Looking for invisible planets in transiting systems

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Kozai Effect: The Basics

- Aspect of Three-Body Problem
  - Exchange of energy causes oscillations in inclination and eccentricity
- Two regimes:
  - Analytically solvable (Kozai-Lidov)
  - Chaotic system (Eccentric Kozai-Lidov)

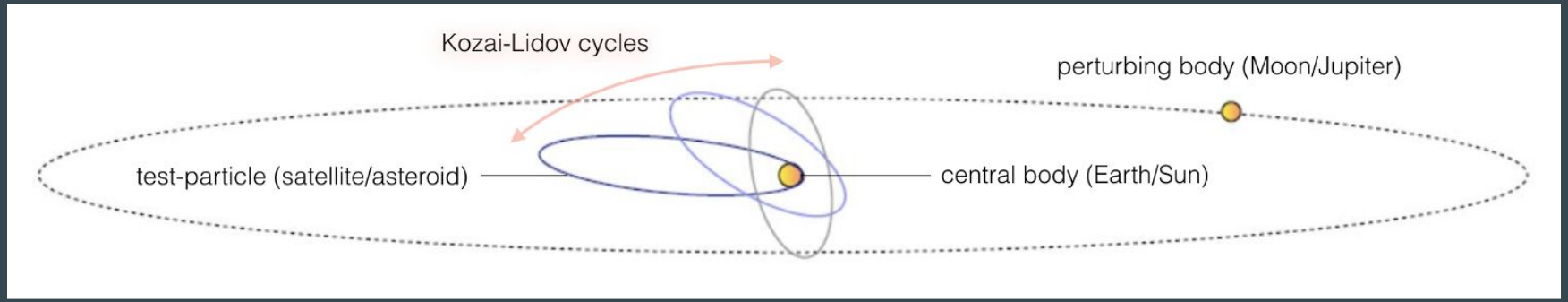
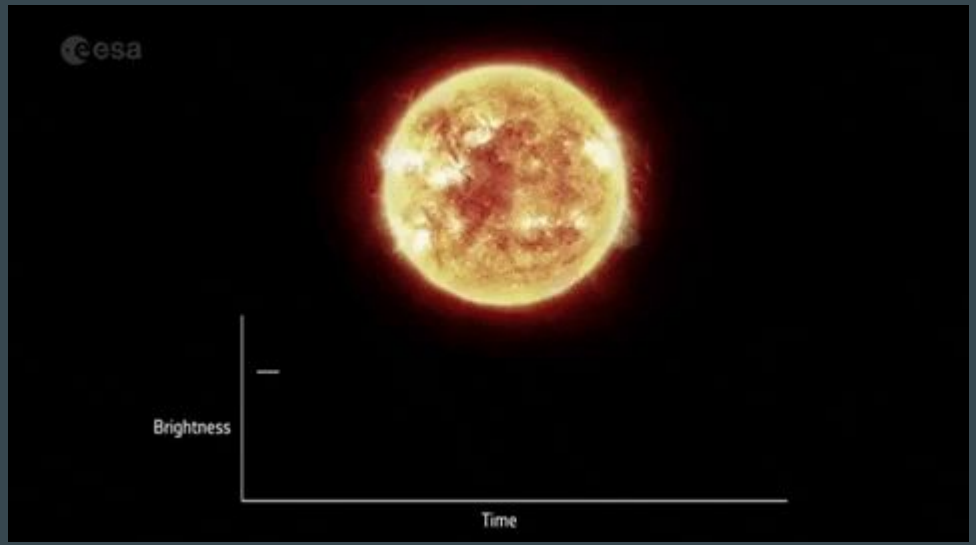


Image from Konstantin Batygin: www.planetary.org

Kozai Effect: Systems of Interest



Animation Credit: ESA

- Satellites around the Earth (Lidov)
- Asteroids in the solar system (Kozai)
- Trinary star systems
- Binary black holes interacting with surrounding stars
- **Extrasolar planetary systems**

Verifying Analytical Results with Simulations

Predicted Range of Oscillation:

Eccentricity: [0.3, 0.55]

Inclination: [23˚, 48˚]

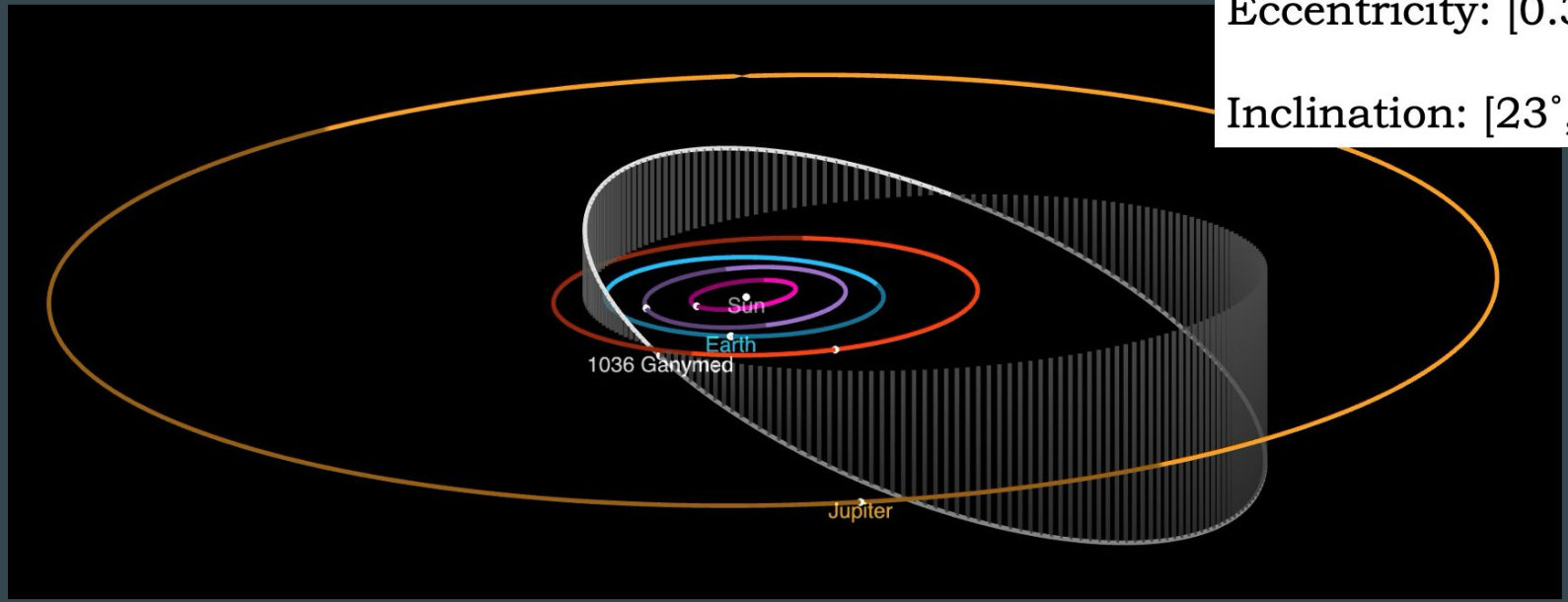
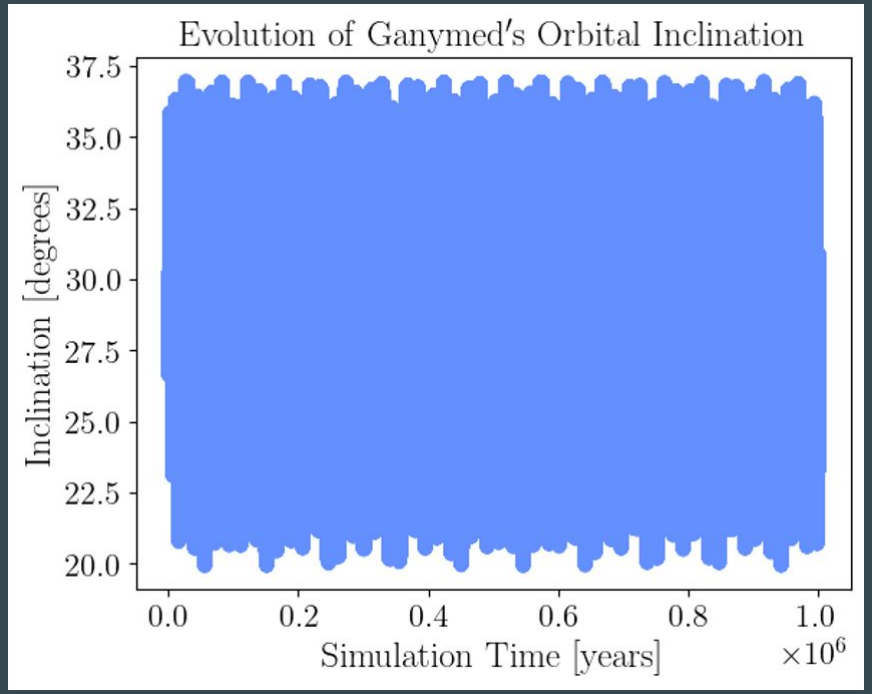
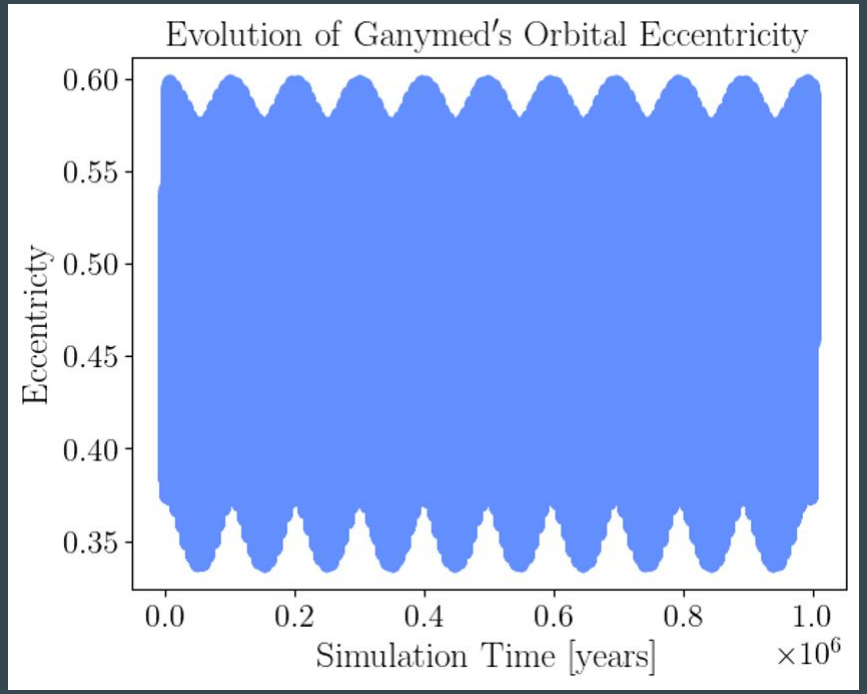


Image Credit: JPL-Caltech, “Orbit Viewer”

Verifying Analytical Results with Simulations





Inclination: $[23^\circ, 48^\circ]$

Eccentricity: $[0.3, 0.55]$

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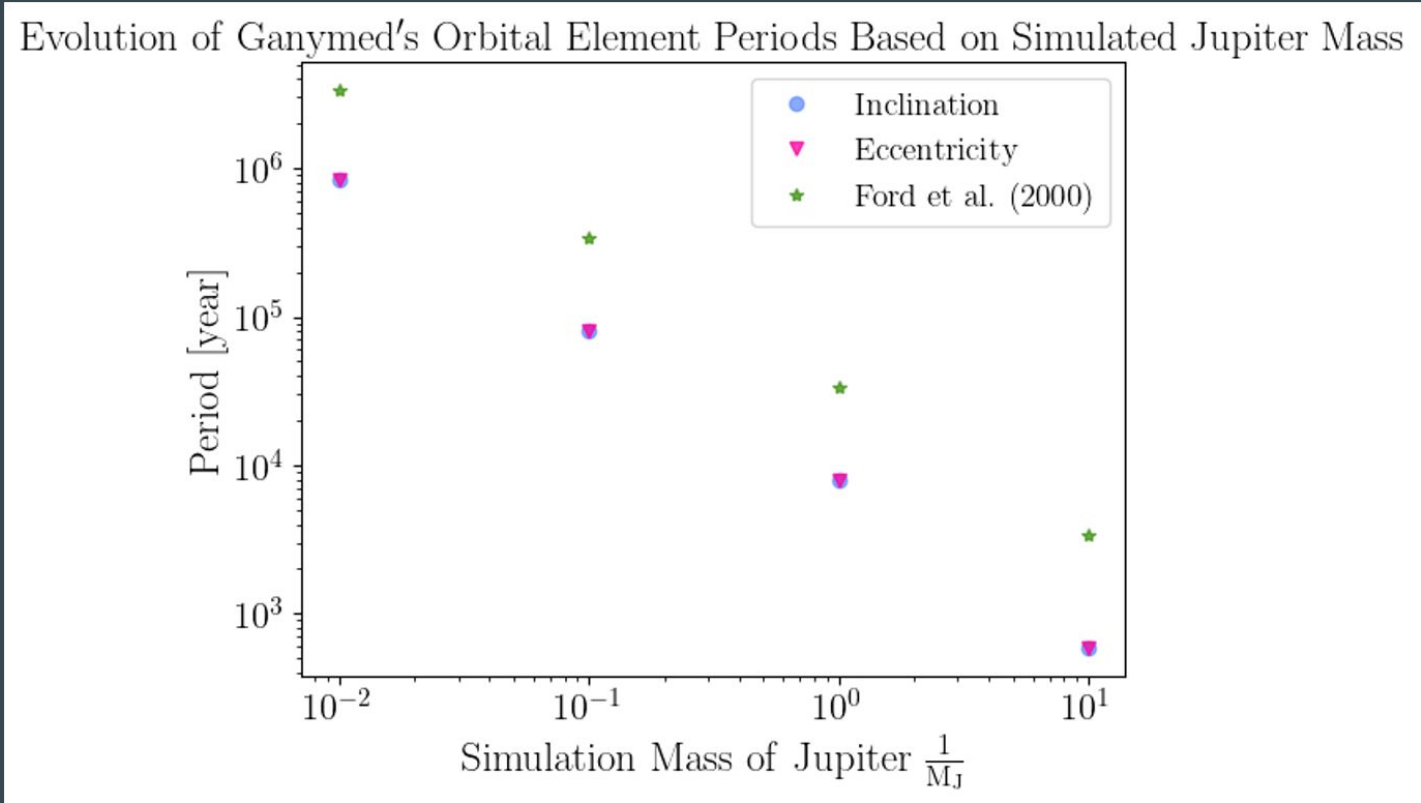
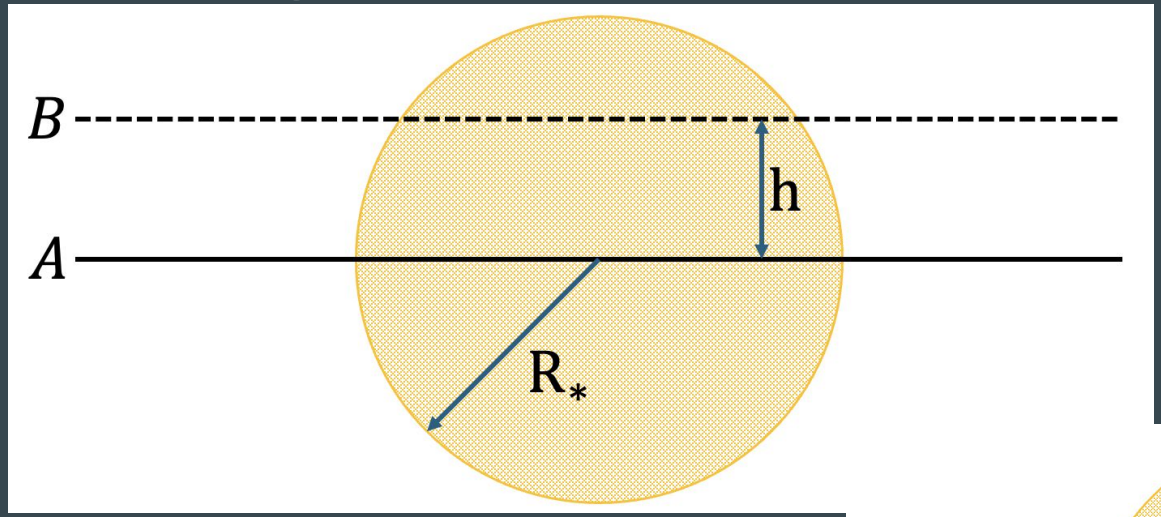
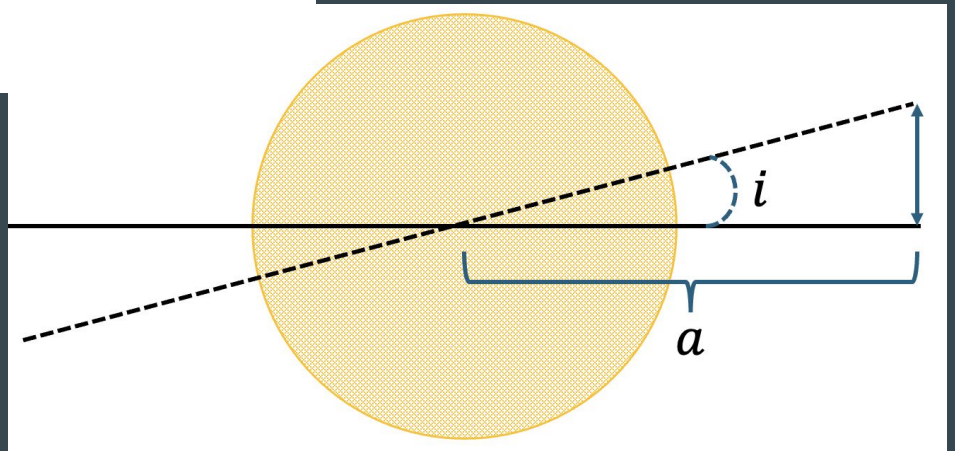


Fiducial Transiting System

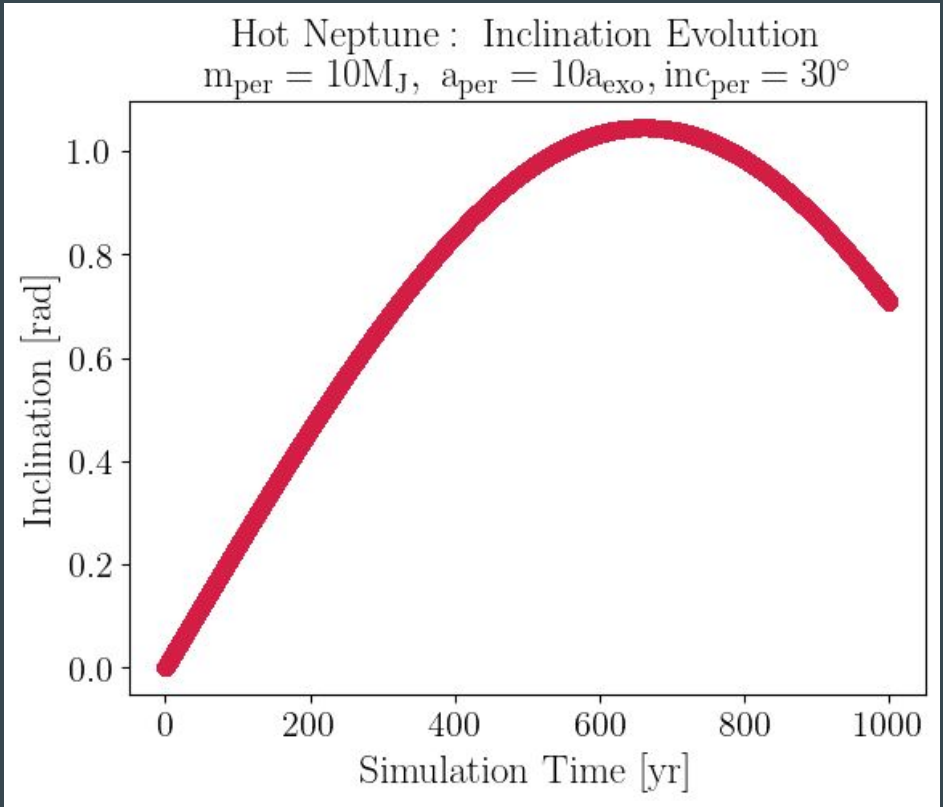
- Similar to many observed transiting “hot gas giants”
- Modeled as hot Neptune orbiting Sun-like star
  - Mass: Neptune
  - Orbital radius: ~1/10 Mercury (a = 0.041 AU, P = 3 days)
  - Inclination: 0˚ (across equator of star)
- Perturbing body:
  - Mass: 10x Jupiter (186x transiting planet)
  - Orbital radius: ~Mercury (a = 0.41 AU, P = 96 days)
  - Inclination: 30˚ (unobservable via transit)
- Look for change in duration of transit due to changing inclination of orbit

Transiting Systems - Laboratory for Kozai Variations





Rate of Inclination Change



$$\frac{\mathrm{d\ inc}}{\mathrm{d}t} = 0.091\ \mathrm{deg/yr}$$

Viability of Observing Kozai Variations

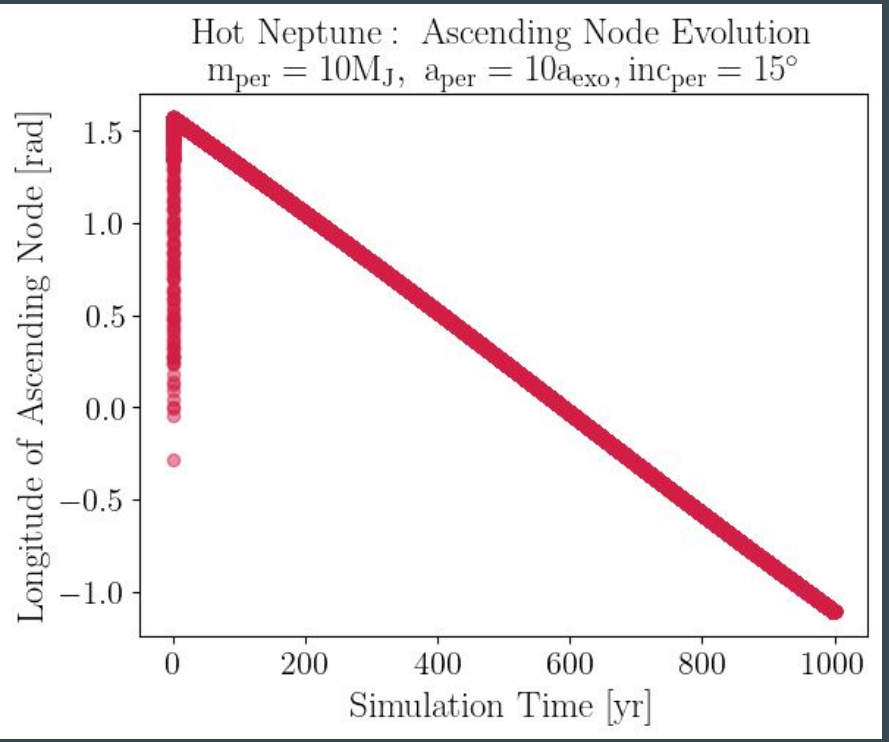
- Optimistic Case - TRAPPIST-1 b:
  - Requires inclination change of 1.12°
  - Observe over 12 years
- Realistic Case - WASP-126 b:
  - Requires inclination change of 2.44°
  - Observe over 27 years

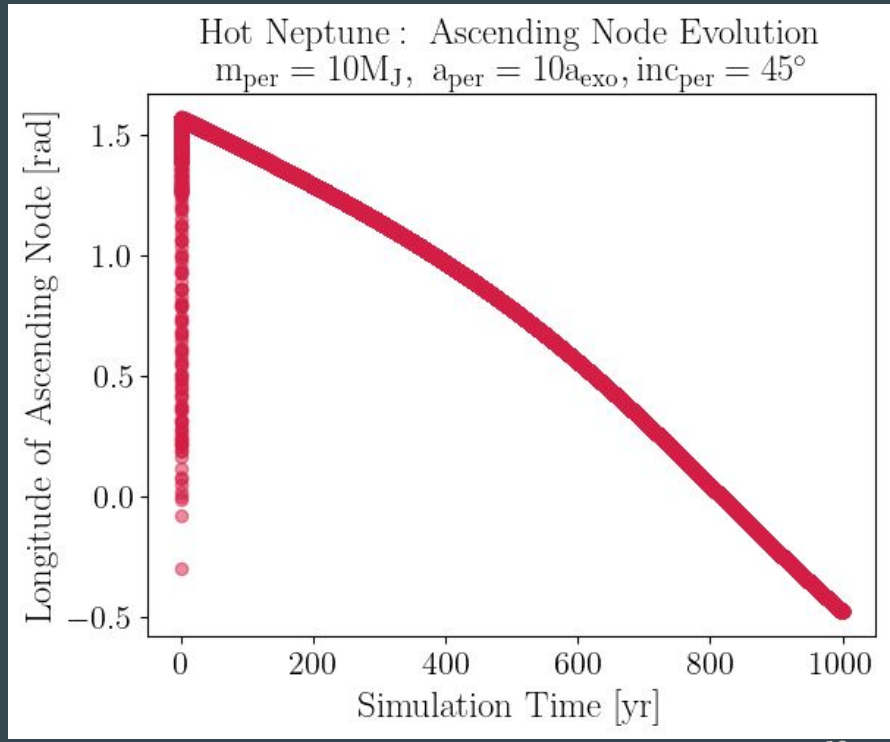
Feasible to be observed in a lifetime - poor choice in thesis topic

Summary

- Rate of inclination change:
  - Linearly depends on perturber mass
  - Roughly scales with perturber orbital radius to the third
  - *Approximately* scales linearly with initial perturber inclination
- Potential for Kozai effect to cause transit timing variations on observable timescales?
  - Constraints on perturbing body parameters to be determined
  - Additional effect: precession of inner planet's orbit can affect time at which transits occur

Simulation Results to be Verified





References for those who care …

REBOUND N-body code:

https://rebound.readthedocs.io/en/latest/

NASA Exoplanet Archive

https://exoplanetarchive.ipac.caltech.edu/

E-mail: mrs1407@rit.edu or mwrsps@rit.edu

Verifying Analytical Results with Simulations

$$P_e = \zeta P_1 \left(\frac{m_0 + m_1}{m_2} \right) \left(\frac{a_2}{a_1} \right)^3 \left(1 - e_2^2 \right)^{\frac{3}{2}}$$

$$10^{-1} < \zeta < 10^{1}$$

Kozai Effect: Systems of Interest

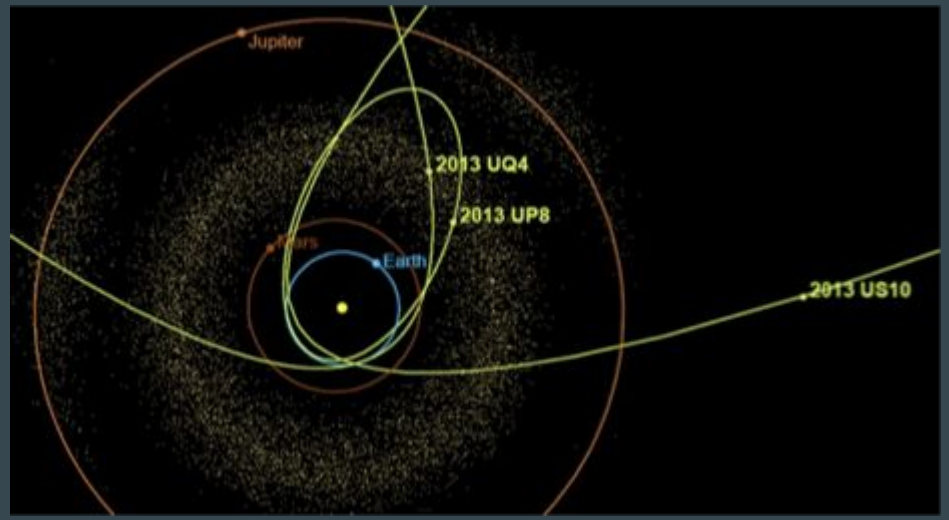


Image Credit: NASA/JPL-Caltech

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