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Dynamics of the Oort cloud and formation of interstellar comets

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Summary

The **goal** of my thesis is to undertake a comprehensive study of the solar system's Oort cloud and the formation and evolution of interstellar comets.

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. S1.

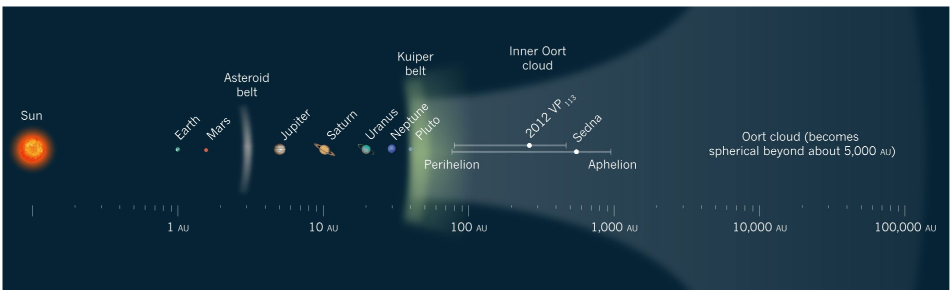

Figure S1: The solar system. Taken from Schwamb (2014).

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 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). Below, I summarize each chapter and the key research questions addressed in this thesis.

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).

Chapter 2 Based on: *The origin of interstellar asteroidal objects like 1I/2017 U1 'Oumuamua*, MNRAS 479, L17-L22 201, (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, and had three other close encounters during its journey towards the Sun. 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 Based on: *Galactic tide and local stellar perturbations on the Oort cloud: creation of interstellar comets*, A&A 629, A139, (Torres et. al., 2019). 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., 2017; Torres et. al., 2019). 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 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 $\sim$1.1% of the comets have increased to extend into interstellar regions. 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 (de la Fuente Marcos & de la Fuente Marcos 2019).

Chapter 4 Based on: *Dynamical evolution of the solar system debris disk in its birth cluster*, submitted to A&A recommended for publication (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 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 I 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 found that the creation of the Oort cloud was triggered by secular encounters, which produce the scattered disk, Sedna, and Oort Cloud like objects, while the giant planets creates Kuiper belt objects. Additionally, approximately 36% of the planetesimals are ejected becoming interstellar comets.

Chapter 5 Based on: *Dynamical evolution of exo-Oort clouds around the Sun's closest neighbours stars due to local stellar perturbations and the Galactic tidal field*, submitted to A&A, (Torres et. al., 2020). Using the catalogue of the closest stars constructed in (Torres et. al., 2017; Torres et. al., 2019), and the methods developed in (Torres et. al., 2019; Torres et. al., 2019b), 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 248. I find that on average the stars in the solar neighbourhood experience around 40–55 close encounters during 20 Myr, 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.