Resonant Origins for Pluto's High Inclination

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April 7, 2008

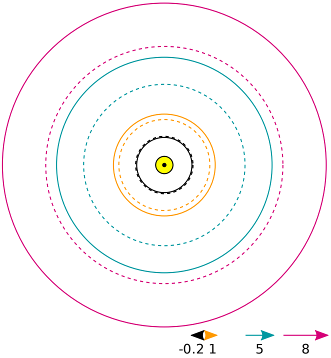
Goals

Explain Pluto's high eccentricity ($e = 0.24$) and high inclination ($i = 17°$) using resonances

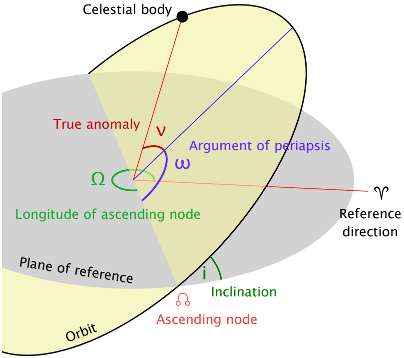
- Three candidates
  1. 6:4 mean motion resonance
  2. 1:1 secular resonance
  3. 2:1 secular resonance

Planetary Migration by Scattering Planetesimals

- Planets other than Jupiter preferentially scattered planetesimals inward, migrated outward
- Migrations move locations of resonances, catching Pluto
- If migration rate is slow enough, characteristic effect on resonances is rate-independent



Orbital Elements & Symmetries



Orbital Elements: a, e, i, Ω, $\varpi = \Omega + \omega$, λ ($\dot{\lambda} \approx n$)

Secular Variables

$$h = e \sin(\varpi)$$

$$k = e \cos(\varpi)$$

$$p = \sin(i/2) \sin(\Omega)$$

$$q = \sin(i/2) \cos(\Omega)$$

Eigenfrequencies: f, g

Resonant Behavior

Mean Motion Resonance

Simple ratio of orbital periods (dependent on λ, n)

Secular Resonance

Simple ratio of precession periods (averaged orbits)

- Form resonant arguments subject to symmetries
  - Good: $6\lambda_P - 4\lambda_N - 2\Omega_P, \quad 2\Omega_P - \Omega_N - \Omega_J$
  - Bad: $3\lambda_P - 2\lambda_N - \Omega_N, \quad 2\Omega_P - \Omega_N$
- Capture
- Jump

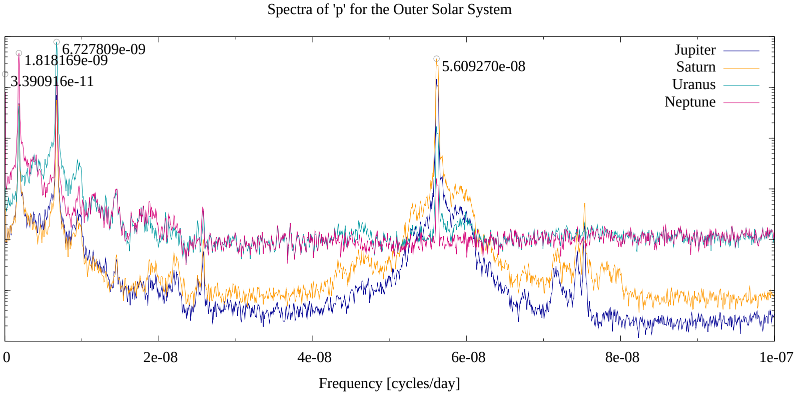
Simulation and Analysis

Both of pre-existing and new software used throughout project.

- Used *HNBody* and *HNDrag* to simulate Solar System over billions of years ($>$ 24 GB of data generated)
- To determine secular eigenfrequencies, wrote code to perform FFT on orbital elements
- Features of *PowerSpectrumEstimator*:
  - Data windowing to reduce spectral leakage
  - Overlapping data segments to minimize variance
  - Automatic peak finding with inverse quadratic interpolation
  - Removal of aliased peaks
  - Orthogonality of total angular momentum

Example: Outer Solar System p Spectra

Matches g_6 to better than 1%; matches g_7 to within 7%; matches g_8 to within 25%; g_5 is effectively 0

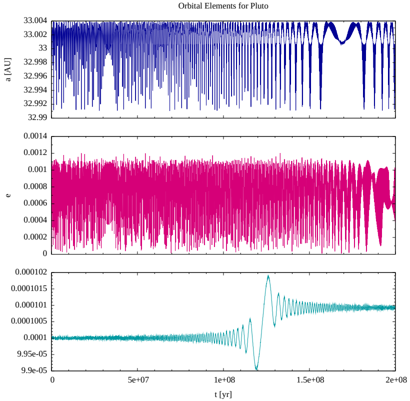


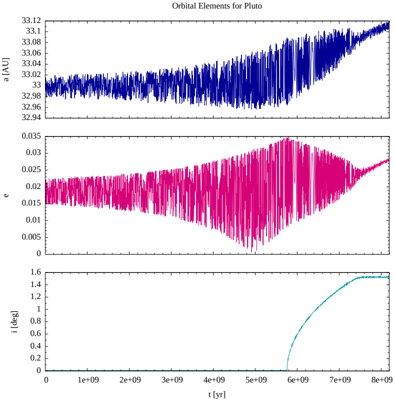
Candidate #1 – 6:4 Mean Motion Resonance

Pluto is currently trapped in a 3:2 eccentricity resonance $(3n_P - 2n_N - \dot{\varpi}_P)$ and a Kozai resonance $(\dot{\Omega}_P - \dot{\varpi}_P)$. Together, these imply a 6:4 inclination resonance $(6n_P - 2n_N - 2\dot{\Omega}_P)$.

- Initially, these were split (no Kozai resonance)
- Being first-order, eccentricity resonance is stronger
- Simulations rule out capturing in inclination resonance first
- What about afterwards?

Examples of Mean Motion Resonances





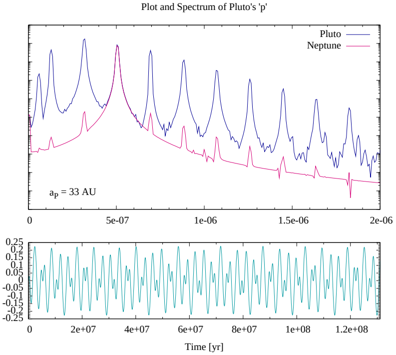
Migration rates too slow, inclination rise too small

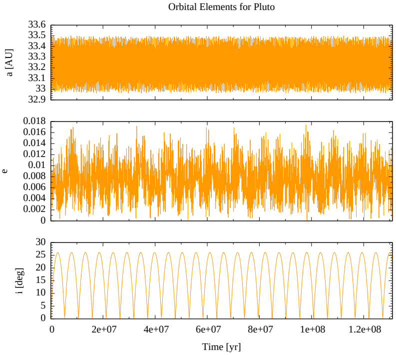
Candidate #2 – 1:1 Secular Resonance

A 1:1 resonance ($\dot{\Omega}_P - \dot{\Omega}_N$) should be easier to find and more powerful than a 2:1 resonance.

- Studied an idealized Jupiter+Neptune+Pluto system
- May have been present at Solar System formation
- Could capture into 3:2 mean motion resonance at just the right time, maintain high inclination

Example of 1:1 Secular Resonance





Static inclination resonance extremely broad and powerful (3 AU, 25°)

Secular Resonances in the Solar System

In full Solar System, 1:1 resonance is not as broad or powerful. Still, migrating across makes jump or capture possible.

- Inclination jump of 10° observed near initial conditions
- Capture raises more questions: when/how did it break out?
- Leaves observed 2:1 resonance a coincidence

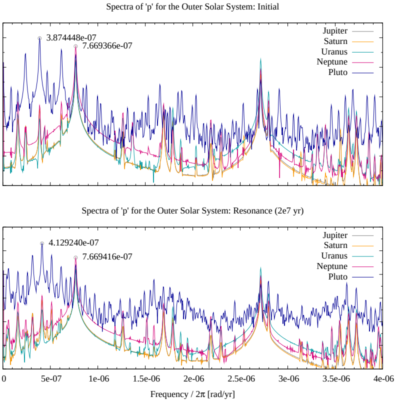
Early proximity to 1:1 indicates that 2:1 was not active prior to capture in eccentricity resonance.

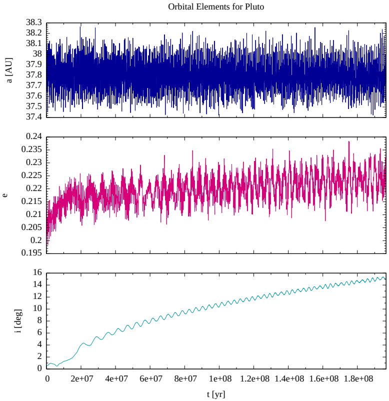
Candidate #3 – 2:1 Secular Resonance

By raising $M_U \to 1.8 M_U$, we could create conditions where $2p_1 \approx g_8$. By dragging Pluto directly, we could study strength of jump and capture.

- Raising $M_U \iff$ increasing Uranus's initial position
- Jump is too weak (2°) to explain current inclination
- What about capture?

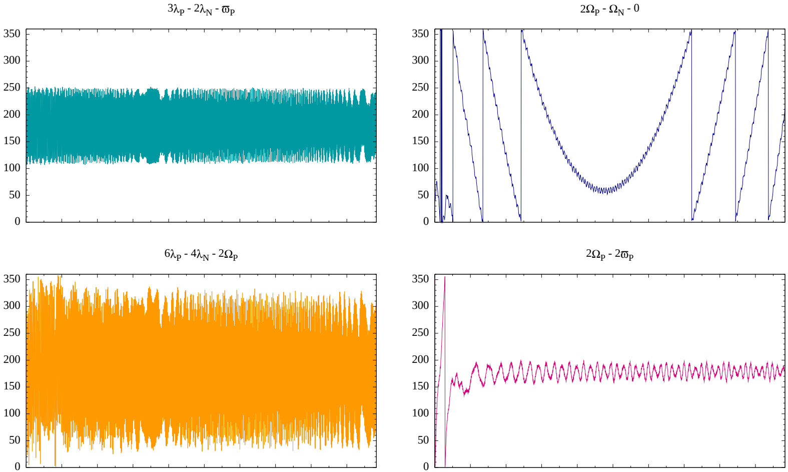
Example of 2:1 Capture





Capture is possible! Yields $i \rightarrow 16°+$

Active Resonances in 2:1 Capture



Summary

Currently, no overwhelmingly likely explanation. However, some can be ruled out while others can be constrained.

Resonance	Grade	Pros	Cons
Mean Motion	D	Currently active	Could not capture Too weak
Secular 1:1	B	Strong enough Possibly active in early solar system	Not active today Large jump instead of capture
Secular 2:1	B+	Possibly active today Capable of capture	$M_U \rightarrow 1.8M_U$ Dragging Pluto, not Neptune