Stable Orbits In the Kepler-1625 b Satellite System*

R. A. Moraes[1], G. Borderes-Motta[2], O. C. Winter[1] and J. Monteiro[1]

[1] UNESP, Univ. Estadual Paulista - Grupo de Dinâmica Orbital & Planetologia, Guaratinguetá, CEP 12.516-410, São Paulo, Brazil
[2] Bioengineering and Aerospace Engineering Department, Universidad Carlos III de Madrid, Leganés, 28911, Madrid, Spain

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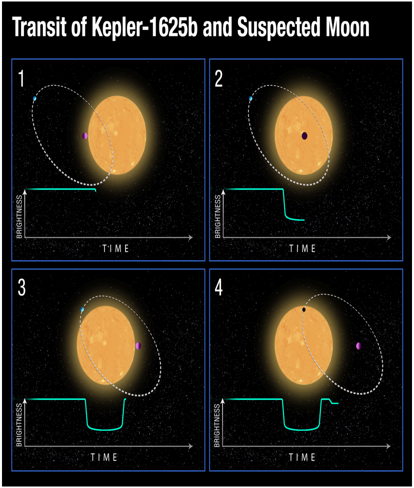
Kepler-1625 system

- **Star: Kepler-1625**
  - Mass: $M_\star \sim 1.079\ M_\odot$.
  - Radius: $R_\star \sim 1.793\ R_\odot$.
- **Planet: Kepler-1625 b**
  - Mass: $M_p \sim 3.0\ M_J$.
  - Radius: $R_p \sim 1.18\ R_J$.
  - Semi-major axis: $a_p \sim 0.84$ au.
  - Orbit is circular and coplanar.
- **Satellite Candidate: Kepler-1625 b-I**
  - Proposed by Teachey, Kipping Schimidt (2018).
  - Neptune-like satellite.
  - Semi-major axis: $a_s = 40\ R_p$.
  - Orbit is proposed to be circular, but inclined.



Credits: NASA, ESA, D. Kipping (Columbia University), and A. Feild (STScI).

Main Goals

To answer the following questions:

1. Given that Kepler-1625 b-I is stable, is it possible to have another Earth-like moon in this system?
2. If another massive satellite is stable in the system, is this satellite orbiting a preferable location?
3. How Kepler-1625 b-I will dynamically affect this extra satellite?

How to do it?

- N-body numerical simulations.
- Numerical package POSIDONIUS.
- The system integrated was composed by the planet (Kepler-1625 b), the satellite candidate (Kepler-1625 b-I) and the additional Earth-like satellite.
- Effects considered:
    - Gravitational interactions: planet-satellites and satellite-satellite.
    - Tides raised by the satellites on the planet and by the planet on the satellites.
    - Rotational flattening of the planet and the satellites.

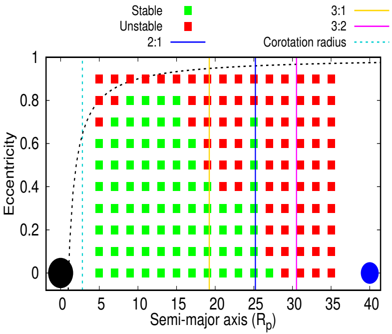
Initial Set-up

160 simulations!

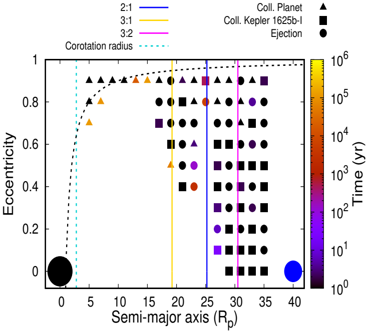
- **Star is neglected.**
- **Central Planet (Index p):**
  - $M_p = 3.0\ M_J$.
  - $R_p = 1.18\ R_J$.
  - $k_{2,p} = 0.380$.
  - $\tau_p = 1.842 \times 10^{-3}\ s$.
  - Initial Period: $10\ h$.
- **Kepler-1625 b-I (Index 1):**
  - $M_1 = 1.0\ M_{Nep}$.
  - $R_1 = 1.0\ R_{Nep}$.
  - $k_{2,1} = 0.340$.
  - $\tau_1 = 0.766\ s$.
  - Initial Period: $16\ h$.
  - $a_1 = 40\ R_p$.
  - Orbit initially circular and coplanar.
- **Extra Satellite (Index 2):**
  - $M_2 = 1.0\ M_{\oplus}$.
  - $R_2 = 1.0\ R_{\oplus}$.
  - $k_{2,2} = 0.305$.
  - $\tau_2 = 698\ s$.
  - Initial Period: $24\ h$.
  - Coplanar.
  - Initial semimajor axis distribution (a_2): From 5 to $35\ R_p$, with $\Delta a_2 = 2\ R_p$.
  - Initial eccentricity distribution (e_2): From 0.0 to 0.9, with $\Delta e_2 = 0.1$.

Results

1. Given that Kepler-1625 b-I is stable, is it possible to have another Earth-like moon in this system?
   - Yes! From the 160 simulations we performed, 50% ended with two stable satellites.



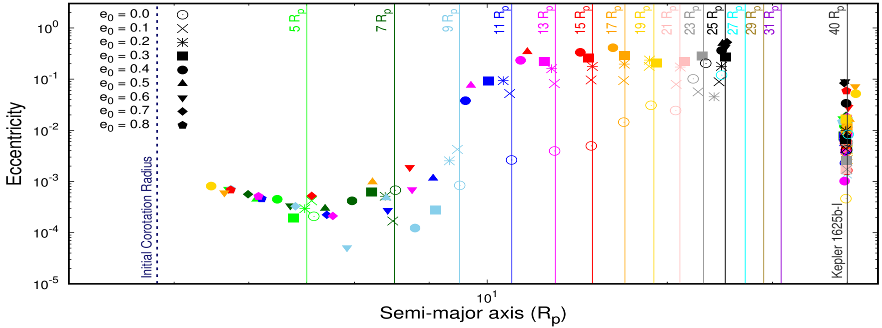
Grid with initial conditions.



Fate of the unstable systems.

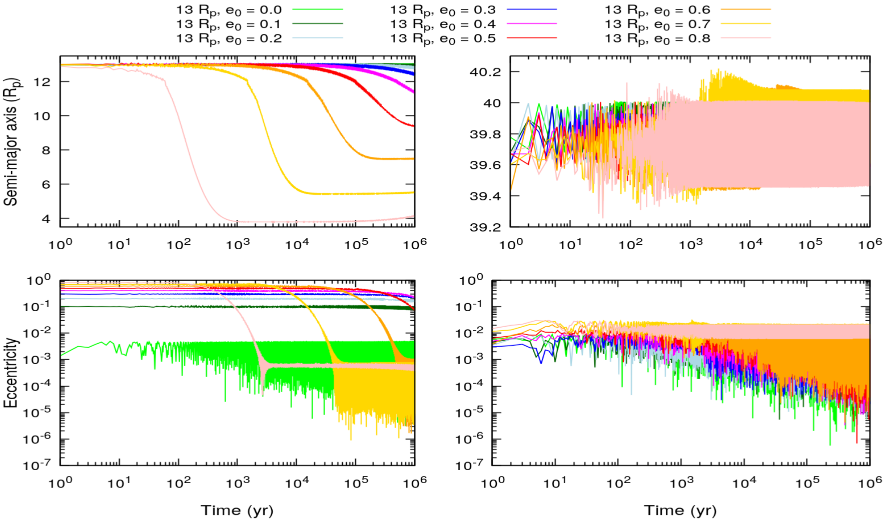
Results

2. If another massive satellite is stable in the system, is this satellite orbiting a preferable location?
   - No! The stable satellites either migrated because of the action of tides or stayed near their initial position because the tides are weaker at farther distances or the satellites are locked in resonances.



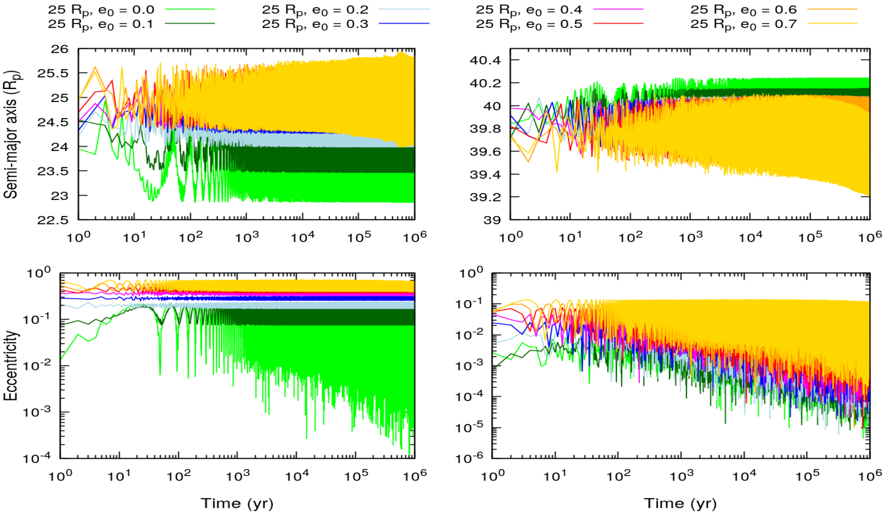
Final distribution of the stable systems.

Results - Example of Migration



Evolution of the Earth-like satellites starting at $13\ R_p$ (left side) and Kepler-1625 b-I (right side).

Results - Example of Satellites in Resonance (2:1)



Evolution of the Earth-like satellites starting at $25\ R_p$ (left side) and Kepler-1625 b-I (right side).

Results

3. How Kepler-1625 b-I will dynamically affect this extra satellite?

   - The satellites starting at inner distances are not significantly affected by Kepler-1625 b-I because the evolution of these satellites is dictated by the tidal interactions between the extra satellites and the planet.
   - Satellites initially closer to Kepler-1625 b-I $(a_0 \geq 27\ R_p)$ became unstable almost immediately because of the strong gravitational influence of Kepler-1625 b-I.
   - Most of the stable satellites starting at $25\ R_p$ (except the satellite initially circular) are locked in a 2:1 mean motion resonance with Kepler-1625 b-I. This satellites will likely be unstable if they were not in resonance.