Dynamics of the Oort cloud and formation of interstellar comets
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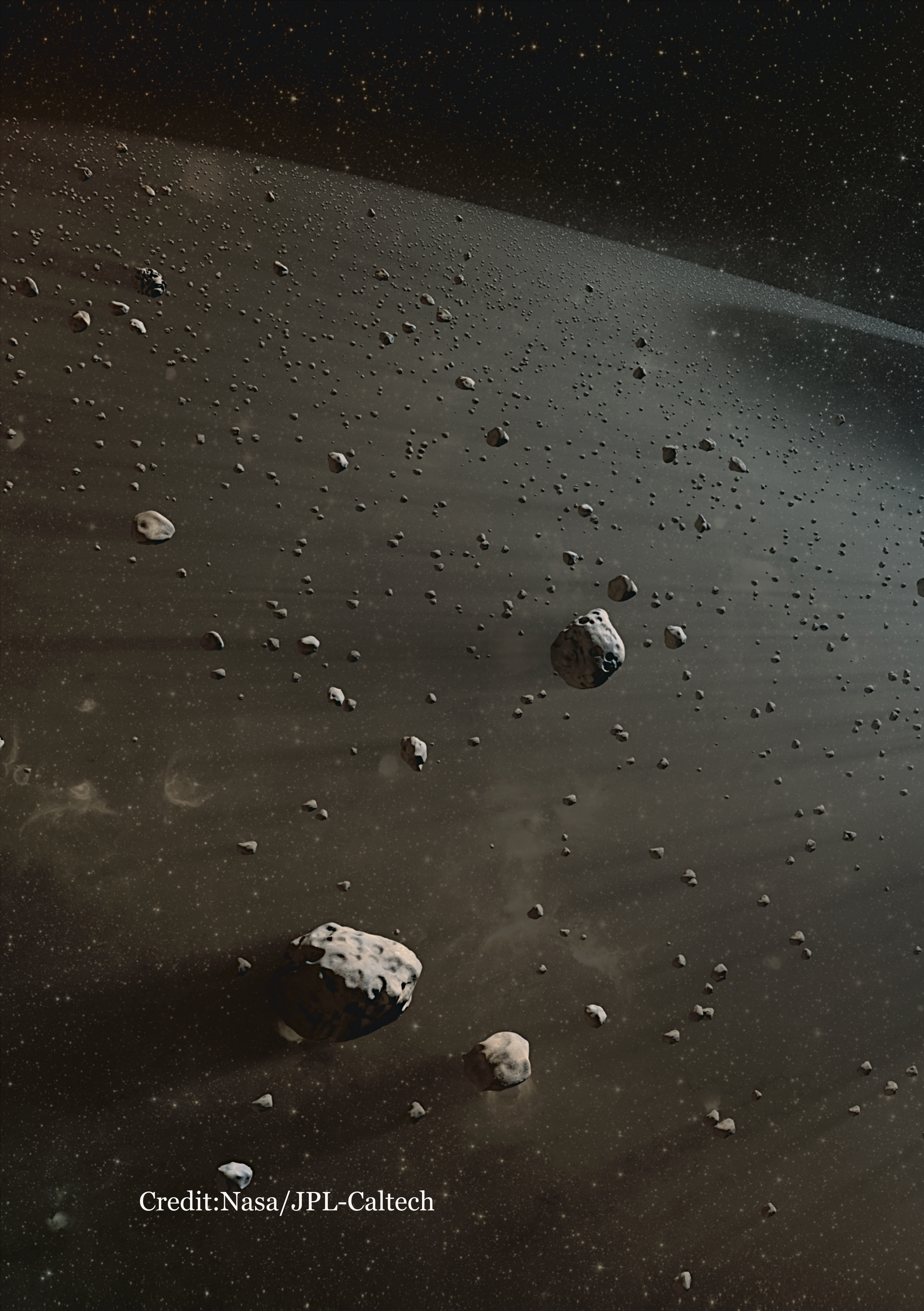

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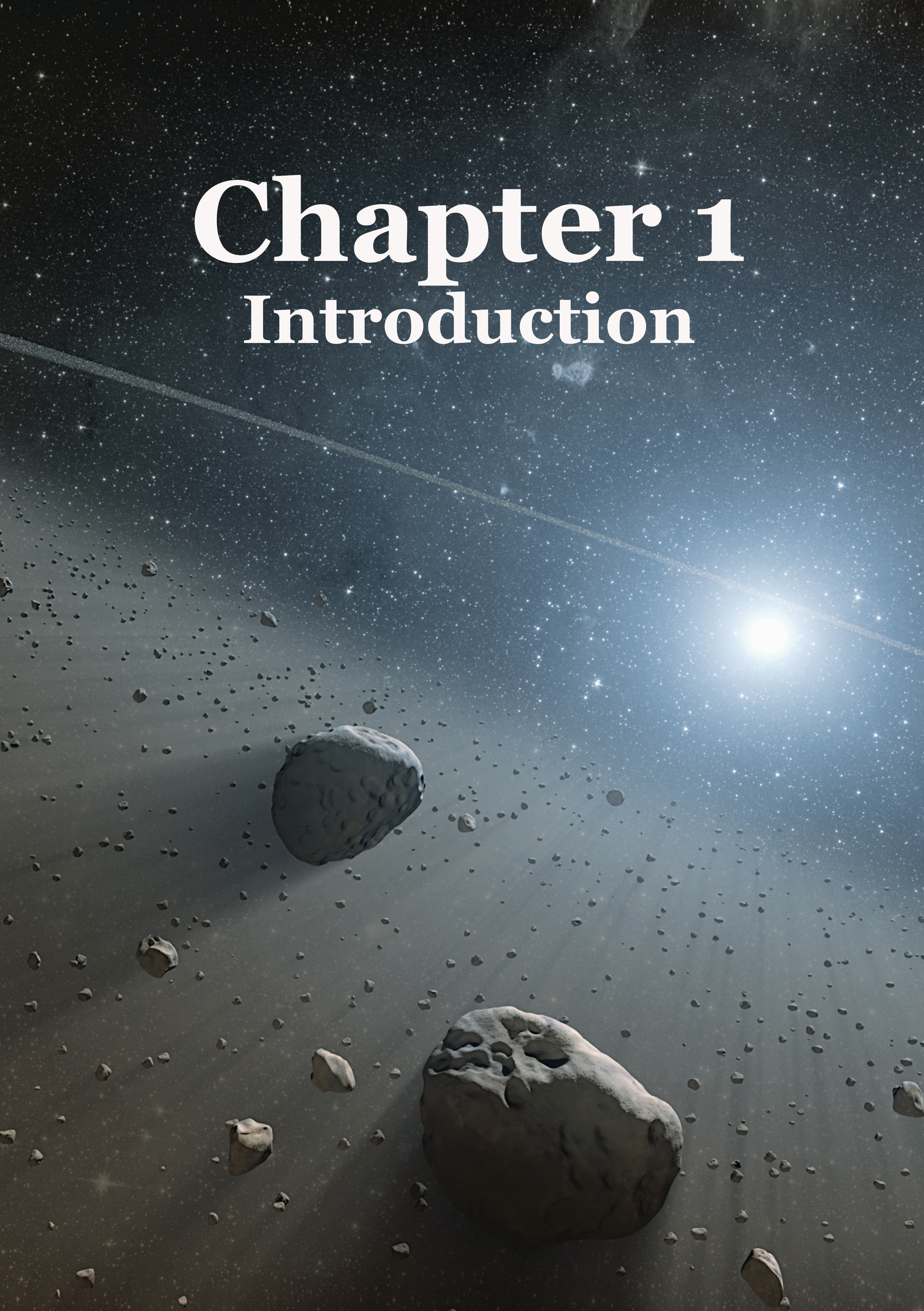
Chapter 1
Introduction



The solar system was formed approximately 4.56 billion years ago. Despite the numerous theories that have been developed over the years, the formation and evolution of the solar system still remains unclear (Pfalzner et al. 2015, and references therein). However, several advances have been made in our knowledge about the solar system. The most accepted theory about its formation and early evolution describes a gravitational collapse of a dense cloud of interstellar gas and dust. The conservation of angular momentum induced a rapid rotation of the collapsing cloud, flattening it until it became a protoplanetary disk. In the central, most dense region of the disk, a star was created — our Sun. In a similar manner, clumpy structures developed in the disk. These eventually grew to form the planets, dwarf planets and moons. The leftovers of this process led to the formation of small bodies, such as asteroids and comets. This is how the five main types of objects in the solar system were formed; the Sun, planets, dwarf planets, moons, and minor bodies (asteroids and comets). A schematic representation of the solar system is shown in Fig. 1.1.

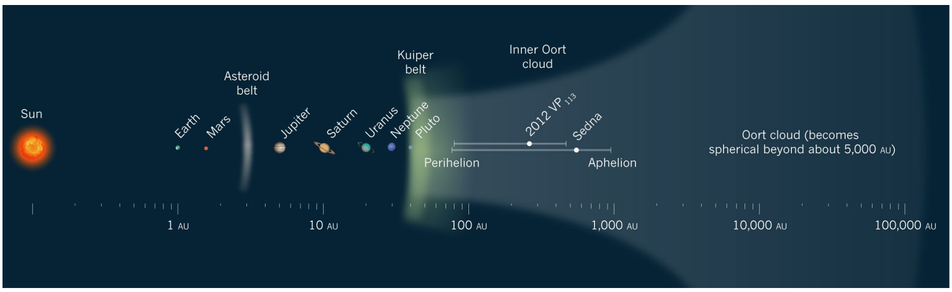


Figure 1.1: The solar system. Taken from Schwamb (2014).

The Sun is the main object in the solar system. It is a yellow dwarf star with a mass of $\sim 2 \times 10^{30}$ kg or $1\,M_\odot$ and temperature at the centre of $\sim 1.5 \times 10^7$ K. It is mainly made up of hydrogen (~73%) and helium (~25%), and it is located at the centre of the solar system where its gravity holds the entire system together. Planets are celestial bodies that orbit around the Sun. They are sufficiently massive for the gravitational forces that hold them together to be strong. These strong forces cause the interior of planets to be hot and melt, which in turn leads to their characteristic round shape. Additionally, planets cleared their orbit from smaller bodies. There are eight planets in the solar system: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune. Planets are located in the inner part of the solar system, which is commonly called the planetary region. The planetary region extends from the innermost planet (Mercury) located at 0.38 au from the Sun to the outermost one (Neptune) at 30 au.

Moons are celestial bodies that orbit around a planet or dwarf planet. To date, 182 moons have been discovered in the solar system. In contrast to planets, dwarf planets (e.g., Pluto, Ceres, Makemake) do not have a sufficiently strong gravitational field to empty their surroundings of small objects. They are therefore found in regions full of smaller rocks, such as in the asteroid belt and in the transneptunian region. The asteroid belt is situated between the orbits of Mars and Jupiter. The transneptunian region extends from the orbit of Neptune ($\sim$30 au) out to the outer edge of the scattered disk, around 100 au from the Sun.

Finally, the minor bodies are dived in two categories: asteroids and comets. They are located in three main regions: the asteroid belt, Kuiper belt/scattered disk and the Oort cloud. Asteroids are small and often irregularly shaped celestial bodies mainly found in the asteroid belt. Comets, on the other hand, are icy objects that belong to the Kuiper belt/scattered disk and the Oort cloud. The Kuiper belt/scattered disk, is the source of short-period comets (comets with orbits lasting less than 200 years). The Kuiper belt extends from 30 au to $\sim$50 au, while the scattered disk extends from $\sim$50 au to $\sim$100 au. The Oort cloud, the source of long-period comets (comets with orbits lasting more than 200 years), starts right after the scattered disk and extends half the way to the nearest star to the Sun, Proxima Centauri (Oort 1950).

To better understand the formation and evolution of the solar system, dynamical models are needed. In particular, the study of comets can reveal critical pieces of information about this process. The orbits of the comets in the inner part of the Oort cloud form a frozen record of the evolution of the solar system. At present, comets in this region are located at such large distances from the center of the solar system that perturbations from planets are negligible. They are rather at risk to be ripped away by passing stars or even the gravitational field of the Milky Way itself. Especially comets in the outermost regions are sensitive to such external influence, already during the early phases of the formation of the solar system (e.g., Torres et al. 2019a,b). These external influences have been shaping the Oort cloud over its history, producing comet showers reaching into the planetary region and stripping comets out into the interstellar space, forming interstellar comets.

Studying the dynamical evolution of comets can help us to constrain and to understand the formation and evolution of the solar system. Both the history of encounters between the solar system and nearby stars and the effect of the tides from the Galaxy are key components. The current distribution of nearby stars and the Galactic potential are reasonably well known. The Gaia mission (Gaia Collaboration et al. 2018, 2016) delivered a magnitude-limited complete sample of nearby stars. These stars dominate the local Galactic potential, and they give rise to occasional close encounters. Therefore, data from Gaia can be used as templates for the initial conditions in detailed simulations at different moments in time. Combining analytical, observational and numerical techniques are the key components to constrain and better understand the formation and dynamical evolution of the solar system.

In this thesis, I explored the formation and dynamical evolution of comets in the Kuiper belt/scattered disk and the Oort cloud, accounting for external perturbations such as passing stars and the galactic tidal field. As a consequence of these perturbations, the formation and evolution of interstellar comets were investigated. This thesis is divided into four main chapters. Chapter 2 treats the origin of the interstellar object 1I/2017 U1 ‘Oumuamua by comparing estimates based on observations with simulations (Sect. 2). Chapter 3 focuses on the dynamical evolution of the Oort cloud after the interaction with passing stars and the Galactic tidal field (Sect. 3). In Chapter 4, I studied the formation and evolution of the solar system’s Kuiper belt/scattered disk and Oort cloud in the early stages of their formation, when the Sun was still in its birth cluster (Sect. 4). Finally, Chapter 5 explores the formation of interstellar comets from the neighbouring stars of the Sun (Sect. 5). A summary of the main results of each chapter can be found in Sect. 1.3. The key research questions addressed in this thesis are:

1. What is the effect of multiple stellar encounters and the Galactic tidal field on comets in Oort cloud-like structures? (Chapters 3 and 5).
2. Was the formation of the Oort cloud triggered by planet-disk interaction and stellar encounters in the early solar system? (Chapter 4).
3. Where do interstellar comets come from and how do they form? (Chapters 2 and 4).

Section 1.1

Comets

Comets are icy objects that travel from the outer parts of the solar system (beyond the orbit of Neptune) into the planetary region. Once they approach the Sun, they are heated by solar radiation and become active. The sublimation of water ice produces a tail composed of dust and gas, commonly known as a coma (Nesvorny2017). The study of comets started thousands of years ago when the first civilizations painted on the walls of caves what now can be interpreted as a comet. There are three main categories of comets: short period (Sect. 1.1.1), long period (Sect. 1.1.2), and interstellar (Sect. 1.1.3). The study of comets can reveal key processes during the formation and early evolution of the solar system. Chemical studies indicated that comets carry organic molecules and share the same origin (Eistrup et al. 2019). They have, therefore, been considered as building blocks of life. This view is now also supported by the Rosetta mission (Glassmeier et al. 2007; Alves et al. 2015), which recently successfully visited a comet (67/P Churyumov-Gerasimenko). Rosetta discovered amino acids, glycine and phosphorus (all key components of DNA and cell membranes) in the coma of 67/P Churyumov-Gerasimenko (Altwegg et al. 2016) along with other organic compounds (Alves et al. 2015; Capaccioni et al. 2015). These results suggested a strong possibility that comets play an important role in the emergence of life on Earth (e.g., Rettberg et al. 2002; Horneck et al. 2010; Wickramasinghe 2011). With the recent discovery of the first interstellar comet (1I/'Oumuamua, Williams 2017) and the indications of water on the second (2I/Borisov, McKay et al. 2019), a new era in the study of comets has begun.

1.1.1 Short period comets

Comets with orbital period (P) shorter than 200 yr are classified as a short-period comet (SPCs). Short-period comets are subdivided into two types: Halley-type comets (HTCs) and Jupiter family comets (JFCs) (Morbidelli 2005; Nesvorný et al. 2017). These classifications are mainly based on the period of the comets, P_{JFC} <20 yr and P_{HTC} >20 yr). In the solar system, there are 393 short-period comets confirmed (Minor Planet Center 2020). The primary source of SPCs is the Kuiper belt and scattered disk, also known as the transneptunian region (Fig. 1.2).

Figure 1.2: Artistic representation of the Kuiper belt. Taken from ESA.

The formation and dynamical evolution of comets in the transneptunian region was mainly due to giant planets (Jupiter, Saturn, Uranus, and Neptune). The giant planets of the solar system did not occupy their current orbits after the gas was removed from the protoplanetary disk of the solar system. Several theories have been proposed to explain the migration of the giant planets. Fernández & Ip (1984) and later Malhotra (1993) showed that a disk of planetesimals around the giant planets would have driven the migration. However, a smooth planetesimal-driven migration could not explain several aspects of the orbital distribution of the Kuiper belt and scattered disk. Later, Thommes et al. (1999) showed that a dynamical instability produced among the giant planets would lead to an excitation of the Kuiper belt, which, in turn, forced the planets to their current orbits. A culmination of all these theories led to the development of the classic *Nice Model* (named after the city Nice in France, Gomes et al. 2005; Tsiganis et al. 2005; Morbidelli et al. 2005).

According to the Nice Model, the giant planets formed in a compact configuration with Jupiter around 5.5 au. Saturn was placed in such a way that it was slightly interior to the 2:1 mean motion resonance between itself and Jupiter. Neptune and Uranus were placed in orbits around 11–15 au. Simulations showed (Morbidelli et al. 2007) that a disk with a mass of ~ 35 $M_{\oplus}$ led to a slight migration of the orbits of Jupiter and Saturn until they crossed the 2:1 mean motion resonance, which made the system unstable. As a result of this instability and the interaction between the giant planets and the planetesimal disk, the short-period comets were formed

1.1.2 Long period comets

The outer regions of the solar system are populated by a large number of comets with period $P >$200 yr, known as long period comets (LPCs). Beyond the Kuiper belt/scatter disk and almost extending to the nearest stars (out to 100,000 au), resides the Oort cloud, the origin of LPCs (Fig. 1.3). The Oort cloud was proposed in the late 1950s, by the Dutch astronomer Jan Hendrik Oort at the Sterrewacht Leiden. Oort (1950) realized that long period comets, with semi-major axes (a) larger than 40 au bound to the Sun must come from an area well beyond Neptune. Oort (1950) pointed out that there is a spike in the distribution of $1/a$ of the long period comets with an

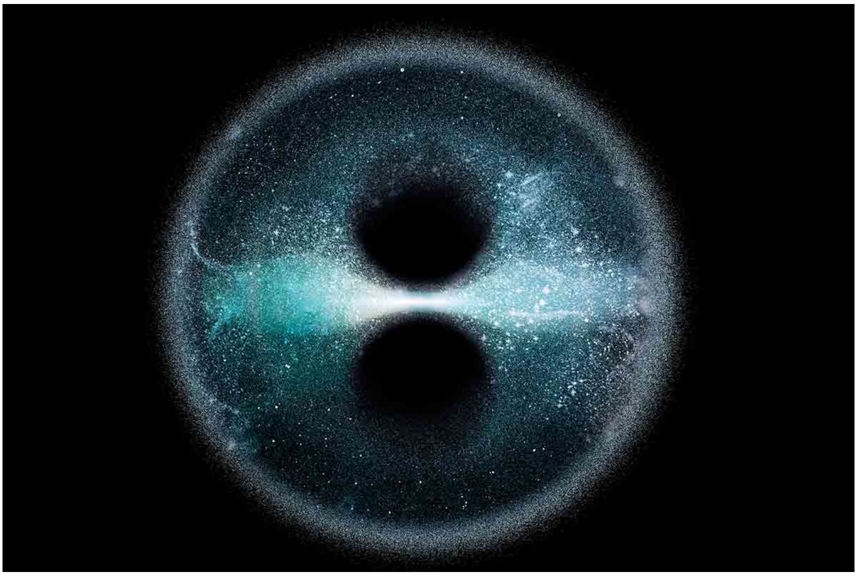


Figure 1.3: Artistic representation of the Oort cloud. Taken from Science Photo Library / Claus Luna.

$a < 10^4$ au (see Fig. 1.4 taken from Wiegert & Tremaine 1999). The LPCs also showed an isotropic distribution of their orbital inclinations. These findings argue for the existence of a reservoir of objects in quasi-spherical symmetry surrounding the solar system.

The estimated number of LPCs is around 1×10^{12} with a total mass of $\sim 4 \times 10^{25}\ kg$ (Morbidelli 2005), however, only about 1,065 have been observed (Królikowska & Dybczyński 2019). The Oort cloud is diveded into two main regions: the *inner* one is usually reserved for comets that reside in the cloud with semi-major axes $a < 20,000$ au, which are invisible unless there is a comet shower; and the *outer* that refers to comets with semi-major axes $a > 20,000$ au. The shaped of Oort cloud has remained unobserved to date, but its existence is derived from observations of LPCs.

Shortly after the solar system was formed, small bodies called planetesimals remained among the giant planets region (5<a<30 au). The giant planets scattered the planetesimals throughout the solar system until they reached eccentric orbits with large semi-major axis, but with a perihelion distance still in the planetary region. Those that reached a semi-major axis of $\sim$ 10,000 au started to feel a Galactic tide strong enough to modify their orbit on a timescale of an orbital period. Scattering by planets

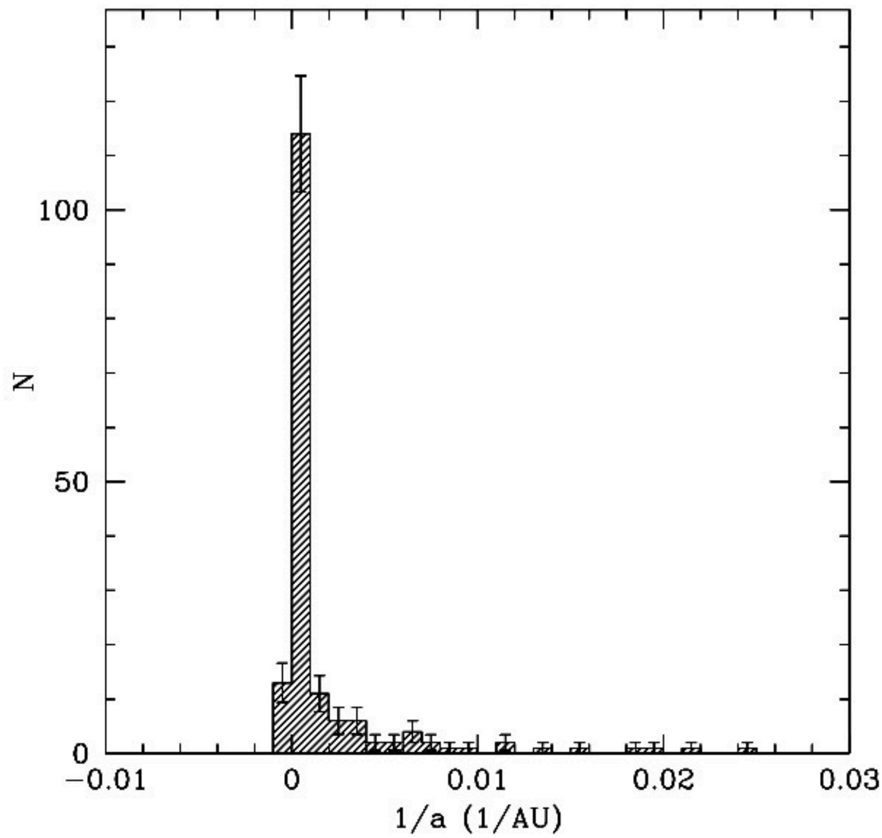


Figure 1.4: The differential distribution of LPCs as a function of the inverse semi-major axis. The big spike at $1/a < 10^{-4}$ is due to the "new comets", and is usually called the Oort spike (taken from Wiegert & Tremaine 1999).

alone should distribute planetesimals in a disk-like structure, close to the ecliptic plane (path of the Sun's motion as seen from the Earth). However, since the long-period comets are only loosely bound to the solar system, their orbits are significantly influenced by the Galactic tide, pushing them to large eccentricity e and inclinations i. Their perihelion distances were lifted beyond the planets' reach, thus they could not be scattered anymore and they became Oort cloud objects (Brasser & Morbidelli 2013, and references therein).

The evolution of the comets in the Oort cloud is strongly affected by the overall gravitational field due to mass distribution in the galaxy (galactic tide), sporadic passing stars, and giant molecular clouds, pulling up the comet perihelion out of the planetary region (e.g., Heisler & Tremaine 1986; Rickman 2014; Torres et al. 2019b). Passing stars change the perihelion distances of LPCs much more than they change the overall size of their orbit, deflecting the cometary trajectories and injecting the comets into the inner solar system ((Morbidelli & Nesvorny 2019)). In practical terms, the role of passing stars is to reshuffle the comet distribution in the Oort cloud, and to refill the high inclination region where comets are pushed into the planetary region by the Galactic disk's tide.

On the other hand, comets with a high inclination relative to the galactic plane under the effect of the tides from the galaxy increase their orbital eccentricity and decrease their perihelion distance q, so that they become planet-crossers. If this evolution is fast enough that q decreases from beyond $10\,au$ to less than $\sim 3\,au$ within half an orbital period, the comet becomes active during its first dive into the inner solar system without having interacted with Jupiter or Saturn during its previous orbits, namely it appears as a "new comet" (Dones et al. 2004). The rate at which comets are fed into the planetary region from the Oort cloud due to the galactic tide is probably slightly larger than the influx due to stellar passages (Heisler & Tremaine 1986). Assuming that the galaxy has a disk-like structure, the galactic tide would have a *disk* and *radial* force components. The z component of the *disk* causes the oscillation in and out of the planetary region in q, with a period of the order of $1\ Gyr$ for comets with $a \sim 10,000\,au$ and initial $q \sim 25\,au$. The *radial* component breaks conservation of the component of *a* comet's angular momentum perpendicular to the galactic plane, modulating the cometary perihelion distances (Heisler & Tremaine 1986; Duncan 2008). In general terms, the external perturbation of the Oort cloud delivers a rate of comets to the planetary system due mainly to galactic tides and during rare comet showers caused by an unusually close stellar passage.

1.1.3 Interstellar comets

Interstellar objects (ISOs) are asteroids or comets located in the interstellar space and are not bound to any stellar system. Before becoming ISOs, they most probably belonged to the reservoir of asteroids or comets in other planetary systems like the main asteroid belt, Kuiper belt and Oort cloud in our solar system. The origin of ISOs can be explained by several scenarios, like giant planet ejection, the mass loss associated with the creation of white dwarfs and binary systems or stripped from another star (e.g., Portegies Zwart et al. 2018; Bannister et al. 2019). In our solar system, there is two detected ISOs up to date, 1I/'Oumuamua (Williams 2017; Meech et al. 2017, Fig. 1.5 top panel) and 2I/Borisov (Borisov 2019, Fig. 1.5 bottom panel). However, the number density of ISOs in the interstellar space is expected to be large, about 0.1 per cubic au (Portegies Zwart et al. 2018; Do et al. 2018).

1I/'Oumuamua was discovered on 2017 October 19 by the PanSTARRS Near-Earth Object survey (Meech et al. 2017). Its closest approach to the Earth was at 0.16 au. The surface composition of 'Oumuamua showed red features at optical wavelengths of ~10-20%/100 nm (Bannister et al. 2019), similar to minor bodies in the solar system and consistent with organic-rich surfaces. The extreme brightness variations (a factor of ten, >2.5 magnitudes) implied that the core of 'Oumuamua was rotating in an excited state and its shape was highly elongated (Meech et al. 2017). Even though 'Oumuamua looked like a minor body from the solar system (due to its red colour), its highly eccentric orbit ($e \simeq 1.2$) and high velocity at infinity $V \simeq 26\, km\, s^{-1}$ (Williams 2017) reveal its interstellar origin. On the other hand, 2I/Borisov was discovered on 2019 August 30. The surface composition showed a similar colour to that of 'Oumuamua, however, 2I/Borisov was found to be actively outgassing (Jewitt & Luu 2019). 2I/Borisov's trajectory is extremely hyperbolic ($e \simeq 3.36$) with a high velocity at infinity $V \simeq 32.2\, km\, s^{-1}$Borisov 2019; Jewitt & Luu 2019. 'Oumuamua and Borisov's origin is still unknown, however, their high velocity implies that it was ejected during its host star's protoplanetary phase, and therefore is part of the left-over debris of star and planet formations processes in the galaxy (e.g., Portegies Zwart et al. 2018; Bannister et al. 2019; Higuchi & Kokubo 2019).

Figure 1.5: Top: artistic representation of 1I/'Oumuamua (taken from ESO/M. Kornmesser). Bottom: image of 2I/Borisov (taken from NASA, ESA, and D. Jewitt (UCLA)).

Section 1.2

Methods and data

1.2.1 Gaia

The European Space Agency's Gaia Spacecraft[1] launched in December 2013 (Perryman 2003; Gaia Collaboration et al. 2016, 2018): aims to make the most extensive and precise three-dimensional map of our Galaxy. This is done by surveying an unprecedented more than 1 billion stars, with about 70 observations of each star. Gaia provides us with the astrometric properties (positions and motion on the plane of the sky) of approximately 1 billion stars, radial velocities of about 150 million stars, and physical parameters like temperature and chemical composition of observed stars, extra-solar planets, near-Earth objects, among several other objects in the Galaxy. The scientific goals of the mission mainly focus on the study of the structure and dynamics of the Galaxy, star formation history, stellar astrophysics, photometric variability, planetary systems, solar system, and fundamental physics (Perryman 2003).

In the particular case of the solar system, Gaia is detecting nearly all of the local stellar systems within 50 pc from the Sun (compared to the 20% identified with Gaia's predecessor Hipparcos (Perryman et al. 1997; Anderson & Francis 2012). This allows the trajectories of a large number of stars in the solar neighbourhood to be traced back far in time. The accurate data from Gaia is cornerstone for the work presented in this thesis. With this information, I have synthesized an accurate census of the distribution and motions of stars in the solar neighbourhood. With this, in turn, I could determine the frequency and encounter history of nearby stars and the solar system and their impact on the comets of the Oort cloud.

The first Gaia data release (Gaia DR1, Gaia Collaboration, Brown et al. 2016) provided astrometry and photometry for over 1 billion sources with magnitude brighter than 20 and, positions, parallaxes, and proper motions for about 2.5 million Tycho-2 stars (TGAS, Michalik et al. 2015).

To estimate the current 3-dimensional positions and velocities of stars, I combined their positions, parallaxes and proper motions from the TGAS catalogue with their radial velocities presented in catalogues from RAVE-DR5 (Kunder et al. 2017), Geneva-Copenhagen (Nordström et al. 2004), Pulkovo (Gontcharov 2006), and XHIP (Anderson & Francis 2012) catalogues. To identify the past and future stellar encounters with the solar

[1] http://sci.esa.int/gaia/

system, I then used these 3D positions and velocities for the stars in the immediate solar neighbourhood (< 30 pc) to compute their trajectories backwards and forwards in time (± 10 Myr). The orbital integration of the stars was performed using an axisymmetric Galactic potential included in the module *Galaxia* in the AMUSE framework (Portegies Zwart & McMillan 2018).

The outcome of these simulations resulted in a catalogue of nearby stars to the Sun in the last 10 Myr and the coming 10 Myr (Torres et al. 2018). This catalogue served as a base to determine with more accuracy the closest encounters with the solar system. Particularly, the star Gliese 710 was found to have its closest approach to the Sun in $1.35 Myr$ at a distance of 0.06 pc (Torres et al. 2018) instead of 0.33 pc as it was predicted using Hipparcos data (e.g., Jimenez-Torres et al. 2011). Additionally, the catalogue of nearby stars provided the initial conditions necessary for calculating the close encounters that 1I/'Oumuamua had in the past 10 Myr before encountering the solar system (Portegies Zwart et al. 2018).

With the second release of Gaia (Gaia DR2, Gaia Collaboration et al. 2018), the accuracy of the data and the number of sources increased significantly with respect to the first data release. About 1.7 billion sources and approximately 7.2 million radial velocities were presented in the DR2 of Gaia. I updated the catalogue of stellar encounter (Torres et al. 2018, 2019a) with the more precise data from Gaia DR2 and now also including radial velocities from the catalogues of RAVE-DR5 (Kunder et al. 2017), GALAH DR2 (Buder et al. 2018), LAMOST DR3 (Zhao et al. 2012), APOGEE DR14 (Abolfathi et al. 2018), and XHIP (Anderson & Francis 2012). I used this catalogue, to study the dynamical evolution of the comets in the Oort cloud (Sect. 3) and the exo-Oort clouds around Sun's neighbour stars (Sect. 5) accounting for the cumulative effect of passing stars and the Galactic tidal field.

1.2.2 AMUSE

The Astrophysical Multi-purpose Software Environment or AMUSE[2] (Portegies Zwart & McMillan 2018) is an open source component library and a community effort with the main development by a team at Leiden Observatory. In AMUSE, existing numerical codes are combined into one single system employing a framework written in Python. AMUSE is made for performing astrophysical simulations and it is primarily created for the

[2] https://amusecode.github.io

fields of gravitational dynamics, stellar evolution, hydrodynamics and radiative transfer with Python framework. The AMUSE architecture is based on three main components: the user script, AMUSE library and the community codes. The user script is written by the user and acts as the interface to the AMUSE framework. The AMUSE library provides an object-oriented interface on top of the legacy codes, created for unit handling and data conversion. It contains the state engine and the associated data repository. A few examples of community codes that are included in AMUSE are Hermite0, Bonsai, Kepler, Mercury, Gadget-2, Huayno, Twobody, among several others. The user script and the AMUSE library that communicates with the code to perform the calculations. Overall, AMUSE is developed so that several different codes can be used to model and give a more complete picture of one astrophysical problem.

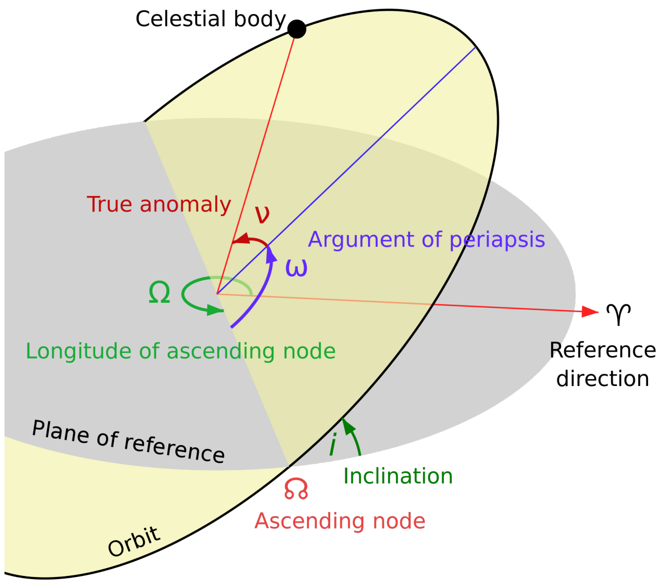


Figure 1.6: Orbital elements for a celestial body. Taken from Science Photo Library.

Taking advantage of the flexibility of AMUSE to use different codes to solve multiple physical problems, all the numerical tools of this thesis were built within the AMUSE framework. The community codes used in this work are: Kepler, ABIE, LonelyPlanets, Rebound, Gala, NBODY6++GPU, and Galaxia. Below I summarise the numerical tools developed and the codes used for the chapters in this thesis.

Chapter 2 – To find the possible home for 1I/'Oumuamua, I used the code Galaxia (Martínez-Barbosa et al. 2016) to perform the orbital integration of the stars within 50 pc from the Sun and 'Oumuamua. Galaxia is a galaxy model which contains axisymmetric and non-axisymmetric structures of the Milky Way. To perform our calculations, I adopted an analytic axisymmetric model of the Galaxy accounting for a spherical nucleus and bulge (Hernquist 1990), an axisymmetric disk (Miyamoto & Nagai 1975; Bovy 2015), and a spherical dark matter halo (NFW, Navarro et al. 1996). The galactocentric position of the Sun and the local circular velocity parameters were taken from Reid et al. (2014): $Z_\odot = 27$ pc, $R_\odot = 8.34$ kpc, and $V_{c,\odot} = 240$ km/s. The peculiar velocity of the Sun was adopted from Schönrich et al. (2010): $(U_\odot, V_\odot, W_\odot) = (11.1, 12.24, 7.25)$km/s.

Chapters 3 and 5 – I explored the dynamical evolution of the comets in the Oort cloud under the effect of passing stars and the Galactic tidal field. To do this, I first constructed an artificial Oort cloud. I used the package Kepler to calculate the orbital elements and perform the orbit integration of the particles in an isotropic and spherical distribution emulating the Oort cloud. The main function in the user script was built in such a way that it returns relative positions and velocity vectors in cartesian coordinates for the particles with orbital elements –semi-major axes, eccentricities, and mean anomalies. I considered that the 3D orientation of orbits were random (inclination, the longitude of ascending node and argument of periapsis). The distribution of the particles in the Oort cloud are set spherically symmetric and isotropic following a uniform distribution in the orbital elements $cosi$, ϖ,Ω, and M (Fig. 1.6). The initial eccentricities, e, are selected with a probability density distribution $p(e) \propto e$ and the perihelia, q, are chosen outside of the planetary region ($q >$32 au). The semi-major axes, a, are distributed proportional to $a^{-1.5}$ over the range $3{\times}10^3$-10^5 au.

Then using the GPU-accelerated direct N-body code ABIE (Cai et al. in prep) and the Astropy-affiliated python package for galactic dynamics Gala (Price-Whelan 2017), I integrated the orbits of the particles in the Oort cloud for a period of 20 Myr. ABIE and Gala were coupled in such a way that ABIE advances the positions of the Oort cloud particles and Gala calculates the accelerations on each particle due to the Galactic tidal field, based on the positions provided by ABIE. The calculated accelerations are subsequently inserted into the Gauss-Radau integrator in ABIE as additional forces. Additionally, the trajectories of nearby stars and their effect on the Oort cloud was calculated in ABIE by providing their positions and velocities as input.

Chapter 4 – To study the dynamical evolution of the solar system debris disk in a dense environment we used the codes LonelyPlanets which combines NBODY6++GPU (Wang et al. 2015) and Rebound (Rein & Liu 2012). I first used NBODY6++GPU with a Plummer sphere model (Plummer 1911) to simulate the open cluster, with an initial mass function ranging from 0.08 to 100 $M_\odot$ (Kroupa 2001), 2000 stars, and a virial radius of 1 pc. Using LonelyPlanets the solar system is constructed by placing the host star (a Sun-like star with 1 $M_\odot$), the giant planets (Jupiter, Saturn, Uranus, and Neptune), and a debris disk of 2000 test particles. Then the solar system and the cluster are evolved for 100 Myr. During this calculation, the code uses a data structure in a space with k dimensions (K-D tree algorithm) to find the five closest stars to the Sun at any given time. These five 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.

Section 1.3

Thesis

The major results of this thesis can be summarized in three main parts. The formation and density distribution of interstellar comets (Chapter 2 and Chapter 4). The prediction of a new type of comets: the transitional interstellar comets (Chapter 3 and Chapter 5). And, a new mechanism for the formation and evolution of short and long-period comets (Chapter 4). Below, I summarize each chapter.

Chapter 2 *The origin of interstellar asteroidal objects like 1I/2017 U1 'Oumuamua* (Portegies Zwart, Torres et al. 2018). I studied the origin of the interstellar object 1I/ 'Oumuamua by comparing estimates based on observations with simulations. Using the astrometric data from Gaia-TGAS (Gaia Collaboration, Brown et al. 2016), I integrated the orbit of 'Oumuamua and all the stars within 50 pc from the Sun. I find that about 1.3 Myr ago 'Oumuamua passed nearby the star HIP 17288 (label a in Fig. 1.7), and had three other close encounters during its journey towards the Sun (Fig. 1.7). I explored the different scenarios of formation for 'Oumuamua and concluded that objects like 'Oumuamua are formed in the debris disc as a leftover from the star and planet formation process, and subsequently liberated. I find that the mean galactic density of interstellar comets in the solar neighbourhood is $\sim 10^{14}$ per cubic parsec, which menas that we expect about 2–12 such visitors per year within 1 au from the Sun.

Chapter 3 *Galactic tide and local stellar perturbations on the Oort cloud: creation of interstellar comets* (Torres et al. 2019a). Using the positions, parallaxes and proper motions from the Gaia survey and combining them with radial velocities from RAVE-DR5 (Kunder et al. 2017), GALAH DR2 (Buder et al. 2018), LAMOST DR3 (Zhao et al. 2012), APOGEE DR14 (Abolfathi et al. 2018), and XHIP (Anderson & Francis 2012). I constructed a catalogue of the Sun's neighbour stars. Then, I calculated the closest encounters that the Sun has had with other stars in the recent past and will have in the near future (Torres et al. 2018, 2019a). I find that the star GJ710 will approach the Sun in 1.3 Myr at the distance of 0.06pc instead of 0.3pc as predicted by previous studies (e.g., Dybczyński & Berski 2015, and references therein). Then, using the catalogue of nearby stars, I studied the

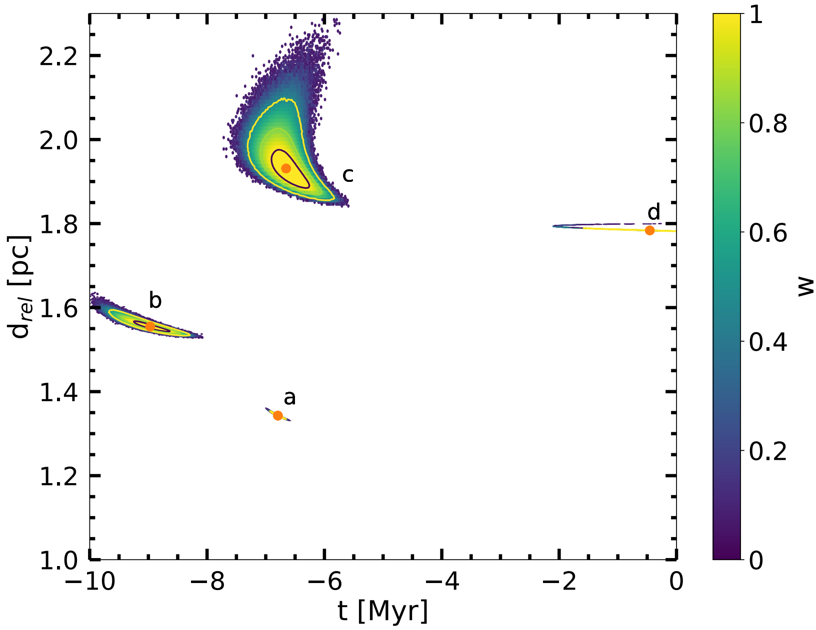


Figure 1.7: Probability density distribution in time of closest approach (t) and relative distance (drel) between ‘Oumuamua and the four closest stars. Labels a (GDR1 5108377030337405952), b (GDR1 4863923915804133376), c (GDR1 5140501942602437632), and d (GDR1 1362592668307182592) corresponds to the closest star to ’Oumuamua. Adapted from Portegies Zwart, Torres et al. (2018).

dynamical evolution of comets in the Oort cloud, accounting for the perturbation of the galactic tidal field and the cumulative effect of nearby passing stars. I find that the comets at the edge of the Oort cloud (80,000-100,000 au) get heavily perturbed and, as a result, the semi-major axis of ∼1.1% of the comets have increased to extend into interstellar regions (Fig. 1.8). Since the comets are still bound to the solar system, we consider them *transitional interstellar comets* (TICs). The first TIC candidate is the comet C/2018 V1 proposed by de la Fuente Marcos & de la Fuente Marcos (2019).

Chapter 4 *Dynamical evolution of the solar system debris disk in its birth cluster* (Torres et al. 2019b). I studied the creation and evolution of the solar system's Oort cloud in the early stages of its formation when the

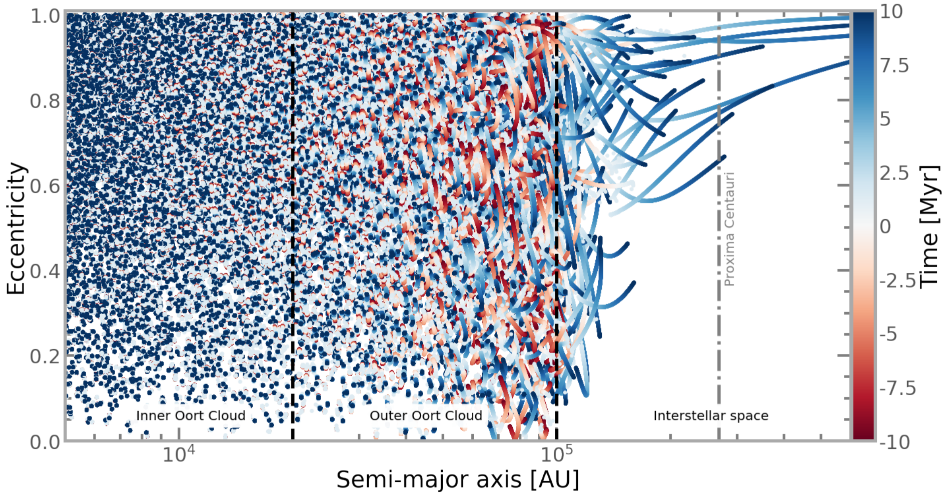


Figure 1.8: Orbital evolution of the particles in the simulated Oort cloud. The figure shows the evolution of the eccentricity as a function of the semi-major axis over the period of 20 Myr (±10 Myrs.). The colour bar represents the integration time. Adapted from Torres et al. (2019a).

Sun was still in its birth cluster (Torres et al. 2019b). I constructed two models for the solar system. In the first model, I assumed a compact debris disk (16-35 au), while the second we assumed an extended debris disk (40-1000 au). For both models, I account for the perturbations of the giant planets and nearby stars in the cluster. I find that the most efficient way to perturb a disk is when the angle of interaction between the solar system and the perturber is between 0-30 degrees independently of the size of the disk. Additionally, I find that the creation of the Oort cloud was triggered by secular encounters, which produce the scattered disk, Sedna, and Oort Cloud like objects (Fig. 1.9), while the giant planets creates Kuiper belt objects. Additionally, approximately 36% of the planetesimals are ejected becoming interstellar comets.

Chapter 5 *Dynamical evolution of exo-Oort clouds around the Sun's closest neighbours stars due to local stellar perturbations and the Galactic tidal field* (Torres et al. 2020). Using the catalogue of the closest stars constructed in Torres et al. (2018, 2019a), and the methods developed in Torres et al. (2019a,b), I calculated the closest encounter for each of the Sun's neighbour stars within 3 pc and with accurate astrometric data from Gaia DR2, i.e., Proxima Centauri, Barnard star, Gliese 65, Ross 154, and Ross

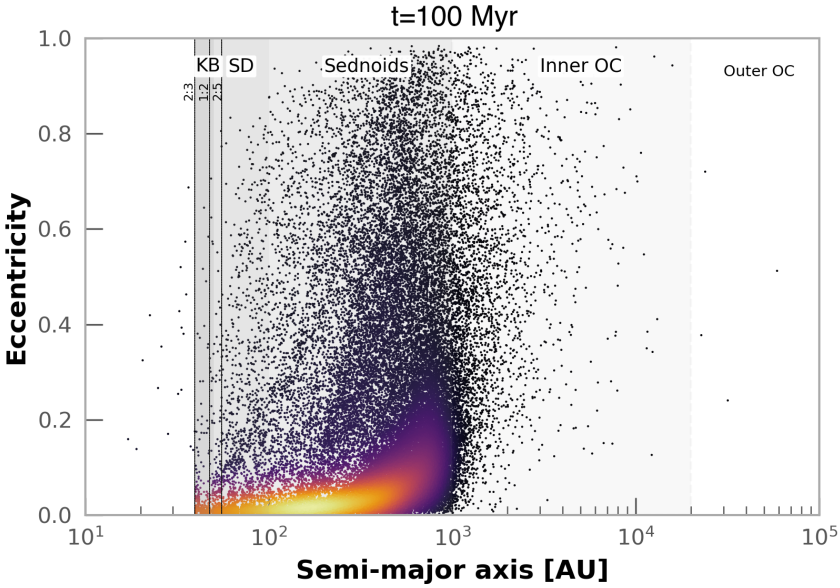


Figure 1.9: Semi-major axis as a function of eccentricity (top panel) and orbital inclination (bottom panel). The gray areas represent the different regions of the solar system (Kuiper belt (KB), scattered disk (SD), Sednoids, inner and outer Oort cloud (OC)), while the dashed lines show the 2:3, 1:2, and 2:5 resonances with Neptune. The integration time is set to 100 Myr. Adapted from Torres et al. (2019b).

248. I find that on average the stars in the solar neighbourhood experience around 40-55 close encounters during 20 Myr (Fig. 1.10), primarily with M-dwarf stars. I then calculated the effect of passing stars and the Galactic tidal field on the comets in exo-Oort clouds around the Sun's neighbour stars. The most perturbed system over a time interval of 20 Myr is Gliese 65 followed by Ross 154, Barnard's star and Ross 248 and finally Proxima Centauri. For Gliese 65 the production rate of transitional interstellar comets and interstellar objects is about 40×10^8 TIC Myr^{-1} and 1.4×10^{10} ISO Myr^{-1}. For the rest of the systems the rate of TIC production is about 2.1 to 3.8×10^8 TIC Myr^{-1}. This implies that a considerable number of interstellar comets reside in the local neighbourhood. Therefore the Sun and its neighbours are visited by interstellar comets originating from other stars. In this way, it is plausible that an interstellar comet cloud exists.

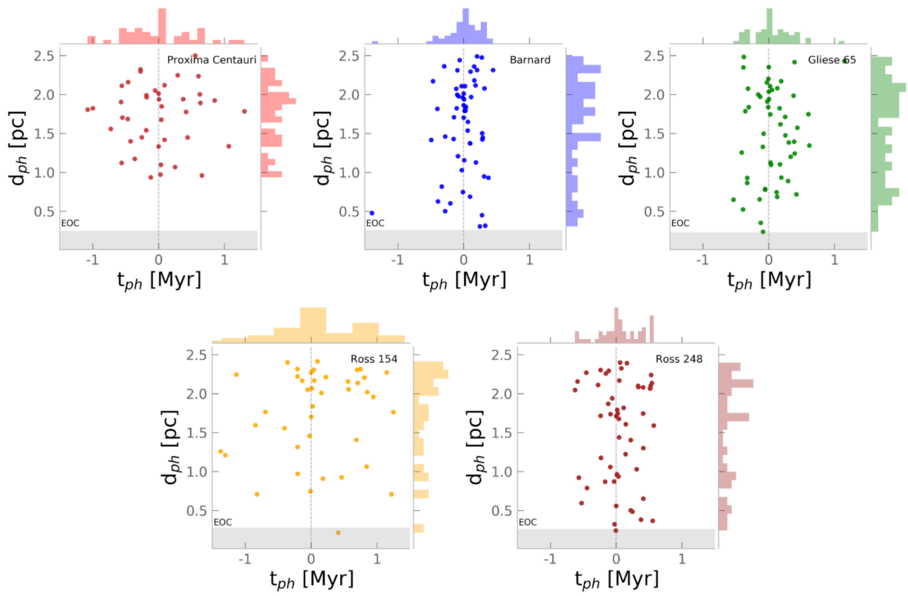


Figure 1.10: Closest approach distance vs time. The first panel corresponds for the closest encounters for Proxima Centauri (red), followed by the systems Barnard (blue), Gliese 65 (green), Ross 154 (yellow), and Ross 248 (brown). The histogram in each panel represents the distribution of the particles. The shaded areas represent the boundaries of the outer Oort cloud for each star, respectively. Adapted from Torres et al. (2020).