THE FATE OF NEPTUNE'S PRIMORDIAL TROJAN COMPANIONS LOST DURING PLANETARY MIGRATION.

Steve Kortenkamp, *Planetary Science Institute, 1700 East Ft. Lowell, Suite 106, Tucson, AZ, 85719-2395 (kortenka@psi.edu).*

An earlier paper (Kortenkamp *et al.* 2004) investigated the survivability of Trojan-type companions of Neptune during primordial radial migration of the giant planets Jupiter, Saturn, Uranus, and Neptune. A standard planet migration model was used in which the migration speed decreases exponentially with a characteristic time scale τ (see Fig. 1). A series of numerical simulations were performed, each involving the migrating giant planets plus $\sim$1000 test particle Neptune Trojans with initial distributions of orbital eccentricity, inclination, and libration amplitude similar to those of the known jovian Trojans asteroids. The simulations were analyzed to measure the survivability of Neptune's Trojans as a function of migration rate. The results of this analysis are summarized in the next paragraph.

Orbital migration with the characteristic time scale $\tau = 10^6$ years allows about 35% of pre-existing Neptune Trojans to survive to 5τ, by which time the giant planets have essentially reached their final orbits. In contrast, slower migration with $\tau = 10^7$ years yields only a $\sim$5% probability of Neptune Trojans surviving to a time of 5τ. The loss of Neptune Trojans during planetary migration occurs almost exclusively during discrete prolonged episodes when Trojan particles are swept by secondary resonances associated with mean-motion commensurabilities of Uranus with Neptune. These secondary resonances arise when the circulation frequencies, f, of critical arguments for Uranus-Neptune mean-motion near-resonances (e.g., $f_{1:2}^{UN}$) are commensurate with harmonics of the libration frequency of the critical argument for the Neptune-Trojan 1:1 mean-motion resonance ($f_{1:1}^{NT}$). Trojans trapped in the secondary resonances typically have their libration amplitudes increased until they escape the 1:1 resonance with Neptune. Even tightly bound Neptune Trojans with libration amplitudes below 10° can be lost when they become trapped in 1:3 or 1:2 secondary resonances between $f_{1:2}^{UN}$ and $f_{1:1}^{NT}$. Figure 2 below demonstrates this escape process. With $\tau = 10^7$ years the 1:2 secondary resonance was responsible for the single greatest episode of loss, ejecting nearly 75% of existing Neptune Trojans.

One shortcoming of the modeling described above is that the evolution of the Neptune Trojans was not followed after they escaped from their tadpole orbits. Escaping Trojans were removed from the simulations when they either (1) suffered a close-encounter with Neptune, or (2) their libration amplitudes exceeded 180°. The first of these reasons was a programmatic necessity, as the integrator could not accurately handle close-encounters. The second was an attempt to increase run-time efficiency of the simulations, some of which were running on rather dated computers. For the modeling presented here new simulations were carried out using the *Mercury* hybrid N-body integrator of Chambers (1999). In *Mercury* Chambers has combined a Wisdom-Holman (1991) symplectic integration algorithm (Levison and Duncan 1994) with a Bulirsch-Stoer (Stoer and Bulirsch 1980) integrator for handling close-encounters. The *Mercury* package also allows for a user-defined force to be easily added to both the symplectic component and the general Bulirsch-Stoer close-encounter component. In this case a drag force was added to cause a smooth radial migration of the planets as shown in Fig. 1. The Trojan companions were treated as test particles and were not subject to the migration-inducing drag force.

In the new simulations the post-escape evolution of each Neptune Trojan particle is followed either to the end of the simulation or until one of a number of pre-determined criteria are met (e.g., scattering beyond 100AU). The new simulations confirm the earlier results of Kortenkamp *et al.* (2004). That is, slow migration with $\tau \sim 10^7$ years results in severe losses of Trojans, with secondary resonances forcing Trojans onto ever larger tadpole orbits. The new simulations also show a wide variety of possible fates for Neptune's primordial Trojans. In many cases the escaping Trojans can survive for extended periods on horseshoe orbits. In a few cases the bodies on horseshoe orbits are perturbed back onto leading or trailing tadpole orbits. Close-encounters with Neptune were very common for escaping Trojan particles. While impacts with Neptune occurred for somewhat less than 1% of the escaping particles, deep close-encounters ($d <$ 0.5 Hill Radii) were more frequent. This suggests that Trojans escaping during Neptune's migration might be a viable source of its captured irregular satellites. Impacts and close-encounters with the other three giant planets also occurred but the similarity between the orbits of Neptune and its escaping Trojans indicates that encounter velocities with Neptune are significantly lower than with the other planets.

Another common fate of Neptune's escaping Trojans was scattering directly into several of the planet's outer mean motion resonances that are known to contain Kuiper belt objects. These resonances include the 2:1, 3:2, and 4:3, among others. Once trapped in these outer mean motion resonaces the bodies were swept along by the still-migrating Neptune. Scattering into resonances with planets other than Neptune was also possible. Rather surprizingly, a few escaping Neptune Trojans were temporarily trapped as Trojans of Uranus.

A small number of escaping Neptune Trojans were able to evolve interior to Jupiter's orbit and have their perihelia dip into the inner solar system. One such particle reached an asteroidal-like Earth-crossing orbit for a couple million years.

References:
Chambers, *MNRAS* **304**, 793–799 (1999);
Kortenkamp *et al.* , *Icarus* **167**, 347–359 (2004);
Levison and Duncan, *Icarus* **108**, 18–36 (1994);
Stoer and Bulirsch, *Introduction to Numerical Analysis*, Springer-Verlag, New York (1980);
Wisdom and Holman, *AJ* **102**, 1528–1538 (1991);

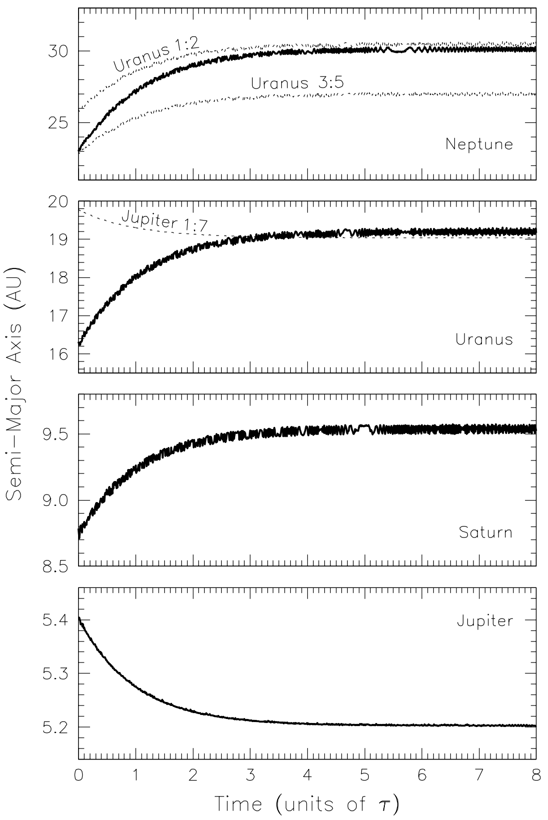

Figure 1: Four panels showing examples of the evolution with time of the semi-major axes of the four giant planets in an exponential migration simulation. The planets were subject to mutual gravitational perturbations and a drag force which caused their orbits to migrate—Jupiter inward; Saturn, Uranus, and Neptune outward. Time is expressed in units of τ, the characteristic migration time scale. After a time of 5τ migration is 99.33% complete and subsequent orbital evolution is dominated by mutual planetary gravitational perturbations rather than the migration force. Dashed lines indicate the locations of the 3:5 and 1:2 mean-motion resonances with Uranus and the 1:7 mean-motion resonance with Jupiter.

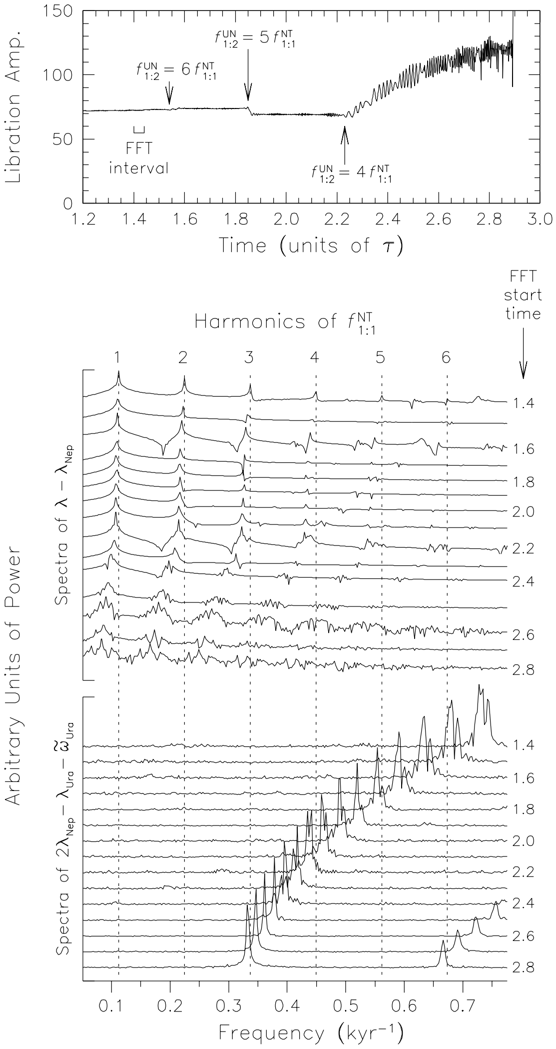

Figure 2: Top panel shows evolution of the libration amplitude for one Neptune Trojan lost during a $\tau = 10^7$ year simulation. A fast Fourier transform (FFT) was used to obtain power spectra of critical arguments for both the Neptune-Trojan 1:1 resonance ($\phi^{NT}_{1:1} = \lambda - \lambda_{Nep}$, middle panel) and the Uranus-Neptune 1:2 near-resonance ($\phi^{UN}_{1:2} = 2\lambda_{Nep} - \lambda_{Ura} - \tilde{\omega}_{Ura}$, bottom panel). Each FFT used 4096 points sampled every 100 years (see FFT interval bar), resulting in a Nyquist critical frequency (5 kyr^{-1}) well removed from the range shown here. The start times of the FFTs are indicated to the right of the spectra. Spectra of $\phi^{NT}_{1:1}$ (middle panel) are shown in units of log power in order to simultaneously resolve the fundamental frequency ($f^{NT}_{1:1}$) and its higher harmonics. The initial positions of the first six harmonics of $f^{NT}_{1:1}$ are indicated by the dashed lines. As $f^{UN}_{1:2}$ converges toward $f^{NT}_{1:1}$ it overtakes the 6th and then the 5th harmonics of $f^{NT}_{1:1}$. The Trojan particle experiences sudden changes in libration amplitude during these passages (indicated in top panel). At about $2.23\,\tau$ (see spectra taken at $2.2\,\tau$) the 4th harmonic of $f^{NT}_{1:1}$ becomes locked to $f^{UN}_{1:2}$.