# THE FATE OF NEPTUNE PLANETESIMALS

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Recent observational confirmation of the existence of small bodies near and beyond the orbit of Neptune [1,2] is a very exciting development in Solar system dynamics. The population of this *Kuiper Belt* for the region between 30 AU and 50 AU heliocentric distance is presently estimated at approximately 35,000 objects larger than 100 km [1] and upwards of 10**9 cometary size objects (less than about 10 km in size) [3]. It appears likely that the orbital distribution of these objects was largely determined by dynamical processes in the early history of the Solar system that preferentially swept most Kuiper Belt objects into the narrow stable libration zones at Neptune's mean motion resonances, particularly into the 3:2 and the 2:1 resonances located at semimajor axes of 39.5 AU and 47.8 AU, respectively [4]. Here I show that a small but notable fraction of objects in initially near-circular, low-inclination orbits in the vicinity of Neptune would have been captured at the L4 and L5 Lagrange points and survived in that dynamical state the entire orbital evolution of Neptune during the early history of the Solar system.

It is well known that most circular, coplanar orbits of test particles in the immediate vicinity ($\sim$ 1–2 Hill radii) of any planet's orbit are unstable on very short timescales, typically a few synodic periods. However, within this region of instability one can generally find at least two small stable zones near the triangular Lagrange points, L4 and L5, centered 60 degrees ahead and behind a planet in its own near-circular orbit. For the outer planets, there have been two previous dynamical stability surveys of these regions [5,6] which have mapped out the stable regions near the L4 and L5 points of each of the giant planets. These studies numerically integrated the orbits of test particles for up to 20 million years; the test particles were subject to the gravitational perturbations of all four giant planets whose current orbits were also integrated self-consistently. In particular, these studies confirm the existence of a significant zone of stability about both the L4 and the L5 point of Neptune.

In the early history of the Solar system during the late stages of planet formation the giant planet orbits may have evolved significantly due to exchange of angular momentum and energy with residual planetesimals [7]. I have shown previously that this process would have "sculpted" the orbital distribution of objects in the trans-Neptunian Kuiper Belt such that most of those objects interior to about 50 AU heliocentric distance would reside in the 3:2 and 2:1 mean motion resonances with Neptune. This model provides a convincing explanation for the origin of Pluto's highly eccentric and resonance locked orbit. Furthermore, Pluto's orbital eccentricity provides an estimate for the extent of early radial migration of Neptune [4,8].

Here I use the same model to determine the orbital evolution of small objects in the immediate vicinity of Neptune's orbit. The orbits of the giant planets are allowed to evolve adiabatically to the present configuration; the numerical simulation includes the mutual gravitational perturbations of the giant planets self-consistently. (Details are given in ref. [4].) Specifically, Neptune's orbital radius increases from about 23.2 AU to its current value of 30.2 AU with an e-folding timescale $\tau$ of 4 million years. One hundred test particles are initially distributed randomly in an annular region of half width 1 AU centered at the mean initial orbital radius of Neptune; their initial eccentricities are distributed randomly between 0 and 0.05, and their initial inclinations are distributed randomly between 0 and 5 degrees.

The test particles and planets were integrated simultaneously for 100 million years. The results are as follows. Not surprisingly, a large fraction — 77/100 — of the particles suffered close encounters with Neptune, typically within a few ten-thousand years, although 20 particles lasted longer than 10 million years before a close encounter with Neptune. The orbits of the latter (as well as the remaining 23 test particles) adiabatically evolved together with Neptune's orbit so that their semimajor axes were on average the same as Neptune's semimajor axis throughout the evolution. In other words, these particles had been captured in 1:1 mean motion resonance with Neptune, and a secular transfer of angular momentum and energy from Neptune to these particles ensured that their orbits expanded together with Neptune's. (We emphasize that in this model there is no "external" force on the test particles, save solar gravity and the perturbations from the giant planets.)

It is interesting to look in some detail at the characteristics of the 23 test particles that did not suffer a close encounter for the entire duration of the integration. Their initial (as well as final) semimajor axes were within 0.5 AU of Neptune's. Five of these were found in libration about L4 and eight about L5; the rest were in so-called "horseshoe" orbits that encircle both the L4 and the L5 points. The longitude excursions of the L4 and L5 librators range from $\sim 10°$ to $\sim 100°$. The 8/5 ratio of L5 librators to L4 librators is intriguing, but it is impossible to say from this small-number statistics how significant it might be; I plan to improve the statistics to address this question. However, the basic question of the survival of Neptune Trojans during the early orbital migration of the giant planets has been answered in the affirmative. The results show that a small fraction of Neptune planetesimals survive at the Lagrange points. This may prove useful (in conjunction with the anticipated detection of Neptune Trojans in ongoing observational surveys) in reconstructing the original population of small bodies in this region of the outer Solar system.

**References:**

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