**PLUTO'S INCLINATION EXCITATION BY RESONANCE SWEEPING.** 

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Pluto's peculiar orbit -- its large eccentricity and its 3:2 mean motion resonance lock with Neptune -- is best understood within the planet migration and resonance sweeping scenario proposed in Malhotra (1993) [1]. In this scenario, Pluto is supposed to have formed in a low-eccentricity low-inclination orbit in the primordial planetesimal disk beyond Neptune. The model proposes that during the late phases of the formation of the giant planets, an outward migration of Neptune's orbit caused the trans-Neptunian region to be swept by Neptune's exterior mean motion resonances, thereby capturing Pluto (and other trans-Neptunian objects) in the 3:2 resonance, and exciting its orbital eccentricity. The magnitude of Neptune's migration needed to excite Pluto's eccentricity from near zero to its presently observed value was estimated from the relation

$$\Delta e^2 \approx \frac{1}{3} \ln \frac{a_{N,final}}{a_{N,initial}} \qquad (1)$$

to be $\Delta a_N \approx 5$ AU. (Eqn. 1 is obtained from an analysis of the sweeping of the eccentricity-type mean motion resonance with critical argument, $\phi_1 = 3\lambda - 2\lambda_N - \varpi$.)

The recent detection of large numbers of Kuiper Belt objects locked in the 3:2 mean motion resonance with Neptune supports this scenario [2]. Furthermore, the maximum eccentricity amongst these observed objects is 0.335 [3], which can be used to revise the above estimate for Neptune's migration to $\Delta a_N \approx 8.6$ AU. Non-zero initial eccentricities prior to resonance capture would reduce this estimate. On the other hand, the maximum eccentricity possible for long term stability of 3:2 resonant orbits, while not very precisely determined [4,5], is not greatly in excess of the observed maximum. Thus the magnitude of Neptune's migration cannot be more precisely constrained from the observed eccentricity distribution alone.

Numerical analysis of the resonance capture and sweeping of Pluto and the Kuiper Belt [1,6] has shown the concept to be plausible, but several questions remain to be addressed. In particular, the evolution of orbital inclinations is of great interest in understanding the origin of Pluto's large inclination as well as the distribution of inclinations of other resonance-locked Kuiper Belt objects, with implications for the initial distribution of planetesimal eccentricities and inclinations in the trans-Neptunian region as well as for the timescale of planet migration [6,7].

We show in Figs. 1 and 2 the results from two numerical simulations of giant planet migration and resonance sweeping of the Kuiper Belt. 806 test particles representing KBOs were initially spread between 28 AU and 63 AU with the surface density varying as $a^{-2}$; their initial orbits were of zero inclination and eccentricity. The numerical model includes the four giant planets and assumes adiabatic planet migration such that planetary semimajor axes vary according to $a(t) = a_\infty - \Delta a \exp(-t/\tau)$, where $a_\infty$ is the present semimajor axis, and $\Delta a = +0.2, -0.8, -3.0, -7.0$ AU for Jupiter, Saturn, Uranus and Neptune, resp. The timescale

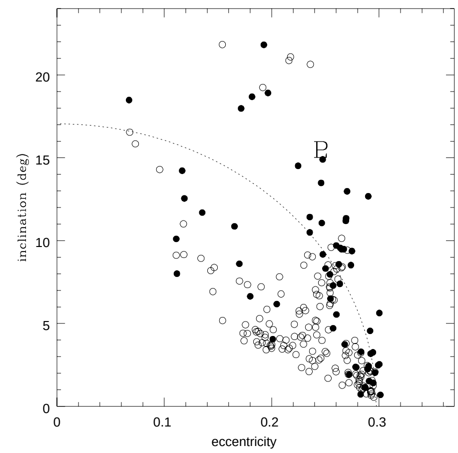


Figure 1: The final eccentricities and inclinations of KBOs captured into the 3:2 resonance in two numerical simulations of resonance sweeping of the Kuiper Belt. Results from the first run (with planet migration timescale $\tau = 4$ Myr) are shown as open circles, and from the second run ($\tau = 10$ Myr) as filled circles. The dashed curve indicates the limits imposed by Eqn. (3) for the modeled initial value of Neptune's semimajor axis, assuming initially zero KBO inclination and eccentricity. The location of Pluto is also indicated.

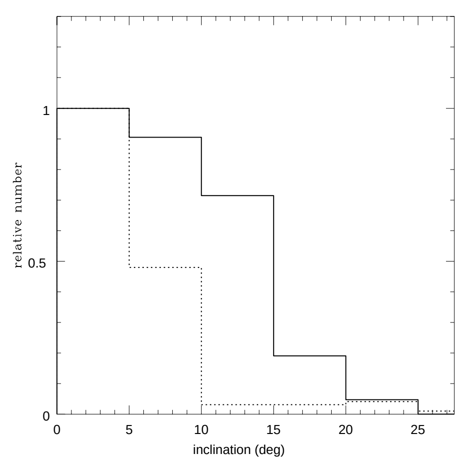


Figure 2: Histogram of inclinations of the same KBOs as in Fig. 1. The dashed line indicates the distribution obtained in the first run, and the solid line for the second run.

$\tau$ was 4 Myr and 10 Myr, respectively, in the two runs, and the simulation lasted 200 Myr. (Other details of the numerical methods are given in ref. 6.) We find that the longer migration timescale leads to larger inclination excitation. (We note, in passing, that the longer migration timescale yields a substantially smaller surviving KB population.) A detailed examination reveals that there are three dynamical mechanisms that excite these inclinations: the $\nu_{18}$ secular resonance, the Kozai resonance, and a mixed-inclination-type mean motion resonance. The critical angles associated with these mechanisms are $\sigma = \Omega - \Omega_N$, $\omega = \varpi - \Omega$, and $\phi_3 = 6\lambda - 4\lambda_N - \Omega - \Omega_N$, respectively. Here $\Omega, \varpi, \lambda$ are the longitude of ascending node, the longitude of perihelion and mean longitude, respectively, of a KBO and the subscript N refers to those elements for Neptune.

The location of the $\nu_{18}$ resonance and its time-variation is rather delicately determined by the mass distribution in the planetary system. In the present Solar system, this secular resonance is located exterior to the 3:2 mean motion resonance, in the range 40 AU to 42 AU, for test particle orbits of low-to-moderate eccentricity [8], and also occurs embedded in the 3:2 resonance zone at large libration amplitudes [9]. While the former location would have varied in an uncertain manner during the planet migration era, it is likely that its initial location was closer to Neptune than at present; the latter location is relatively less sensitive as it is always embedded in the mean motion resonance. This means that 3:2 resonant KBOs could have swept through the $\nu_{18}$ secular resonance both prior to their resonance capture as well as soon after their resonance capture (when they passed through the region of large amplitude resonance libration), obtaining $\Delta i$'s of up to a few degrees during each such event. The magnitude of inclination excitation can be obtained in a perturbative analysis,

$$\Delta i \lesssim \left|\frac{\pi}{\dot{s}_8 - \dot{s}}\right|^{1/2} \mathcal{M}_8, \qquad \mathcal{M}_8 = \frac{1}{4}\frac{m_N}{M_\odot} n\alpha b^{(1)}_{3/2}(\alpha) i_N \tag{2}$$

where $(\dot{s}_8 - \dot{s})$ measures the rate of change of the difference in the secular rates of the nodes of Neptune and a KBO owing to the planetary migration, $n$ is the mean motion, $b^{(1)}_{3/2}(\alpha)$ is a Laplace coefficient, $\alpha = a_N/a$ is the ratio of semimajor axes, and $i_N$ is Neptune's inclination (assumed to be dominated by the $s_8$ mode). Thus, slower rates of orbital migration would lead to larger inclination excitation of a KBO swept by the $\nu_{18}$ secular resonance, consistent with the numerical results.

The Kozai resonance is well known in the context of Pluto's orbit which exhibits libration of its argument of perihelion, with corresponding periodic variations in its eccentricity and inclination. We note that this libration implies degeneracy of the eccentricity-type and inclination-type mean motion resonances (critical arguments $\phi_1 = 3\lambda - 2\lambda_N - \varpi$ and $\phi_4 = 3\lambda - 2\lambda_N - \Omega$, respectively). This degeneracy requires a generalization of Eqn. 1, which, in the lowest order in $e, i$ is given by

$$\Delta(e^2 + i^2) \approx \frac{1}{3}\ln\frac{a_{N,final}}{a_{N,initial}} \tag{3}$$

Numerical simulations show that a significant fraction, $\sim 30\%$, of the KBOs captured sufficiently early into the eccentricity-type 3:2 mean motion resonance have their eccentricities pumped up to $\sim (0.22 - 0.26)$, then ''switch'' to the inclination-type resonance (equivalently, the Kozai resonance) which pumps up their inclination to the limit of Eqn. 3.

The third mechanism, involving the mixed-inclination-type mean motion resonance occurs only rarely in the simulations. Its effect on the inclination is similar to that of the Kozai resonance in that the inclination excitation is constrained by Eqn. (3).

For completeness, we mention also a fourth possibility, namely, long-lived chaotic orbits captured at the edge of the 3:2 mean motion resonance. Subsequent to resonance capture, such orbits typically exhibit intermittent large amplitude resonance librations, their semimajor axis variations remain bounded by the maximum resonance width, while their eccentricities and inclinations exhibit large chaotic variations. (Such behavior in the vicinity of the 3:2 Neptune resonance was first identified in ref. 10.) In our simulations, such orbits typically achieve maximum inclinations in excess of 15 degrees. The inclination excitation in such cases is due to multiple passages across the $\nu_{18}$ secular resonance which occurs near the inner edge of the 3:2 mean motion resonance.

In light of the above insights, we think that the best case scenario for Pluto is: sweeping by the $\nu_{18}$ secular resonance prior to capture into the 3:2 mean motion resonance; capture into the 3:2 mean motion resonance is followed first, by eccentricity excitation, and later by further inclination excitation via the Kozai resonance. Then, Pluto's observed eccentricity and inclination provide a revised estimate for the magnitude of Neptune's migration from Eqn. (3), if we assume zero initial eccentricity and inclination: $\Delta a_N \lesssim 10$ AU.

Finally, we note that our numerical simulations assumed an adiabatic migration of the planets' orbits. In reality, such migration is likely to have had a non-negligible random component. This random component may be very important in determining the inclination distribution of KBOs if it causes repeated crossings of the mean motion resonance boundary where the $\nu_{18}$ resonance is very potent.

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