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Dynamical structure and origin of the Trans-Neptunian population

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Abstract. Before the discovery of the first member of the Kuiper belt in 1992, the trans-Neptunian population was supposed to lie on a flat disk and each member would follow a barely eccentric orbit. While less conventional orbits for the trans-Neptunian objects were being discovered, our understanding of its orbital structure and origin was continually changed. A basic classification of the trans-Neptunian population as to their orbits identifies a classical low inclination Kuiper belt population, a resonant population, a high inclination Kuiper belt population, a scattered population and an extended population. Several mechanisms have been proposed to explain the orbital architecture of the Kuiper belt population. Presently, the most plausible scenarios are unequivocally related with the primordial planetary migration induced by a planetesimal disk. Low inclination orbits in the Kuiper belt may have been moderately pushed out from a dynamically cold primordial disk by the resonance sweeping mechanism. The origin of high inclination objects in the classical Kuiper belt is however to be found in a primordial Neptune scattered population, through a perihelion increasing mechanism based on secular resonances. Another push-out mechanism based on the sweeping of the 1:2 resonance with Neptune has also been invoked to explain the low inclination orbits in the classical Kuiper belt. Assuming these last two mechanisms, Kuiper belt objects do not need to have been formed in situ. This kind of formation process would demand a quite large original mass in the Kuiper belt region, which would have brought Neptune beyond its present position at 30 AU. Thus with the exception of the low inclination classical Kuiper belt objects and a few resonant ones, all other trans-Neptunian objects are present or past scattered objects. This notion also includes the case for Sedna, so far the only certain member of the extended population. In its most plausible formation scenario, it was a primordial scattered object by Neptune whose perihelion was increased by the close passage of a star.

Keywords. trans-Neptunian population, Kuiper belt, planetary migration

1. Introduction

The pioneering idea (Kuiper 1951; Edgeworth 1949) that the Solar System would not have an abrupt outer edge at Neptune's orbit was confirmed by the discovery of the first trans-Neptunian object about 13 years ago (Jewitt & Luu 1993). Despite the confirmation that there really existed a Kuiper belt, the very nature of this belt turned out to be quite different from what initially conjectured. In fact, the trans-Neptunian population is much less massive than suggested by the extrapolation from a minimum-mass solar nebula model. It is also much dynamically hotter than naturally supposed for a lightly perturbed disk of planetesimals beyond Neptune that due to its low mass density was not able to accrete into larger bodies. Both the dynamically excited character of the orbits as well as the mass paucity beyond Neptune point to an originally inner disk of planetesimals that was scattered out through a primordial planetary migration. A small fraction of the original disk was then deposited into fairly stable regions in the Kuiper belt and beyond. This review will focus on the mainstream history of the trans-Neptunian

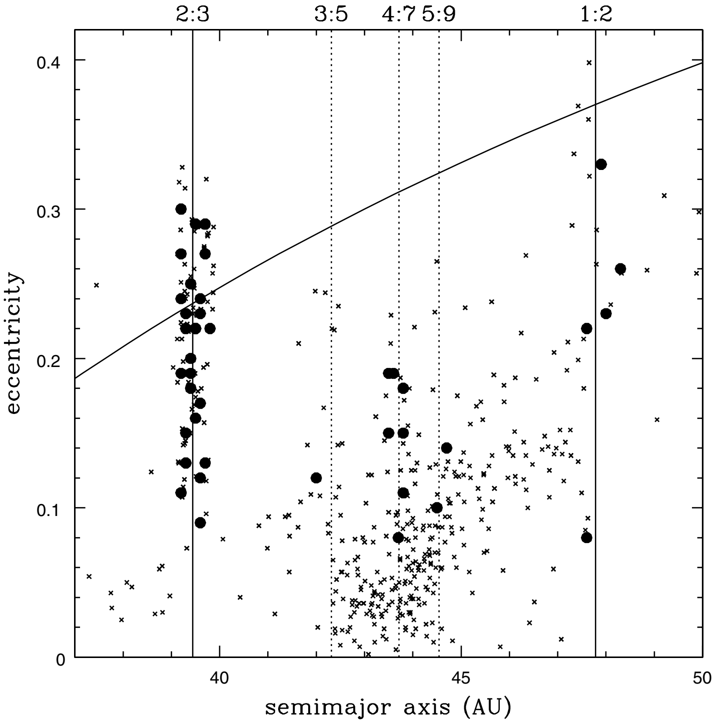

Figure 1. Distribution of semimajor axes and eccentricities for all Kuiper belt objects that have been observed in more than one opposition taken from http://cfa-www.harvard.edu/cfa/ps/lists/trans-Neptunian objects.html as of June/2005. Large circles stand for resonant objects according to Elliot *et al.* (2005).

population dynamics in search of its origin since the discovery of its first member. In section 2, I present a tentative orbital classification of the trans-Neptunian objects and a little about present dynamics of the Kuiper belt follows. The knowledge of this dynamics is essential in order to conclude that the orbital configuration of the trans-Neptunian objects must have an origin beyond present solar system perturbation capabilities. In section 3, I present several theories for the origin of the trans-Neptunian population keeping some chronological order and classifying according to the main theories. In particular, planetary migration theory is given a high priority since I understand that this mechanism is intrinsically related to present trans-Neptunian orbital configuration. Conclusions are drawn in section 4 where I also suggest where we are now and what will come next.

2. Orbital classification of the trans-Neptunian population.

There is not only one possibility of classifying the trans-Neptunian population with respect to their orbits. The simplest classification can distinguish three main groups that we can name as the Kuiper belt, the scattered population and the extended population. Although this last population has so far just one or two representatives, the very specific orbital characteristics of 2003 VB12 (Sedna) undoubtedly distinguishes it from the scattered population. The boundary that separates classical Kuiper belt objects from scattered objects can be the semimajor axis associated with the 1:2 mean motion resonance with Neptune. This number is around 48 AU but 50 AU may work as well. The justification for that limit is the nonexistence of any observed big enough low eccentricity object beyond it (Gladman *et al.* 2001, Allen *et al.* 2002, Bernstein *et al.* 2004). This boundary at least suggests that the 1:2 mean motion resonance with Neptune may have had a decisive influence in its establishment. The nomenclature Kuiper belt is surely suggestive as at first glance it points to a population of objects formed in situ, as some small eccentricity objects might reveal, following the original idea by Kuiper (1951). Nevertheless the Kuiper belt itself is not a uniform population. In fact it can be subdivided into several groups. A useful classification just separates the resonant objects from the non-resonant ones. These latter objects will thus compose the so named classical Kuiper belt. Sometimes the classical belt refers to all objects located between the 2:3 and 1:2 mean motion resonance with Neptune. Anyway the distinction between classical and resonant objects, although theoretically clear, demands a hard task in order to determine a fairly well defined orbit to confirm its resonant status. Recently, Elliot *et al.* (2005) made a comprehensive inventory of Kuiper belt objects placing a good number of the observed objects by their Deep Ecliptic Survey as resonant orbits including high order ones like the 9:5 and 7:4 (see Fig. 1). Anyway many other objects remain to be classified as to its resonant status. This classification can be quite useful since it suggests possible origin scenarios for the Kuiper belt population. A second possible sub-classification for the Kuiper belt orbits distinguishes the high inclination ones from the low inclination ones. Not long after the discovery of the first member of the Kuiper belt, not only eccentric but also very inclined orbits were found. More recently, Brown (2001) determined through statistical inference that there are in fact two different populations in the Kuiper belt, the low inclination and the high inclination ones, sometimes referred to as the cold and hot populations. Correlations of orbital inclinations with color and magnitude (Trujillo & Brown 2002) more accurately established the dual character of the Kuiper belt with respect to the orbital inclination of its members. This new orbital classification more effectively motivated theorists to explain its origin and thus the very origin of the Kuiper belt as a whole.

Figure 1 shows the distribution of semimajor axes with eccentricities for all objects listed in Minor Planet Center electronic pages (available at http://cfa-www.harvard.edu/cfa/ps/lists/trans-Neptunian objects.html and http://cfa-www.harvard.edu/iau/lists/-Centaurs.html) observed in more than one opposition. In this figure we distinguish the resonant semimajor axes and some resonant objects as determined by Elliot *et al.* (2005). Figure 2 depicts the cold and hot population classification, where the objects with inclination smaller than 5° are plotted as circles. One must have in mind that due to observational bias that favors the observation of less inclined orbits we see in Fig. 2 a false ratio between the cold and the hot population. A more realistic ratio between numbers in either population is determined by Brown (2001). In Figure 2, I also plot some of the scattered objects, those closer to the Kuiper belt. It is interesting to note that the cold population seems to invade also the scattered region.

Figure 3 shows the distribution of the semimajor axes and perihelion distances for the scattered and extended populations. It is not difficult to notice that 2000 CR105 and much more specifically Sedna do not belong to the same population as the other scattered objects.

2.1. *Present Kuiper belt dynamics*

A good deal of present orbital configuration of the Kuiper belt can be deduced by its present dynamics (Duncan *et al.* 1995, Morbidelli *et al.* 1995, Malhotra 1996).

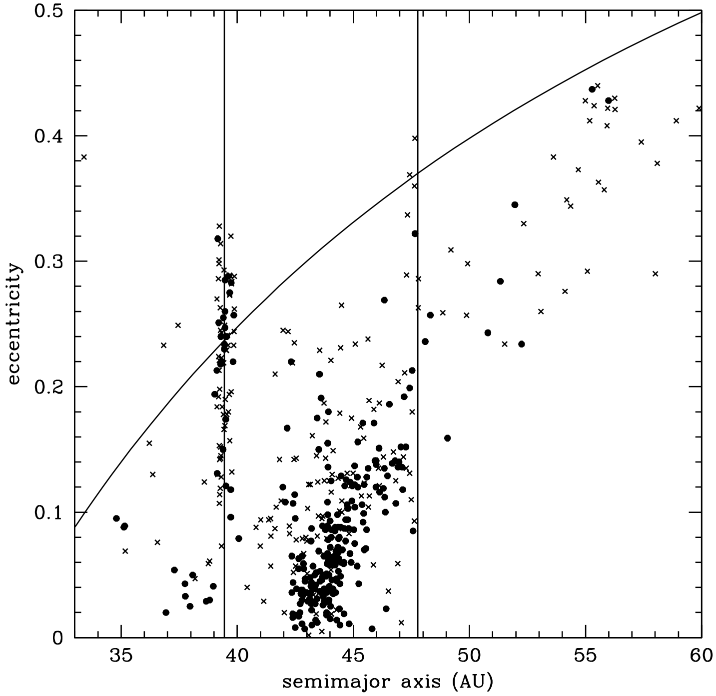

Figure 2. Like Fig.1, now distinguishing the hot (crosses $I > 5°$) and cold (circles $I < 5°$) populations.

A remarkable feature of this orbital distribution is the void of objects just beyond the 2:3 resonance with Neptune. This is caused by the ν_8 secular resonance that can easily empty this region of objects at solar system age. More specific secular and Kozai dynamics can raise eccentricities and inclination in the classical Kuiper belt (Kuchner *et al.* 2002). However this dynamics does not explain the eccentricity and inclination distribution of the observed classical and resonant Kuiper belt. We must find the origin of this high inclination/eccentricity distribution elsewhere.

3. Origin of the trans-Neptunian objects

A consensual point about the origin of trans-Neptunian objects is that they once belonged to an icy planetesimal disk whose members failed to accrete into planet-sized bodies. In fact Kuiper's original conjecture was that these bodies would presently form a disk beyond Neptune. This disk would have been left more or less intact since the end of the formation of the major solar system planets. The continuous discovery of trans-Neptunian objects in excited orbits motivated theorists to seek a way by which these orbits could manage to get excited from a putative dynamically cold disk. It can be instructive to classify these orbit exciting mechanisms by considering two main groups, the static mechanisms group and the migration group. Although it is today almost if not totally consensual that planetary migration of the giant planets once took place in the solar system, it is anyway instructive to review two main non-migration theories for the excitation of the trans-Neptunian orbits. One must bear in mind that these

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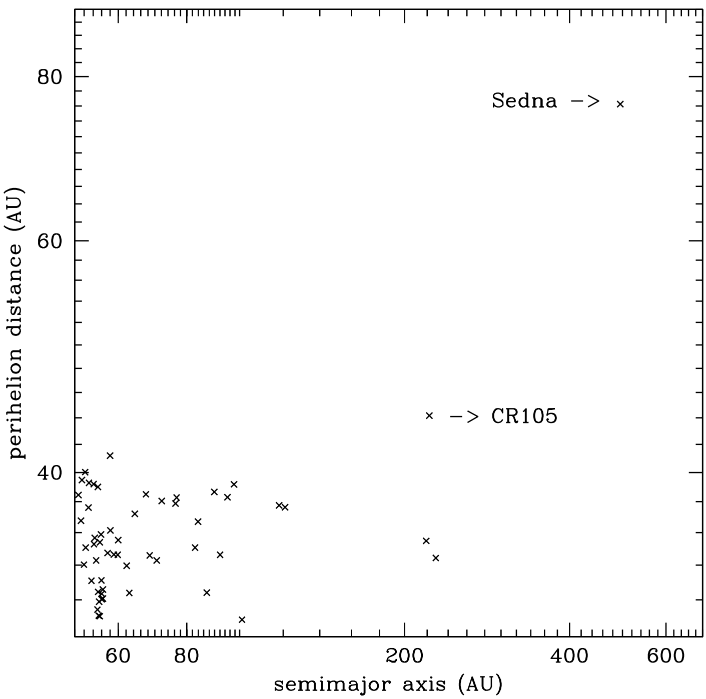

Figure 3. Distribution of semimajor axes with perihelion distances for all trans-Neptunian objects with semimajor axis larger than 50 AU. We notice that 2000 CR105 and Sedna are clearly distinguished as members of a different class of objects.

mechanisms do not in principle negate migration. Nevertheless the consequences of planetary migration on the establishment of the orbital architecture of the trans-Neptunian objects turned out to be so evident that the non-migrating models became of little usefulness.

An important point for the determination of the origin of the trans-Neptunian objects is their present total mass. The classical Kuiper belt mass is now considered to be a few hundredths of an Earth mass. The cold population would have just 0.01 Earth mass and the hot plus scattered population a few times as that (Bernstein *et al.* 2004). The extended population was estimated by Brown *et al.* (2004) to have roughly 5 Earth masses although this estimate is a little crude.

3.1. *The large planetesimal model*

This mechanism was proposed by Morbidelli and Valsecchi (1997) and Petit *et al.* (1999). At that time with a scarce number of known trans-Neptunian objects, this model competed with an already proposed migration model (**?**). The idea of that model is that a large planetesimal (Mars or Earth size) was scattered by the planets and temporarily deposited in the Kuiper region causing the excitation of the Kuiper belt orbits. Eventually the large planetesimal would be scattered out of the solar system by continual perturbations from the planets. The advantage of the large planetesimal model was its generality in producing excited (mainly eccentric) orbits for the Kuiper belt, not only in the resonant regions as in the case for the resonance sweeping model. On the other hand,

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it was not so suitable to explain the resonant population including the remarkable plutinos population. Another difficulty with the large planetesimal model (which was not its own privilege) was its inadequacy to explain the inclinations of the Kuiper belt objects as nicely as their eccentricities. Later it was also noted that the excitation of such a large number of objects that would have been formed in situ would unavoidably induce close encounters of the planetesimals with Neptune thus feeding again its migration towards the edge of the disk (Gomes *et al.* 2004).

3.2. *The passing star model*

Ida *et al.* (2000) proposed that a passing star with a perihelion near 100 AU could raise the eccentricities and inclination of the primordial planetesimal disk creating a distribution of eccentricities and inclinations in the Kuiper region similar to the present one. The dynamically excited planetesimals would thus start a mass erosion process that might account for the mass paucity in the belt. The authors also simulated a planetary migration after the stellar encounter so as to create the resonant Kuiper belt orbits. The advantage of the passing star model was the creation of some high inclinations for the orbits in the Kuiper belt region. Nevertheless the distribution of the orbits would hardly resemble that of the real Kuiper belt. Passing star models have also been invoked to explain the truncation of the Kuiper belt at 50 AU (Melita *et al.* 2000, Kobayashi & Ida 2001).

3.3. *Migration models*

Fernandez & Ip (1984) first showed that a planetary formation scenario where proto planets shared its orbital space with smaller planetesimals would induce the migration of the planets. This model was later improved by the modeling of a planetesimal disk with a larger number of objects (Hanh & Malhotra, 1999; Gomes *et al.* 2004). These more accurate models confirmed the main features already suggested in Fernandez & Ip (1984) which are the outward migration of Neptune, Uranus and Saturn and the inward much shorter migration of Jupiter. This process is based on the exchange of energy and angular momentum between the planets and planetesimals (for details see Malhotra *et al.* 2000; Gomes *et al.* 2004). The main migration theories presented to possibly explain the trans-Neptunian orbital architecture are: the resonance sweeping theory, the Neptune's aphelion theory and the evader's theory. Another useful classification of the migration models distinguishes gradual migration models and abrupt migration models. The next four subsections will deal with these Kuiper belt orbital excitation mechanisms.

3.3.1. *The resonance sweeping model*

In two pioneering papers, Malhotra (1993,1995) showed that Neptune's outward migration into an initially dynamically cold disk of planetesimals would push out along with the planet many planetesimals trapped in mean motion resonances with the outermost planet. This mechanism by the adiabatic invariant theory (Malhotra 1995; Gomes 1997) can also excite the eccentricities of the trapped bodies. By that time many Kuiper belt objects already found shared the 3:2 mean motion resonance with Neptune like Pluto. These objects were thus named plutinos after Pluto. By the adiabatic invariant theory, the increment in a plutinos's eccentricity is an analytical well determined function (Malhotra 1995; Gomes 1997) of the radial displacement of the planetesimal and the planet. Thus from Pluto's well known eccentricity, it was possible to infer the total radial shift experienced by Neptune, about 6 AU. With the aid of Fernandez & Ip (1984) results it was possible to estimate the other planets initial positions, thus many simulations of planetary migration were undertaken considering a standard set of initial positions for the

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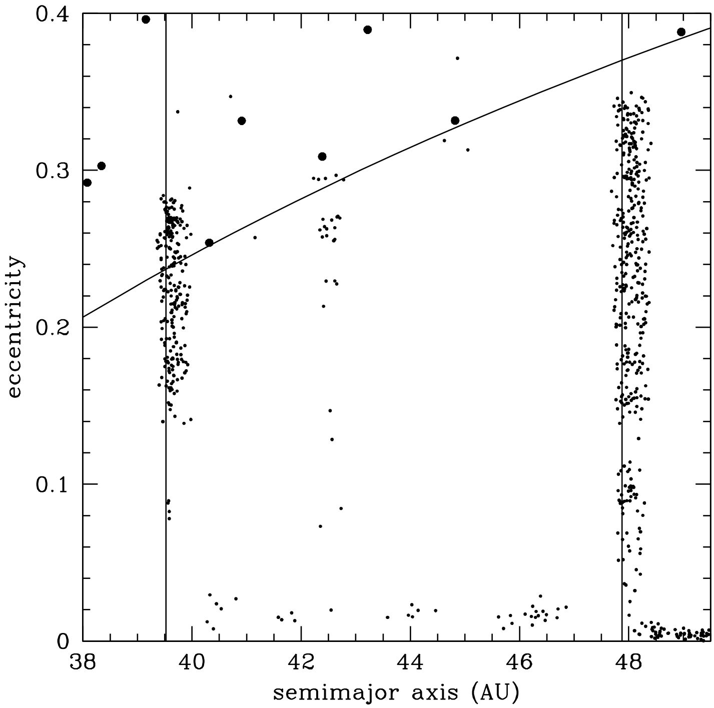

Figure 4. Distribution of semimajor axes with eccentricities of planetesimals from a numerical simulation. The planetesimals were initially distributed in a cold disk outside the orbit of Neptune at 23 AU. The migration was induced by a fictitious force and was made to last for 10 million years after which the planets stopped at their present positions. The migration of Neptune caused planetesimals to be trapped into several mean motion resonances. The orbits with inclinations greater than 5° are represented as the larger circles.

planets which were from Jupiter to Neptune, 5.4 AU, 8.7 AU, 16.3 AU and 23.2 AU. These simulations considered a fictitious force to mimic the planetary migration and the planetesimals assumed massless would experience the planetary gravitational perturbations. Very interesting results came from these simulations showing that plutinos eccentricities could thus be attained. Moreover this model could also account for trapped bodies in other resonances like the 1:2, where objects were really found. Finally the eccentricities of bodies between the 3:2 and 2:1 resonances with Neptune could also be fairly increased due to trapping and release from resonance during migration. Again the difficulty that remained was the explanation of so many orbits with high inclinations in the Kuiper belt that could not be accounted for by the resonance sweeping scenario (see Fig. 4). In particular, plutinos could acquire their inclinations but the process by which this was possible did not create as many high inclination objects as observed (Gomes 2000). Also the adiabatic invariant theory applied to account for Pluto's inclination (through the coupled mean motion plus Kozai resonances) demands a much smaller initial radial distance for Neptune (around 18 AU) if Pluto is to be assumed in an initial dynamically cold orbit (Gomes 1997). This initial position for Neptune (with implied more compact initial orbits for Uranus and Saturn) was considered problematic since many mean motion resonances would be experienced by pairs of planets during migration resulting in a possible destabilization of the system. This was later resolved since the effect of a massive disk on the planets acts to circularize their orbits. The massless disk models considered by then did not show this effect. A more complete model where the disk particles had mass to disturb the planets and to induce their migration was presented in Hanh & Malhotra, 1999. In this work, considering the standard set of initial conditions mentioned above, the authors estimated that the mass for the disk that would bring Neptune to 30 AU should be around 50 Earth masses. The fact that the disk was composed by few particles (1000) implied a too nonuniform migration which impeded the resonance sweeping process, thus very few particles could be trapped in the resonances although the eccentricity raising effect was preserved.

3.3.2. *The Neptune's aphelion model*

The idea that Uranus and Neptune would hardly be formed at their present positions (Levison & Stewart 2001) or even at their shifted location according to the standard initial positions of section 3.3.1 motivated Thommes *et al.* (1999) to propose a model by which Uranus and Neptune formed between the orbits of Jupiter and Saturn, these last ones not very far from their present positions. The orbits of the four planets remained stable while Jupiter and Saturn did not reach the critical mass to start to attract the disk gas. After that, when the gas giants acquired masses similar to present ones, they started to disturb Uranus and Neptune into very elliptical orbits throwing them directly into the planetesimal disk. Because of this great perturbation experienced by the icy giants, the aphelion of the outermost planet temporarily visited the Kuiper belt region, thus exciting the planetesimals orbits in the belt. One of the difficulties with this model had to do with the planets themselves since there is no disk mass big enough to prevent the planets from exiting the solar system due to a strong close perturbation from a gas giant and at the same time small enough to prevent Neptune to go beyond its present position at 30 AU. But as far as the Kuiper belt itself is concerned the temporary passage of Neptune's aphelion at present Kuiper belt region was able to effectively excite again only the eccentricities of the orbits but not their inclinations.

3.3.3. *The evaders model*

Gomes (2003a) envisaged a model where Neptune started its migration between 13.5 and 17.5 AU. A disk of planetesimals would start just beyond Neptune. Several numerical simulations were done for different outer edges of the disk. This disk was simulated with 10000 massive particles that disturbed the planets and induced a planetary migration. The consideration of one order of magnitude higher number of particles allowed a much smoother migration supposedly closer to reality. In fact, in this kind of simulated disk the particles functioned as a fuel for the migration but they also experienced the resonance trapping process proposed by Malhotra (1993). Another consequence of this higher number of simulated particles for the disk was the possibility of allowing the observation in the end of the simulation of some planetesimals deposited in the Kuiper belt as evaders from the scattered population. In fact, mean motion and secular resonances could decrease the eccentricities of a small fraction of all planetesimals that became scattered by the planets during migration. This very migration could also help in erasing the return path for the particles experiencing eccentricity decrease since the planet-particle dynamics would become irreversible. These particles deposited in the Kuiper belt present high inclinations due to its past history of close encounters with the migrating planets, as Fig. 5 shows. These inclinations have a distribution compatible with the inclination distribution of the dynamically hot Kuiper belt population (Gomes 2003a). Although the fraction of planetesimals initially in the disk deposited in the Kuiper belt through this process is

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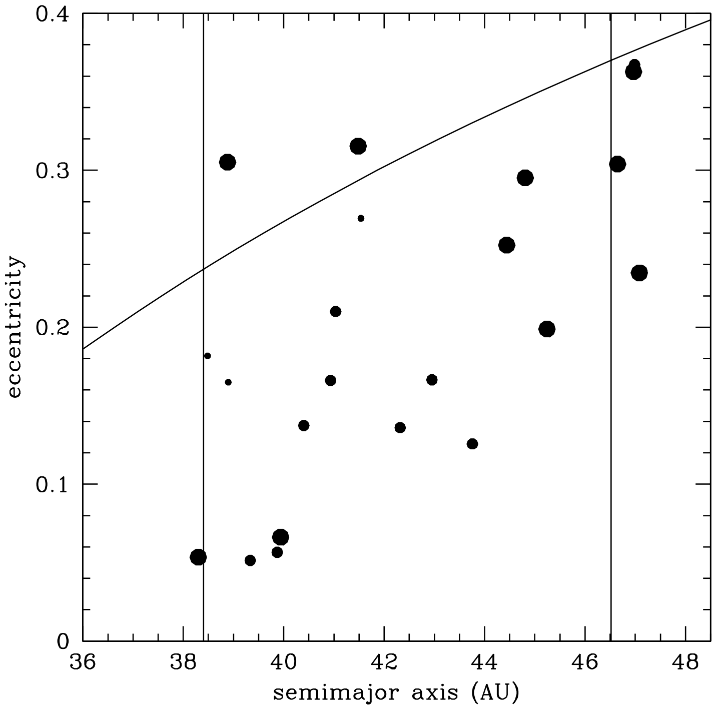

Figure 5. Distribution of semimajor axes with eccentricities of planetesimals from a numerical simulation. The planetesimals were initially distributed in a cold disk outside the orbit of Neptune around 15 AU. The planetesimals perturbed the planetary orbits thus inducing a migration. After one billion years some planetesimals scattered by Neptune had their perihelia increased due to secular and mean motion resonance effects from the planets, thus being deposited in the Kuiper belt (Gomes 2003a). The small circles stand for orbits with inclination lower than 5° Large circles represent planetesimals orbits with inclinations between 5° and 20°, whereas very large circles stand for orbits with inclination greater than 20°

very small (about 0.2 % at solar system age) it is however large enough to account for the present hot Kuiper belt mass. Therefore, another new idea brought up by this scenario is that there is no more need for mass erosion in the Kuiper belt, at least as far as the hot population is concerned, since the present mass of hot Kuiper belt objects turns out to be the same as the original one. However there was now the low inclination population to be explained. Considering them as objects formed in situ and eccentricity-excited by the resonance sweeping process, an estimated mass of 10 Earth masses originally in the Kuiper belt region is required to form the big enough objects in present Kuiper belt (Stern & Colwell 1997; Kenyon and Luu 1998). This requires, just for the cold population, a mass erosion process to present estimated 0.01 Earth mass of around 99.9 %, not well explained by fragmentation theories (Davis & Farinella 1997; Kenyon & Luu 1999). Moreover this high mass in the original outer planetesimal disk would force Neptune to beyond its present position somewhere in the present Kuiper belt (around 45 AU) (Gomes *et al.* 2004). These findings surely suggest a push-out mechanism also for the cold population. Levison & Morbidelli (2003) proposed such a scenario in which objects trapped into the 1:2 mean motion resonance with Neptune during its outward migration are released before the end of migration leaving low inclination objects with moderate

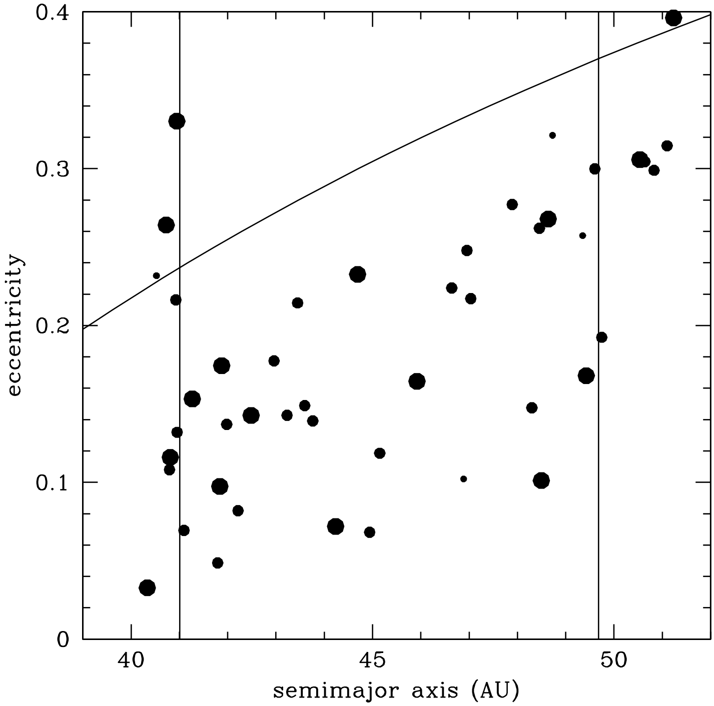

Figure 6. Same as Fig. 5 now for an abrupt migration model in which Uranus and Neptune are thrown into the planetesimal disk starting the late heavy bombardment (Gomes *et al.* 2005a). This orbital distribution stand for 700 million years after the beginning of the bombardment. We still notice the formation of high inclination Kuiper belt objects.

eccentricities in the present Kuiper belt region. This process is based on the effect of secular resonances on the planetesimals trapped in the 1:2 resonance with Neptune. These resonances show up because Neptune's perihelion precession rate is changed due to the perturbation from the great amount of mass trapped in the 1:2 resonance. The decisive consequence of these secular resonances is that planetesimals eccentricities of orbits in the 1:2 resonance do not increase uniformly by the adiabatic theory. Some planetesimals thus remain with low eccentricities and are eventually released from resonance into the classical Kuiper belt.

3.3.4. *Gradual versus abrupt migration models*

Most of the migration models described above is also associated to a gradual migration. The gravitational interaction of a cold disk of small planetesimals with planets will naturally induce a slow migration of the planets with planetary eccentricity damping. This gradual migration is favorable for the adiabatic resonance trapping process (**?**) and the push-out mechanism (Levison & Morbidelli 2003) to create the low inclination objects. It is also compatible with the process that creates the high inclination population (Gomes 2003a). Migration will not proceed smoothly either if the planetesimals are too large†

† using few too large planetesimals to simulate a massive disk that induces migration is an artifice to enable a not too long computation time for the numerical integration; on the other hand real large planetesimals may have existed in the disk (terrestrial planet size, probably in

or if the planets experience close encounters that throw them abruptly into the disk. The Neptune's aphelion model above described can be classified as an abrupt migration model, since the planets experience close encounter due to their initial conditions near the gas giants and the fast gas accretion of Jupiter and Saturn. More recently another abrupt migration model was suggested (Tsiganis *et al.* 2005; Morbidelli *et al.* 2005; Gomes *et al.* 2005a) by which Jupiter and Saturn would have crossed their 1:2 mean motion resonance after an initial slow migration. This resonance passage may have been delayed 700 million years after which Uranus and Neptune would be thrown immediately into the disk triggering the late heavy bombardment in the inner solar system. This process also allows the major planets to stop at their right positions with the right eccentricities and inclinations and also Jupiter Trojans can be captured from the disk population directly into coorbital regions with Jupiter. Abrupt migration theories are not however suitable to explain resonance trapping via adiabatic theory, thus not only Malhotra (1993, 1995) resonance sweeping theory does not apply but also the Levison & Morbidelli (2003) push-out mechanism is weakened, since this theory is based on an initially very smooth migration of Neptune to allow a great number of planetesimals trapped into the 1:2 resonance. On the other hand, the creation of high inclination objects by Gomes (2003a) does not need a long regular migration of Neptune. An abrupt migration model as described above can account for the mechanism that places high inclination objects in the Kuiper belt (see Fig. 6).

3.4. *The origin of the scattered and extended populations*

Besides planetary migration, an unavoidable consequence of the primordial close encounter interaction between the major planets and a disk of planetesimals is the creation of a population of objects scattered by the planets. At solar system age, most objects are scattered out of the solar system but a non-negligible amount remains. These objects have large semimajor axes but their perihelia are not much larger than Neptune's semimajor axis at 30 AU, a clear signature of a past history of close encounters between the planetesimal and Neptune. An estimated mass of a few hundredths of an Earth mass (Bernstein *et al.* 2004) will be left in this population after 4.5 billion years not only by chance but also by mechanisms that turns the orbits stable for the solar system age. A known mechanism is the trapping of scattered objects into coupled mean motion/Kozai resonances that induce an increase of the object's perihelion distance thus placing it far from destabilizing close encounter perturbations from Neptune. If this resonance mechanism happens while Neptune is still migrating, high perihelion fossilized orbits can be created. When migration is ceased, temporary (though long) high perihelion orbits can be also created, as Fig. 7 shows (Gomes 2003b; Gomes *et al.* 2005b). This process will anyway produce a larger number of high perihelion orbits with small semimajor axis as compared with high perihelion orbits with large semimajor axis. Fig. 7 however shows that the two highest perihelion orbits already found for a trans-Neptunian object also have large semimajor axes. This suggests that these objects (Sedna and 2000 CR105) must have had their perihelia increased by some other process than the mean motion + Kozai resonance mechanism from Neptune. Although 2000 CR105 might marginally be created by such a process, Sedna would not (Gomes *et al.* 2005b) so there is more than a statistical inference for a specific origin for these objects. Among several possible mechanisms that can raise the perihelion of a scattered object, the most serious candidate is the passage of one or several stars near a primordial solar system (Fernandez and

its inner part) and a more realistic simulation including both large and small planetesimals is yet to be undertaken

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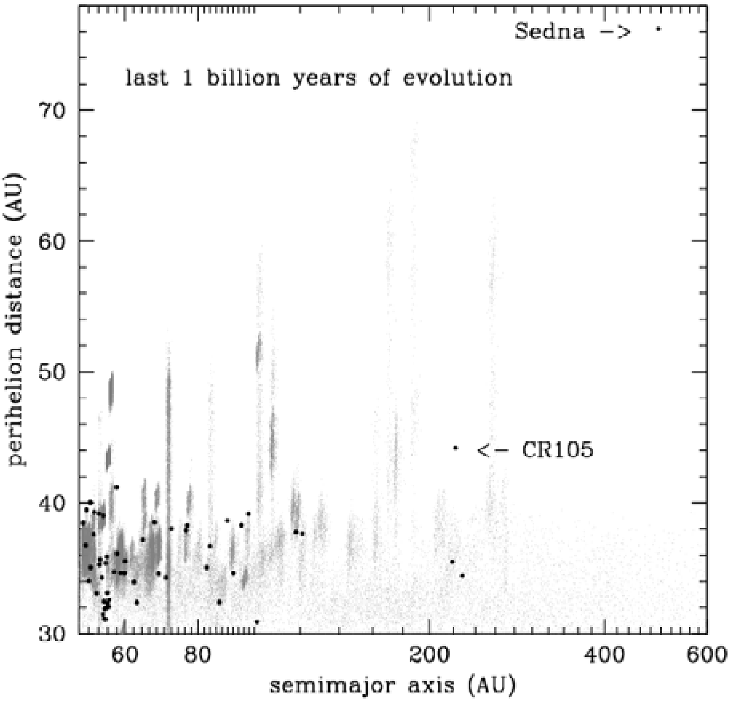

Figure 7. Distribution of semimajor axes and perihelion distances of real scattered and extended population objects (small circles) and from a numerical integration including all four major planets and a disk of planetesimals that induce planetary migration. The integration was carried on to solar system age and orbits were plotted at every million years for the last billion years (small dots). This figure confirms that Sedna cannot be a simple scattered objects and much probably 2000 CR105 is not either.

Brunini 2000; Morbidelli and Levison 2004). This is a reasonable hypothesis as far as we understand that the solar system was formed in a denser star cluster. The creation of populations that include both 2000 CR105 and Sedna can be accomplished by the perihelion raising effect of a passing star (see Fig. 8). A weak point of the passing star theory is the usually low mass of an extended population (about 0.2 Earth mass) created by such a mechanism as compared with the (however crude) estimate of 5 Earth masses for a population of Sedna-like orbits (Brown *et al.* 2004). Another passing star theory worthy commenting (Morbidelli and Levison, 2004) concerns a small (brown dwarf) star that carries with it a disk of planetesimals. Passing near the primordial Sun (200 AU), the brown dwarf system could pass to the Sun some of the brown dwarf's planetesimals, in this case the extended population would be formed by extrasolar bodies. The advantage of this theory is that possibly a substantial fraction of the original brown dwarf disk could have been transferred to the solar system. However we do not know much about brown dwarf disks to give too much a priori credit to this theory. Another interesting theory for the formation of Sedna-like orbits concerns a wide-binary solar system companion (Matese *et al.* 2006). This planet should have a mass larger than Jupiter mass if located in a circular orbit at 5000 AU to create a Sedna-like orbit. To account for 2000 CR105 orbit the planet should have near 10 Jupiter masses at 5000 AU. ..

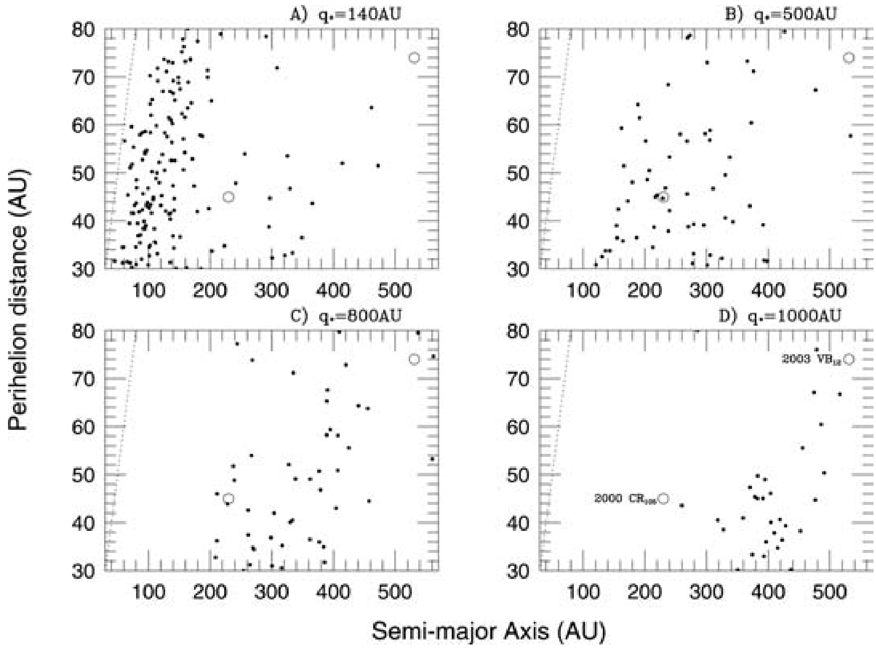

Figure 8. Distribution of semimajor axes and perihelion distances for scattered objects whose orbits were perturbed by a close passing star. The minimum distance of the passing star from the Sun is shown at the right top of each panel (courtesy of Levison and Morbidelli)

4. Conclusions

Since the discovery of the first member of the Kuiper belt, the understanding of the origin of the trans-Neptunian population has been continually challenged. It is now consensual that at least a great part of the trans-Neptunian objects has been shifted outward by the migration of the icy giant planets especially Neptune. This process induced the excited orbits observed in the Kuiper belt and possibly also explains the belt's low mass as an original feature caused by the relatively inefficient processes to bring objects from the scattered population to more stable regions in the Kuiper belt. This is most probably the case for the high inclination objects in the classical and resonant Kuiper belt. The low inclination population in the classical belt can have an explanation in a push-out mechanism from a truncated disk. This mechanism does not however work very well if one must invoke an abrupt migration model as recently suggested (Gomes *et al.* 2005a). Moreover both hot and cold populations would come from about the same region in the primordial planetesimal disk, what is not compatible with the dual character of the Kuiper belt. The formation of the cold belt in situ (or slighted shifted outward by the resonance sweeping mechanism) cannot at this time be ruled out. The most important argument in its favor is the dual character of the classical Kuiper belt population. The correlation of the hot and cold populations with color and magnitude suggests different origins for both populations and the in-situ formation of the cold population would naturally account for that. However this scenario would have also to explain the radical erosion suffered by the mass initially in the Kuiper region that must be reduced to more than two orders of magnitude possibly three orders. Moreover an initial high mass in the Kuiper region would probably have induced an extra migration to Neptune shifting the outermost planet to somewhere in the very Kuiper belt region.

Another challenging characteristic of the trans-Neptunian population concerns the understanding of the origin and orbital distribution of the extended population. Several theories have been proposed that fairly well account for this presently two-member population. As soon as successful observations reveal new members for this population the right theory will be gradually accepted by the scientific community. For now there is plenty of room for theorists.

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