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Structure and Dynamics of the Centaur Population: Constraints on the Origin of Short-Period Comets

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Abstract. The origin of Jupiter-family comets is linked to the intermediate stage of evolution through the Centaur region. Thus the structure of the Centaur population provides important constraints on sources of short-period comets. We show that our model of the Oort cloud evolution gives results which are consistent with the orbital distribution of observed Centaurs. In particular, it explains the existence of the large population of Centaurs with semimajor axes greater than 60 AU. The main source for these objects is the inner Oort cloud. Both Jupiter-family and Halley-type comets are produced by Centaurs originating from the Oort cloud. The injection rate for Jupiter-family comets coming from the inner Oort cloud is, at least, not less than that for a model based on the observed sample of high-eccentricity trans-Neptunian objects.

Key words: Centaurs, comets, dynamics, Oort Cloud, origin, trans-Neptunian objects

1. Introduction

On the way from the outer Solar system to short-period orbits, comets are strongly perturbed by planets, and their final orbits are very different from initial ones. In addition, the unclear physical evolution of comets at small heliocentric distances affects their observed distribution. Therefore, the problem of the origin of short-period comets causes many debates. Centaurs, as a transition population en route from the outer Solar system to the inner planetary region, are less affected by dynamical and physical factors. Thus they provide the important information on sources of short-period comets.

The recent investigation of the orbital distribution of Centaurs (Emel'yanenko et al., 2005) showed that there are two dynamically distinct classes of Centaurs, a dominant group with semimajor axes $a > 60$ AU and a minority group with $a < 60$ AU. It was suggested that the most likely source for the dominant class of Centaurs is the Oort cloud.

In the present paper, we show that this suggestion is consistent with the conventional model of the Oort cloud. This allows us to give new conclusions about the origin of short-period comets.

2. Model

In this paper, we restrict Centaurs by orbits with perihelion distances $5 < q < 28$ AU and $a < 1000$ AU, and the Oort cloud is defined by small bodies on orbits with $a > 1000$ AU.

We investigate the usual model of the Oort cloud formed by the action of planetary, stellar and galactic perturbations for the age of the Solar system. Details of the numerical scheme were described in the work (Emel'yanenko, 2005), where we studied the evolution of near-Neptune and trans-Neptunian objects in high-eccentricity orbits. About 222 objects with initial $25 < q < 36$ AU, $50 < a < 300$ AU, inclinations $0 < i < 40°$ that reached the region $a > 1000$ AU in the work (Emel'yanenko, 2005) have been taken as a basis for the present paper. We have carried out new integrations of 40 orbits for each of these objects, varying the mean anomaly within a small range.

The choice of initial conditions ($25 < q < 36$ AU, $50 < a < 300$ AU, $0 < i < 40°$) is determined by our attempt to investigate the evolution of the Oort cloud formed by objects from the near-Neptune region under the action of planetary, stellar and galactic perturbations. It is known that such objects contribute to the Oort cloud even now (Fernández et al., 2004; Emel'yanenko, 2005). But it is practically impossible to describe exactly the distribution of objects near the stage of the Solar system formation. Nevertheless, we stress that the studied initial distribution is close to that following from the scattered disc model with migrating Neptune (Duncan and Levison, 1997; Gomes, 2003). The distribution of objects in the Oort cloud after 4.5 Gyr of evolution in our computations is given in Figures 1 and 2. In the following, we try to analyze whether such a model of the Oort cloud is consistent with the observed distribution of objects in the Centaur region.

3. Comparison with observed Centaurs

Although there are only four multiple-opposition Centaurs with $a > 60$ AU in the list of Minor Planet Center(1999 TD10: $a = 95.7$ AU, $q = 12.3$ AU, $i = 6.0°$; 2000 OO67: $a = 514$ AU, $q = 20.8$ AU, $i = 20.1°$; 2002 XU93: $a = 67.4$ AU, $q = 21.0$ AU, $i = 77.9°$; 2003 FX128: $a = 104$ AU, $q = 17.8$ AU, $i = 22.3°$), the intrinsic number of such objects is roughly an order of magnitude greater than that for $a < 60$ AU (Emel'yanenko et al., 2005). The distribution of these objects is inconsistent with a source in the trans-Neptunian region.

In order to analyze whether these Centaurs can originate from the Oort cloud, we have analyzed the orbital distribution of simulated objects with $5 < q < 28$ AU for the last billion years of evolution in our integrations ($3.5 < t < 4.5$ Gyr). Figure 3 shows the relative number of perihelion passages

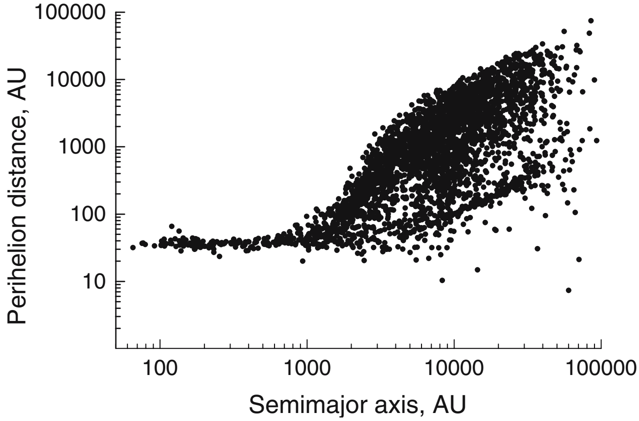

Figure 1. The distribution of *a* and *q* for objects surviving after 4.5 Gyr.

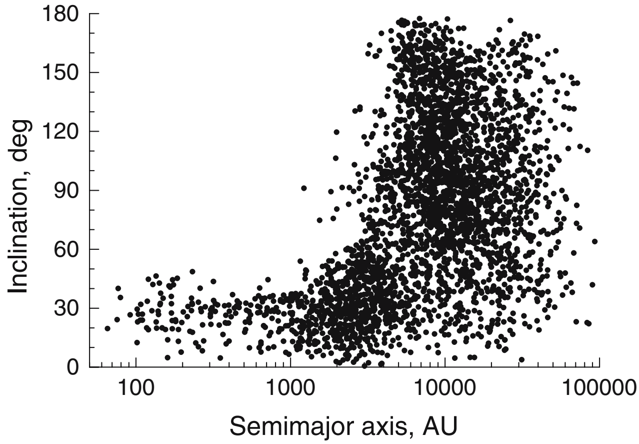

Figure 2. The distribution of *a* and *i* for objects surviving after 4.5 Gyr.

for objects with different values of a. The flux for $a < 1000$ AU is dominant. This is consistent with the fact that all the discovered Centaurs have $a < 1000$ AU. Our estimates give that the flux of objects with $a < 1000$ AU in the region $5 < q < 28$ AU is approximately 3000 times as large as that for 'new' objects ($a > 10^4$ AU) in this region. The number of objects with $a < 1000$ AU, $5 < q < 28$ AU is equal to 0.0023 of the total number of objects in the outer part of the Oort cloud ($a > 10^4$ AU).

Figure 4 shows the relative number of perihelion passages with different values of i for objects with $a < 1000$ AU, $5 < q < 28$ AU. While our computations confirm that 'new' objects ($a > 10^4$ AU) have approximately equal numbers of prograde and retrograde orbits in the region $5 < q < 28$ AU,

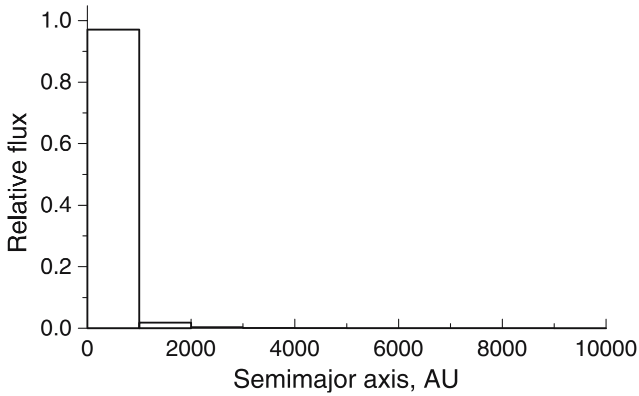

Figure 3. The a-distribution for perihelion passages of objects with $5 < q < 28$ AU after 3.5 Gyr.

objects with $a < 1000$ AU have mainly prograde orbits in this region. This result is consistent with observations of Centaurs.

The majority of discovered Centaurs have $a < 35$ AU. It was shown in (Emel'yanenko et al., 2005) that objects from the trans-Neptunian region and the Oort cloud overlap in this region.

The distribution of perihelion distances for objects captured from the Oort cloud in the region $a < 35$ AU is shown in Figure 5 in comparison with the debiased q-distribution for observed Centaurs in this region assuming a differential power law slope of −4 for a size distribution (the debiasing procedure was described in (Emel'yanenko et al., 2004, 2005)). This q-distribution of objects coming from the Oort cloud is much more consistent with observations than that of objects captured from the trans-Neptunian region (Emel'yanenko et al., 2005).

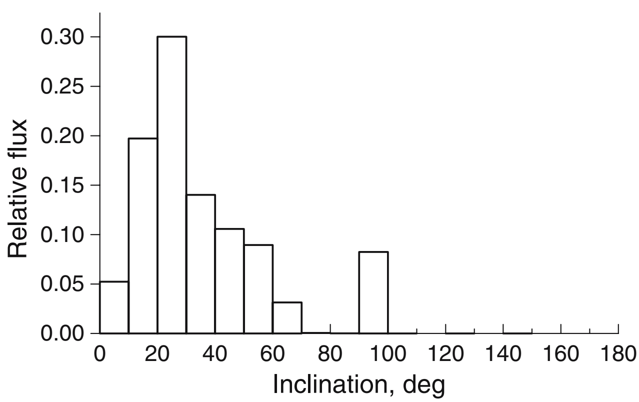

Figure 4. The i-distribution for perihelion passages of objects with $a < 1000$ AU, $5 < q < 28$ AU after 3.5 Gyr.

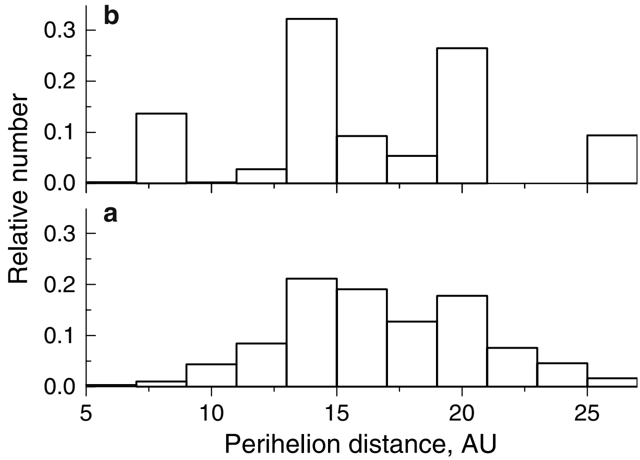

Figure 5. The q-distribution of Centaurs with $a < 35$ AU: a – the distribution of simulated objects after 3.5 Gyr, b – the debiased observed distribution.

4. Dynamics of the Oort cloud objects captured to the Centaur region

Although Figure 1 shows that many objects can survive on orbits with perihelia in the near-Neptune region and $a < 1000$ AU, the population producing Centaurs in our model is different from the scattered disc (Duncan and Levison, 1997; Luu et al., 1997). Figure 6 shows maximum values of a and q which objects captured to orbits with $5 < q < 28$ AU and $a < 1000$ AU for the last billion years reach during their previous evolution under the combined action of planetary, galactic and stellar perturbations. The dynamical history of the majority of such objects includes stages of evolution on orbits located far from the planetary region. According to our calculations the flux of Centaurs originating from objects which have never left orbits with $q < 36$ AU is only 0.14 of the total flux in the Centaur region.

Figure 7 shows the number of perihelion passages with different inclinations in the Centaur region for those objects which have the maximum value of q larger than 50 AU. In this region, the flux is also dominated by prograde orbits. The distribution of semimajor axes in this case is similar to Figure 3: 96% of objects pass perihelia with $a < 1000$ AU.

While scattered disc objects have perihelia mainly between 32 and 36 AU, and the majority of them have orbits within 100 AU (Duncan and Levison, 1997; Morbidelli et al., 2004), the population of the model studied here is located much further at any time. Even in the region $32 < q < 36$ AU only 2% of objects have $a < 100$ AU for the last billion years of our integrations. As a consequence, only 7% of objects in the Centaur region have orbits with $a < 60$ AU. This is close to the observed distribution of Centaurs (Emel'yanenko et al., 2005). In our model, the majority of objects are

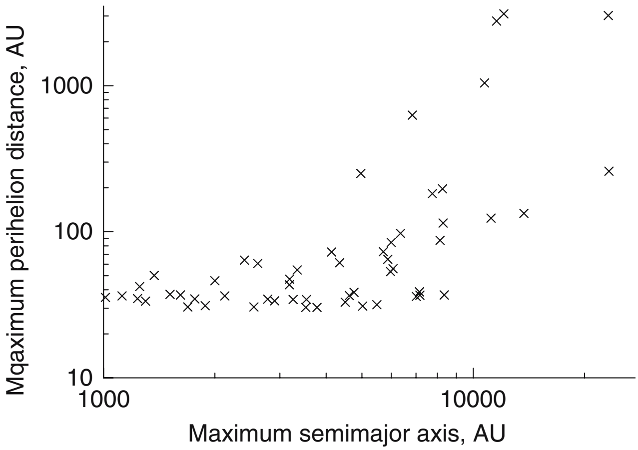

Figure 6. The maximum values of a and q which objects captured to the Centaur region reach during their previous evolution.

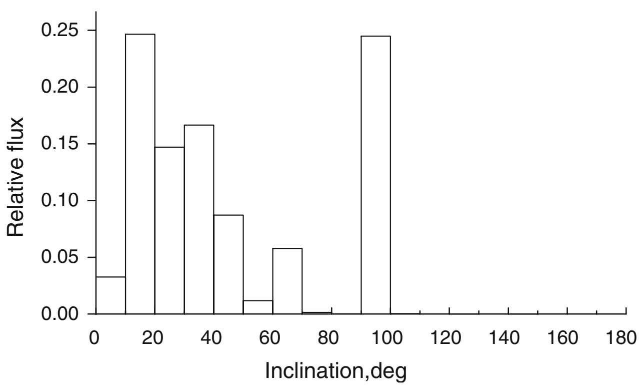

Figure 7. The i-distribution for perihelion passages of objects with $a < 1000$ AU, $5 < q < 28$ AU after 3.5 Gyr. Only objects with the maximum value of q larger than 50 AU are included in this histogram.

injected from the inner Oort cloud to the Centaur region directly by external stellar and galactic perturbations, without visiting the near-Neptune region ($28 < q < 35.5$ AU, $60 < a < 1000$ AU).

Figure 8 shows an example of the evolution from the Oort cloud to a short-period Halley-type orbit through the intermediate stage of Centaurs. The object reaches $a = 1000$ AU near $t = 2.4$ Gyr. The joint action of planetary, galactic and stellar perturbations leads to a slow increase in semimajor axis and perihelion distance. The object has an Oort cloud orbit with $q \sim 100$ AU and $a \sim 10{,}000$ AU for ~ 1 Gyr. At $t = 3.42$ Gyr, following a close star passage, the perihelion distance changes to $q \sim 6$ AU. Then the semimajor axis decreases due to planetary perturbations, and the object becomes a typical Centaur. Afterwards, the orbit evolves to a Halley-type one with $i = 11°$ in ~ 1.8 Myr. The dynamical mechanisms of the evolution from Centaurs to Halley-type orbits were discussed in the paper (Bailey and Emel'yanenko, 1996).

The evolution from the inner Oort cloud to a short-period Jupiter-family orbit is shown in Figure 9. The object has an orbit with $a > 1000$ AU and $q > 50$ AU for the interval of duration ~4 Gyr. Eventually q changes from 54 AU to 30 AU due to a relatively strong stellar perturbation at $t = 4.0$ Gyr. The action of planetary perturbations causes the object to evolve into the Centaur region, and then it finally becomes a member of the Jupiter family. The detailed discussion of the dynamical evolution from Centaurs to Jupiter-family orbits can be found in the papers (Levison and Duncan, 1997; Tiscareno and Malhotra, 2003; Horner et al., 2004).

5. Capture to short-period orbits

In order to estimate the contribution of Centaurs originating from the Oort cloud to short-period comets we have integrated 10 cloned orbits for each of 489 objects reaching $q < 5$ AU in the Oort cloud model. The calculations have shown that both Jupiter-family and Halley-type comets are produced by objects from the Centaur region, but the number of Jupiter-family comets is dominant. For the last billion years of evolution, we have registered 23 objects with Tisserand parameters $T > 2$ and 1 object with $T < 2$ ($i = 115°$) on short-period orbits when their perihelia first drop below 2.5 AU. The distribution of Tisserand parameters and inclinations for Jupiter-family comets is shown in Figure 10.

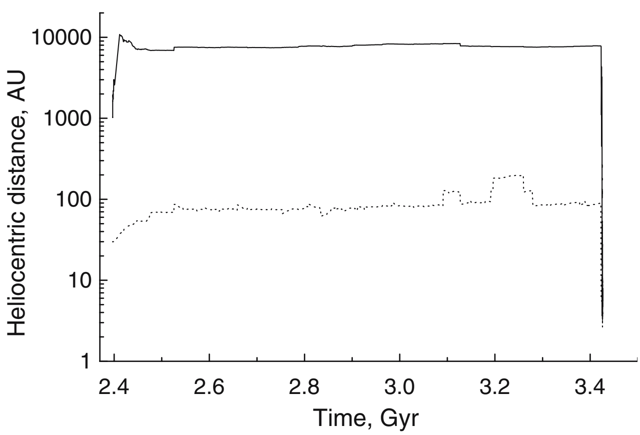

Figure 8 Evolution of a (solid curve) and q (dotted curve) for an object captured from the Oort cloud to a Halley-type orbit through the intermediate phase of Centaurs.

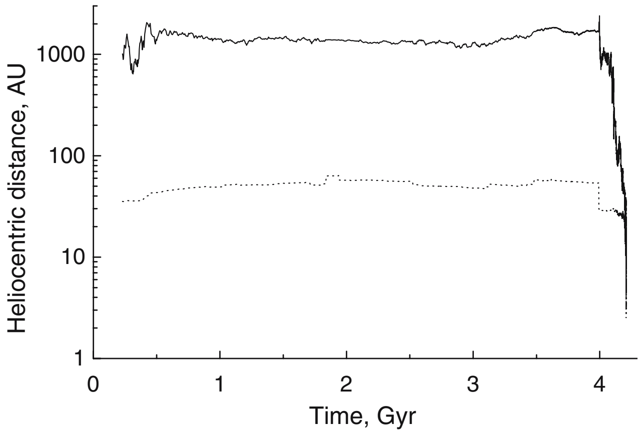

Figure 9. Evolution of a (solid curve) and q (dotted curve) for an object captured from the Oort cloud to the Jupiter family through the intermediate phase of Centaurs.

The median Tisserand parameter of this distribution is 2.75, and the median inclination is 15°.5. These results show that Centaurs originating from the Oort cloud produce typical Jupiter-family comets. But the inclination distribution of this model is slightly broader than the observed one. Probably this indicates that a more flattened population like trans-Neptunian objects contributes to Jupiter-family comets as well. On the other hand, the data on Jupiter-family comets in our model are not large, and they correspond to the evolution for the interval of 1 Gyr. Therefore, uncertainties of statistical characteristics for orbital elements can be significant. We will investigate details of the inclination distribution for Jupiter-family comets in future works.

We have found in our model of the Oort cloud that the ratio of the injection rate $\nu_{\rm JF}$ into Jupiter-family comets with $q < 2.5$ AU per year to the number N_O of objects in the outer part of the Oort cloud ($a > 10^4$ AU) is 0.16×10^{-11}. Then $\nu_{\rm JF} = 0.16 \times 10^{-11} N_O$ year^{-1}. It is interesting that the injection rate into the same region was found to be $\nu_{\rm JF} = 0.36 \times 10^{-10} N_{NNHE}$ year^{-1} for the capture of Jupiter-family comets from the trans-Neptunian region in the model based on the observed high-eccentricity objects (Emel'yanenko et al., 2004), where $N_{\rm NNHE}$ is the number of near-Neptune ($28 < q < 35.5$ AU, $60 < a < 1000$ AU) high-eccentricity objects. This shows that if the number of the Oort cloud comets with $a > 10^4$ AU is only an order of magnitude larger than the number of near-Neptune high-eccentricity objects, then the injection rates into the Jupiter family are comparable.

It is possible to estimate the number of objects in the Oort cloud according to our model. We have registered 51 comets with $a > 10^4$ AU injected in the region $q < 5$ AU for the last billion years of evolution in our integrations and 1344 objects with $a > 10^4$ AU surviving after 4.5 Gyr. Taking a value of 1.5

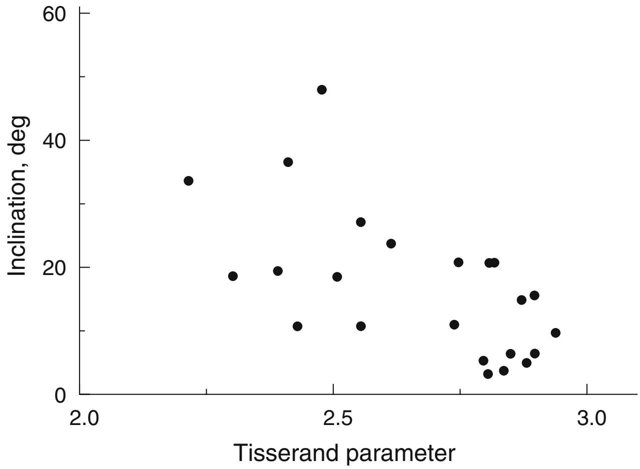

Figure 10. The distribution of Tisserand parameters and inclinations for Jupiter-family comets coming from the Oort cloud through the phase of Centaurs when their perihelia first drop below 2.5 AU.

for the observed flux of 'new' comets with absolute magnitudes $H_{10} < 7$ passing perihelion with $q < 5$ AU per year (Fernández, 1982; Bailey and Stagg, 1988; Fernández and Gallardo, 1999) and assuming that this flux was almost constant during the last billion years, we obtain that there exist 4×10^{10} objects with $a > 10^4$ AU corresponding to comets with $H_{10} < 7$. The number of comets with $H_{10} < 10.9$ is approximately ten times larger if we adopt a slope of 0.28 for the $10^{\alpha H_{10}}$ distribution of H_{10} (Weissman and Lowry, 2001). Then we estimate that $N_O \approx 4 \times 10^{11}$. But, probably this number is a lower limit of the real number for the outer Oort cloud comets, because many of 51 comets are injected into the inner planetary region after rare occasions of close star passages in our calculations. If we assume that the observed flux is not connected with such exceptional events, then it should correspond to a value which is less then the average one estimated on the billion year interval.

Even in the case of $N_O = 4 \times 10^{11}$ the injection rate into the Jupiter family of comets with $q < 2.5$ AU is equal to 0.64 year^{-1}. This is larger than $v_{\rm JF} = 0.36$ year^{-1} obtained in the model of near-Neptune high-eccentricity objects at $N_{\rm NNHE} = 10^{10}$ (Emel'yanenko et al., 2004).

6. Discussion

Our model of the Oort cloud provides results which are consistent with the orbital distribution of observed Centaurs. In particular, it explains the existence of Centaurs with $a > 60$ AU.

Figure 6 shows that members of the population producing Centaurs can reach orbits with $q >> 1000$ AU and $a > 10{,}000$ AU during their dynamical evolution. But the majority of them have perihelia within 300 AU and $a < 10{,}000$ AU. Thus, Centaurs with $a > 60$ AU come mainly from the inner core of the Oort cloud. Small stellar and galactic perturbations play a central role in the diffusion process which leads perihelia of these objects to the planetary region. The flux of Centaurs originating from the Oort cloud is fairly stable because of the relatively long dynamical lifetime of these objects. Dynamical features of this population are different from those of scattered disc objects. In particular, the typical behaviour includes a jump from a beyond-Neptune orbit to the planetary region due to stellar perturbations.

The consideration of the distribution and number of scattered disc objects is outside the scope of this paper. Objects of the present-day high-eccentricity trans-Neptunian population can originate from regions which have not been studied here. Therefore, it is premature to give reliable estimates of the number of scattered disc objects on the basis of computations in this work. The discussion of the ratio of objects in the scattered disc and the Oort cloud can be found in the papers (Fernandez et al., 2004; Emel'yanenko, 2005).

Many objects of our model survive in the trans-Neptunian region after 4.5 Gyr of evolution (Figure 1). The number of objects in near-Neptune high-eccentricity orbits ($28 < q < 35.5$ AU, $60 < a < 1000$ AU) is equal to 0.032 of that for objects with $a > 10^4$ AU. This suggests that there are many trans-Neptunian objects with $a > 250$ AU which have not been discovered due to observational selection effects yet.

According to our computations the majority of Centaurs have already visited the region $a > 1000$ AU. The injection rate for Jupiter-family comets coming from the inner Oort cloud is, at least, not less than that in the model based on the observed sample of high-eccentricity trans-Neptunian objects (Emel'yanenko et al., 2004). Comets are gradually transferred from the Oort cloud to short-period orbits through the intermediate phase of Centaurs.

Acknowledgements

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