The formation of the outer comet Oort cloud. Simulating the first giga-year of the evolution.

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Abstract. Through the numerical integration of orbits of 10 038 test particles, which represent the initial proto-planetary disc, we follow their dynamical evolution during the period of 1 Gyr. We consider the perturbations by four giant planets, Galactic tide, and passing stars. The evolution results in the formation of the distant comet cloud known as the Oort cloud. We show that the population of the outer Oort cloud reaches its maximum at about 210 Myr. From about 500 Myr, it becomes almost stable, with only a moderate decrease. At 1 Gyr, the population decreases to about 40% of its maximum. The efficiency of the formation appears to be very low. Only about 0.29% of all considered particles reside in the outer Oort cloud at 1 Gyr. From about 50 Myr to the end of the simulation, the orbits are not distributed randomly, but high galactic inclinations of the orbital planes are strongly dominant. The dynamical evolution of the particles can be seen in several animations of their appearance in the space as well as in the animations of the evolution of several important quantities describing the process.

1 Introduction

In the process of the solar-system planet formation, small bodies were ejected, by the growing planets, into the interstellar space and large heliocentric distances. Those bodies, which have remained to be gravitationally bound to the Sun, formed a distant cloud. It is now known as the Oort cloud (OC) of comets. Since this reservoir has been little changed after the formation of the solar system, its dynamical study provides an unique opportunity to verify our knowledge of the cosmogony of early solar system.

From the point of view of our capability to observe the comets coming from the continuous OC, the cloud is divided to the inner and outer parts. While the perturbers of the OC (Galactic tide, stars and gaseous clouds of interstellar matter passing nearby) can effectively reduce the perihelia of comets in the outer OC, the comets from the inner OC can enter the zone of visibility only after a long orbital evolution, which is impossible to be traced backward. As a consequence, we can well study only the dynamics of the outer part of the OC.

In our work, we assume the standard (with the surface-density profile proportional to $r^{-3/2}$) proto-planetary disc (PPD), which is represented by 10 038 test particles (TPs) in almost circular and co-planar orbits, and, via numerical integration, follow the dynamical evolution of these orbits during the first giga-year of the solar-system existence. More specifically, we consider a part of this disc spanning from 4 to 50 AU from the Sun. Since only the outer OC was formed during the considered period, we focuss our attention only to characteristics of this cloud. In the numerical integration, we consider the gravitational perturbations by four giant planets, Jupiter to Neptune, being in their current orbits and having their current masses, as well as the perturbations by the Galactic tide and nearly passing stars.

Our simulation is similar to those performed by Duncan et al. (1987) and Dones et al. (2005) (see also Dones et al., 2004). We adopt some more advanced initial assumptions. Duncan et al., using computational technique available that time, used the simplified assumption that initial orbits of TPs were already very eccentric. In total, they considered 1716 TPs and performed the integration of their orbits for 4.5-Gyr period. Similarly, Dones et al. considered 2000 TPs in so-called "cold run" and 1000 TPs in so-called "hot-run". The TPs in their models were initially distributed in the disc from 4 to 40 AU and the TP dynamics was studied for 4 Gyr.

2 The formation of the Oort cloud

On the basis of our simulation, we can sketch the following facts about the OC formation, mainly about its outer part. The evolution of the OC population is illustrated in Fig. 1. We can see that the population of the outer cloud sharply rises in the very beginning of simulation. After about the first mega-year, the increase is less steep. The population reaches its maximum at about 210 Myr after the beginning. A lot of comets are obviously not in very stable orbits, therefore the magnitude of the gradient of subsequent decrease can be compared with the magnitude of previous increase. Only at about 500 Myr, the cloud starts to consists of the bodies in a relatively stable orbits and the formation of this part of the OC can be regarded as practically complete. Of course, the outer perturbers (Galactic tide and passing stars) act continually causing a moderate decrease after this time.

A more detailed inspection of the final population, at 1 Gyr, reveals that only 29 of 10 038 TPs (i.e. $\approx 0.29\%$) reside in the outer OC in the end of our simulation. This is a considerably lower efficiency of the outer-OC formation

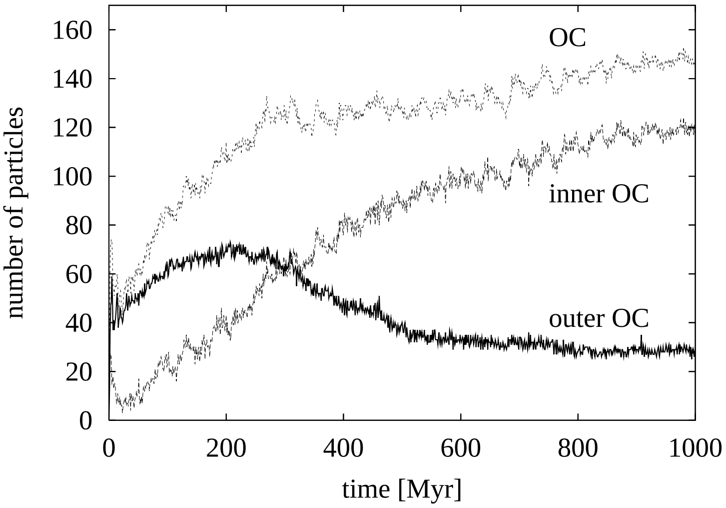

Fig. 1. The evolution of the population of entire Oort cloud as well as its inner and outer parts during the first giga-year of the solar system existence.

than those obtained in the previous simulations. Duncan et al. (1987) found that about 5% TPs were situated in the outer OC after 4.5 Gyr (though they considered the border between the inner and outer cloud in a smaller heliocentric distance and, thus, a little larger outer OC than in our work), and Dones et al. (2005) found 2.5% of TPs in the outer cloud at 4 Gyr (they also considered the little larger outer OC). Some differences in the initial assumptions should not crucially influence the result. A reason for the large difference is not known and will be searched for in a future study.

As seen in Fig. 1, the population of the inner OC is 4 times larger than that of the outer OC at 1 Gyr. We can expect that this ratio will further increase with time. This prediction from our simulation is more consistent with the corresponding result by Duncan et al. (1987), who found 20% of TPs in the outer OC at 4.5 Gyr, than with the result by Dones et al. (2005) predicting the 1:1 ratio at 4 Gyr.

Concerning the end states at 1 Gyr, it appears that the largest fraction of TPs is ejected into the interstellar space. Numerically, this is 6 532 of 10 038 TPs (65%). The fraction of 1 247 TPs (12%) ended in a collision with a massive body, mainly with the Sun. Only about 1.5% ended in the OC. The other TPs survive with the perihelion distance shorter than 45 AU.

It has been believed for a long period that most of the OC comets were created in a cool, outer part of the PPD (e.g. Weissman, 1990; Meech and Svoreň, 2004). The source regions of the comets in the outer OC in our simulations are indicated in Fig. 2. The shadowed bars illustrate the numbers of outer-OC residents originating in the region of shown heliocentric distance at 1 Gyr. The

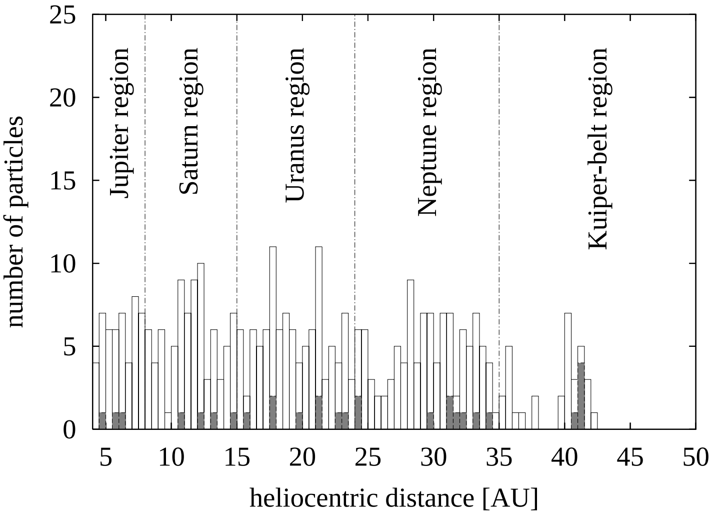

Fig. 2. The amounts of the comets moved into the outer OC from the shown intervals of heliocentric distance. The shadowed bars illustrate the distribution of these comets at 1 Gyr, while the empty bars illustrate the cumulative distribution of comets, which occurred in the outer OC whenever during the first giga-year.

empty bars represent the corresponding numbers for the comets, which ever occurred, at least for a while, in the outer OC during the studied period.

A more exact statistics implies that there are 11%, 14%, 27%, 29%, and 19% comets in the outer OC originating in the Jupiter, Saturn, Uranus, Neptune, and Kuiper-belt regions, respectively. Though the fraction from the Uranus-Neptune-Kuiper-belt region still dominates, the fraction from the more inner Jupiter-Saturn region is equal to 1/4. Therefore, it is not very surprising if a comet with the chemical composition corresponding with the origin in a hotter region of the solar system is discovered (e.g. comet C/1999 S4, at which Boehnhardt (2001) and Mumma et al. proved its Jupiter-Saturn formation region).

In our work, the outer border of the initial PPD is larger (50 AU) than in the previous studies. An unexpected fruit of this enlargement is the discovery of quite significant fraction of outer-OC comets originating beyond about 35 AU. This region has been regarded as not very active, dynamically. The explanation of this surprise can obviously be the fact that the concerning TPs originate in a narrow interval of heliocentric distance from 41 to 42 AU, which corresponds with the 5:3 mean-motion resonance with Neptune.

The mentioned fact, that the bodies in orbits beyond ≈ 35 AU are not very dynamically active, can also be seen in Fig. 3 illustrating the distribution of the TPs still residing (after 1 Gyr) in the planetary region. The population beyond ≈ 35 AU is relatively conserved, expect of the Neptune's 5:3 mean-motion resonance. Another survivors reside near the Jupiter's orbit, at about 5 AU. These

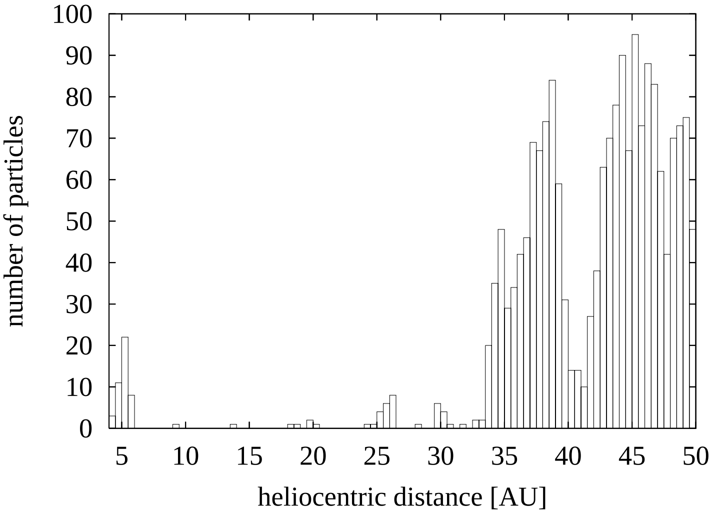

Fig. 3. The distribution of surviving bodies in the region of initial proto-planetary disc considered after 1 Gyr of their dynamical evolution.

bodies can certainly be identified with the well-known Jupiter trojans. Between 5 and 35 AU, there are only few bodies. The animation (see the next section) reveals that their position is not stable. This transiting population obviously represents the well-known group of Centaurs (and Jupiter-family comets, possibly).

On the basis of their simulation, Duncan et al. (1987) claimed that the orientation of orbits in the comet cloud is completely randomized, by the outer perturbers, after about 1 Gyr. Our result is again different in one aspect. In the distribution of the cosine of galactic inclination, a peak at the value of $cos(i) = 0$ occurs after about 50 Myr and survives till the end of the simulation at 1 Gyr (Fig. 4). The explanation seems to be the dominance of the disc component of the Galactic tide among the outer perturbers. Neslušan and Jakubík (2005) presented an example of a comet with very short perihelion distance in the moment, when the minimum of this element occurs during the corresponding libration cycle. The libration cycle of the inclination is bounded with that of the perihelion distance. In the example, the galactic inclination approached the value of $i = 90^o$, corresponding with $cos(i) = 0$, for a relatively very long time during its libration cycle. Such a behaviour of the inclination can be expected at each comet in the orbits with libration-cycle minimum perihelion distance in the zone visbility. If the inclination is high for a long time, then this circumstance must be reflected in the corresponding distribution.

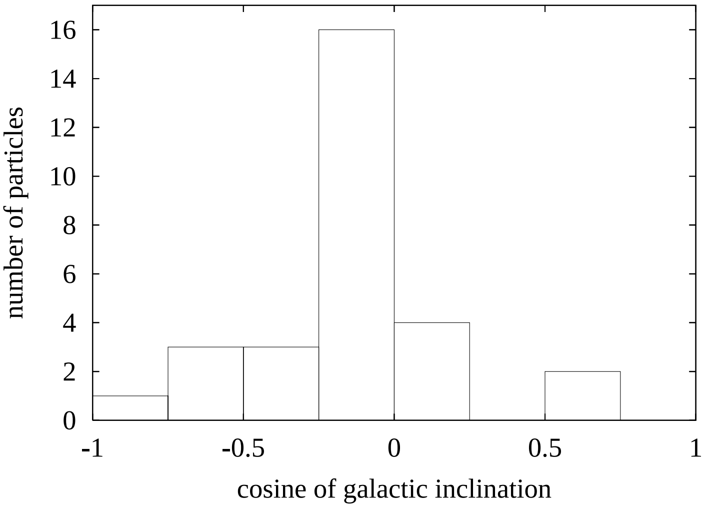

Fig. 4. The distribution of the cosine of galactic inclination of the comets residing in the outer OC at 1 Gyr.

3 The description of the animations provided

The process of the OC formation is too difficult to be described in detail, in a text. Its important features are better seen in a series of snapshots. On http://www.ta3.sk/~ne/GCCP07_ANIMS/, there are following animations showing the evolution of the characteristics of the TPs considered.

(1) PPD_pole_myr.mpg, PPD_pole_gyr.mpg – the dynamical evolution of TPs in the PPD; view from the pole.

(2) PPD_edge-on_myr.mpg, PPD_edge-on_gyr.mpg – the dynamical evolution of TPs in the PPD and surrounding region; edge-on view.

(3) OC_slant_myr.mpg, OC_slant_gyr.mpg – the dynamical evolution of the comet population inside the sphere of radius equal to 175 000 AU; slant view.

(4) OC_at_1gyr.mpg – a "sightseeing tour" through the OC with the instantaneous structure recorded exactly at 1 Gyr after the beginning of the simulation. The "flight" begins from the distance of 178 000 AU and goes on inward, down to 120 AU. The view is slant.

(5) fig2_myr.mpg, fig2_gyr.mpg – the evolution of the occurrence of TPs in the outer OC with respect to their place of origin, indicated at the abscissa. The shadowed bars illustrate the distribution in the given moment and empty bars illustrate the cumulative distribution of the TPs, which ever occurred (from the beginning of the simulation to the given time) in the outer OC. The last snapshot of the second animation is identical to Fig. 2.

(6) fig3_myr.mpg, fig3_gyr.mpg – the evolution of the TP population surviving in the planetary region, its part from 4 to 50 AU corresponding to the

extent of initial PPD considered. The last snapshot of the second animation is identical to Fig. 3.

(7) fig4_myr.mpg, fig4_gyr.mpg – the evolution of the distribution of orbital galactic inclination of comets in the outer OC. The last snapshot of the second animation is identical to Fig. 4.

The animations (1)–(3) and (5)–(7) show the appropriate evolution in two intervals: the rapid evolution during the first mega-year is shown in the first ("myr") movie, while the overall evolution from the beginning up to 1 Gyr is shown in the second ("gyr") movie.

4 Conclusions

Our simulation of the OC formation, using a larger number of TPs than by the authors in the past, confirms the main, well-known features of this process: (i) the forming planets eject a much larger fraction of the TPs into the interstellar space than into the comet cloud gravitationally bound to the Sun; (ii) nevertheless, the Galactic tide detaches the perihelia of many TPs from the planetary perturbing region and stabilizes these TPs in the distant reservoir; (iii) except of the dynamically active outer comet cloud, the inner cloud is formed as well; (iv) Galactic disc is the dominant outer perturber of the comet orbits in the OC; (v) though the Galactic tide and passing stars gradually erode the OC, the rate of the erosion is slow enough to allow the OC existence at the present; (vi) Jupiter's trojans occur soon and most of them survive during the entire age of the solar system; (vii) a lot of TPs survive in the region of heliocentric distances beyond ≈ 35 AU that is consistent with the observed Kuiper belt.

However, our simulation also predicts some details that are different from the well-known scenario of the formation process: (i) the efficiency of the OC formation, especially its outer part, is several times lower than yielded from the previous simulations; (ii) it is not clear what was the ratio of the sub-populations of inner and outer clouds, because various simulations give different values; (iii) either the time shedule of when the OC population reached its maximum and from what time is in a quasi steady-state is not clear; (iv) a significant fraction of outer-OC comets originate in a relatively hot, Jupiter-Saturn region of the PPD; (v) another non-negligible fraction is found to originate from the Kuiper-belt region, from the Neptune's 5:3 mean-motion resonance (semi-major axes ≈ 42.25 AU); this finding implies a question if some comets do not originate from even more distant resonances, beyond 50 AU, which have not been studied, yet. All this implies that the further studies clarifying the particular controversies are still necessary. (The more comprehensive description of our work and its results will be presented elsewhere (Dybczyński et al., 2007).)

Acknowledgements. L.N., M.J., and T.P. thank to the project "Enabling Grids for E-scienE II" for the provided computational capacity and support in development of the computer code, which was necessary for a management of tasks on the GRID. Especially, they thank Dipl. Eng. J. Astaloš for his kind assistance. They also acknowledge the partial support by VEGA – the Slovak Grant Agency for Science (grant No. 7047). G.L. thanks the "Trinacria Virtual Laboratory" (http://www.trigrid.it/) for the computational resources and technical support.

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