Forming the Kuiper Belt by the Outward Transport of Objects During Neptune's Migration

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The 'dynamically cold Kuiper belt', which consists of objects on low inclination orbits between $\sim$40 and $\sim$50 AU from the Sun, currently contains less than 1/10 Earth-masses of material[1][2]. This value is surprisingly low because, accordinging to accretion models[3][4], the objects observed there would not have grown to their present size unless the cold Kuiper belt originally contained tens of Earth-masses of solids. While several mechanisms have been proposed to produce the observed mass depletion, all have significant limitations[5]. Here we show that the objects currently observed in the dynamically cold Kuiper belt were most likely formed interior to ~ 35 AU and were pushed outward by Neptune's 1:2 mean motion resonance during its final phase of migration. Combining our mechanism with previous works[6][7], we conclude that the *entire* **Kuiper belt formed closer to the Sun and was transported outward during the final stages of planet formation.**

Since its discovery 10 years ago[8], a picture has emerged that shows a Kuiper belt with two major components: a dynamically *cold* population –made of objects on orbits with inclinations $i < 4°$– and a *hot* population –whose inclinations can be as large as 30°, and possibly larger[9]. These populations have different physical properties[10][11]. In addition, there is a small population (roughly 10% of the total[1]) of objects trapped in mean motion resonances with Neptune. The objects in all three structures are confined to have semi-major axes less than $\sim 50\,\mathrm{AU}$[12][13], where the whole Kuiper belt seems to have an abrupt end (see Figure 1a).

A study of the currently available literature suggests the following story for the early evolution of the Kuiper belt. First, the proto-planetary disk was truncated at roughly 50 AU by one of several possible mechanisms [14] [15] [16] [17]. Then, the dynamical evolution of objects during Neptune's outward migration[18][7] gave rise to the resonant populations[7][6], the hot population[6][19], and a related structure known as the *scattered disk*[20][21]. In this picture, the objects in the cold population are primordial and thus we are faced with the mass depletion problem mentioned above.

Here we argue that the initial proto-planetary disk was truncated somewhere near the current location of Neptune (at $30\,\mathrm{AU}$). Placing the edge of the disk at this location provides a natural explanation for why Neptune is where it is — it migrated until it hit the edge of the disk [22]. Not only the hot population[6] but also the cold population formed interior to this edge, and was pushed out to its current position during Neptune's migration. This circumvents the mass depletion problem because the mass required to grow the objects was never in the Kuiper belt. However, the push-out mechanism for the cold population must be different from (but work in conjunction with) that proposed by Ref[6] for the origin of the hot population. This is because the model in Ref[6] involves objects that were scattered by Neptune and thus had their inclinations excited, while the inclinations of objects in the cold belt are small. We present a new dynamical mechanism that meets this constraint.

We started our search for a new push-out mechanism by focusing on Neptune's 1:2 mean motion resonance (MMR). The fact that the visible outer edge of the cold belt is close to this MMR's current location at 48 AU (Figure 1a) suggested to us that this resonance might be responsible for this population. Previous studies[7] have shown that as Neptune migrated outward, some objects in primordial, low-inclination low-eccentricity orbits were trapped in this MMR and were pushed outward, along with the resonance. In addition, it was shown that 1:2 MMR does not excite inclinations. Thus, we reasoned that this resonance could have been responsible for the delivery of objects to the region between 40 and 48 AU (the current location of the resonance) while keeping the population dynamically cold. However, the standard 'adiabatic model' of resonance trapping predicts that, as the bodies are pushed outwards, their eccentricities monotonically increase. So, as the MMR is pushed through the cold belt, the eccentricities of trapped objects would be larger than the observed cold Kuiper belt objects (see caption of Figure 1b for details).

But, does the adiabatic theory apply to this case? To answer this question, we have simulated, using direct N-body techniques, the evolution of a system containing the 4 giant planets embedded in a planetesimal disk. The disk extended originally from 10 to 35 AU and contained 50 Earth masses, with a surface density proportional to the inverse heliocentric distance. The disk was modeled using 15,634 equal mass particles, which interacted with the planets but not with each other, as is usually done in this kind of simulation. The initial locations of Jupiter, Saturn, Uranus and Neptune were at 5.4, 8.7, 13.8 and 18.1 AU respectively. We followed the evolution of this system with the symplectic integrator known as SyMBA[23][24]. We found that during the integration, the giant planets migrated due to the interaction with the disk particles, as expected. In addition, there was indeed a population of low-inclination objects captured in Neptune's 1:2 resonance and pushed beyond the original outer edge of the disk, as predicted by the adiabatic theory.

In contrast with the theory, however, we found that some objects in the MMR have eccentricities that oscillate (Figure 2) and thus there was always a population of bodies with small eccentricities (see Figure 1c). These oscillations are the result of a heretofore unknown *secular resonance* that is embedded in Neptune's 1:2 MMR (Figure 3). This secular resonance is generated when there is a significant amount of mass ($\sim 3M_\oplus$) in the 1:2 MMR (see Figures 3's caption for details).

The fundamental question now is how far can the bodies be pushed within the 1:2 MMR and still exhibit large eccentricity oscillations. Unfortunately, we cannot answer this with our current simulations for computational reasons. Since the amount of CPU time required for our simulations is linear in the number of disk particles, we were forced to keep the number of particles less than roughly 10^4. In reality, the disk was made of many billions of much less massive objects.

Consequently, Neptune's migration was much more jumpy in our simulation than it was in reality, which had the effect of artificially clearing objects from the 1:2 MMR (and other resonances) when it was at 38 AU, well before it entered the region of the cold Kuiper belt.

To overcome this problem, we performed a second simulation, in which planetary migration is not directly the result of the interaction with the disk particles, but instead is primarily induced by the inclusion of an artificial drag term in the planets' equations of motion. For this drag we employ the prescription in Ref[7], so that planetary migration is perfectly smooth and exponentially decreasing on a timescale of 40 My. The initial orbital configurations of the planets and particles in the 1:2 MMR are those obtained from the previous simulation when the resonance is exactly at the disk's edge. All other disk particles are discarded from the system. The initial total mass of the population in the 1:2 MMR is $\sim$3 Earth masses. During the integration the disk particles responded to the planets, but not to each other. The planets responded to each other, the disk particles, and the drag force. We found that, throughout the migration process, there were always a number of objects in the 1:2 resonance that had small eccentricities (Figure 1c). Investigations of the behavior of these particles show that they are indeed undergoing oscillations in eccentricity due to the self-induced secular resonance described above.

So, we can now produce resonant objects on low eccentricities as the resonance moved between 40 and 48 AU, but we still have not reproduced the observations. At the end of the simulation described in the previous paragraph, most of the objects are in the 1:2 resonance and not in the cold non-resonant population. Our model is not releasing enough of the objects from the resonance during the migration. This is because these simulations are the opposite extreme of our N-body simulations, i.e. the migration is perfectly smooth. Perfectly smooth migration can only occur in an idealized disk composed of an infinite number of infinitely small objects.

In reality, Neptune's migration, and thus that of its MMRs, must have been somewhat jumpy because of the presence of relatively massive objects in the disk[25]. Thus, we performed another simulation in which we modeled this by providing, at random times, instantaneous 'kicks' to Neptune's velocity in random directions. Figure 1d shows the resulting orbital distribution of the dynamically cold population produced in the simulation in which velocity kicks with magnitude $10^{-4}/\sqrt{p}$ km/s –where p was a uniform random number between 0 and 1– are applied every 5000 years. The magnitude and frequency of these kicks statistically correspond to what Neptune would experience if there were one or two objects of $\sim$2 lunar masses crossing its orbit at any one time. The $1/\sqrt{p}$ dependence is introduced to reproduce the statistical distribution of impact parameters. There is reasonably good agreement between the observed orbital distribution of the cold population (Figure 1a) and the results of our simulation. It is also important to note that our new mechanism makes mainly cold objects — 63% of the particles between 42 and 50 AU have inclinations less that 4° and all have inclinations less than $\sim 15^{\circ}$.

We actually performed 12 'jumpy migration' simulations with different values of the magnitude and frequency of the kicks. The run shown in Figure 1d produced the semi-major axis – eccentricity distribution most similar to that observed. Reducing the magnitude or the frequency of the kicks leaves progressively more particles in the 1:2 resonance at the end of the simulation, eventually coming in conflict with the observations. Conversely, increasing the magnitude or the frequency of the kicks leads to simulations where the resonance is depleted significantly before it reaches its final location and thus leaves no objects in the outer Kuiper belt, which again is in conflict with the observations.

The final cold belt population generated by our model represents only $\sim 1\%$ of the population originally in the massive planetesimal disk beyond the initial location of the 1:2 MMR. Obviously, this fraction is model-dependent, but it is necessarily small and explains the small mass of the current population. It is due to a series of successive diminutions related to: (i) the capture efficiency in the 1:2 MMR; (ii) the probability to be released from the resonance due to Neptune's encounters with the massive bodies; and (iii) the probability to have, at the time of the release from the resonance, an eccentricity sufficiently small to ensure survivability during the subsequent evolutionary phases.

The results presented in this letter have profound implications for our understanding of the origin of the outer Solar System. In combination with the results in Ref[7] and Ref[6], this work implies that the *entire* Kuiper belt formed interior to its current location, and achieved its present-day position as a result of Neptune's outward migration. Unfortunately, the astronomical community does not, as yet, possess the computational prowess to perform simulations of the entire process which includes all three mechanisms. Therefore, issues concerning whether this scheme can explain the ratio of the number of objects in the respective populations (resonant, cold, and hot), the exact orbital elements of the Kuiper belt objects, and the origin of the physical differences between the populations, must remain for future models to address.

However, even in its current form, our scheme has many merits including a natural explanation for the location of the Kuiper belt's edge. Although several mechanisms have been proposed to explain the truncation of the proto-planetary disk[14][15][16][17] (a requirement of our model), none can explain why it is near the location of Neptune's 1:2 MMR. Our model explains this observation as a natural consequence of the dynamical evolution after the edge forming event. Indeed, it predicts that although a few objects may eventually be discovered beyond the resonance on low-inclination, nearly-circular orbits (because they can be formed by other dynamical mechanisms), they will be rare. Hence the Kuiper belt's effective edge should be precisely at the current location of Neptune's 1:2 mean motion resonance.

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Figure Captions:

Figure 1 — The semi-major axis — eccentricity distribution for various 'cold' populations. In all cases only objects with inclinations less than 4° are plotted. a) Real Kuiper belt objects. Only those objects that have been observed over multiple oppositions are plotted to ensure accurate orbits. b) Migration if the resonant particles (but not other particles if they are present) are massless. The colors represent different times and thus the 1:2 MMR were at different locations: 6Myr (black), 8Myr (green), 16Myr (blue), 25Myr (red), 38Myr (purple), and 98Myr (orange). At these times, Neptune was at approximately 22 AU, 24 AU, 26 AU, 28 AU, and 30 AU, respectively. The back and green data were taken from our direct N-body simulation while the rest were taken from our *smooth migration runs.* Secondary clumps of a given color are objects that fell out of the 1:2 MMR and subsequently were trapped in other resonances. The dotted curve is the expected lower limit of the eccentricity as predicted by the adiabatic theory: $\sqrt{1/2 \log(a/a_{\rm edge})}$, where a is their current semi-major axis and $a_{\rm edge}$ is the primordial outer edge of the disk. So, if we place the original edge at, say, 30 AU the expected eccentricity at 40 AU should be greater than 0.38. If this were true, we cannot produce the cold population, which is between $\sim$40 AU and 48 AU and has eccentricities less than $\sim$0.2, with the adiabatic model. c) Our simulation in which the resonant particles are massive. The colors have the same meaning as in panel B. d) Our final

simulation with a massive disk particles and jumpy migration. The data were taken at 1Gyr and only those particles with semi-major axes greater than 41 AU were plotted so to keep it consistent with the definiation of the cold belt.

Figure 2 — The evolution of eccentricity of particles in the 1:2 MMR in various physical situations. The black curve shows the eccentricity evolution of a resonant particle in our N-body integration after the resonance was pushed beyond the original disk edge (which occured at t=5.9 My). Large-amplitude secular oscillations temporarily drive the eccentricity down to $e \sim 0$. The gray curve shows the behavior of a resonant particle's eccentricity when the population of massive 1:2 resonant bodies are replaced by an equal population of massless particles. In this case the overall eccentricity evolution is dominated by the monotonic growth, as predicted by the adiabatic theory. Therefore, the mass of the resonant population is the key to having a population of small-eccentricity objects as the 1:2 MMR sweeps through the region now occupied by the cold Kuiper belt.

Figure 3 — The power spectrum of the periapse precession of Neptune's orbit that illustrates the origin of our new secular resonance. A secular resonance occurs when the body's longitude of perihelion precesses at the same rate as one of the frequencies of the planets. In a system consisting of only the four giant planets, the precession of Neptune's perihelion has four independent frequencies. The

dotted gray curve shows the frequency power spectrum of Neptune's longitude of perihelion in a planetary system where the semi-major axes of Jupiter, Saturn, Uranus, and Neptune were at the giant planets were at 5.5, 9.3, 15.4, and 22.0 AU, respectively. The slowest frequency is $\sim 1.5 \times 10^{-6}$ y^{-1}, which is much faster than the precession frequencies of the perihelia of the bodies in the 1:2 MMR. Thus, no secular resonance occurs. However, when a non-negligible ($\sim 3M_{\oplus}$) amount of mass is placed in Neptune's 1:2 MMR, more frequencies are introduced in the power spectrum of Neptune's perihelion. If the mass were concentrated in one body only one new independent frequency would be introduced. But, if the mass is distributed among a population of objects with a variety of orbits and precession rates, Neptune's precession contains many more frequencies and many of these frequencies overlap forming bands in the power spectrum. The solid black curve shows that case when we placed 780 particles, with a total mass of $3M_{\oplus}$, in the resonance. Note that in this case the spectrum of Neptune exhibits frequencies of roughly 10^{-7} y^{-1}, which are of the same order of the precession frequencies of the 1:2 MMR particles. Therefore, each body in the 1:2 resonance 'sees' a frequency in Neptune's motion that is close to its own thereby causing a secular resonance. This situation forces large amplitude oscillations of the eccentricity, like those illustrated in Figure 2.

Figure 1:

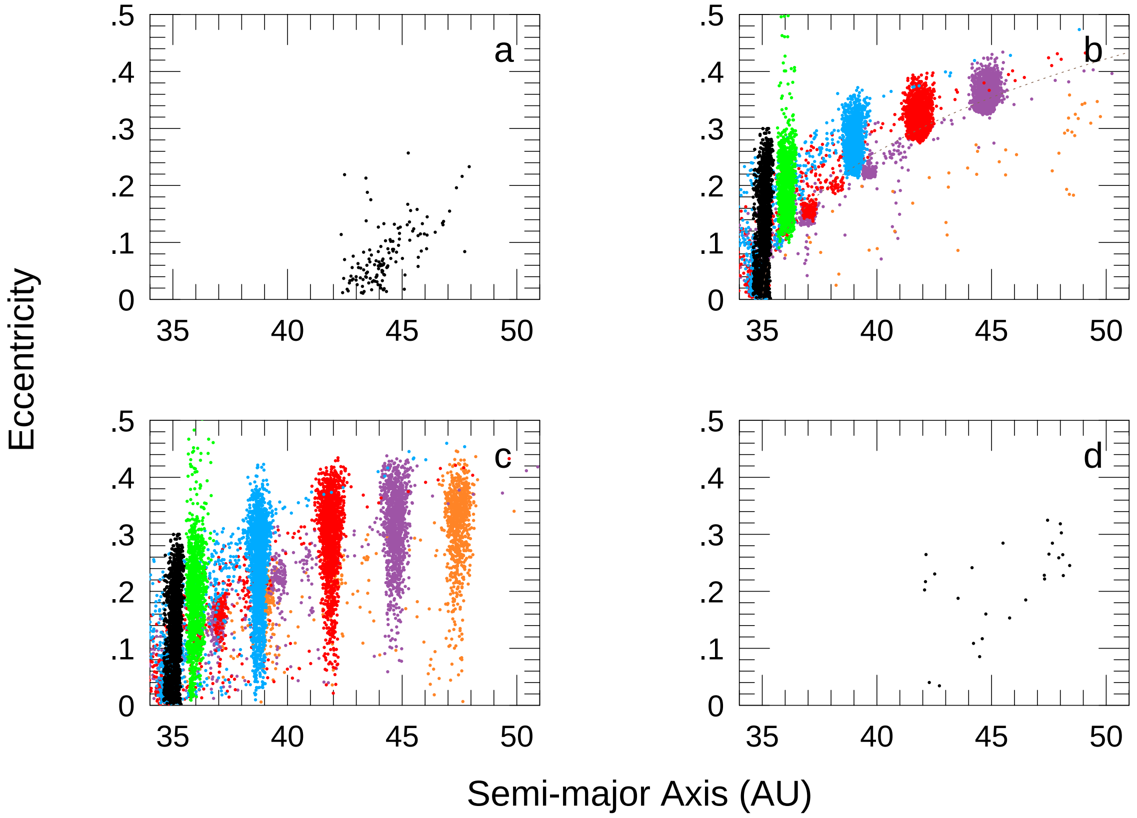


Figure 2:

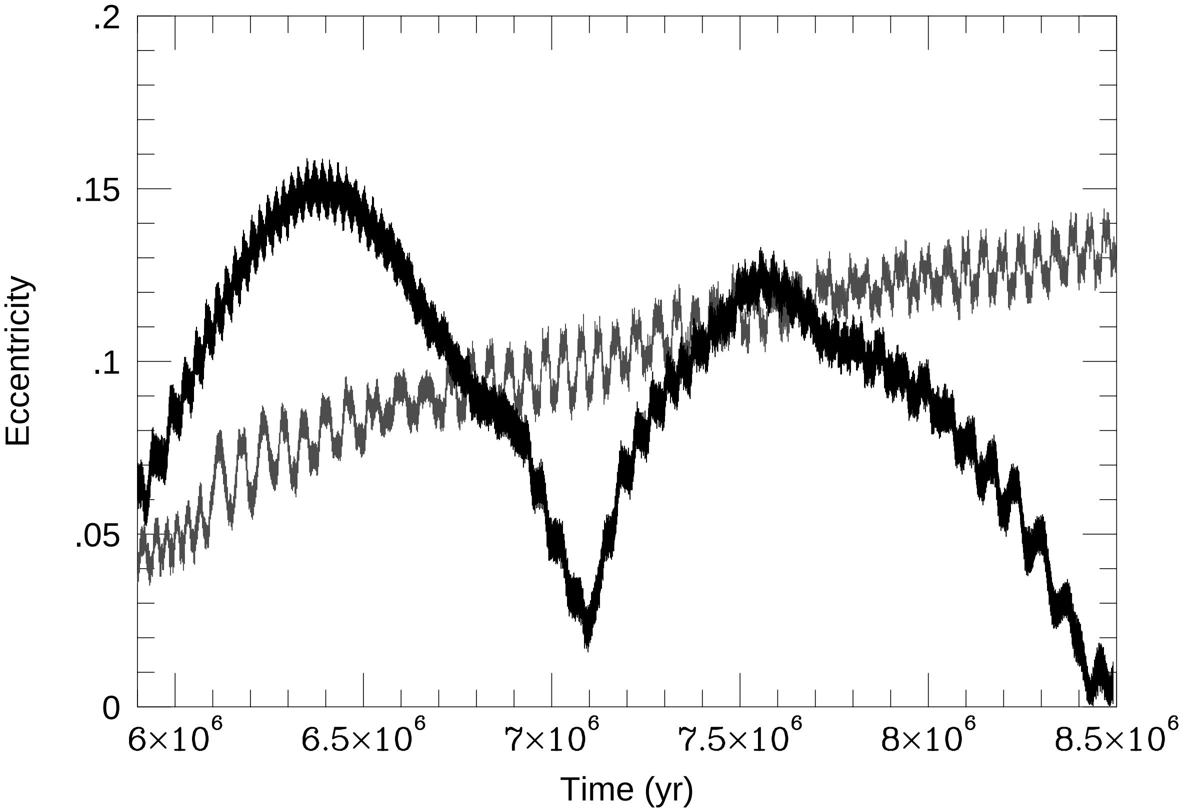
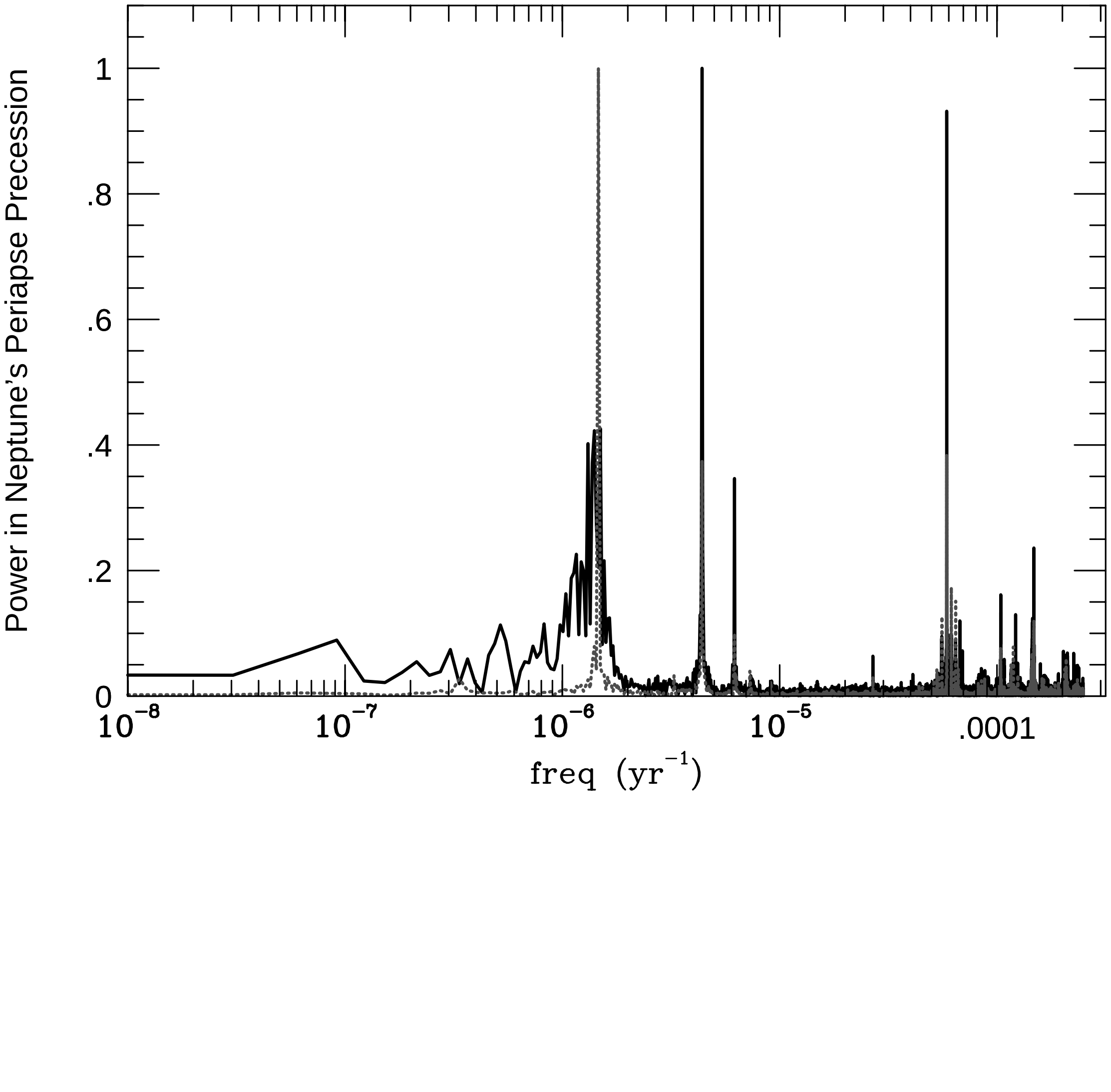

.2
.15
.1
.05
0
Eccentricity
6×10^6
6.5×10^6
7×10^6
7.5×10^6
8×10^6
8.5×10^6
Time (yr)

Figure 3:



Power in Neptune's Periapse Precession
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.4
.6
.8
1
10^{-8}
10^{-7}
10^{-6}
10^{-5}
.0001
freq (yr^{-1})