# Why Is It So Difficult To Tilt Uranus?

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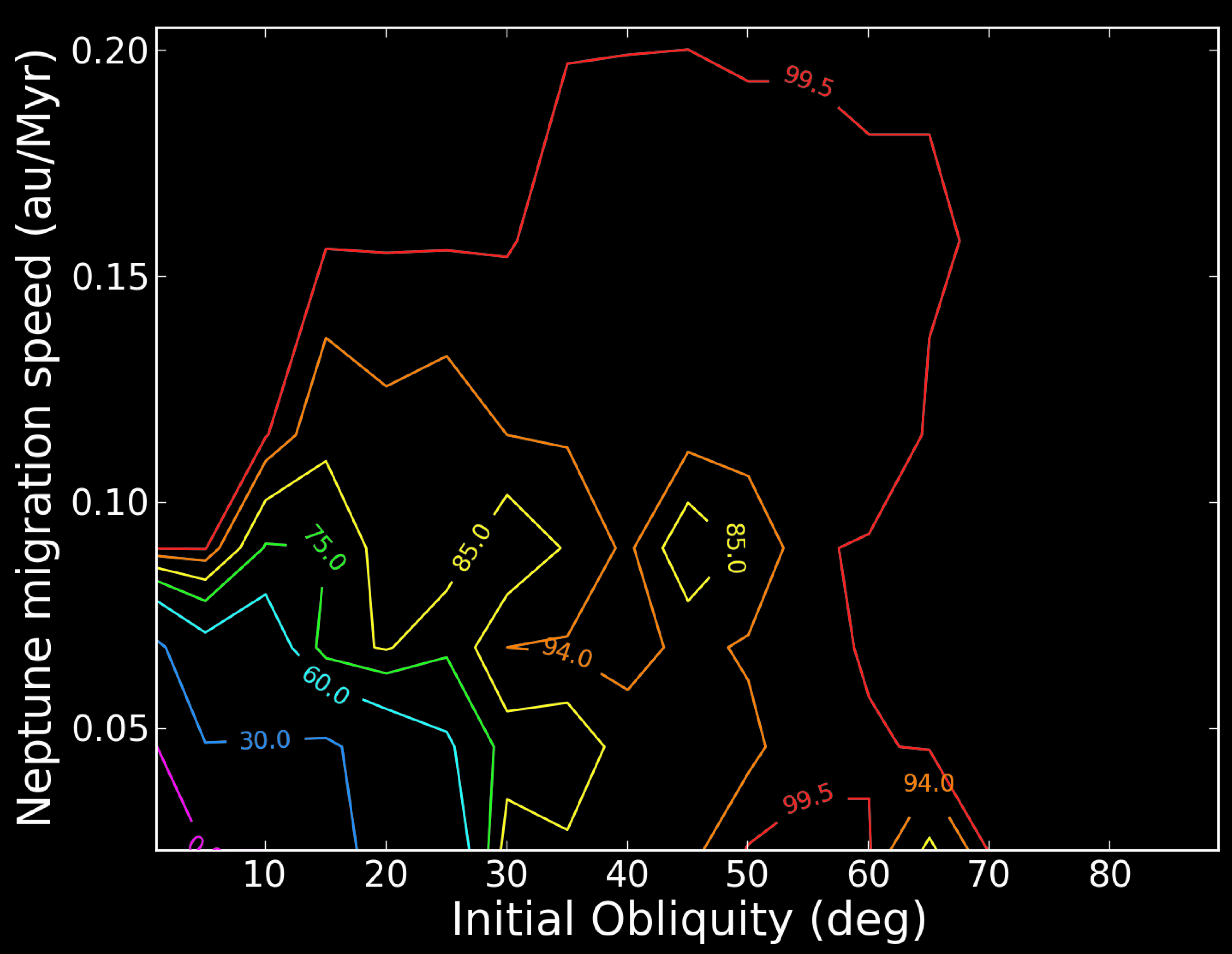
## ABSTRACT

The leading hypothesis for the origin of Uranus' large obliquity (98°) is a polar strike from an Earth sized object, but to tilt Saturn similarly would require an impactor roughly 10x as massive. A more likely cause for Saturn's tilt (27°) is a spin-orbit resonance with Neptune [1,2]; might the same process work for Uranus? It initially seems unlikely, as at its current location Uranus' axial precession period is too long to resonate with any of the giant planets' orbital precession frequencies. If we place Uranus between Jupiter and Saturn, however, then Uranus' spin axis would precess much more quickly. Uranus and Neptune were probably formed between Jupiter and Saturn [3,4,5] because the conditions there allow for the ice giants to be built rapidly. A resonance for our closer Uranus still requires a distant planet, nevertheless, a condition that can be satisfied if Neptune is ejected from Jupiter and Saturn first with Uranus following significantly later. This scenario, while contrived, is consistent with at least some versions of the *Nice* model and allows us to fully test the resonance hypothesis. We discovered that even with these optimistic assumptions, i) a resonance capture requires a migration timescale on the order of 100 Myr, and ii) it is impossible to tilt Uranus beyond 90°. Increasing Neptune's migration speed precludes resonant capture, and instead results in a resonance kick. In the most favorable cases, a resonance kick could raise Uranus' obliquity by 40° on a time span of about 50 Myr. We conclude that even in our best scenario, a resonance cannot fully account for Uranus' tilt, and, furthermore, a 40° kick would only reduce the total mass of the subsequent impactors by about 20%.


| Mass Range | $\omega_U$ (rad/hr) | Number Of Collisions 1 | 2 | 3 |
|---|---|---|---|---|
| Minimum | 0 | 0.41 | 0.42 | 0.45 |
| Most Probable | 0 | 0.41 | 0.90 | 1.20 |
| Maximum | 0 | 2.90 | 3.42 | 4.05 |
| Minimum | 0.3653 | 0.60 | 0.60 | 0.63 |
| Maximum | 0.3653 | 2.55 | 3.22 | 3.93 |

This table shows the total mass, in Earth masses, imparted that is required to generate Uranus at its current obliquity and spin period. The individual impactors are all equally massive in these simulations. The first three rows assume Uranus' initial spin state was slow, while the final two start Uranus at about its current spin period (17.2 hours). In all cases, Uranus' initial obliquity is ε=0°.



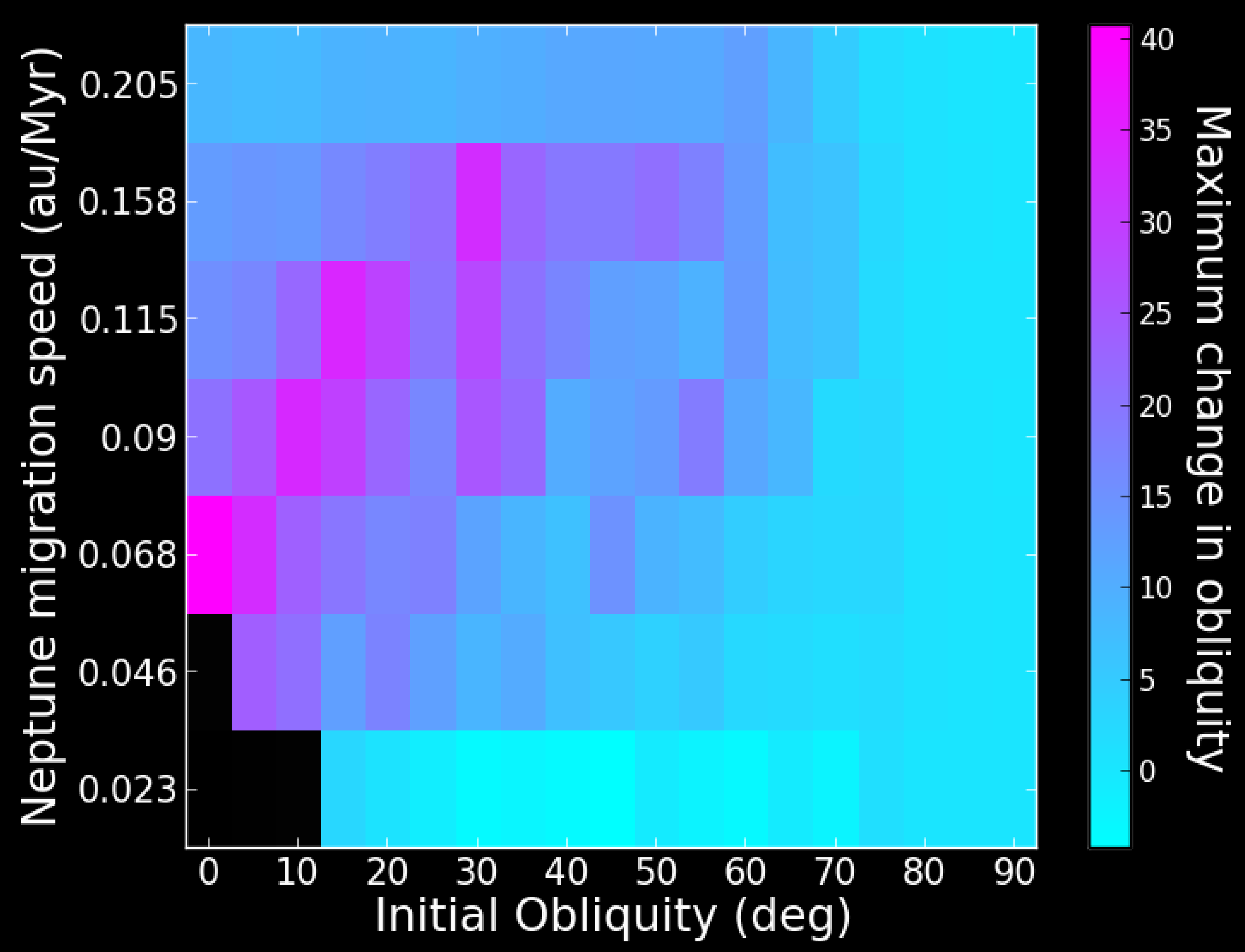




Figure 1: (left) This shows the percentage of resonances that produce kicks for a range of initial obliquities and migration speeds. Captures occur in the lower left corner. (right) This shows the corresponding maximum change in obliquity for resonant kicks. The blank section to the lower left correspond to captures. The scale ranges from large 40° kicks (pink) to 0° (cyan). The bright feature extending linearly up and to the right showing kicks up to Δε ≈ 40° is just below the adiabatic limit, the maximum migration speed that still allows captures.






References

[1] Ward & Hamilton, 2004; [2] Hamilton & Ward, 2004; [3] Thommes et al., 1999; [4] Thommes et al., 2002; [5] Thommes et al., 2003