# Neptune's Migration into a Dynamically Hot Kuiper Belt

Saint Mary's University
Halifax, Nova Scotia, Canada

Joseph M. Hahn
Institute for Computational Astrophysics
Saint Mary's University

Renu Malhotra
Lunar and Planetary Laboratory
University of Arizona

DEPARTMENT OF PLANETARY SCIENCES
LUNAR AND PLANETARY LABORATORY
The University of Arizona, Tucson AZ 85721

## 1 Introduction

The Kuiper Belt is the vast swarm of comets that orbit at the Solar System's outer edge. This Belt is comprised of debris that was left over from the epoch of planet formation, and this swarm's distribution of orbit elements preserves a record of events that had occurred when the Solar System was still quite young. One goal of this study is to decipher this Kuiper Belt record, which to date remains quite open to interpretation...

Figure 1 shows the orbits of the known Kuiper Belt Objects (KBOs), and reveals the Belt's three primary populations:

- the Plutinos which inhabit Neptune's 3:2 resonance
- the Main Belt KBOs between the 3:2 and the 2:1 resonances
- the Scattered Objects, which are the more distant KBOs in eccentric orbits having perihelia $30 \lesssim q \lesssim 38$ AU

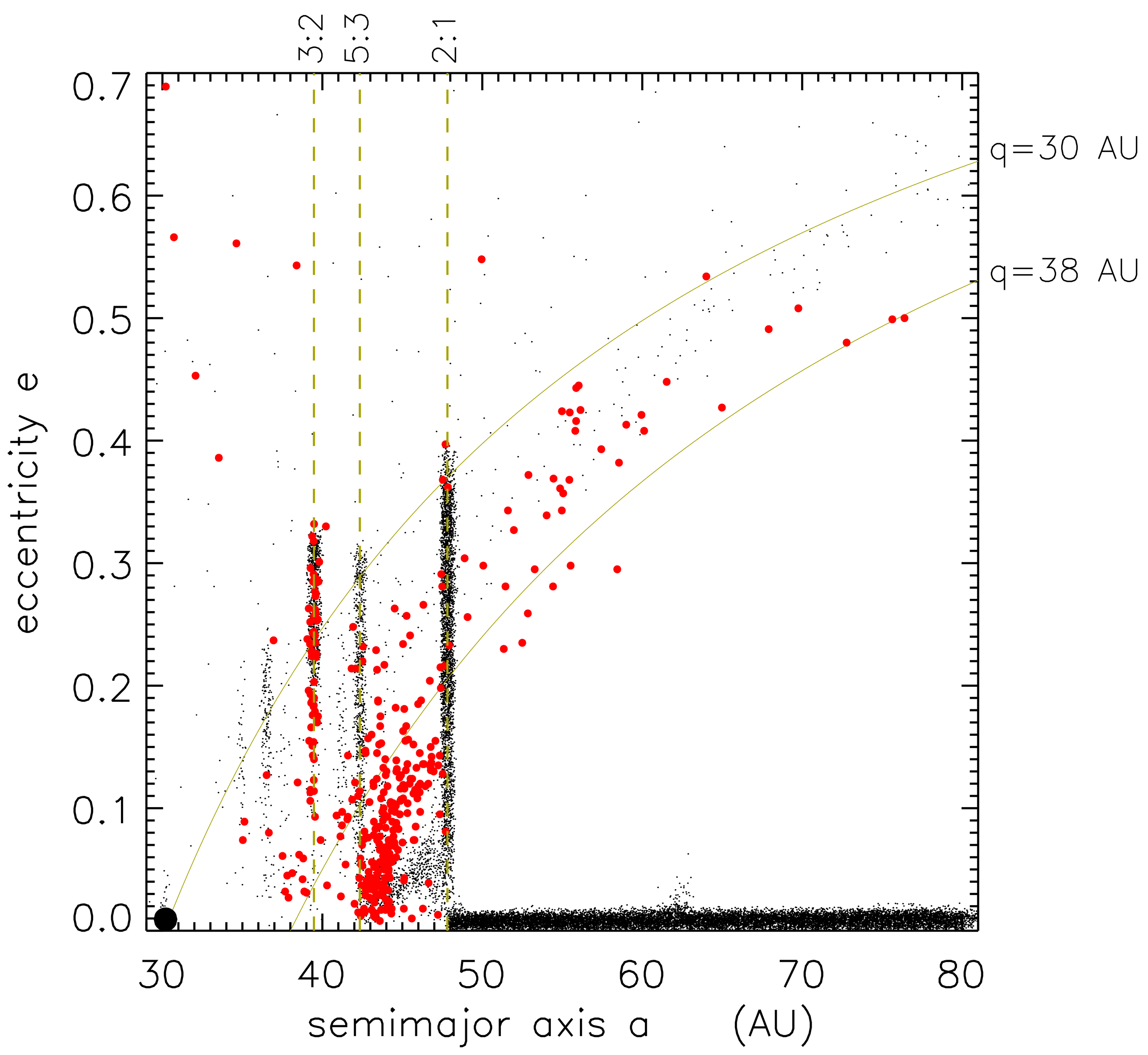


Figure 1: Red dots are the observed KBO semimajor axes $a$ and eccentricities $e$ reported by the Minor Planet Center. Dashed lines indicate some of Neptune's mean motion resonances, and orbits above the $q = 30$ AU curve are Neptune–crossing. The small black dots are the results of an Nbody simulation wherein Neptune's orbit is forced to expand outwards $\Delta a = 8.6$ AU over a $\tau = 10^7$ year timescale into a dynamically cool swarm of massless particles having initial $e$ and $\sin(i)$ of $\sim 10^{-3}$. All of the systems shown here are evolved for $5 \times 10^8$ years.

The large number of Plutinos at Neptune's 3:2 resonance is usually interpreted as evidence that Neptune's orbit had expanded outwards soon after that planet's formation (Malhotra 1993). This scenario is also illustrated in Fig. 1 which shows the results of an Nbody simulation wherein Neptune's orbit is forced to slowly expand outwards into a dynamically cool Kuiper Belt. Neptune's orbital expansion causes its mean–motion resonances to sweep across the primordial Kuiper Belt, and this allows the 3:2, the 2:1, and to a lesser extent the 5:3 to capture these KBOs by expanding their orbits and pumping up their $e$'s. Obtaining the maximal $e = 0.33$ observed at the 3:2 resonance requires Neptune's orbit to have expanded $\Delta a = 8.6$ AU.

Note that this particular simulation of planet migration does not account for the large eccentricities of $e \sim 0.1$ seen among the Main Belt KBOs. Evidently, another event was also responsible for having stirred up the Kuiper Belt, and this may have occurred prior to or after the epoch of planet migration.

## 2 Migration into a hot Kuiper Belt

The simulation reported in Figure 2 shows the endstate that results when the Kuiper Belt is initially hot, *i.e.*, $e$ and $\sin(i) \sim 0.1$ prior to the onset of Neptune's migration. Comparison with Fig. 1 shows that the higher–order mean–motion resonances (e.g., the 3:1, 5:2, 7:3, etc.) become more effective at trapping KBOs when the disk is initially hot. This finding was initially reported by Chiang *et al.* (2003) who showed that migration into a hot Kuiper Belt can account for the orbits of 1998AW$_{31}$, 1999HB$_{12}$, and 2001KC$_{77}$ which librate at Neptune's 5:2 resonance. In this simulation, resonance trapping is evident at all of the usual low–order resonances as well as at the 5:3, 7:4, 9:4, 7:3, 5:2, 8:3, 3:1, 7:2, and 4:1. Note that trapping by these high–order resonances can promote some KBOs into very eccentric orbits where they might masquerade as a Scattered Objects.

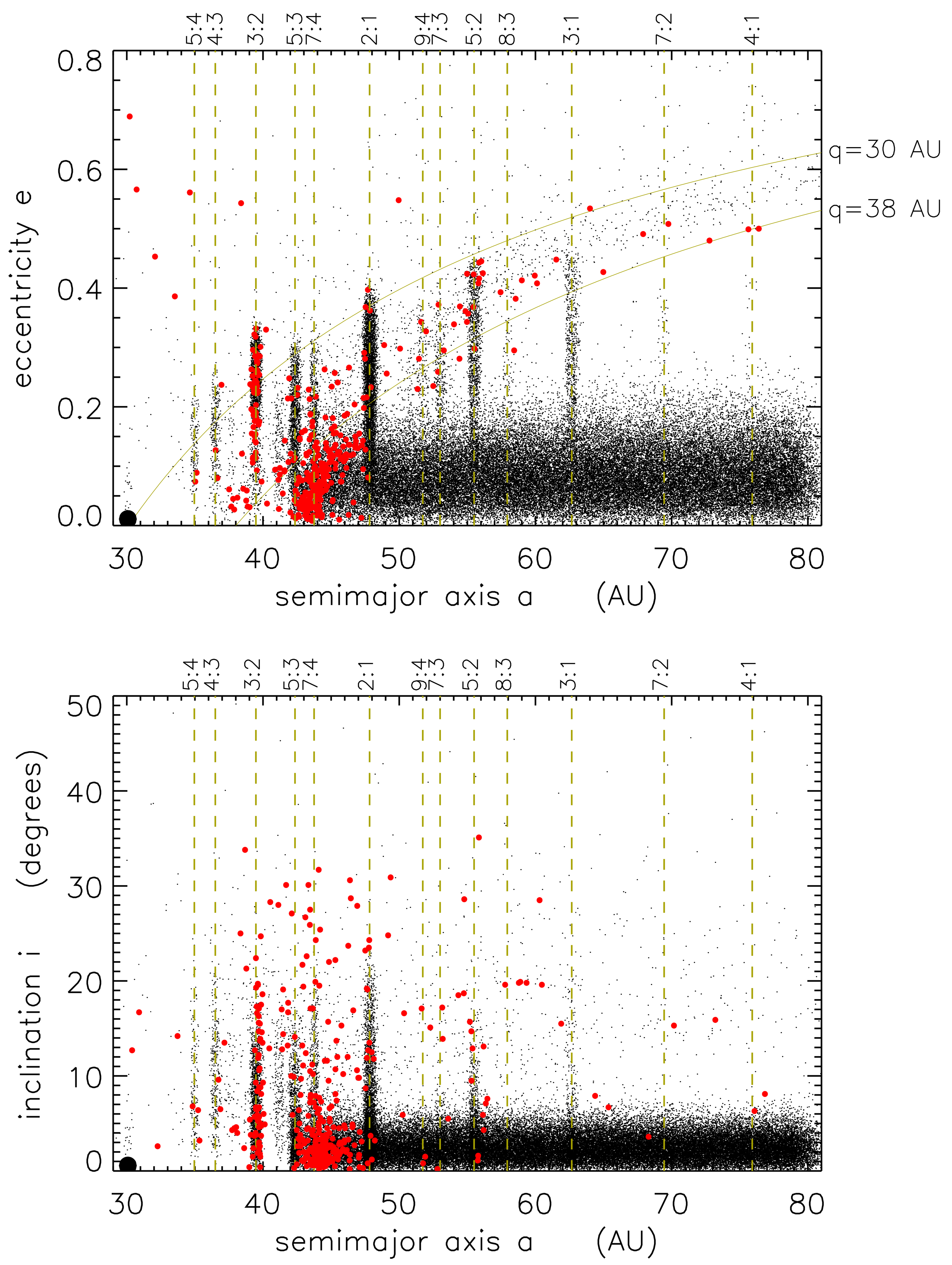


Figure 2: Red dots are the observed KBO orbits while the small black dots are the result of a planet–migration simulation with particles having initial $e$ and $\sin(i) \sim 0.1$. Neptune's orbit is indicated by the large black dot, and the other nearby dots are Neptune Trojans.

## 3 Neptune's Trojans

The low–$e$ dots near $a = 30$ AU in Figure 2 indicate that a number of particles also manage to persist in Neptune–like orbits. These of course are Trojans that co–orbit at longitudes $\pm 60°$ from Neptune—see Fig. 3. In fact, $10\%$ of all particle's initially placed near Neptune's L4 and L5 Lagrange points survive to the end of the simulation. Consequently, if slow and smooth planet migration really did occur, then it is reasonable to expect Neptune's Lagrange points to be well–populated by many other Trojans. Figure 3 also shows object 2001QR$_{322}$ which was recently identified as Neptune's only known Trojan (Chiang *et al.* 2003). The observed paucity of Neptune Trojans suggests that, if others exist, they are likely fainter than 2001QR$_{322}$ which is a $m_V = 22$ object of diameter $\sim 200$ km.

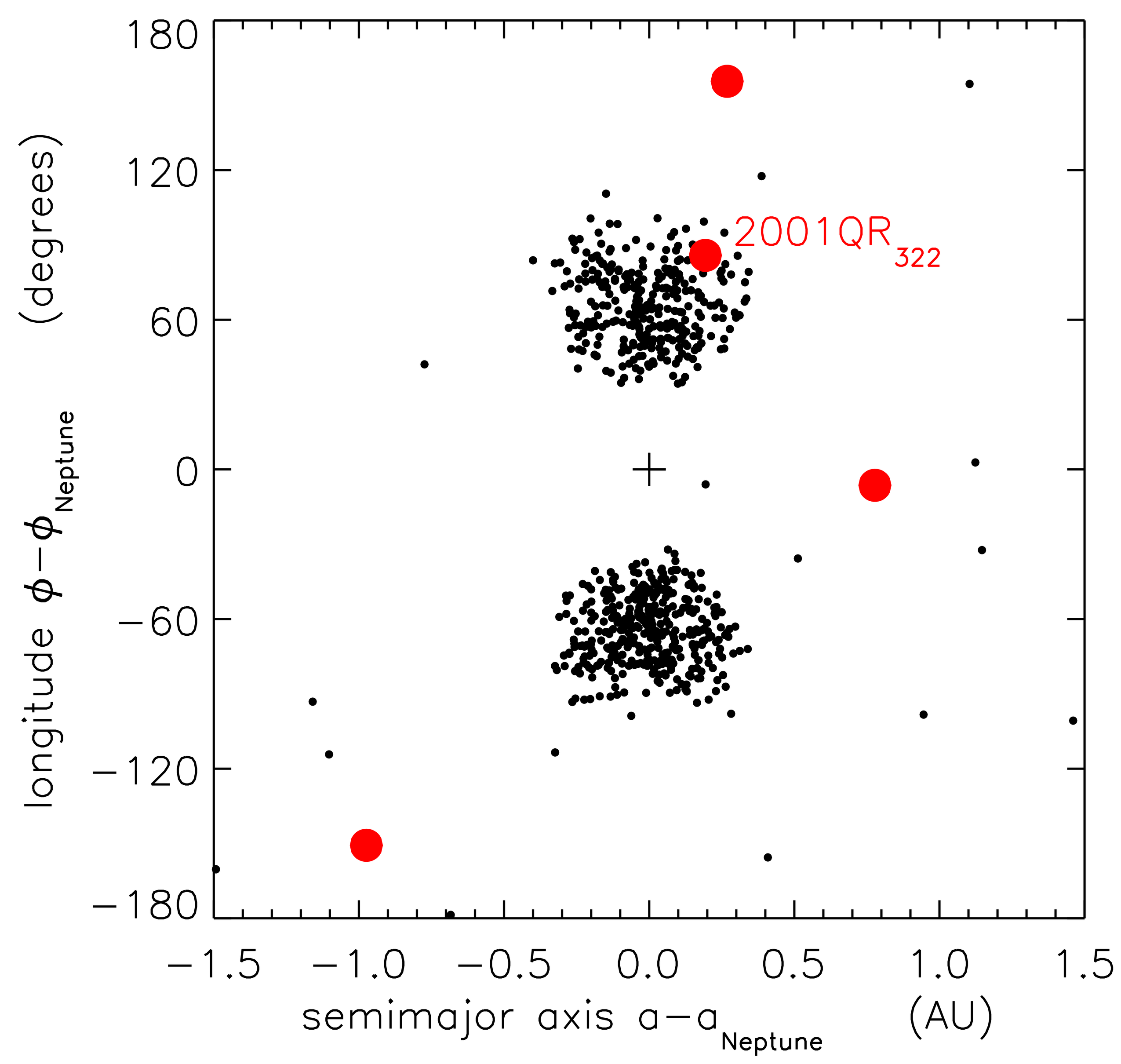


Figure 3: The black dots are the Trojan objects that lead/trail Neptune $(+)$ by longitudes of $\pm 60°$, as well as a few 'field' KBOs and Centaurs. Red dots are the observed field KBOs and Centaurs, as well as Neptune's only known Trojan, 2001QR$_{322}$.

## 4 Summary of findings

- Nbody simulations of Neptune's migration into a dynamically hot Kuiper Belt having initial $e$ and $\sin(i) \sim 0.1$ results in an endstate that is qualitatively quite similar to the observed KBO orbits (see Fig. 2)
- As first reported by Chiang *et al.* (2003), the capture of KBOs at Neptune's numerous higher order resonances is much more efficient when the Kuiper Belt is initially hot. Figure 2 shows that capture is quite evident at the 5:3, 7:4, 9:4, 7:3, 5:2, 8:3, 3:1, 7:2, and the 4:1 resonances, as well as at the more familiar 2:1, 3:2, etc. These captured KBOs tend to have lower libration amplitudes of $|\Delta\phi| \lesssim 90°$.
- The eccentricity–pumping that is a consequence of resonance capture can easily cause these KBOs to masquerade as the Scattered Objects seen in Fig. 2. Of course, Scattered Objects can also loiter near resonances due to a phenomenon known as resonance sticking (Malyshkin and Tremaine 1999). However such Scattered Objects will have high libration amplitudes $|\Delta\phi|$ that are closer to $180°$. As new observations make KBO orbits more accurate over time, it will be quite interesting to see if many more of the putative Scattered Objects are instead inhabitants of these high–order resonances.
- Smooth planet migration also permits Neptune to retain about $10\%$ of its initial Trojan population. Thus it is possible that Neptune's L4 and L5 points may still be densely populated with unseen Trojans. If so, then they are likely smaller and fainter than Neptune's only known Trojan, 2001QR$_{322}$, which has $m_V = 22$ and a diameter $\sim 200$ km.
- Continued telescopic surveys for the small bodies in the outer Solar System, particularly Neptune's Trojans, the resonant and Scattered Objects, and the outer edge of the Main Belt, will place important constraints on these and other models of the outer Solar System's early history.

## 5 Acknowledgements

The systems described here were evolved using the MERCURY6 Nbody code (Chambers 1999) on the McKenzie Beowulf cluster that CITA kindly made available to the authors.

## 6 References

Chambers, 1999, A hybrid symplectic integrator that permits close encounters between massive bodies, MNRAS, 304, 793.

Chiang *et al*, 2003, Resonance occupation in the Kuiper Belt, AJ, 126, 430.

Malhotra, 1993, The origin of Pluto's peculiar orbit, Nature, 365, 819.

Malyshkin and Tremaine, 1999, The Keplerian map for the planar restricted three–body problem as a model of comet evolution, Icarus, 141, 341