# Simulating the Formation of the Oort Cloud by the Grand Tack

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## 1 Project Summary

As of today, multiple theories concerning the formation of the Oort and Hills clouds exist. Examples are Hills (1981), where nearby passing stars perturb the orbits of objects in the Hills cloud in such a way that they form the Oort cloud, and Levison et al. (2010), where over 90% of the Oort cloud objects were actually captured by the sun from around other stars in its birth cluster. However, none of these theories is considered confirmed, so that the formation of the clouds remains a mostly unanswered question. In this project, we therefore will test another hypothesis concerning the formation of the Oort cloud: "The Oort cloud was formed due to the migration of Jupiter and Saturn in the first 5 Myr after formation of the solar system".

## 2 Background

### 2.1 The Oort Cloud

The Oort cloud is proposed to be an isotropic sphere with predominantly icy planetesimals surrounding the Sun at distances ranging from 2.000 to 200.000 AU (Morbidelli 2005). As of today, this is still a very mysterious structure, since it has never been directly observed. Its existence was inferred in 1950 by Dutch Astronomer Jan Hendrik Oort, who used observations of 22 then newly detected long period comets (Oort 1950). Some 30 years later, Jack G. Hills proposed the existence of an inner and outer Oort cloud, the former now known as the Hills cloud (Hills 1981). While objects from the Oort cloud fall into the planetary orbits at a steady rate, objects from the Hills cloud only enter when a nearby star passes by the sun at a sufficiently close distance (approximately the semi major axis of the orbit of the comets), causing a short but intense infall of objects.

## 2.2 Grand Tack Model

Whereas initially it was thought that the orbits of the planets had never evolved much from their initial states, this belief has recently been challenged; the so-called 'Grand Tack Hypothesis' postulates that in about the first 5 My years of the solar system, a fully formed Jupiter moved inwards from 3.5 AU towards the sun, as close as some 1.5 AU (Walsh et al. 2011). Saturn, a short while later, also moved inward but faster than Jupiter, until it was captured in a 2:3 resonance with Jupiter. When this happened, both planets started migrating outward to their present day orbits, pushing Uranus and Neptune outwards with them. During these movements, the giants crossed through the protoplanetary disk of planetesimals still present around the sun, destabilizing their orbits. Our hypothesis originates from the idea that these planetesimals were scattered outwards to form the Oort cloud. Simulations were already performed in 2004 by Dones et al. (2004), who showed that test-particle comets near Jupiter up until the Kuiper belt would be scattered outwards and reach a nearly isotropic inclination distribution with semi-major axes of 3000 - 200000 AU after 4 Gyr, which is in line with current understandings of the Oort cloud.

# 3 Description of the Proposed Work

To test our hypothesis, we will simulate the early solar system as a 5 body problem (i.e. the Sun, Jupiter, Saturn, Uranus and Neptune) with different initial conditions for the size, eccentricities and locations of negligible mass planetesimals. The choice for a 5- instead of N-body simulation is a necessary assumption; as N will be very large (At least on the order of $10^4$), having to calculate N-1 forces for all N bodies will take an extensively large amount of time. Calculating 5 forces for N bodies decreases this time by a factor of at least $\frac{N-1}{5}$ (depending on the N-body solving algorithm). This does come at the cost of a loss in accuracy, but taking into account that the current Mass-estimate for the Oort Cloud is about 5 Earth masses (Morbidelli 2005) distributed over a volume of about $10^{50}$ m$^3$, we expect this loss in accuracy to be negligible. Furthermore, we will neglect passing stars, since it has been shown that these will only perturb the motion of comets almost directly on their path, a relatively small tunnel (with radius 450 AU for a 1 $M_\odot$ star with velocity 20 km s$^{-1}$) compared to the whole cloud (Weissman 1996). Once a working model has been found, the effect of passing stars on the randomization of the Oort cloud could be investigated. The effect of galactic tides of the Milky Way – which possibly have a large effect on the formation of the Oort cloud – is initially also neglected, though may later be added to the model by for instance increasing the 5-body system to a 6-body system with the Galactic Center as latest addition. Molecular cloud encounters are rare and therefore also neglected.

The initial conditions for the simulation will be partly based on Weissman (1996) and Dones et al. (2004). For the simulations, we have decided to make use of the AMUSE-framework (McMillan et al. 2012). More specifically, we will use the pure N-body code `ph4`, which is an N-body solver that can run up to $10^5$-body simulations and is based on the fourth-order Hermite prediction-corrector scheme. Furthermore, it can be GPU-accelerated, which should be possible with the system we are using (see Section 4), allowing for faster calculations than the `Hermite` N-body solver.

The formation of the Oort Cloud is one of the remaining mysteries in our solar system. Solving this mystery would directly influence and improve our understanding of the early, as well as the present solar system. On larger scales, this understanding can teach us about the probability and possibility of similar structures in other planetary systems and the potential influence that they may have. As the Oort cloud has still not been directly observed, this project might in turn also give us stronger constraints on its structure. This would allow for better preparation of interstellar missions, as these will eventually all have to cross through the cloud.

## 4 Resources

The simulations mentioned above are expected to take considerable amounts of time on a regular computer. Therefore, should the integration time be estimated too large after the first tests, the simulations will instead be run on the ALICE High Performance Computing Facility at the University of Leiden[1]. We will first test what timestep is necessary for integration, to rule out significant perturbations on the long run; afterwards we will estimate the computation time of the complete 4 Gyr simulation.

## References

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[1] For more information, refer to https://www.universiteitleiden.nl/en/research/research-facilities/alice-leiden-computer-cluster

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