Neptune's Migration into a Dynamically Hot Kuiper Belt

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1 Introduction

The Kuiper Belt is the swarm of comets that inhabit the Solar System's outer edge. This Belt is debris 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...

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

- resonant KBOs that inhabit Neptune's various mean-motion resonances
- Main Belt KBOs that lie between the 3:2 and the 2:1 resonances
- the so–called Scattered Objects, which are the more distant KBOs in eccentric orbits having perihelia $30 \lesssim q \lesssim 40$ AU

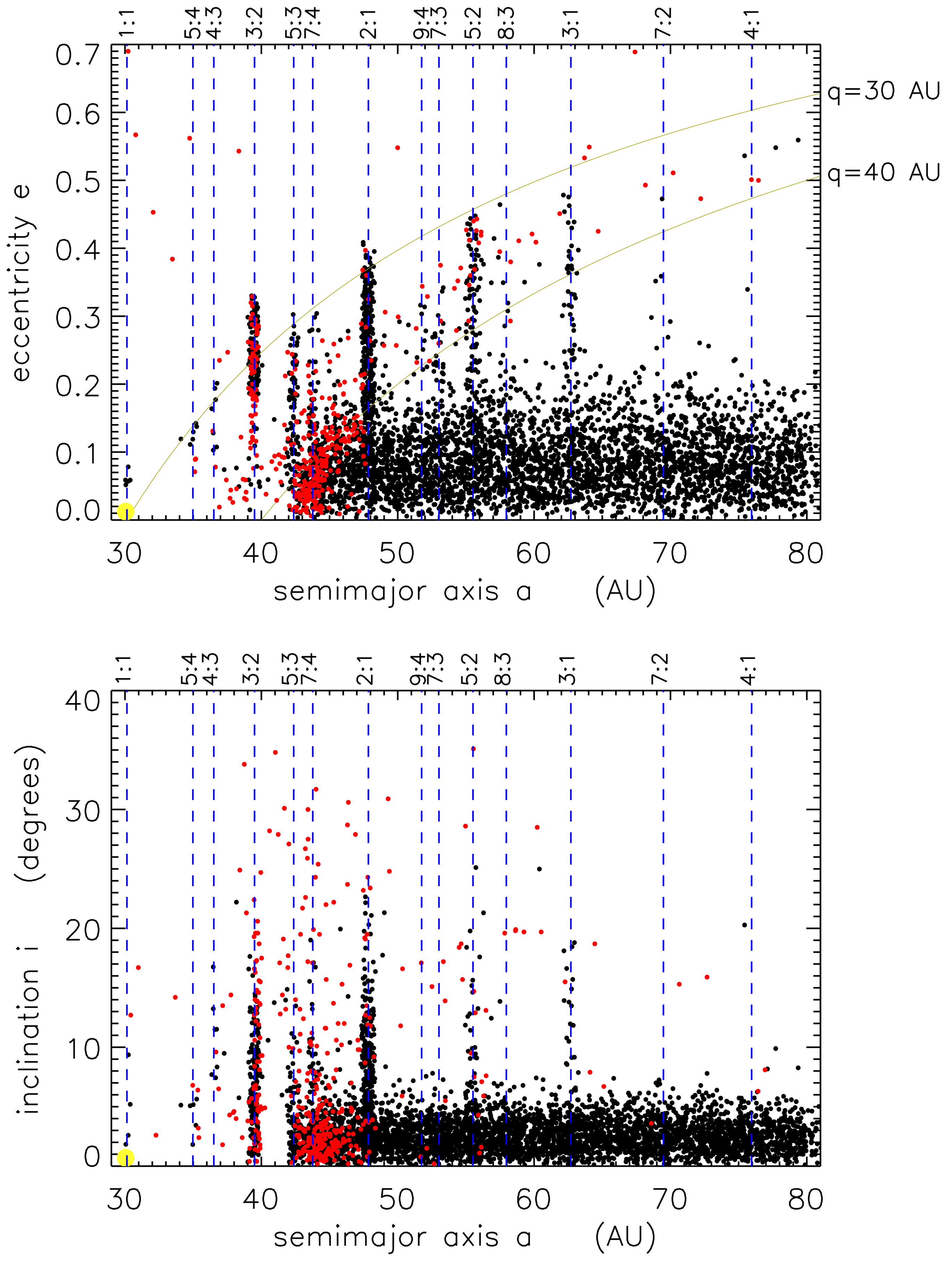

Figure 1: Red dots are the observed KBO semimajor axes a and eccentricities e reported by the Minor Planet Center. Dashed lines indicate Neptune's mean motion resonances. The small black dots are the results of an Nbody simulation wherein Neptune's orbit slowly expands outwards into a dynamically hot swarm of massless particles having initial $e \sim \sin(i) \sim 0.1$; this system is then evolved over the age of the Solar System. About $\sim 10\%$ of the initial Trojan population also survived at Neptune's 1:1 resonance.

2 Migration into a Hot Kuiper Belt

Neptune's outwards migration causes numerous particles to accumulate at the planet's mean–motion resonances. Simulations by Malhotra (1995) have shown that if Neptune's migrates into a dynamically cold Kuiper Belt, trapping occurs at principally at Neptune's 3:2, 5:3, and the 2:1. However Figure 1 shows that if Neptune migrates outwards into a dynamically hot swarm of particles having $e \sim 0.1 \sim \sin(i)$, then trapping also becomes possible at Neptune's many other weak, higher–order resonances. 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 the seven KBOs known to librate at Neptune's 5:2 resonance. However our higher–resolution study shows that additional trapping also occurs at Neptune's 7:4, 11:6, 13:7, 13:6, 9:4, 7:3, 12:5, 8:3, 11:4, 3:1, 7:2, and the 4:1.

3 The Extended Scattered Disk

Prior simulations have shown that scattering by Neptune can loft particles into wide, eccentric orbits having semimajor axes $a \gtrsim 50$ AU and perihelia $30 \lesssim q \lesssim 40$ AU that lie between the yellow curves in Figure 1; this population is usually identified as the so–called Scattered Disk (Duncan & Levison 1997).

Our simulations also produce a densely populated Scattered Disk, but one that is rapidly eroded over time due to subsequent encounters with Neptune. This erosion is in fact so severe that very few Scattered particles actually persist over the age of the Solar System. Of those particles in Figure 1 having $a > 50$ AU and $e > 0.25$, only about 10% of these particles are truly scattered; the remaining 90% are resonantly trapped particles.

The red dots in Figure 2 also shows the observed KBOs that inhabit very wide orbits having $a \sim 100$'s of AU, as well as the simulated population (black dots). All of the observed KBOs with $a \gtrsim 100$ AU are truly Scattered Objects, and nearly all have perihelia $q \lesssim 40$ AU. However there are two exceptions to this: 2000 CR_{105} and 2003 VB_{12} (Sedna) which have respective perihelia of $q = 44$ and $q = 76$ AU. These are the two most prominant members of what Gladman it et al. (2002) call the Extended Scattered Disk. The origin of these high–q objects is mysterious; since these orbits are decoupled from Neptune's 30 AU orbit, they are quite difficult to achieve via direct scattering. Nonetheless, Figure 2 shows that our simulation of 10^4 particles has yielded *one* particle in the Extended Scattered Disk (the large black dot) having $a = 92$ AU and $q = 44$ AU. Although we have not yet identified the mechanism that is responsible for transporting this Scattered particle into this high perihelia orbit, a resonance that acts over a billion–year timescale seems likely.

Note also the simulated particles represented by crosses in Figure 2. Even though their perihelia of $42 < q < 55$ AU that indicate that they also inhabit the domain of the Extended Scattered Disk, they are in fact resonant particles trapped at the 3:1, 7:2, and 4:1 resonances. These particles also had initial semimajor axes of $a > 47$ AU, which is noteworthy since, if any resonant KBOs are ever discovered in these orbits, they would provide strong evidence that the outer edge of the Solar System lies beyond $a > 47$ AU. Alternatively, their continued absence from ever–deeper surveys of the Kuiper Belt can be interpreted as evidence that the Kuiper Belt's primordial edge was inside of 47 AU.

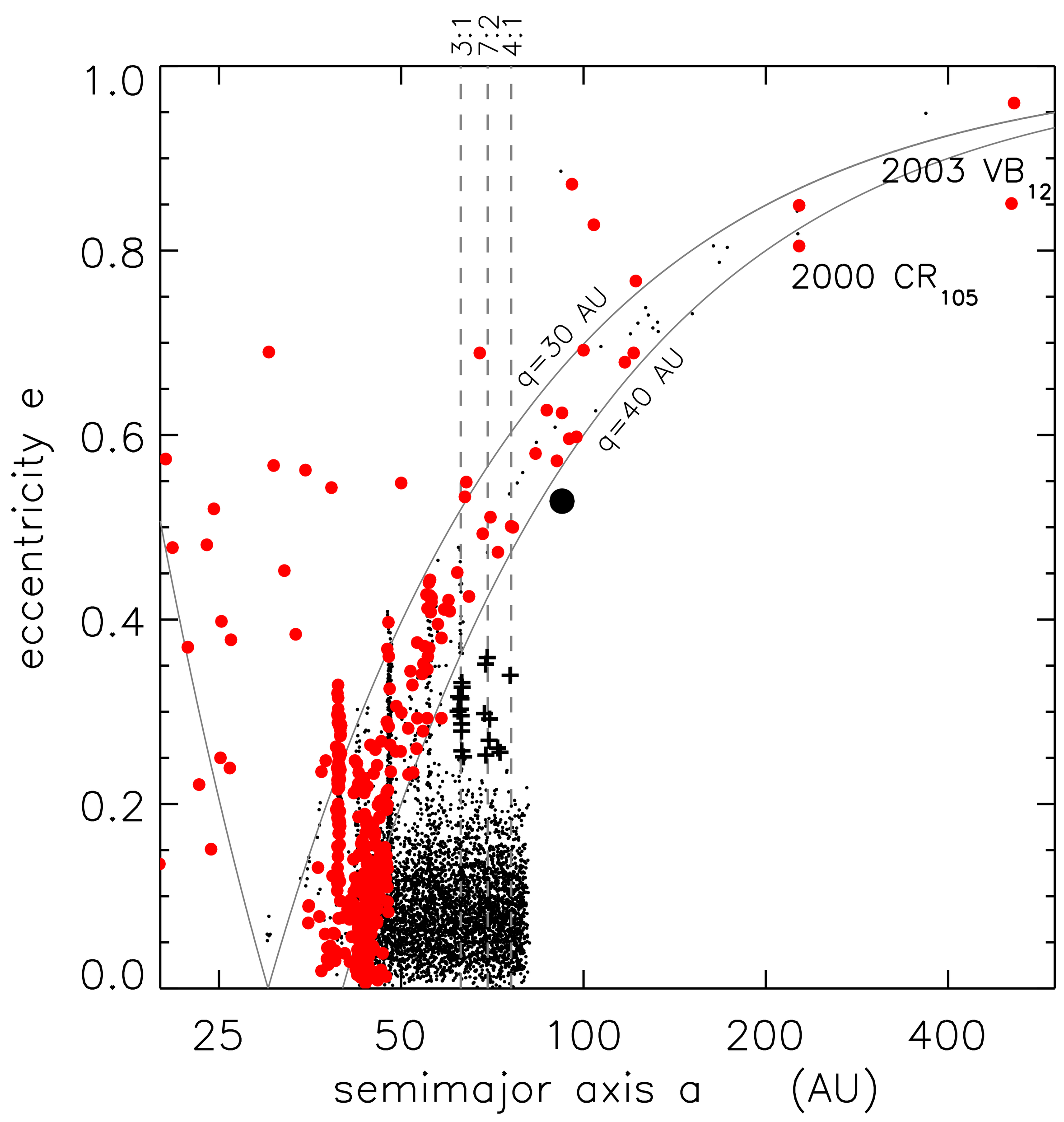

Figure 2: Observed (red) and simulated (black) orbit elements. The large black dot is the one simulated member of the Extended Scattered Disk.

4 Acknowledgments

The simulation reported here was evolved using the MERCURY6 Nbody code (Chambers 1999) on CITA's McKenzie Beowulf cluster (funded by CFI and OIT) and on the ICA's Pluto cluster (funded by CFI), with additional support to JMH provided by NSERC.

5 The KBO Inclination Distribution

The inclinations of the observed and simulated populations are compared in Figure 3. This figure shows that the planet–migration scenario envisioned here can easily account for bulk of the KBOs having inclinations $i \lesssim 15°$. However this model produces insufficient numbers of higher–i particles. Nonetheless, we do find that some resonant and Scattered particles have their inclinations pumped up to $i \sim 15$–$30°$ long after planet migration has ceased, an example of which is shown in Figure 4.

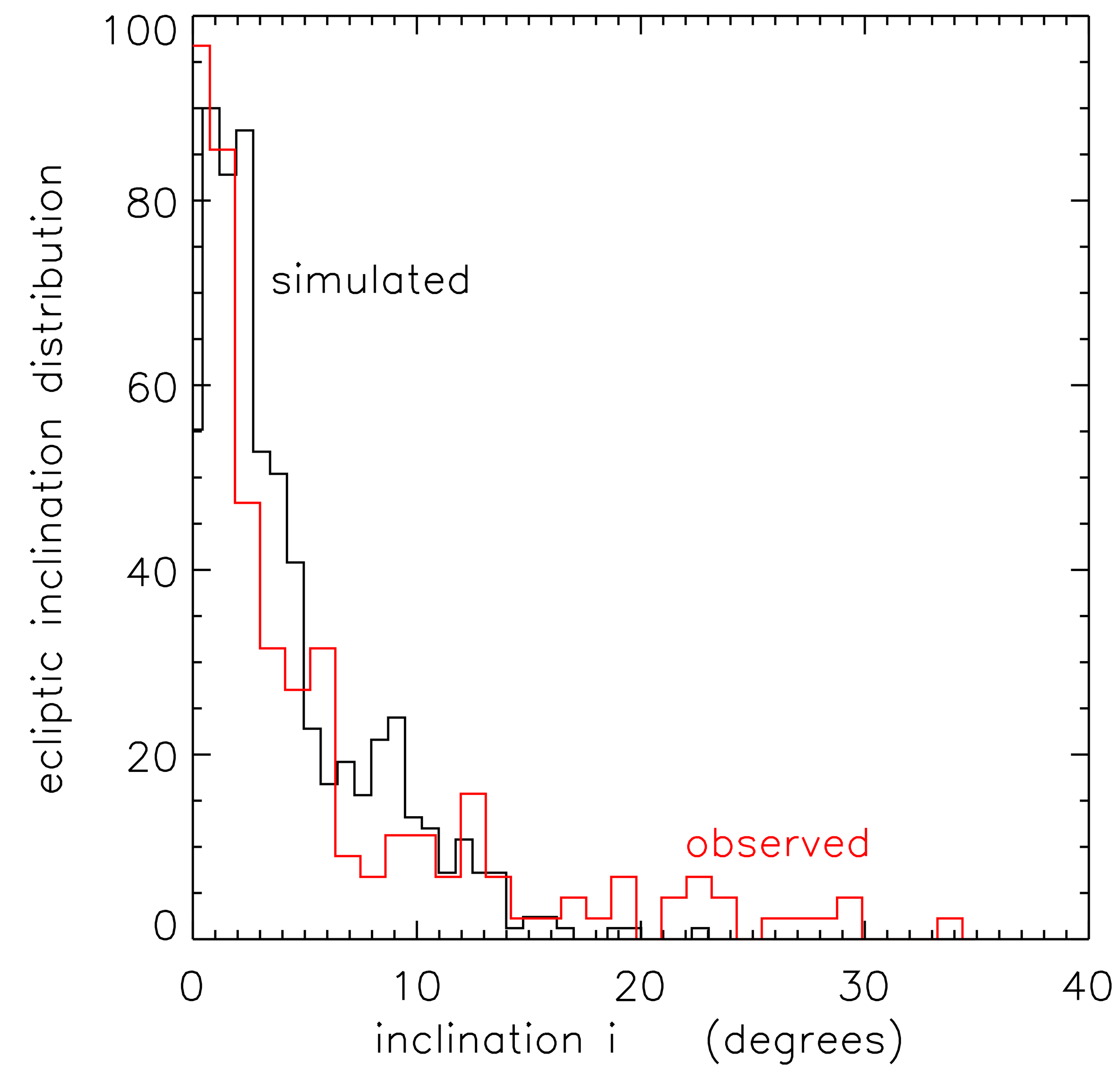

Figure 3: The ecliptic inclination distribution for observed (red) and simulated (black) bodies having latitudes within $\pm 1°$ of the ecliptic plane and perihelia $q < 42$ AU. Note that restricting our attention to these low–latitude objects lessens the telescopic selection effect that favors lower–i KBOs (e.g., Brown 2001).

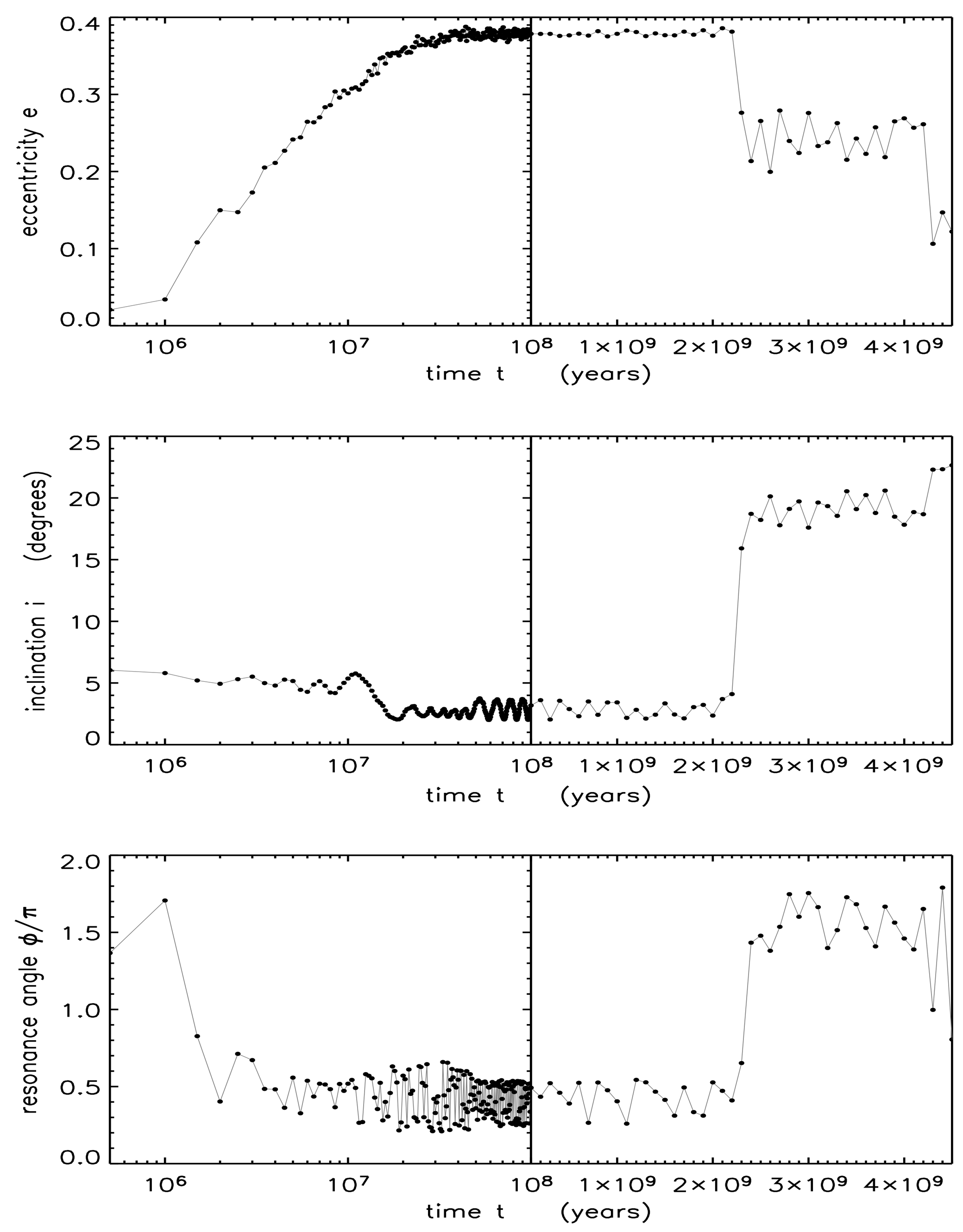

Figure 4: This particle is trapped at Neptune's 2:1 resonance, and as it switches its libration center ($\phi = 90° \to 270°$) at time $t \sim 3 \times 10^9$ years, its inclination is suddenly pumped up to $i \sim 20°$.

6 Summary of findings

- Simulating Neptune's migration into a dynamically hot Kuiper Belt shows that particles get trapped at exotic mean motion resonances: the 7:4, 11:6, 13:7, 13:6, 9:4, 7:3, 12:5, 8:3, 11:4, 3:1, 7:2, and 4:1
- Most survivors in the $30 < q < 40$ AU zone beyond $a > 50$ AU are not Scattered particles but were trapped at resonances during migration
- Although the simulation yields some particles having very high inclinations of $i \sim 15$–$30°$, they are not produced in the observed proportions.