2-Gyr Simulation of the Oort-cloud Formation II. A Close View of the Inner Oort cloud after the First Two Giga-years

Giuseppe Leto · Marián Jakubík · Tomáš Paulech · Luboš Neslušan · Piotr A. Dybczyński

Abstract We simulate the formation of the Oort cloud (OC) till the age of 2 Gyr starting from an initial disc of planetesimals made by 10 038 test particles. The results on the outer part of the distant comet reservoir are reported by Neslušan et al. (this issue). Here we deal with the evolution of the population and structure at 2 Gyr of the complementary inner part of the Oort cloud. The dynamical evolution of the massless test particles was followed via the numerical integration of their orbits. We considered the perturbations produced by four giant planets assuming they have their current orbits and masses, as well as the perturbations caused by the Galactic tide and passing stars. The efficiency of the formation of inner OC is found to be very low: only about 1.1% of all considered particles ended in this part of the OC. At 2 Gyr, the dynamics of the inner cloud is mainly governed by the dominant z-term of the Galactic tide. The number density of the bodies is proportional to the heliocentric distance, r, as $r^{-3.53}$. The directional distribution of orbits is still strongly inhomogeneous. There are large empty regions in the space angles around the Galactic

G. Leto (✉)
Catania Astrophysical Observatory, Via Santa Sofia 78, Catania I-95123, Italy
e-mail: gle@astrct.oact.inaf.it

M. Jakubík · L. Neslušan
Astronomical Institute, Slovak Academy of Sciences, Tatranská Lomnica 05960, Slovakia

M. Jakubík
e-mail: mjakubik@ta3.sk

L. Neslušan
e-mail: ne@ta3.sk

T. Paulech
Astronomical Institute, Slovak Academy of Sciences, Dúbravská 9, Bratislava 84504, Slovakia
e-mail: astrotom@savba.sk

P. A. Dybczyński
Astronomical Observatory, A. Mickiewicz University, Słoneczna 36, Poznań 60 286, Poland
e-mail: dybol@amu.edu.pl

Equator points with the galactic longitude 90 and 270° (non-rotating frame), or there are only few bodies having the ecliptical latitude higher than +60° or lower than 60°. A strong concentration of objects at the Ecliptic is apparent up to $\approx 1,000$ AU, with a possible—but still not proved—extension to $\approx 1,500$ AU. Beyond $r \approx 6,000$ AU, bodies directly above and below the Sun, with respect to the Ecliptic, are absent.

Keywords Solar system: formation · Oort cloud

1 Introduction

This work is based on a simulation of the formation of the Oort cloud and describes the evolution till 2 Gyr of the so called inner OC. The simulation starts after the giant planet are formed. The Proto-Planetary Disc (PPD) is composed of $\sim 10,000$ massless test particles (TPs), and evolves under the perturbations due to giant planets, Galactic-tide and stellar close encounters. The inner OC as been hypothezed from the analyses of the properties of the dynamically *new* comets. Tracing their dynamical properties back in time along the last perihelion passage researchers noticed that the original (before entering the planetary region) semi-major axes of new comets were not shorter than a typical lower limit a_c. That limit was assumed as a dividing border between the so called inner and outer part of the OC. In the real Solar System, the comet cloud probably does not have such discontinuity and, most likely, it continually extends inward. The limit we actually experience is probably due to our limited observational capability. An introduction to the work and the complementary results on the outer part of the distant comet reservoir are reported by Neslušan et al. 2009 (this issue). Detailed description of the model and the full discussion of the results can be found in Dybczyński et al. 2008 and Leto et al. 2008, 2007.

2 Results

In the following we classify a given TP as a member of the inner OC if its perihelion distance is $q \geq 50$ AU and its semi-major axis is $2,000 < a \leq a_c$, where we adopt $a_c = 25,000$ AU, see Leto et al. 2008 for a detailed discussion on this definition.

2.1 Population Evolution

The left plot in Fig. 1 shows the evolution of the inner OC population along the time. During the first mega-year the inner-OC population quickly rises due to the ejections of TPs from the Jupiter-Saturn region, after reaching a very early maximum, it steeply decreases. Few mega-years after the beginning, it again increases till the maximum at about 1250 Myr. From this time, the erosion of the inner OC dominates over an increase of its population.

According to our simulation and definitions of the inner and outer OC, the formation efficiency of the inner OC is 1.1%. At 2 Gyr 90% of the TPs residing in the OC are in the Inner OC, 10% in the outer OC.
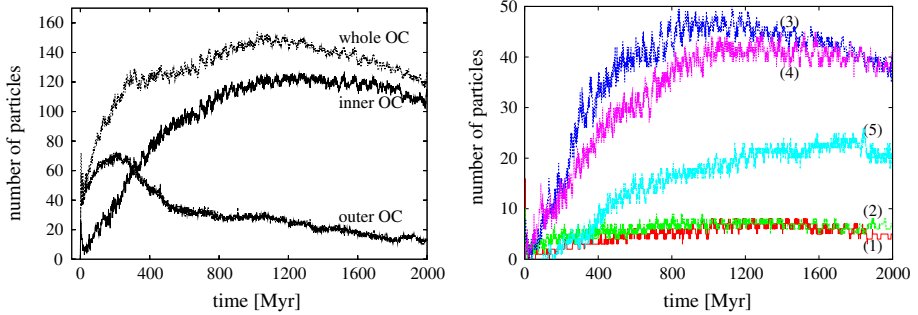
Fig. 1 *Left:* Time evolution of the population of the inner OC. *Right:* Distributions of TPs in time for different originating regions: *red line* (1) for Jupiter region, *green* (2) for Saturn, *blue* (3) for Uranus, *magenta* (4) for Neptune, and *cyan* (5) for KB. (Color figure online)

2.2 Population Origins

The TPs distributions versus time for different originating regions of the PPD are shown in Fig. 1 (*right*). Some consideration can be made: (a) The initial increase is due to Jupiter and Saturn regions TPs, (b) after ≈ 500 Myr the number of the TPs originating in the EKB region appears to be larger than each of the amounts from the Jupiter and Saturn regions, and clearly exceeds these amounts at 2 Gyr, (c) the largest amounts of Inner-OC TPs originate from the Uranus and Neptune regions, and (d) from 1.250 to 2 Gyr the inner-OC population slowly decreases

The composition of the Inner-OC population at 2 Gyr results as follows: 4% TPs from Jupiter region (4–8 AU), 6% from Saturn region (8–15 AU), 35.5% from Uranus region (15–24 AU), 35.5% from Neptune region (24–35 AU), and 19% from Kuiper-belt region (35–50 AU). A large number of TPs into the inner-OC are moved from the initial heliocentric distance 35–37 AU region that is the 4:3 mean-motion resonance with Neptune.

2.3 Radial Structure Evolution

At the end of the simulation the distribution of TPs in inner-OC is centrally concentrated, and the number density of the TPs residing in the OC in the interval $5,000 < r < 100,000$ AU can be fitted by the power law with the index of slope $s = -3.529$, see Fig. 2.

Fig. 2 Distribution of the particles along heliocentric distance at 2 Gyr residing in the Oort cloud (*cross-hatched bars*) and still bound to the Sun (*empty bars*). The solid line is the power law that best fits the data
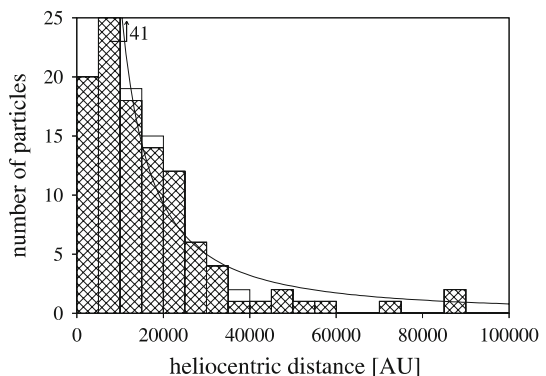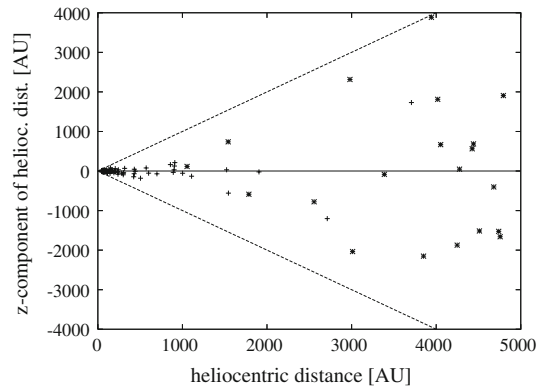
Fig. 3 *z*-component of heliocentric distance vs. heliocentric distance of the TPs

2.4 Flatness at 2 Gyr

The orbits in the innermost part of inner OC have a low inclination to the Ecliptic as expected, inclinations larger than $45°$ occur for $a \geq 4,000$ AU. TPs belonging to the central region of the Inner-OC, at least for $r \leq 1,000$ AU are located in a disc shaped region near the Ecliptic (see Fig. 3). Beyond this distance, more TPs are situated at a larger distance from the Ecliptic.

Our 2 Gyr results describe an interesting evolution scenario but cannot be extrapolated to the current inner OC as the evolution seems to be in a quasi steady-state only during the final short period, the extrapolation up to 4.5 Gyr can be an over-interpretation at this stage of the computation (see Leto et al., 2008, Sect. 2.4). Further simulations are already ongoing.

References

P. A. Dybczyński, G. Leto, M. Jakubík, T. Paulech, L. Neslušan, The simulation of the outer Oort cloud formation - The first giga-year of the evolution. A&A **487**, 345–355 (2008)

G. Leto, M. Jakubík, T. Paulech, L. Neslušan, PA. Dybczyński, The structure of the inner Oort cloud from the simulation of its formation for two Giga-years. MNRAS **391** 1350–1358 (2008)

G. Leto, M. Jakubík, L. Neslušan, P.A. Dybczyński, T. Paulech, The outer Oort cloud formation: Simulation of the first Gyr evolution, in *Proceedings of the Symposium "Grid Open Days all'Universita' di Palermo"*, (Consorzio COMETA, Palermo, Italy, 2007), pp. 53–58 ISBN 978-88-95892-00-9

L. Neslušan, P.A. Dybczyński, G. Leto, M. Jakubík, T. Paulech, 2-Gyr simulation of the Oort-cloud formation, I. Introduction on a new model of the outer Oort-cloud formation. This issue