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NOTE

Neptune Scattered Planetesimals Could Have Sculpted the Primordial Edgeworth–Kuiper Belt

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We show that Neptune-scattered planetesimals of a few Earth masses could have excited the eccentricities of the vast majority of bodies in the primordial Edgeworth–Kuiper belt. This could result in scuplting the belt to its currently observed structure and in depleting most of its primordial mass by: (i) injecting most of the bodies from the stable into the unstable regions in the inner belt; (ii) enhancing the role of mutual catastrophic collisions in the outer belt. © 1997 Academic Press

Introduction: The observed structure of the belt. Although our view of the present structure of the Edgeworth–Kuiper belt (EKB) is still quite limited and full of biases, the discovered objects seem to have a peculiar orbital distribution: (i) all the bodies with semimajor axis smaller than 40 AU are in mean motion resonances with Neptune and have large eccentricities ($e > 0.1$); (ii) no objects have been found on non-resonant quasi-circular orbits (NRQC region hereafter) with a semimajor axis between 36 and 40 AU and eccentricity smaller than 0.05, though these orbits are stable over the age of the Solar System according to the numerical integrations by Duncan *et al.* (1995); (iii) beyond 40 AU the median eccentricity of the EKB objects is still rather large (about 0.05, taking into account only the observed bodies with fitted eccentricity and excluding those on provisional circular orbits—see MPEC 1997 B09) and a few bodies have been discovered on orbits with inclination larger than 10° (despite the observational biases), so that the present EKB does not seem to be a dynamically cold disk (Jewitt *et al.* 1996).

Moreover the most recent estimates (Weissman and Levison 1996) show that the mass of the present EKB is at least two orders of magnitude smaller than that predicted by extrapolation of the current surface density of non-volatile material in the outer planetary regions (Edgeworth 1949, Kuiper 1951), and a recent paper by Stern (1996) shows that objects of few hundred kilometers in size could have been formed only in a massive primordial EKB. These facts indicate that there must have been an important mass depletion phase in the early history of the EKB.

Models proposed so far and open problems. Two major models have been proposed by Malhotra (1995) and Levison *et al.* (1997) in the attempt to explain some of the observed features of the present EKB. Malhotra hypothesizes that, in the early stages of the Solar System, Neptune was slowly migrating outward under the effect of multiple encounters with planetesimals (Fernández and Ip 1984), implying that the mean motion resonances with Neptune were slowly sweeping through the primordial EKB. As a consequence, most bodies would have been adiabatically captured into these resonances and would have subsequently increased their eccentricities, until Neptune came to its present semimajor axis. This model would explain why so many objects are currently found in mean motion resonances at $a < 40$ AU and why their eccentricities are generally large. However, it does not explain why the median e and i of the non-resonant bodies beyond 40 AU are so large, and it predicts a large number of bodies in the 1/2 resonance with Neptune, where conversely no object has been discovered yet.

Levison *et al.* suggest that, during the mass-loss phase of the primordial EKB, the ν_8 resonance had to move from a primitive position close to Neptune out to its present position at 40–42 AU. The ν_8 resonance occurs when the EKB body's perihelion precesses at the same average rate as that of Neptune, and its general effect is to pump up the eccentricity. Therefore, due to the sweeping of the ν_8 resonance, all the primordial bodies with $a < 40$ AU would have moved to $e > 0.05$. This would explain why the NRQC region is now empty and, since the only stable orbits at large eccentricity are in mean motion resonances (Morbidelli *et al.* 1995, Duncan *et al.* 1995), why all the surviving bodies with $a < 40$ AU are resonant ones. However, the predicted maximal eccentricity at $a < 40$ AU is 0.25 while bodies are observed up to $e \sim 0.32$ in the 2/3 resonance; moreover this model cannot explain the eccentricity and inclination distribution of the observed bodies beyond 42 AU, since this region should not have been swept by secular resonances.

Neither of these two dynamical models can provide an explanation of the strong mass depletion of the EKB. The latter is usually attributed to the role of catastrophic collisions among the EKB bodies.

Stern and Colwell (1997) claim that 90–95% of the mass in the 30–50 AU zone could have been removed by high velocity impacts which reduced the objects down to dust, which was then transported away by radiation. However, this result requires mean eccentricities of EKB bodies

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of order 0.25, and the mass loss reduces to 80–90% for mean eccentricities of order 0.025; none of the dynamical models proposed so far can easily explain such a level of excitation beyond 42 AU. Moreover, in Davis and Farinella (1997) model the mass depletion would result much smaller than the one expected by Stern.

Fernández and Gallardo (1997) propose that the mass of the EKB could have been reduced to its present level by the heavy primordial bombardment produced by comet-sized Neptune scattered planetesimals. They also conjecture that such bombardment could have excited the eccentricities and the inclinations of the EKB objects.

Our approach. The structure of the observed EKB is very similar to the structure of the asteroid belt: actually, also in the outer asteroid belt there are stable regions at small eccentricity (Duncan 1994) which are completely depleted and all the outer asteroids have large eccentricities and are trapped in either the 3/2 or 4/3 resonance with Jupiter. The mean eccentricities and mean inclinations of the populated orbits all over the asteroid belt are rather large, with some massive bodies (like 2 Pallas) with inclinations as large as 30°. The mass of the asteroid belt is at least a factor 100 smaller than its primordial one.

Although in a recent paper by Liou and Malhotra (1997) the sculpting of the outer asteroid belt is explained as a result of mean motion resonance sweeping forced by the inward migration of Jupiter, most of the above listed features are often attributed to the primordial effects of Earth-sized Jupiter scattered planetesimals, which would have dynamically heated the asteroid belt (Wetherill 1989). This similarity led us to investigate whether a reasonable population of large Neptune scattered planetesimals (LNSPs hereafter) could have been responsible for the present structure of the EKB.

The primordial existence of LNSPs is predicted by modern models of planetary formation. Fernández and Ip (1996) show that the accretion of Neptune requires the presence of a mass as large as $60M_\oplus$ in Neptune's environment, and predict also the formation of planetesimals with masses in the range 1–$5M_\oplus$. Moreover, the obliquity of the spin axis of Uranus implies that a collision with a primordial planetesimal of about $1M_\oplus$ must have occurred in the final stages of planetary formation (Safronov 1996, Parisi and Brunini 1996) and thus indicates that planetesimals of a few Earth masses should not have been rare in the primordial outer Solar System.

Along similar lines, but with a different purpose, Ip (1989) showed that LNSPs could have driven inward orbital diffusion of some EKB bodies.

Our numerical experiment. In order to understand what the possible evolutions of LNSPs are, we have considered 100 test planetesimals with the following randomly chosen initial conditions: semimajor axis $a \in [32, 34]$ AU (uniformly distributed in $1/a$), perihelion distance $q \in [30.5, 31.5]$ AU, and inclination $i \in [0, 1.5]°$. We expect that the primordial large planetesimals which formed outside Neptune should have had orbits in such a range, at the beginning of their interaction with the planet. In fact, they should have formed on very low-i orbits (since they originated from a disk-like nebula) and not further than 34–35 AU (otherwise they would have never interacted with Neptune—see Duncan *et al.* 1995—unless some phenomenon, such as the ν_8 secular resonance sweeping, forced them to high eccentricity); moreover their perihelion should have been decreased to less than 31.5 AU before having the first strongly scattering planetary encounters. Note that, with these initial conditions, all the test planetesimals have aphelion distance smaller than 37 AU; therefore only those which undergo the Neptune's scattering action can cross such limit and penetrate the deep EKB.

The numerical integration of the test LNSPs evolution has been done in the framework of the restricted three body problem, assuming for simplicity Neptune on its present elliptic orbit, and using the RADAU integrator (Everhart 1985). We have not taken into account Jupiter, Saturn, and Uranus because we know that the primordial planetary system was probably somewhat different from the present one and we want to be sure that our results are not strongly determined by some specific secular resonance, the location of which could have been different in the primordial system. Therefore, we have chosen on purpose the simplest dynamical model, believing that it is also the most generic one. Conversely, the use of the restricted three body problem to investigate the evolution of large planetesimals is certainly an approximation, since we neglect the planetesimal's perturbation on Neptune's motion; however, such an approximation should be acceptable for the statistical purposes of our study, at least as long as the planetesimal's mass is not too large compared to that of Neptune.

Each integration has been stopped when the test planetesimal either came to a perihelion distance smaller than 20 AU (where the gravitational interactions with Uranus would become dominant) or was ejected on a hyperbolic orbit. If neither of these conditions occurred, the simulation was stopped after 50 Myr of integration time (15 out of 100 test planetesimals survived 50 Myr).

Figure 1a gives the mean number of passages N of a LNSP, as a function of the distance from the Sun. Only passages with inclination smaller than 3° are counted; this arbitrary limit is motivated by the fact that we expect the primordial EKB population to be on low-inclined orbits, so that only LNSP's passages close to the invariable plane are important. Figure 1b gives the mean relative velocity U of such passages with respect to an EKB population on 0-inclination circular orbits at heliocentric distance d. Note the threshold at 37 AU where N has a sharp drop and U a sharp increase: this is due to the fact that our population of LNSPs has been chosen on initial orbits with Q up to 37 AU. Therefore, this threshold could be easily moved either inward or outward by playing on the initial aphelion distribution of the LNSP population. Conversely, beyond the initial maximal aphelion distance, the number of passages depends in a random way on the initial conditions, as shown in Fig. 1c; the same is true for the encounter velocity with the EKB population. This makes us confident that our results in such regions are statistically robust and would not change much if the initial conditions of the LNSPs were modified.

While we were revising this paper, we received a preprint by Duncan and Levison (1997) concerning the formation of an extended *Scattered Disk*. Their integrations, done in the framework of the present outer planetary system, show that a significant amount of bodies, dynamically coupled to Neptune, can be scattered out to even more than 100 AU, with residence times up to a few Gyr. This result confirms qualitatively our result in a more accurate dynamical model and indicates that the effect of LNSPs might have been even larger than indicated by our simulation.

The probability that an EKB body, with a distance between d and $d + \Delta d$ from the Sun and an inclination smaller than 3°, encounters a LNSP within a distance b during a single passage can be easily computed as the ratio between the volume spanned by a disk of radius b, i.e., $\pi b^2\, \Delta d$, and the total volume $4\pi d^2 \sin 3°\, \Delta d$, which gives

$$P_S(d, b) = b^2/(4d^2 \sin 3°)$$

(this formula is valid only if $b < d \sin 3°$).

The probability that an EKB body encounters one out of n LNSPs during one of its N passages is $P(d, b) = 1 - [1 - P_S(d, b)]^{nN}$. This equation can be inverted, giving the distance b at which an EKB body has a probability P to encounter at least one LNSP during one passage: $b(d, P) = 2[1 - (1 - P)^{1/nN}]^{1/2}\, d\sqrt{\sin 3°}$. Given b and the mass M (in solar units) of the LNSP, according to two-body encounter dynamics (Öpik 1976), the EKB body receives a relative velocity impulse

$$\gamma = 2 \arctan \frac{Md}{bU^2} \sim \frac{M\sqrt{nN}}{\sqrt{|\log(1 - P)|}\,U^2}, \tag{1}$$

where U is the relative velocity at encounter, measured in units of the circular velocity at distance d. Formula (1) can also be expressed in terms of the radius R of the LNSP, its escape velocity $v_{\rm esc}$ and the encounter velocity $v_{\rm enc}$ as $\gamma = 2 \arctan Rv_{\rm esc}^2/(2bv_{\rm enc}^2)$. Recall that a relative impulse

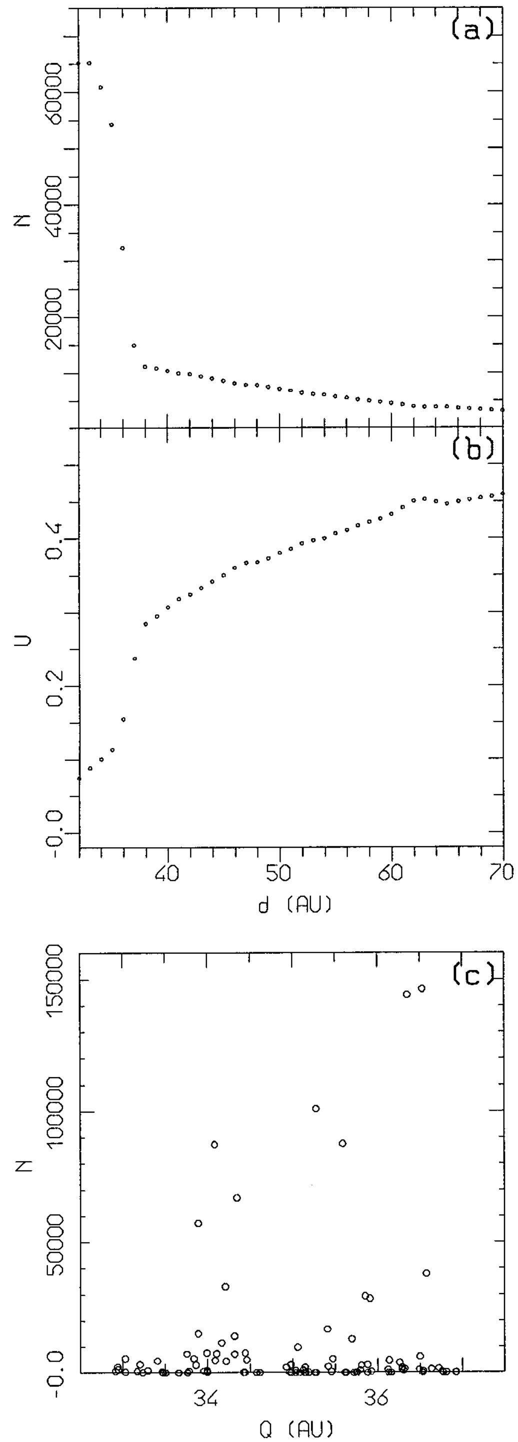

FIG. 1. Pictures (a) and (b) show, as a function of the distance d from the Sun, the mean number N of passages with inclination smaller than 3° of a test LNSP, and its mean encounter velocity U with the EKB population, the latter assumed to be on circular orbits. U is measured relatively to the circular orbital velocity at distance d. Picture (c) shows the number of passages of 40 AU of each test planetesimal, as a function of its initial aphelion distance.

velocity γ implies, for an originally circular planar orbit with semimajor axis a, a change of orbital elements of order $\delta a/a \sim \delta e \sim \delta i \sim \gamma$ (δi is measured in radians here). The right hand side of (1) is derived by replacing b with his expression and expanding $(1 - P)^{1/nN}$ as $1 + 1/nN \log(1 - P) + O[(1/nN)^2]$.

Results and discussions: The effects of LNSPs action. We have considered a population of 5 planetesimals of $2M_\oplus$. More precisely we have assumed in formula (1) $n = 5$, $M = 2M_\oplus$, and the mean values of N and U reported in Fig. 1, and we have computed the velocity impulse γ that 90, 50, and 10% of the EKB bodies should have received, as a function of their semimajor axis.

The results are illustrated in Fig. 2a. The impulse velocity γ exhibits a sharp "wall" at about 37 AU, as a consequence of the assumed initial distribution of LNSPs aphelia, then decreases smoothly. Between 37 and AU, $\gamma > 0.05$ for 90% of the bodies. Recalling that $\delta e \sim \gamma$, this implies a very efficient depletion of the NRQC region. Moreover, 50% of the bodies at 42–43 AU should have suffered an eccentricity increase of order 0.07, which is consistent with the median eccentricity of the observed bodies in that region. Our model also shows that the inclinations of the EKB bodies should have been stirred up (recall that $\delta i \sim \gamma$); for example, about 10% of the bodies at 43 AU would have inclination larger than 10°.

All these results seem to be well consistent with the observations. Conversely, we notice a discrepancy concerning the eccentricity distribution in the 2/3 resonance with Neptune: the discovered bodies have eccentricities in the range 0.1–0.32, while we predict at 39.5 AU a median value of about 0.1. To fit the observational data, γ's sharp "wall" should be at about 39–40 AU, rather than 37 AU, which seems to imply that the population of LNSPs had originally aphelia up to the 2/3 resonance position.

The LNSPs model also provides a good explanation for the large mass depletion of the EKB, although the dominating mechanisms in the inner and in the outer EKB are different.

In the inner part of the belt, once at larger eccentricity, only the EKB bodies which happened to be in a mean motion resonance with Neptune were dynamically stable. At $e \sim 0.1$ the relative volume of stable regions between 33 and 42 AU is about 7% (Duncan *et al.* 1995); therefore an EKB body which was kicked at large eccentricity by a LNSP had only a 7% chance to be injected into a stable region. Moreover, most EKB bodies had to suffer multiple encounters with the LNSPs, so that they were frequently kicked in and out of the mean motion resonances, since the typical $\delta a \sim \gamma a$ had to be equal to a few AU, while none of the resonances is wider than 1 AU. However, this scattering process was not entirely symmetric, because the bodies temporarily outside the resonances had a non-negligible probability to be eliminated by a Neptune encounter before having a chance to be kicked back into a mean motion resonance. Therefore, when the EKB ceased to evolve after the elimination of the last LNSP, probably only a few percent of the original population of EKB bodies were in a stable mean motion resonant configuration and could survive up to the present time.

In the outer part of the belt ($a > 42$ AU) the stable regions of the EKB are too extended, so that the impulse velocities provided by LNSPs were not large enough to kick the EKB bodies directly into the unstable regions. However, the eccentricities of the bodies should have still been pumped to a few percent: such excitation increased the mean relative velocity among EKB objects, thus starting the role of catastrophic mutual collisions in the process of mass depletion (Stern 1997, Davis and Farinella 1997).

Dependence of our results on LNSP masses. Since formula (1) scales roughly as $\gamma \sim M\sqrt{n}$, the results would be the same considering a population of 20 LNSPs of 1 Earth mass or 500 planetesimals of 1 Mars mass. This sequence shows that, for a fixed amount of total mass, few large planetesimals play a greater role than a lot of smaller ones; it also shows that Chiron-sized NSPs should not have played a relevant role in stirring up the eccentricities of the EKB, contrary to what has been con-

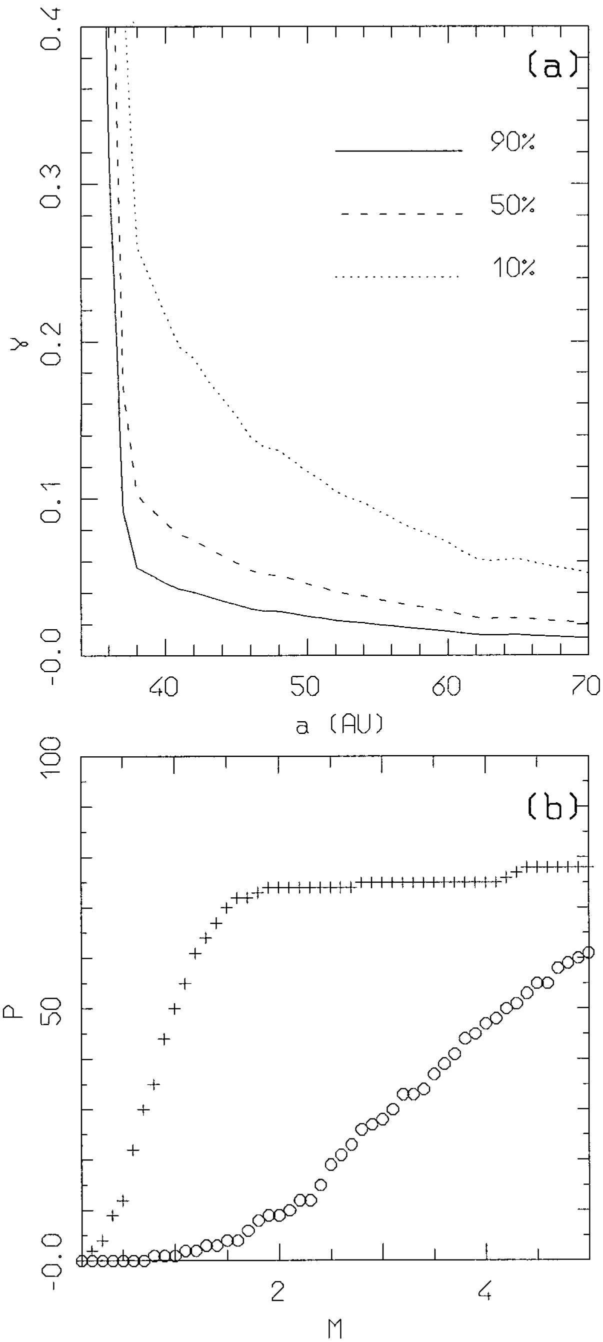

FIG. 2. (a) As a function of their semimajor axis, the impulse velocity γ that 90, 50, and 10% of the EKB bodies should have received under the perturbation of 5 LNSPs of $2M_\oplus$. Recall that γ is related to the change of orbital elements by the relation $\delta a/a \sim \delta e \sim \delta i \sim \gamma$. (b) The open circles show the probability P for one single LNSP of mass M (in Earth mass units) to excite above 0.05 the eccentricity of 90% EKB bodies at 40 AU; the crosses show the probability to kick 90% of the adiabatically captured EKB bodies out of the 2/3 resonance.

jectured (without quantitative computations) by Weissman and Levison (1996).

Our considered population of 5 LNSPs of $2M_\oplus$ may appear too massive. There are no precise constraints available from theories of planetary formation as to how many LNSPs might have existed. However, recall that the evolution of our test planetesimals shows a large variety of behaviors: there are "exceptional" evolutions which dominate the statistics of the passages through the EKB. In fact a single LNSP of a few Earth-masses following one of these exceptional evolutions would have been sufficient to excite the eccentricities of all the EKB bodies.

The problem is to quantify the probability of these atypical behaviors. For this purpose we have computed independently, for each of our 100 test evolutions, the minimal mass $M_{\min}$ required for a single body on that orbit to pump $e > 0.05$ for 90% of the EKB bodies at $a < 40$ AU.[1] Then for a given LNSP mass M we counted the number of test evolutions with $M > M_{\min}$, thus getting the probability that a single body could produce the required eccentricity pumping. The result is shown in Fig. 2b (open circles): this probability is only about a few percent for 1 LNSP of $1M_\oplus$, but increases to 10% for 1 LNSP of $2M_\oplus$, to 30% for 1 LNSP of $3M_\oplus$, and to more than 60% for 1 LNSP of $5M_\oplus$.

In Fernández and Ip (1996) simulations planetesimals of masses from 1 to $5M_\oplus$ are always produced as a subproduct of Neptune's formation: the result illustrated in Fig. 2b then shows that such LNSPs had a non-negligible probability to excite the eccentricities of the EKB bodies, thus contributing significantly to sculpt the belt to its presently observed structure.

Conclusions. We have shown with a very simple quantitative model that a reasonable number of Neptune scattered planetesimals of 1–5 Earth masses could have excited the eccentricities of the vast majority of bodies in the primordial EKB. As a consequence of global eccentricity excitation, the belt's structure would be like the one that seems to be outlined by the results of the first 5 years of observations.

Of course, our results depend strongly on the assumed initial orbital distribution of the LNSP population. In order to recover all the details of the present EKB structure, some fine tuning on the LNSP initial conditions would be necessary. For instance we have shown that, if the fact that no objects exist in the 2/3 resonance with $e < 0.1$ is confirmed, then the initial distribution of LNSPs aphelion distances should have extended to about 40 AU.

In the present paper we do not try such fine tuning: the "real" structure of the EKB is still too uncertain, and we leave this job for the future. At the present state of the observational art, it is still not possible to completely exclude that the EKB has the structure predicted by Malhotra's theory (Marsden, private communication). If Malhotra's predictions turn out to be right, this would give a very important indication on the non-existence of LNSPs. Indeed, Malhotra's mechanism can work only in a very gentle, adiabatically changing, system. LNSPs would have the effect to kick out of the 2/3 resonance most of the captured bodies, thus stopping their evolution toward large eccentricities. To highlight this last point, in Fig. 2b (crosses) we show the probability for one single LNSP of mass M to change 0.5 AU the semimajor axis of 90% of the EKB bodies at 39.5 AU (which would force their extraction from the 2/3 resonance). It turns out that 1 planetesimal of $1M_\oplus$ would have 50% probability to extract 90% of the original 2/3 resonant bodies.

We believe that, when the real structure of the EKB is determined with sufficient accuracy, it will be possible to derive very strict constraints on the primordial population of Neptune scattered planetesimals and, in turn, on the formation of the outer planetary system.

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[1] We could have chosen other conditions, for instance to pump above 0.03 the eccentricities of 50% of the EKB bodies at 60 AU: this however would provide a less restrictive condition.

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