Earth Moon Planet (2009) 105:379–383
DOI 10.1007/s11038-009-9303-1

The Outer Part of the Scattered Disc from the Simulation of the Formation of Small-body Reservoirs

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Received: 14 November 2008 / Accepted: 3 April 2009 / Published online: 23 April 2009

Abstract Considering the model of the initial disc of planetesimals consisting of 10,038 test particles, we simulated the formation of small-body reservoirs in the outer Solar System for the 2-Gyr period. We present the results from the simulation, which concern the part of the scattered disc with objects that have the semi-major axes larger than 50 AU and do not cross the Neptune's orbit. A suitable border between the scattered disc and the inner Oort cloud, in terms of semi-major axis, appears to be no more than 2,500 AU. The simulated and observed values of perihelion distance and inclination to the Ecliptic typically cover the range between 30 and 40 AU and from 0° to 30°, respectively. No simulated or observed values of the inclination exceed 45°. The distributions of eccentricity and inclination in the simulation are more consistent with their observed counterparts, if the primary observational selection effects are imitated in the simulated distributions.

Keywords Solar system: formation · Scattered disc

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1 Introduction

In two previous works (Dybczyński et al. 2008; Leto et al. 2008), we performed a simulation of the evolution of the once existing proto-planetary disc (PPD) considering the massless test particles (TPs). In more detail, we considered the model of the initial disc of planetesimals consisting of 10,038 TPs. We studied their dynamics during 2 Gyr. The influence of four giant planets, Galactic tide, and nearly passing stars was considered. (A more detailed description of the initial conditions can be found in Dybczyński et al. 2008) On the basis of this simulation, we described the formation and some structural characteristics of the outer (Dybczyński et al. 2008) and inner (Leto et al. 2008) Oort cloud (OC, hereinafter).

In this contribution, we again use the data from the former simulation, especially the end-state at 2 Gyr, and describe some features of the structure of outer part of the trans-Neptunian scattered disc (or "outer scattered disc"; OSD, hereinafter). An object is regarded as a resident of the OSD, if its semi-major axis is larger than 50 AU, eccentricity exceeds 0.15, and it does not cross the orbit of Neptune. The part of the scattered disc satisfying this definition can be well-distinguished from the Edgeworth–Kuiper belt. This is the reason why we study the outer part separately. Few objects of the extended scattered disc, satisfying the above definition and having so large perihelia that they seem to be beyond the influence of Neptune, are studied together with the OSD objects.

To compare our results from the simulation with observational data, we select the OSD objects from the databases of the Centaurs and scattered-disc objects (213 orbits) and trans-Neptunian (TN) objects (1,075 orbits). The databases were downloaded from the Minor Planet Center web site on February 28, 2008.

2 The Border Between the Scattered Disc and Inner Oort Cloud

According to the recently published paper by Kaib and Quinn (2008), a body is member of the OC if its perihelion distance is larger than 45 AU. In contrast to this definition or those of several other authors, we regard the bodies as OC residents only when the outer perturbers (Galactic tide, passing stars, etc.) can significantly influence their orbits.

The bodies in the vicinity of the planetary region are exclusively perturbed by the giant planets, by Neptune in particular. If a planetary perturbation considerably enlarges the aphelion distance of a body, it becomes to be significantly perturbed by the outer perturbers, especially the Galactic tide. In this context, we can distinguish between two dynamical regimes: (i) a body is perturbed only by planets and (ii) a body is perturbed by both planets and outer perturbers. In this section, we attempt to reveal a border between these regimes. In other words, we attempt to find a border between the most distant TN populations and inner-most part of the OC.

The planetary perturbations become weak, when a perturbed-body perihelion distance is enlarged far beyond Neptune. Therefore, the perihelion distance cannot exceed a certain upper limit, if the given body is perturbed only by planets. In this situation, bodies can only occur at very large heliocentric distances when they move in orbits with an enlarged semi-major axis. However, their perihelia still remain in the planetary region. Therefore, the eccentricity, e, of bodies reaching the OC region must approach unity.

A characteristic consequence of the action of the dominant outer perturber, z-component of the Galactic tide, are periodic variations of orbital elements, except of the semi-major axis which changes negligibly. When the tide becomes efficient, the previously enlarged eccentricity of some bodies again decreases. We found that such a decrease is clearly evident for the bodies in orbits with $a > rapprox\,2,500\,\mathrm{AU}$. This implies that the border between the OSD and inner OC is $a_b \lessapprox 2,500\,\mathrm{AU}$, in terms of the semi-major axis. Of course, we must remember that this border is time-dependent, in principle. The Galactic tide also changes the orbits with a very small a-value, if there is enough time. It is reasonable to consider only a significant change that can occur during the age of the Solar System.

3 Some Features of the Structure of OSD

After the selection of bodies in orbits with $a \geq 50$ AU, $e > 0.15$, and not crossing Neptune's orbit (i.e. with $q > Q_N$, where $Q_N = 30.32$ AU is Neptune's aphelion distance), their simulated distribution in the $e{-}a$ phase space is shown in Fig. 1a. It exhibits a characteristic bow-like structure, which starts at low eccentricities and gradually approaches the eccentricity $e = 1$. The condition that OSD objects must not cross the Neptune's orbit implies a forbidden region of the $e{-}a$ phase space above the thick, solid curve in Fig. 1, in which no OSD object can be situated. The thin, dotted curve in Fig. 1 delimits the region with the perihelion distances $q > 40$AU on the other-hand side. Few points below this curve correspond to the bodies that have $q > 40$ AU and are usually classified as residents of the extended scattered disc.

The phase space corresponding to the low values of e, farer from the upper-e border (thick solid curve in Fig. 1) is almost empty. This fact is obvious in the situation, when only the planets perturb the orbits of TN bodies and the perihelion distance cannot be typically enlarged beyond about 40 AU as we found. Nevertheless, if the initial PPD extended beyond 50 AU, then the corresponding population of bodies with a very low eccentricity should still be present in this region. The dynamical regime of such bodies is however different from that of scattered-disc objects. So, we distinguish between the two groups requiring that the OSD objects have $e > 0.15$. In our simulation, TN bodies with $a > 50$ AU and $e \to 0$ are missing since we deliberately truncated the initial PPD at 50 AU.

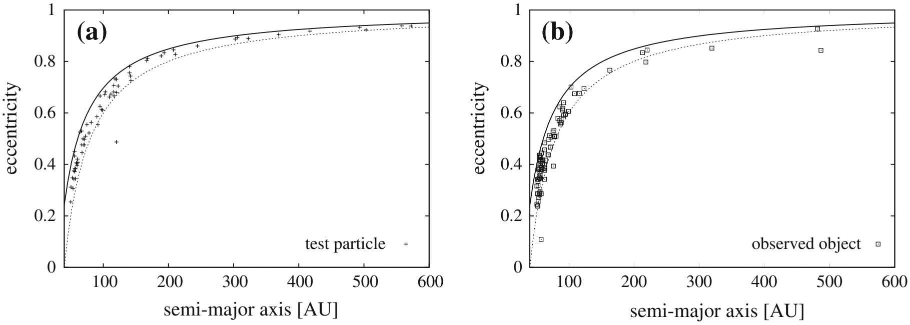

Fig. 1 Distribution of OSD objects in the eccentricity vs. semi-major axis phase space for the interval of semi-major axis $50 \leq a \leq 600$ AU. The distribution of TPs in our simulation at 2 Gyr is shown in plot (**a**) and that of all known observed objects in plot (**b**)

The truncation of the real classical Edgeworth–Kuiper belt beyond 50 AU heliocentric distance has, however, been an enigma for several decades.

When comparing simulated and observed distributions of three orbital elements, the following features of the OSD can be stated. A direct comparison is unfortunately impossible due to the observational selection effects. For a single-parameter theoretical distribution, we imitate the primary selection effects that occur due to the decrease of apparent brightness of objects with increasing heliocentric and geocentric distances. We neglect the effects due to the inhomogeneity of observations searching for the TN objects in the sky, which have been concentrated mainly near the Ecliptic. These effects are practically impossible to be described and imitated. Although the imitation of only primary selection effects does not cover all the selection effects, it still helps us to reveal a trend of the bias in a given distribution that can be expected due to the observational selection. In addition, the inhomogeneity of observations does not largely affect the OSD population, since these objects have been searched and discovered at large angular distance from the Ecliptic, where the observational bias is lower.

Dealing with the distribution of the perihelion distance, q, of OSD objects, a direct comparison between its simulated and observed distribution is impossible because of the poor statistics. We can only state that q of the objects in orbits with $a \geq 50$ AU and not crossing the Neptune's orbit in both distributions typically ranges from about 30–40 AU. There is only a single TP in the theoretical distribution slightly exceeding 40 AU and another TP with $q = 61.6$ AU, $a = 120.1$ AU, $e = 0.487$, and $i = 42.9°$. Few orbits in the observed distribution with $q > 41$ AU and especially $q > 44$ AU (orbits of members of the extended scattered disc) do not correspond with any orbits obtained within our simulation. Further studies of this part of the TN phase space are needed. The q-distribution does not seem to be much affected by the observational bias.

In the distribution of the eccentricity, e, of the OSD objects, constructed on the basis of our simulation, higher values are more abundant and the maximum occurs at 0.65–0.7. Because of the observational selection effects, we have discovered a relatively lower number of OSD objects with high e-values. This fact can be demonstrated applying the correction for the primary selection effects to the distribution. In this "biased" distribution, the maximum appears at 0.4–0.45 values and the distribution is much more similar to the observed one. A common feature of both theoretical and observed e-distributions is the absence of bodies with $e < 0.22$ (our definition constrains the eccentricity as $e > 0.15$). This is obviously a consequence of the fact that typically $q < 40$ AU and $a \geq 50$ AU by definition.

The inclination to Ecliptic, i, of OSD objects typically spans from 0° to about 30°. Only few bodies move in orbits with $i > 30°$ (most of them are in the simulated distribution) and no TP or known real object in the database has $i > 45°$. According to our results, the observational bias causes a shift of the maximum in the i-distribution from $10°-15°$ to $15°-20°$.

Acknowledgements M.J., T.P., and L.N. thank the project "Enabling Grids for E-sciencE II" (http://www.eu-egee.org/) for the provided computational capacity and support in the development of the computer code, which was necessary for the management of tasks on the GRID. They also acknowledge the partial support of this work by VEGA—the Slovak Grant Agency for Science (grants Nos. 7009 and 7047). P.A.D. acknowledges the partial support of this work from the Polish Ministry of Science and High Education (year 2008, grant No. N N203 302335). G.L. thanks the PI2S2 Project managed by the Consorzio COMETA, http://www.pi2s2.it and http://www.consorzio-cometa.it for the computational resources and technical support.

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