THE COMMON ORIGIN OF THE HIGH INCLINATION TNO'S

RODNEY GOMES
GEA/OV/UFRJ & ON/MCT, Ladeira do Pedro Antonio, 43 20080-090 Rio de Janeiro, RJ, Brazil

Abstract. Numerical integrations of the four major planets orbits inside a primordial planetesimals disk show that a fraction of Neptune primordial scattered objects are deposited into the classical Kuiper Belt at Solar System age. These objects exhibit inclinations as high as 40° and can account for present high inclinations population in the classical Kuiper Belt. The same mechanism can also originate high perihelion scattered objects like 2000 CR_{105}. The process that in the end produced such objects can be divided into two phases, a migration phase where nonconservative dynamics acted to produce some stable objects already at 10^8 years and a nonmigrating phase that helped to establish some other objects as stable TNO's. Low inclination CKBO's have in principle an origin through the resonance sweeping process, although some results from numerical integrations at least suggest a possible origin also from the primordial Neptune scattered population.

1. Introduction

Since the discovery of the first member of the EKB in 1992 (Luu and Jewitt, 1993), scientists have been puzzled by the gradual revelation of a lot of intriguing characteristics of the Kuiper Belt. As orbital distribution is concerned, the basic unexpected feature is the general excited configuration of the transneptunian population. A few years after that discovery, Malhotra (1993, 1995) devised the resonance sweeping mechanism by which a primordial migrating Neptune would trap planetesimals in mean motion resonances bringing them outwards along with Neptune. The resonance trapping mechanism also induced eccentricities excitations to the planetesimals orbits. When migration ceased, the final orbital configuration of the objects outside Neptune would show many planetesimals in mean motion resonances with Neptune and others that escaped from a previous resonant status and were added to the CKB. The migration scenario would fairly well reproduce the resonant KBO's and also the CKB as far as eccentricities are concerned. However as increasing number of high inclination objects were being discovered, the resonance sweeping scenario would gradually fail to answer all the questions.

However, the idea that the planets really migrated in the early Solar System due to energy and angular momentum exchange with planetesimals in a disk (Fernandez and Ip, 1984) was at the same time gradually gathering new evidence. An important example of that evidence was the conclusion (Levison and Stewart, 2001) that Neptune and Uranus could not be formed in situ. In fact, that work suggests that the planets would initially have much more compact orbits, including

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the possibility that they would be formed in the Jupiter–Saturn region (Thomes et al., 1999). Even considering that this could be an extreme assumption, it is probable that Neptune must have migrated well in excess of 10 AU. Considering that the migration scenario was still promising in providing a more complete explanation for the orbital configuration of the EKB, I undertook a series of numerical integrations of the four major planets in initial compact orbits plus a planetesimal disk just outside Neptune. This disk is composed of 10000 objects that perturb the planets but not themselves. The initial conditions for most of these integrations are described in Gomes (2003). In Section 2, I present some extra discussion about the process of perihelia increase for Neptune scattered objects that can yield final high inclination TNO's. Section 3 presents some extra results from the numerical integrations described in Gomes (2003) and new results from an extra run considering a disk with surface density variation as r^{-4}. In Section 4, I discuss the Kuiper Belt two-population hypothesis. Finally, conclusions and discussions are given in Section 5.

2. Perihelia Increase for Neptune Scattered Objects

The results in this section come from a numerical integration of the four major planets started at their present positions and 5000 massless particles started close enough to Neptune so that they soon get scattered by this planet. Figure 1, top panel, shows the distribution of semimajor axes with eccentricities for the surviving objects after 3×10^8 years. In the lower panel, I plot the distribution of semimajor axes and perihelion distances for the orbits beyond the 1:2 resonance with Neptune. The integrations are undertaken using the SWIFT integrator (Levison and Duncan, 1994). We get temporary lowering of eccentricities in both cases. For the classical Kuiper Belt, these perihelia increases are usually associated with secular resonances whereas for objects beyond the 1:2 resonance they are caused by the association of mean motion resonances with the Kozai resonance. Figure 2 shows the evolution of the eccentricity and the difference of the longitude of perihelion to the argument related to the ν_8 secular resonance for a specific object that experienced a low eccentricity incursion in the classical Kuiper Belt. This angle is filtered from Neptune's longitude of perihelion through frequency analysis. We notice that this object is experiencing the ν_8 secular resonance most of the time and after 3×10^8 years the object was still in its low eccentricity incursion. The semimajor axis of this object was around 44 AU most of the time.

Because the objects considered here were assumed massless, the Neptune-particle dynamics is conservative. In this case the dynamics is reversible and the object is expected to eventually return to its earlier Neptune crossing orbits. We do not know however how long a temporary low eccentricity incursion may last in this conservative dynamics. In Gomes (2003), I argue that when Neptune is migrating by the gravitation interaction with close encountering planetesimals, individual

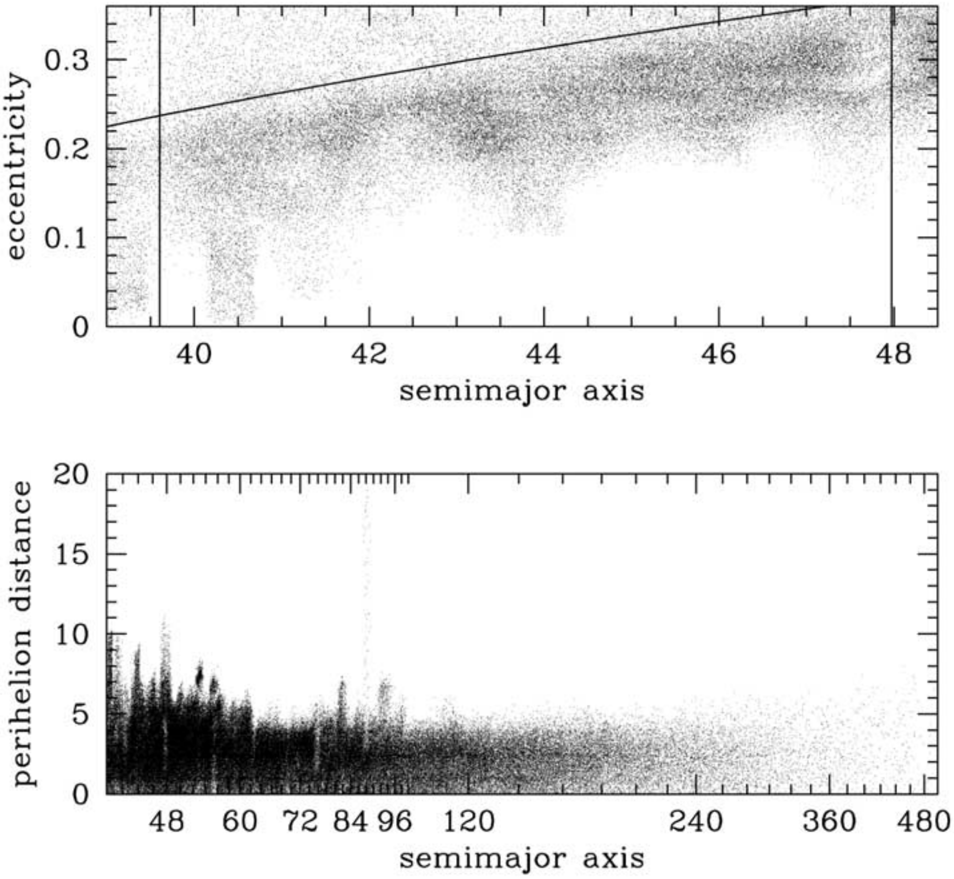

Figure 1. Above, distribution of semimajor axes and eccentricities of massless particles taken at every 5×10^5 years for an integration with the four major planets, carried on to 3×10^8 years. Below, distribution of semimajor axes with perihelion distances with respect to Neptune. Only particles that survived the 3×10^8 years are plotted. These particles were started near Neptune and got scattered by it in a short time.

Neptune-particle dynamics is no longer conservative, so the particle may lose its way back to the Neptune crossing region and thus get trapped in relatively stable high inclination moderate eccentric orbits in the Kuiper Belt, thus accounting for the high inclination TNO’s. It does not however mean that conservative dynamics would not be able to produce members of the Kuiper Belt coming from a past history as Neptune scattered objects, if a large enough number of particles were initially considered. In fact, Figure 2 suggests at least that the temporary low eccentricity incursions can be rather long. Although integrations with migrating planets would produce more extreme cases already at 10^8 years, it is possible that on carrying on the above integration without migration for the Solar System age we may get stable high inclination TNO’s in the end. It must be noted that this result,

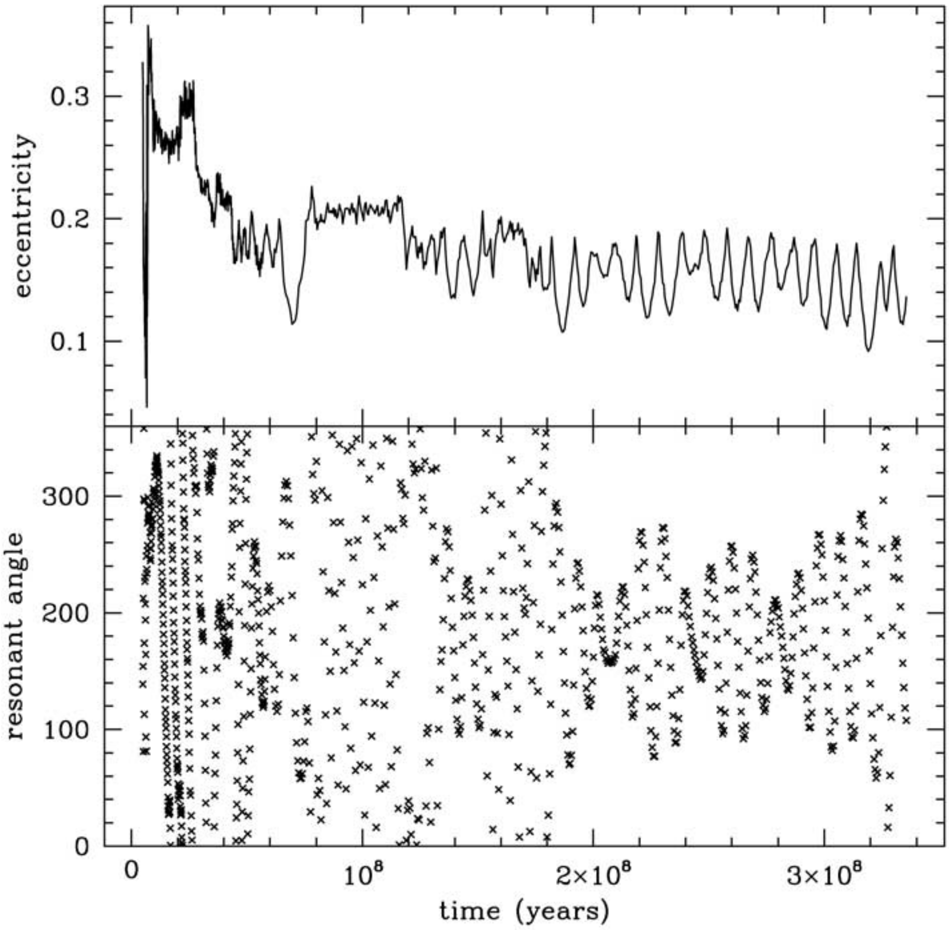

Figure 2. Evolution of the eccentricity and the difference between the longitude of the perihelion and the argument associated to the ν_8 resonance for a particular particle taken from those plotted in Figure 1, which experienced low eccentricity incursions in the CKB

if obtained at all, would have mostly a theoretical character, since considering a large number of scattered objects with their real masses would necessarily induce Neptune's migration. The real scenario must include a planetary migrating phase in the first hundred million years creating a number of objects with fairly high perihelia followed by* a conservative phase in which the orbits will fix as stable TNO's.

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* This threshold is not precisely defined since migration fades out slowly.

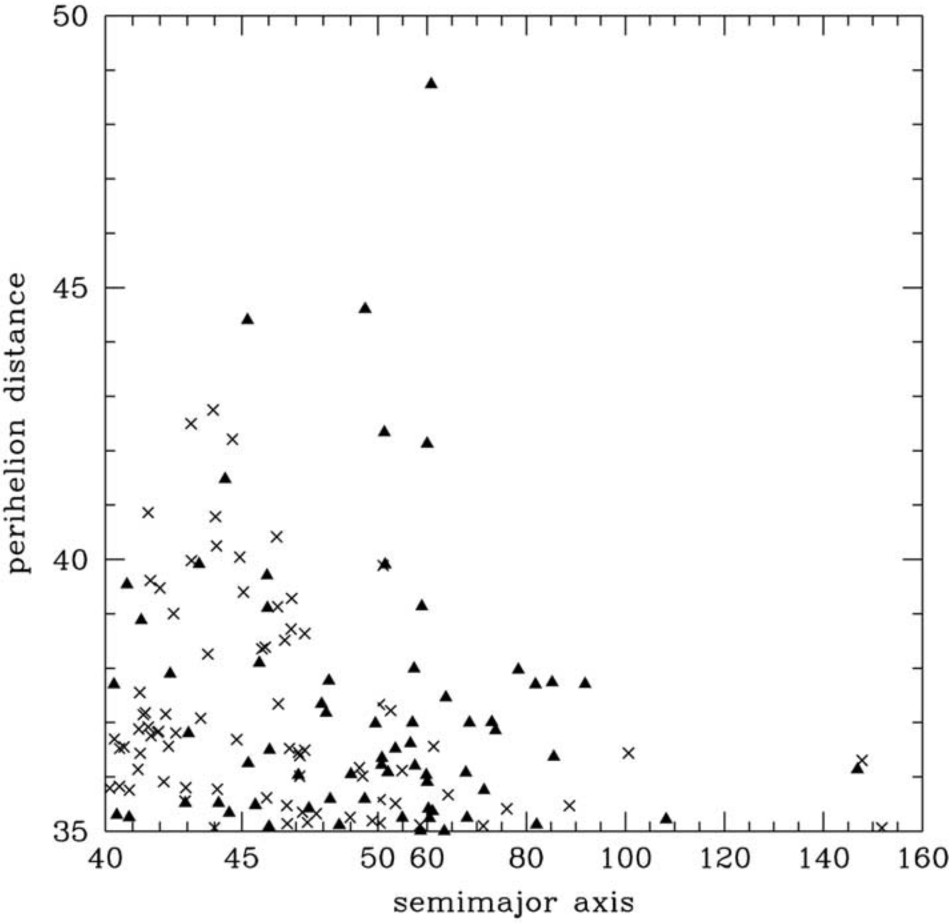

Figure 3. Final distribution of semimajor axes and perihelion distances of massive planetesimals that were scattered by Neptune, taken from seven numerical integrations, with migrating planets (Gomes, 2003). Triangles stand for objects with inclination higher than 20°. Results after 10^8 years.

3. High Inclination Transneptunian Objects

Most of the results in this Section come from numerical integrations of the four major planets' orbits perturbed by a planetesimal disk. These integrations are separated into seven runs and their details are described in Gomes (2003). An important feature of the model considered in Gomes (2003) is the use of a truncated disk a little below 30 AU. Beyond that, a much less dense disk was considered just to experience the effects of resonance sweeping by Neptune, but this outer disk had a negligible effect in inducing extra migration of Neptune. The motivation of the truncated disk was in principle to force Neptune to stop near 30 AU and thus have a more reliable production of high inclination TNO's. In this sense, the model would have mostly an artificial character. However, from the dynamics point of view, this

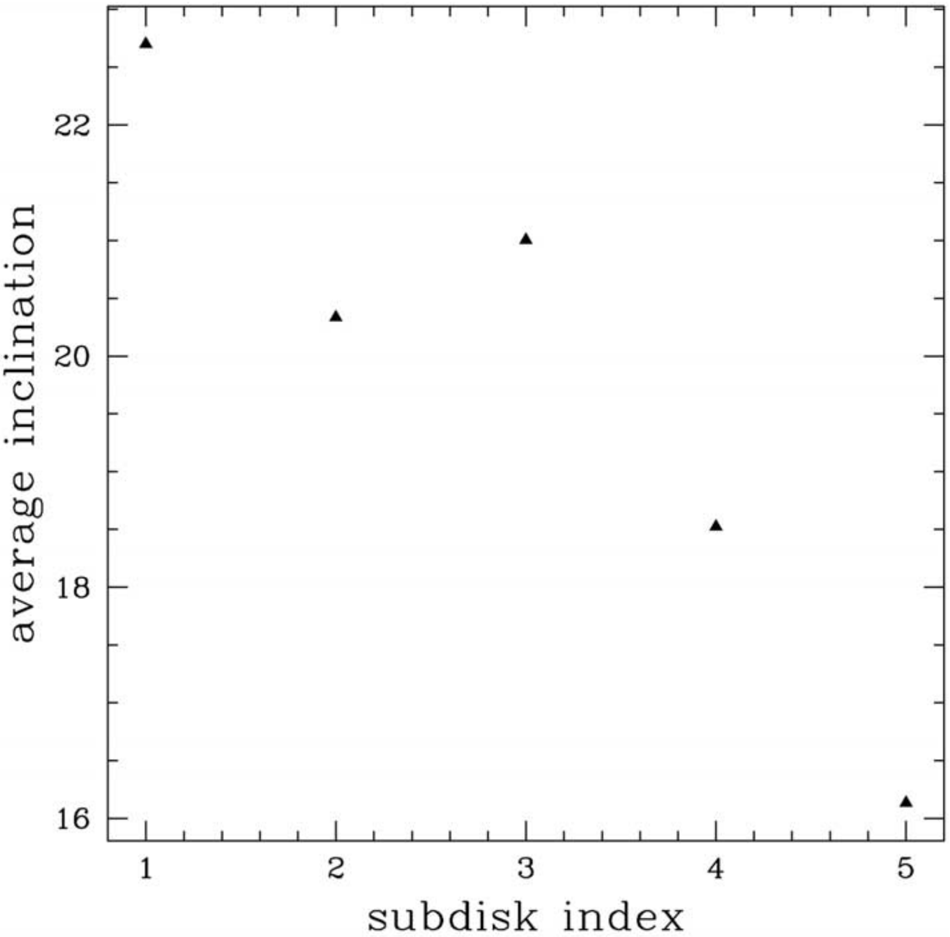

Figure 4. Distribution of average inclinations in sections of the disk with the sections. The disk is divided into five sub-disks of equal radial extension. Numbers 1 to 5 stand for the innermost to the outermost section.

truncated model may happen not to be really artificial since there are difficulties for Neptune to stop at 30 AU considering regular planetesimals disks extending further out (for instance to 50 AU). This problem is discussed in more detail in Gomes et al. (2003). In Figure 3, I show the distribution of semimajor axis with perihelion distances of the planetesimals orbits after 10^8 years, coming from the seven runs, all objects belonging to the initial truncated inner disks. The orbits with inclination above 20° are represented by triangles.

In Figure 4, I consider the initial inner disks divided into five smaller consecutive disks of equal radial extension, where the sub-disks are represented in the horizontal axis by numbers 1 to 5 from the innermost to the outermost one. The vertical axis represents the average inclination of the final orbits (after 10^8

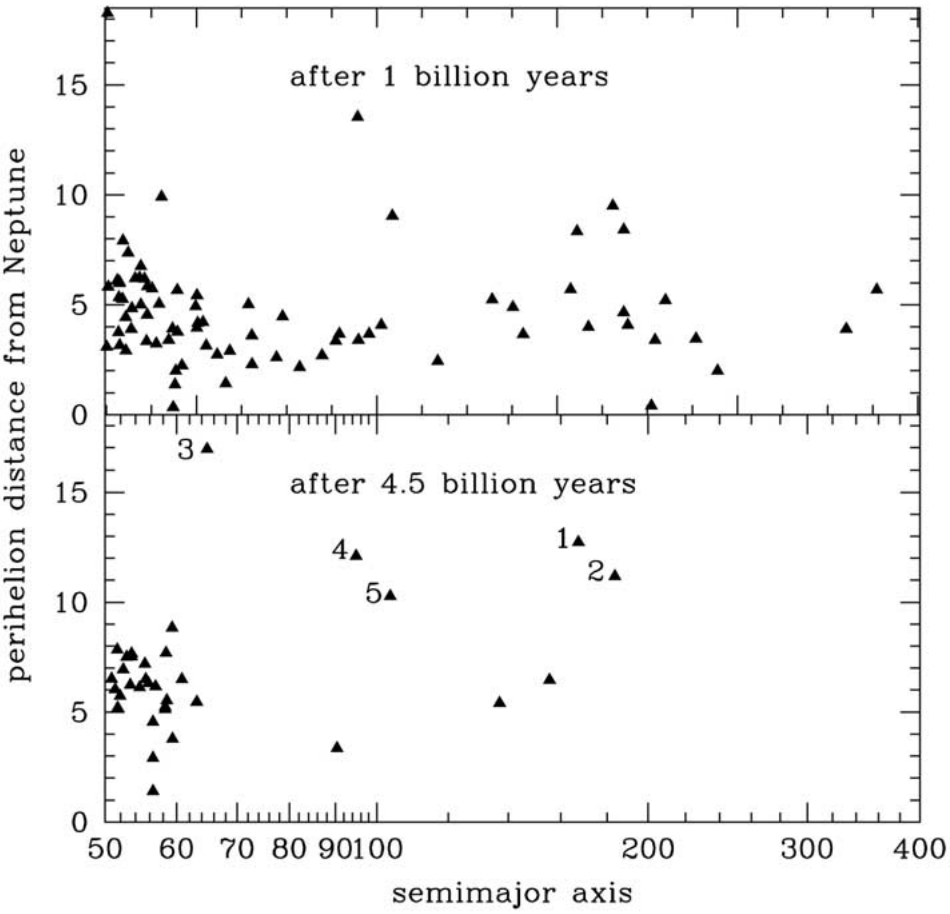

Figure 5. Distribution of semimajor axes with perihelion distances of objects, coming from a numerical integration with the four major planets and a massive planetesimals disk. The surface density distribution in the disk varies as r^{-4} and has a total mass equal to 50 Earth masses, extending to 50 AU. Above, results after 10^9 years of integration, below, after 4.5×10^9 years.

years) of the objects initially in the sub-disk represented in the horizontal axis. Only orbits with a perihelion $p > 35$ AU are considered. We notice a statistically significant negative correlation, with $r = -0.941$ and only 4.3% chance that the null hypothesis would produce such number. The nonaveraged set of data also exhibits statistically significant correlations between initial semimajor axis and final inclination. The interpretation of this result must lie in the fact the innermost objects will on average experience more close encounters with more planets thus further exciting their inclinations. This result also suggests a possible correlation of inclinations and magnitude for the real TNO's, without necessarily having to invoke a two-population distribution (Levison and Stern, 2001).

Next I present the results from an extra run, integrated with the MERCURY package (Chambers, 1999), with the following characteristics: the initial semimajor axis for planets from Jupiter to Neptune are: 5.45, 8.7, 15.5 and 17.8 AU. The disk extends from 18 AU to 50 AU and has a surface density variation as r^{-4} and total mass equal to 50 Earth masses. After 10^9 years Neptune was around 31 AU. Figure 5 shows the distribution of semimajor axes and perihelion distances referred to Neptune's semimajor axis after one billion years and 4.5 billion years. For this case, the last 3.5 billion years were integrated considering only the hot population (the objects that were scattered by Neptune) although keeping their real masses. This procedure forced migration to virtually stop at 1 billion years, although by that time migration was proceeding very slowly anyway. This example shows the production of quite extreme cases of objects with high perihelion distances. The most noteworthy cases are marked with numbers in Figure 5 and their dynamical evolution is described next.

Figure 6 shows that Object 1 stayed most of the time near the 37:3 resonance with Neptune (we find a resonance angle librating for some parts of the total time). The ups and downs of the eccentricity, followed in an opposite way by the inclination shows that a Kozai mechanism is also working.[⋆] In particular, at around 2×10^9 years, the main eccentricity decreasing event takes place. Note that the 37 : 3 resonant angle librates and the argument of the perihelion, although still circulating, reduces its variation speed. At around 4.15×10^9 years the perihelion distance reached a value in excess of 18 AU beyond Neptune's semimajor axis. Object 2 (Figure 7) remained for the last two billion years near the 14:1 resonance with Neptune. During about 6×10^8 years, we notice the libration of the resonant angle here also associated with a libration (in this case a real Kozai resonance) of the perihelion argument. During this time, the relative perihelion distance reached nearly 22 AU. Figure 8 shows the orbital evolution of Object 4 during the first 1.2×10^9 years. For the rest of the time its orbital evolution did not present any significant change. The most important eccentricity decreasing event took place between 7×10^8 and 8×10^8 years. This was caused by the association of the 11:2 mean motion resonance with Neptune with the Kozai mechanism. A remarkable difference between the first two examples and the case of Object 4 is that the perihelion increasing mechanism for the first two examples occurred during the last 3.5×10^9 years in an 'almost conservative' regime[⋆⋆] whereas, in the last case, the eccentricity decreasing mechanism took place during the migration regime. Interestingly, for this case, the orbital evolution during the 'conservative' regime was very stable with no remarkable variation of the semimajor axis, eccentricity or inclination. This poses a question of how necessary is the migration period to create present high perihelion scattered objects? Object 4 argues that at least some of the

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[⋆] The term mechanism is used instead of resonance because we really do not observe a libration of the perihelion argument but only a deceleration in its variation.

[⋆⋆] Note that the objects in the integration for the last 3.5 billion years were considered with their masses.

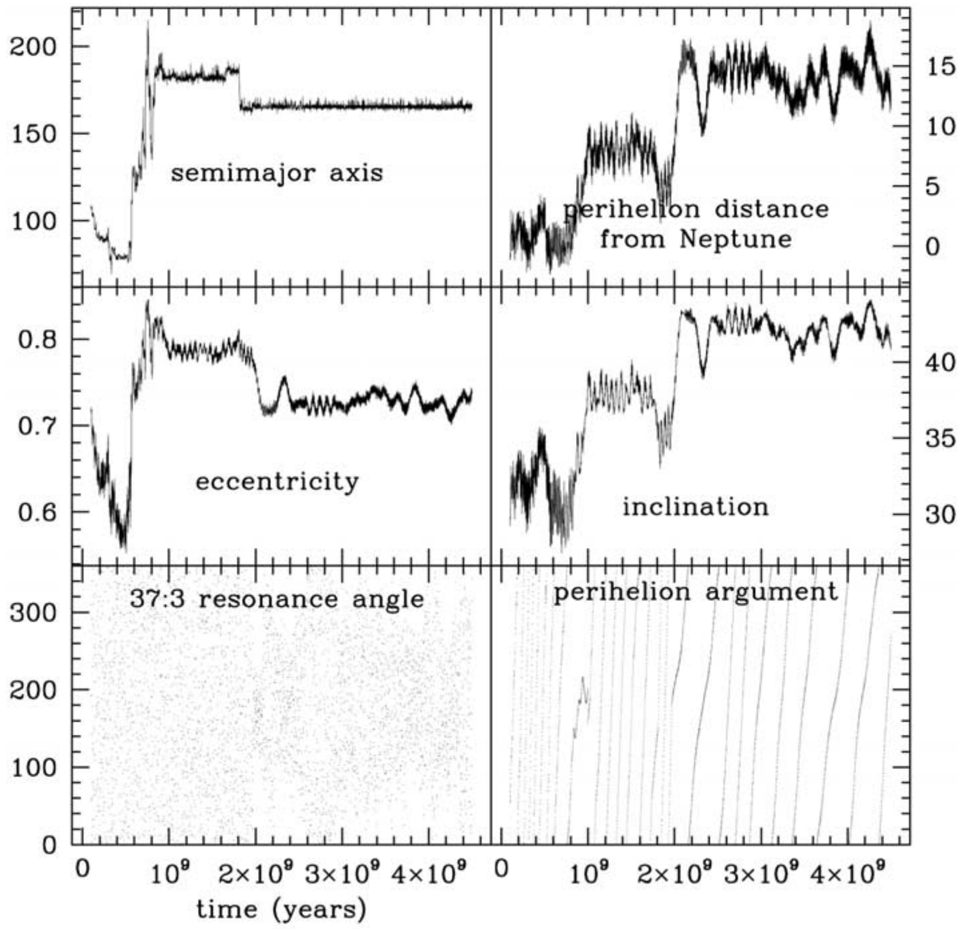

Figure 6. Orbital evolution of Object 1 in Figure 5, for the Solar System age

stable scattered objects must have an origin from the primordial migration period. On the other hand, Objects 1 and 2 seem to suggest that the post-migration phase may indeed be responsible for the production of some high perihelion scattered objects. In this case, these objects exhibit some long term unstable character since they can return back to their low perihelion regime through the same resonance that induced its temporary high perihelion. As a last comment, Object 3 behaves like Object 1 and 2, being in a low eccentricity incursion caused by the 1:3 resonance, whereas Object 5 behaves like Object 4, being in a very stable configuration for the last 3.5 billion years after getting a fairly high perihelion during the first billion years with migration. The above examples suggest that objects with large

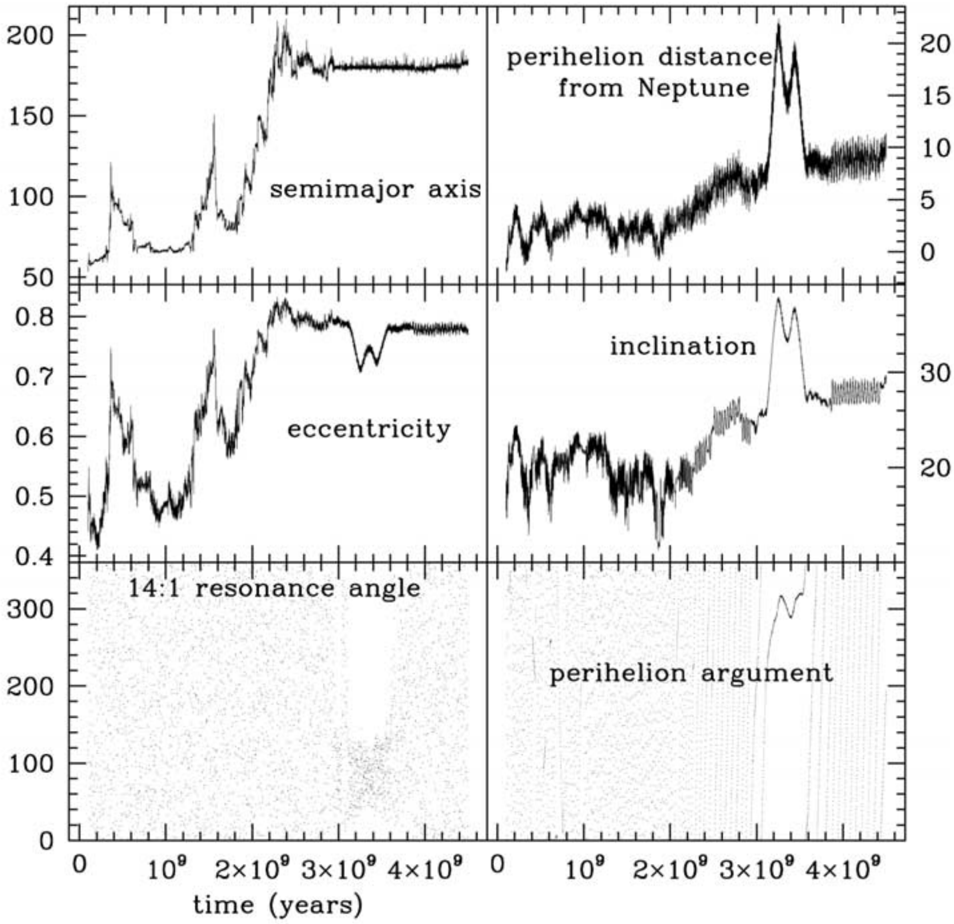

Figure 7. Orbital evolution of Object 2 in Figure 5, for the Solar System age.

semimajor axes and large perihelion distances like 2000 CR_{105} can find a way from the primordial Neptune scattered population.[***].

4. Hot X Cold Population

The process described above and in Gomes (2003) can account for the high inclination TNO's including those in the classical Kuiper Belt. These objects may form a specific population in the CKB named as a hot population (Levison and Stern, 2001; Trujillo and Brown, 2002; Brown, 2001). Similarly, objects that would initially be placed outside somewhat beyond 30 AU, would not be scattered by Neptune but otherwise would suffer resonance sweeping by the same planet. This

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[***] This suggestion would hardly be claimed with just the examples given in Gomes (2003)

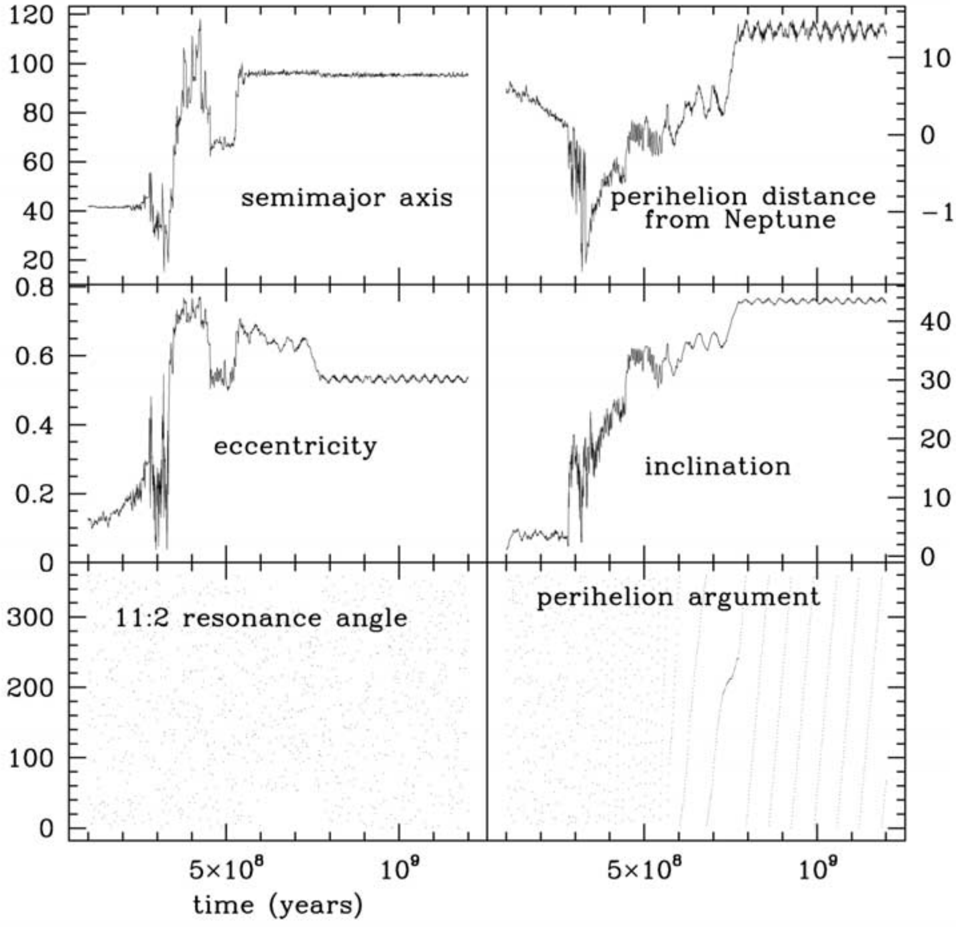

Figure 8. Orbital evolution of Object 4 in Figure 5, for 1.2×10^8 years.

mechanism can produce fairly eccentric orbits into the CKB with however usually low inclinations. These objects would thus form the cold population if the two-populations hypothesis is correct. This bimodal distribution scenario is not however fully proved. In this case, one idea is that the primordial Neptune scattered population might also provide enough low inclination/low eccentricity orbits. The results given above and in Gomes (2003) cannot at this time prove this hypothesis. However, integrations that were carried on longer showed a tendency for the average eccentricity to lower. Some low inclination orbits are also produced. Note that, in the real data, there is a lot of observational bias favoring the low inclination orbits. As a final argument to this point, Figure 9 shows the distribution of semimajor axes, eccentricities and inclinations of objects in a displaced CKB for a run with the same conditions as the one described in the last section with however a surface density distribution varying as r^{-2}. These results are given after 2.7×10^9

years of numerical integration, when Neptune was around 47 AU. Note that this example shows some rather unexcited orbits both in eccentricity and inclination. Although this distribution is a little far from the real CKB distribution, we must note however that a more realistic CBK orbital configuration should allow for the exclusion of the excessive number of low inclination objects which suffer from a favorable observational bias. Also, we must note that the CKB presented in Fig. 9 was formed well beyond present Kuiper Belt location, with some different details in the resonant dynamics. On the other hand, the real dynamics should also include an important extra assumption which is the perturbation of the planetesimal disk on itself. New tests with longer total time integrations and more realistically located CKB are presently being done to better test the one population hypothesis coming from a primordial Neptune scattered population.

5. Conclusions and Discussion

The main conclusion from this work is that some objects from the primordial Neptune scattered population were deposited into the classical Kuiper Belt in the age of the Solar System. Moreover, present scattered objects beyond the 1:2 resonance with Neptune and with high perihelia like 2000 CR_{105} has probably an origin in Neptune's primordial scattered population. The inclination of these objects can get as high as 40° or above but more modest values are also obtained by this process. Usually, secular resonances are responsible to lower the eccentricities of objects in the classical Kuiper Belt whereas, for those beyond the 1:2 resonance, high order mean motion resonances associated with the Kozai resonance cause the perihelia increases. The process of bringing these objects into present stable TNO's orbits must have included a nonconservative phase (in the sense of planet-particle dynamics) when the planets were still migrating (Gomes, 2003) and a conservative phase following the migration phase. The first phase would be responsible to bring around 0.1 Earth masses of Objects already at 10^8 years since the beginning of migration. The post-migration phase may have brought some extra objects both to the CKB but mainly to the present scattered population from Neptune's primordial scattered population through temporary, albeit very long, low eccentricity incursions.

Low inclination objects in the CKB must in principle have a different origin than those coming from the primordial Neptune scattered population. The classical idea is that they are formed in situ or moderately pushed outwards by resonance sweeping (Malhotra, 1995). In this case, the relatively large amount of mass initially in the CKB region necessary to form these present large objects must have eroded substantially since then. Since total migration timescale in some cases may last near 5×10^8 years for Neptune to come to 30 AU (Gomes et al., 2003) mass erosion and planetary migration should be considered simultaneously in a simulation. Such a simulation might also explain Neptune stopping at 30 AU. Another idea is that the primordial planetesimal disk never went beyond some limit around

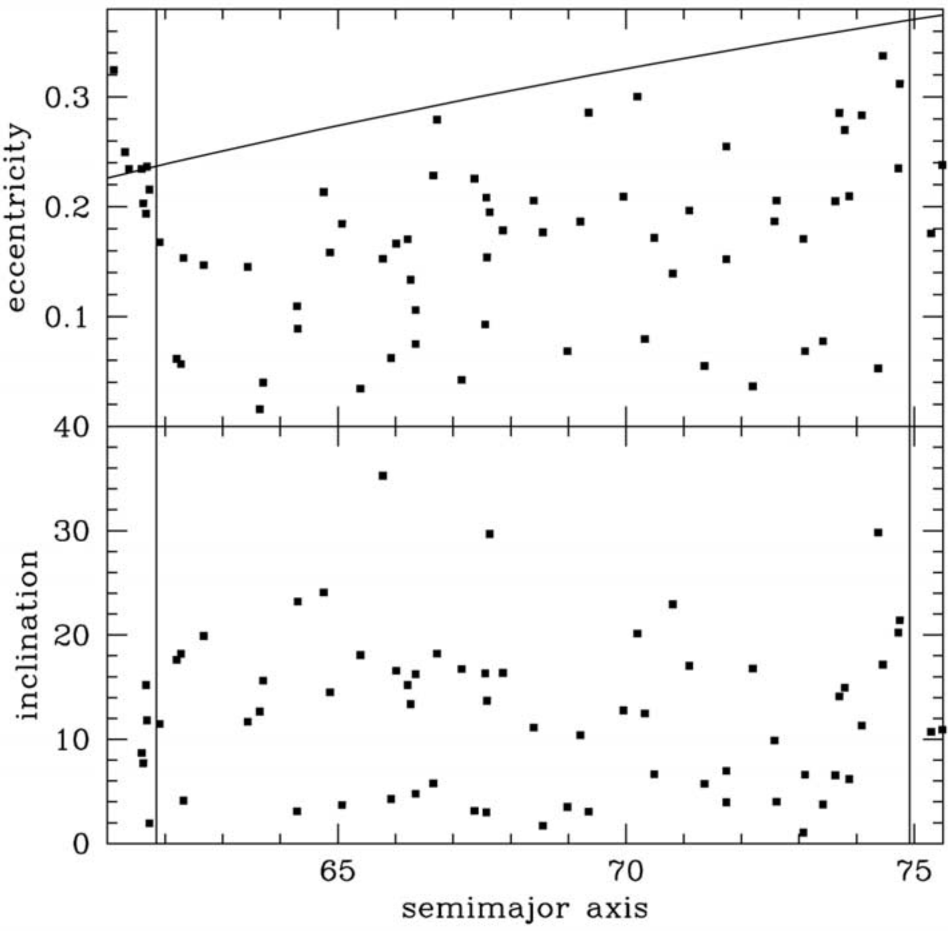

Figure 9. Distribution of semimajor axes, eccentricities and inclinations of objects coming from an integration of the four major planets in a massive planetesimals disk, with 50 Earth masses, extending to 50 AU and with a surface density distribution varying as r^{-2}. The orbits are distributed in a displaced classical Kuiper Belt, since Neptune migrated to near its outer edge after 2.7×10^9 years.

30 AU, as in Gomes (2003). In this case an explanation for the origin of low inclination/low eccentricity CKBO's would be missing. Simulations undertaken with a more complete gravitational model including the perturbation of the disk on individual planetesimals may bring about somewhat different results, possibly including an explanation for the cold population in the CKB.

Acknowledgements

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