encounters on the early solar system

The most important perturbation is due to Uranus which perturbs all the particles between 16 and 20 au (as in systems 14 and 128). Such particles become attached to Uranus in a mean-motion resonance. In both systems 100 and 86 5.5% of the particles end up on hyperbolic orbits, while the two systems have a similar disk structure after 100 Myr (Fig. 4.13). However, system 100 suffered only one close encounter with a very low mass star (0.3) at 273 au at an early stage (~ 20 Myr), while system 86 faced two close encounters, the first one with a red dwarf star with a mass of 0.5 at 488 au and later on with a brown dwarf (0.08) at 899 au. The most perturbed system is no. 157. Approximately 7% of the particles are ejected from the system, attaining hyperbolic orbits. This system faced two very close encounters at 336 au and 507 au, with masses of 0.5 and 0.1 , respectively. Both encounters took place at an early stage (10 and 27 Myr). Even though system 157 faced two close encounters, the particles with semi-major axes between 20 and 36 au do not suffer an important change. As in the previous systems, Uranus produces the strongest perturbation and about 12.5% of the particles between 16 and 20 au enter in resonance with the giant planet.

The dynamical evolution of the particles in a compact disk depends primarily on the evolution of the giant planets. However, close encounters define their further evolution depending on the mass of the perturber. In the five systems presented here we examined different scenarios. For stellar encounters we find that in all the cases a small fraction of the particles was ejected from the systems ($\sim 5\text{--}7\%$) in hyperbolic objects. The number of objects ejected not only depends on the perturbation due to the planet closest to the disk but also depends on the proximity of the encounter. This suggests that the solar system faced at least one encounter in its early evolution, which partly determined in the evolution of the inner regions. It is essential to highlight that in all our experiments, the inner solar system and particularly the planets do not get perturbed even when a close encounter occurs. The scenario presented here is a simplification of the classic Nice model, which however gives us an idea of the relative importance of the giant planets in forming and shaping the Kuiper belt.

4 Formation and Evolution of the Oort cloud

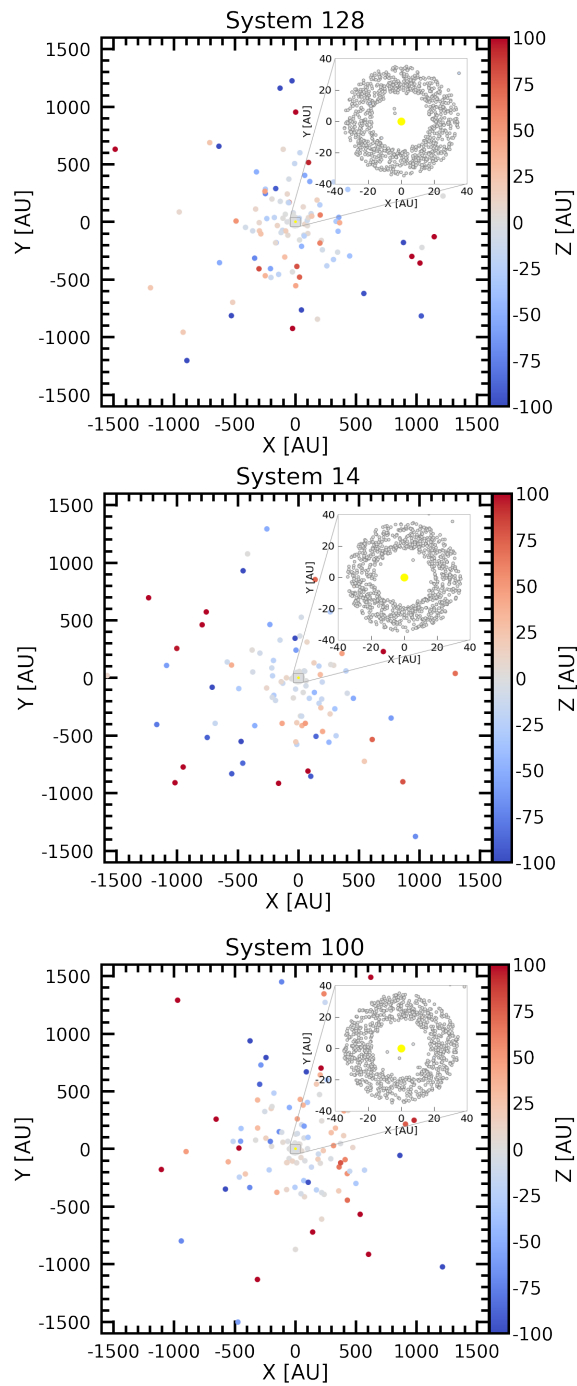


Figure 4.13: Continue...

4.3 Effect of stellar encounters on the early solar system

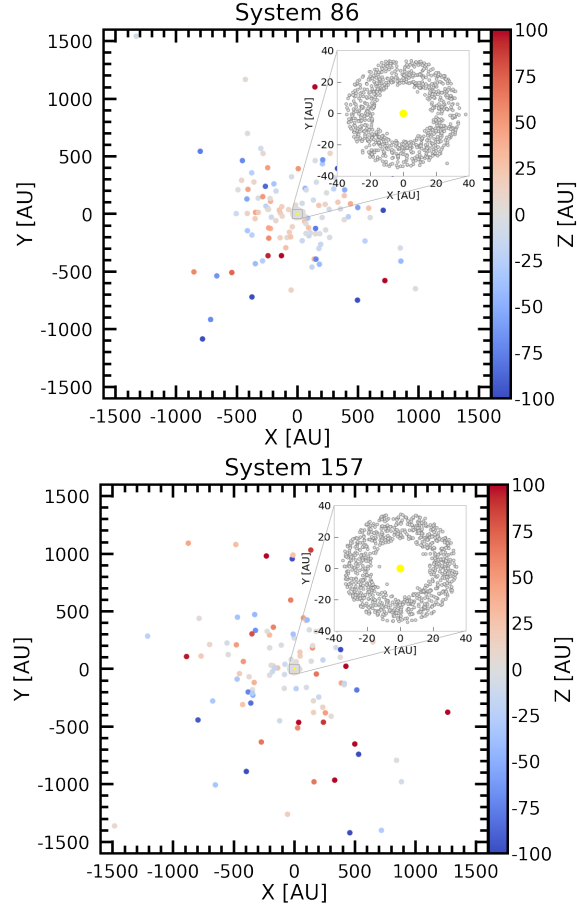


Figure 4.13: Compact N model. Final positions of the particles in the disk show in Cartesian coordinates Y vs X . The dots are colour coded by the value of Z . The units are au. The panels correspond to the systems 128, 14, 100, 86, and 157.

4 Formation and Evolution of the Oort cloud

4.3.3 Extended vs compact models and the Oort cloud

In Sect. 4.3.1 and Sect. 4.3.2 we presented our results for the numerical simulations for the *extended* and *compact* models. First we focused on the effects of a single but close encounter (Sect. 4.3.1 and Sect. 4.3.2) and then studied the effect of multiple encounters (Sect. 4.3.1 and Sect. 4.3.2) in a star cluster environment, over a time span of 100 Myr. For the *Extended 1* model we found that a close encounter with the present day planet configuration of the solar system and a disk extending up to 200 au can produce different structure and populations in the disk but the planets remain in stable orbits. On the other hand for the *Compact 1* model a close encounter triggers the migration and excitation of the planets and the debris disk. The original disk gets perturbed but most of the particles remain in the system. If we compare Fig. 4.3 and Fig. 4.9 we see that the production of unbound particles is higher for the extended case (5.6% of the original disk) than for the compact model (1.4%). It is important to highlight that even when a perturbing star comes close (~ 300 au) to a planetary system the evolution of the planetesimal disk will be determined by its size. If the disk is compact the perturbations due to the planets will dominate over the effect of the stellar encounter. If the disk is large the planets will not suffer any orbital variation, while the planetesimals in the disk can be heavily perturbed.

When considering multiple encounters (Fig. 4.4 and Fig. 4.10) the effect on the disk for the case of the *Extended N* model is similar to the case of one encounter. However, the multiple effects of the passing stars create branches (several populations of objects) in the orbital element diagrams. These structures can be associated with different families in the solar system, particularly the Sednoids region (Jílková et al. 2016; Pfalzner et al. 2018). This region ($100 < a < 1000$ au, Fig. 4.4) is populated with large numbers of objects with eccentricities ranging from 0.2 to 1 with orbital inclinations from 25 to ~ 150 degrees. When we compare this to the *Compact N* model, we can see that the disk is barely perturbed due to the passing stars. The major perturbations are because of the interaction with the giant planets, which produces at least six resonances with the planetesimals with semi-major axes between 16 and 20 au (Fig. 4.10).

Overall the most efficient mechanism to create inner Oort cloud objects in our simulations is through stellar encounters (one or multiple, relatively distant or close). The effect of these perturbations result in an outward of particles from the disk in a short period of time (on the order of a few Myr).

On the other hand giant planets are responsible for shaping the inner solar system on a time scale of the order of tens of Myr. Our simulations suggest that the Kuiper belt objects are the result of dynamical instabilities and interactions with the giant planets, which is consistent with the various instances of the Nice model. Taking this farther, the dynamical evolution of any planetary system will be defined by its birth environment, the size of its disk and the orbital configuration of its planets. If we consider that planet formation is common among stars, Oort cloud and Kuiper belt-like structures should be universal (see also Hands et al. 2019), and shaped by the birth environment of the host star, which also will determine the survivability of these structures. This implies that the creation of interstellar comets should also be common among planetary systems and that interstellar space is populated by a large number of bodies ejected from their systems.

Section 4.4

Interstellar objects

The discovery of the first interstellar comet 'Oumuamua (Williams 2017; Meech et al. 2017), and the recently detected interstellar comet C/2019 Q4 Borisov (Borisov 2019; Guzik et al. 2019) opened up a new era in the study and exploration of the solar system and other planetary systems in our galaxy. The origin of *sōlī lapidēs* (lonely rock) or interstellar objects (asteroid/comet) is still unclear but many scenarios have been proposed to explain their creation and evolution (see e.g., Portegies Zwart et al. 2018; Torres et al. 2019a; Bannister et al. 2019). One scenario for the formation of interstellar objects is due to gravitational instabilities induced by a massive body. This body can be either a nearby planet, a star passing close by, or a combination of both. In the previous sections we studied such scenarios but focused primarily on the particles that remain in the solar system. Hands et al. (2019) points out that a planetesimal can escape a stellar cluster with v_∞ of few km s^{-1} , and there should be several objects ejected from the same cluster making their way through the interstellar space like 'Oumuamua. Torres et al. (2019a) suggested that interstellar space is full of objects which might interact with nearby planetary systems, and therefore it may be common that planetary systems, including the solar system, are polluted with objects originating from interstellar space. In this section we analyse all the particles ejected from the *Extended N* (top panel Fig. 4.14) and *Compact N* (bottom panel Fig. 4.14) models.

4 Formation and Evolution of the Oort cloud

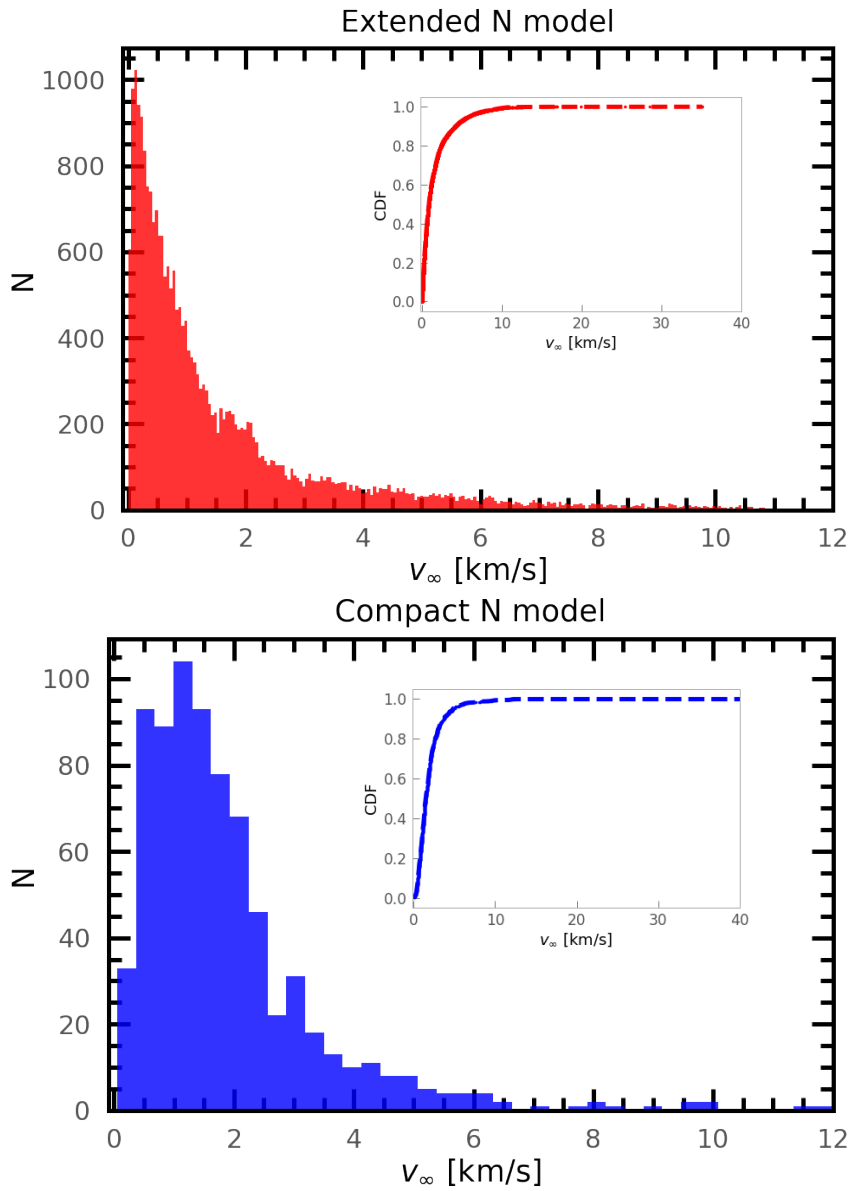


Figure 4.14: Hyperbolic excess velocity for the unbound objects of all the simulated systems, for the extended (top, red) and compact (bottom, blue) models. The histogram show the distribution of the particles, while the inset shows the cumulative distribution.

4.4 Interstellar objects

Our simulations show that the hyperbolic speed v_∞ of the particles ejected from the solar system for the *Extended N* and *Compact N* models is of order $1\text{--}3\text{ km s}^{-1}$ (Fig. 4.14). The planetesimals in the *Extended N* model acquire more energy due to the strong interaction with passing stars and reach velocities from ~ 0.5 up to 40 km s^{-1} (inset top panel Fig. 4.14). Approximately 36% of the total number of particles in the 200 systems become interstellar comets (Fig. 4.14). On the other hand for the *Compact N* model the effect of to the planet-disk interactions is weaker than the effect of a passing star. Around 7% of the particles are ejected from the system with velocities between 0.5 and 40 km s^{-1} (inset bottom panel Fig. 4.14). Overall, the ejection of the asteroids and comets to interstellar space from a cluster environment is dominated by the interaction of stars passing close by. The efficiency increases when the angle of interaction is between 0 and 30 degrees, independent of the distance of the encounter (Fig. 4.3). If the planets near the disk become unstable and the interaction with the disk induces migration, the efficiency of the planets at creating interstellar objects dominates over the stellar encounters (Raymond et al. 2010). However, if the planets orbits are stable only a small fraction ($\sim 7\%$) of particles is ejected.

The further evolution of the interstellar comets will be dominated by the dynamical interaction with other stars in the cluster, and those that manage to escape will also be perturbed by the gravitational tides from the Milky Way. These future perturbations will increase their velocity at infinity passing from few km s^{-1} to tens of km s^{-1} as in the case of 'Oumuamua. The estimations of the number of the local density of interstellar objects range from 10^{14} pc^{-3} (Portegies Zwart et al. 2018), to $8 \times 10^{14}\text{ pc}^{-3}$ (Jewitt et al. 2017), to $2 \times 10^{15}\text{ pc}^{-3}$ (Do et al. 2018). Recently Bannister et al. (2019) estimated the underlying mass density of interstellar objects by considering planet instability models. They found that the total mass of interstellar objects ejected due to a planet-disk interaction is on the order of 0.004 to $3\text{ M}_\oplus\text{ pc}^{-3}$. However, due to the lack of observations of interstellar objects these numbers are still highly uncertain. What is clear from the mentioned works and the results presented in this work is that a large fraction of objects may be ejected from a planetary system and that therefore interstellar space may be full of asteroids and comets.

Summary and Conclusions

We explored the dynamical evolution of the solar system debris disk while the Sun was still in its birth cluster, accounting for planetary perturbations and multiple stellar encounters. The goal is to investigate the role of external perturbations in the formation of the Oort cloud. We also explored the creation of interstellar comets. We aimed to find which stellar flybys can initialise the creation of short and long-period comets, without the perturbations due to the encounter being strong enough to completely destroy the debris disk. We explored two models of the solar system, the *extended* and the *compact* models. For each model, we perturb the system with one close encounter or with multiple encounters. The results can be summarized as follows:

- The dynamical properties of the outer solar system can indeed be produced with the *Extended-N* model, where stellar flybys act as a progenitor to stir up the disk, making the disk more fluffy, and secular planet-asteroid interaction gradually lift up the perihelia of the disk objects and make the distribution more homogenous.
- The solar system is likely to undergo multiple stellar encounters during its time in the birth cluster. One of the consequences of multiple stellar encounters is that they drive particles in the extended disk to migrate outwards and become increasingly eccentric. The semi-major axis of these orbits are large enough for the Galactic tide to be efficient in circularising their orbits (Heisler & Tremaine 1986). This process can be seen in the $a - e$ space as tail-shaped feature. At smaller semi-major axes where the Galactic tide is not efficient, particles remain in (highly) eccentric orbits but will become unstable on secular timescales.
- The gravitational perturbation of a stellar flyby tends to be maximum when the interaction angle is between $0^\circ - 30^\circ$, independent of the size of the disk.
- Planet-disk interaction produces a non-uniform density distribution of Kuiper Belt Objects. Higher density of Kuiper Belt Objects coincide with the low-order mean-motion resonance with the giant planet.

4.5 Summary and Conclusions

- Kuiper belt objects are shepherded by giant planets. The orbital instabilities of giant planets can be triggered by close stellar encounters, which in turn lead to the restructuring of the Kuiper belt, and potentially the production of interstellar objects.
- The formation of the interstellar objects is dominated by relatively close stellar encounters rather than planet-disk interactions.
- The Kuiper belt, scattered disk, the Sednoids region, the Oort cloud, and the formation of interstellar objects in planetary systems may be common if the assumption that stars form in clusters is valid.

Even though our initial conditions for the simulations are based on several assumptions and simplifications that might not fully correspond to the early solar systems, our results provide a possible picture of the ingredients that shaped the solar system in its early stages and suggests that the solar system must have faced at least one encounter in its early stages of formation. Additionally our results imply that the structure and evolution of the solar system may be a consequence of multiple external interactions.

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