Exploring tidal obliquity variations with SMERCURY-T

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Abstract

We introduce our new code, SMERCURY-T, which is based on existing codes SMERCURY (Lissauer et al. 2012) and Mercury-T (Bolmont et al. 2015). The result is a mixed-variable symplectic N-body integrator that can compute the orbital and spin evolution of a planet within a multi-planet system under the influence of the stellar tidal torque. We validate our implementation by comparing our experimental results to that of a secular model. As we demonstrate in a series of experiments, SMERCURY-T allows for the study of secular spin-orbit resonance crossings and captures for planets within complex multi-planet systems. These processes can drive a planet's spin state to evolve along vastly different pathways on its road toward tidal equilibrium, as the tidal torque dampens the planet's spin rate and evolves its obliquity. Additionally, we show the results of a scenario that exemplifies the crossing of a chaotic region that exists as the overlap of two spin-orbit resonances. These processes are and have been important over the obliquity evolution of many bodies within the Solar System and beyond, and have implications for planetary climate and habitability. SMERCURY-T is a powerful and versatile tool that allows for further study of these phenomena.

Methods

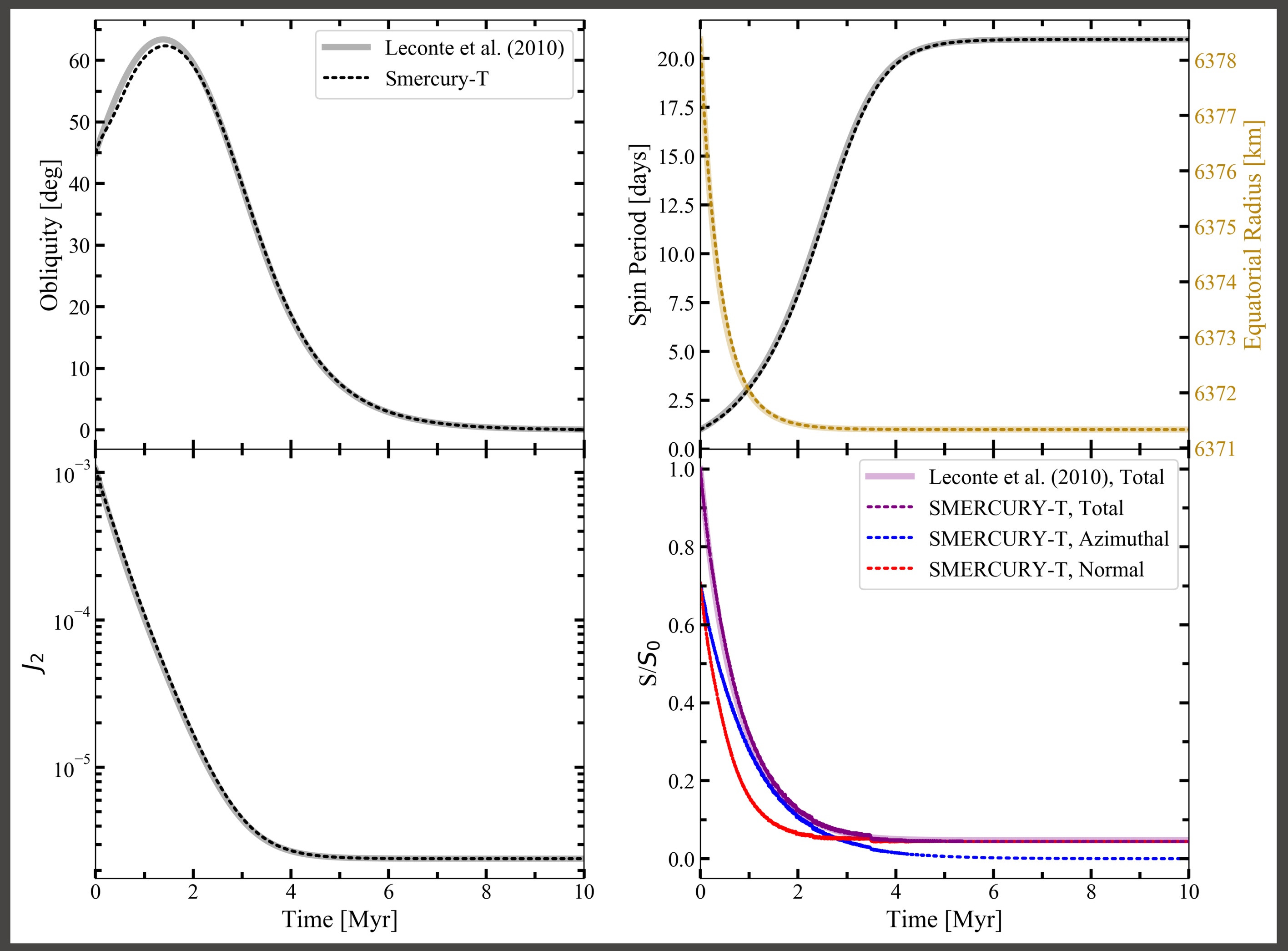
To mesh the code's N-body spin calculations with the addition of the stellar tidal torque, we need to update the planet's J_2 as its spin period and radius evolve over time. We do this by solving the cubic below for the planet's radius, R, from the Darwin-Radau relation:

$$-\frac{4}{m_p}R^3 + \frac{10S^2}{Gm_p{}^4\overline{DC}^2}R^2 + \frac{3}{\pi\rho} = 0$$

From here we retrieve the planet's rotational frequency, ω_p, and compute its J_2 each time step.

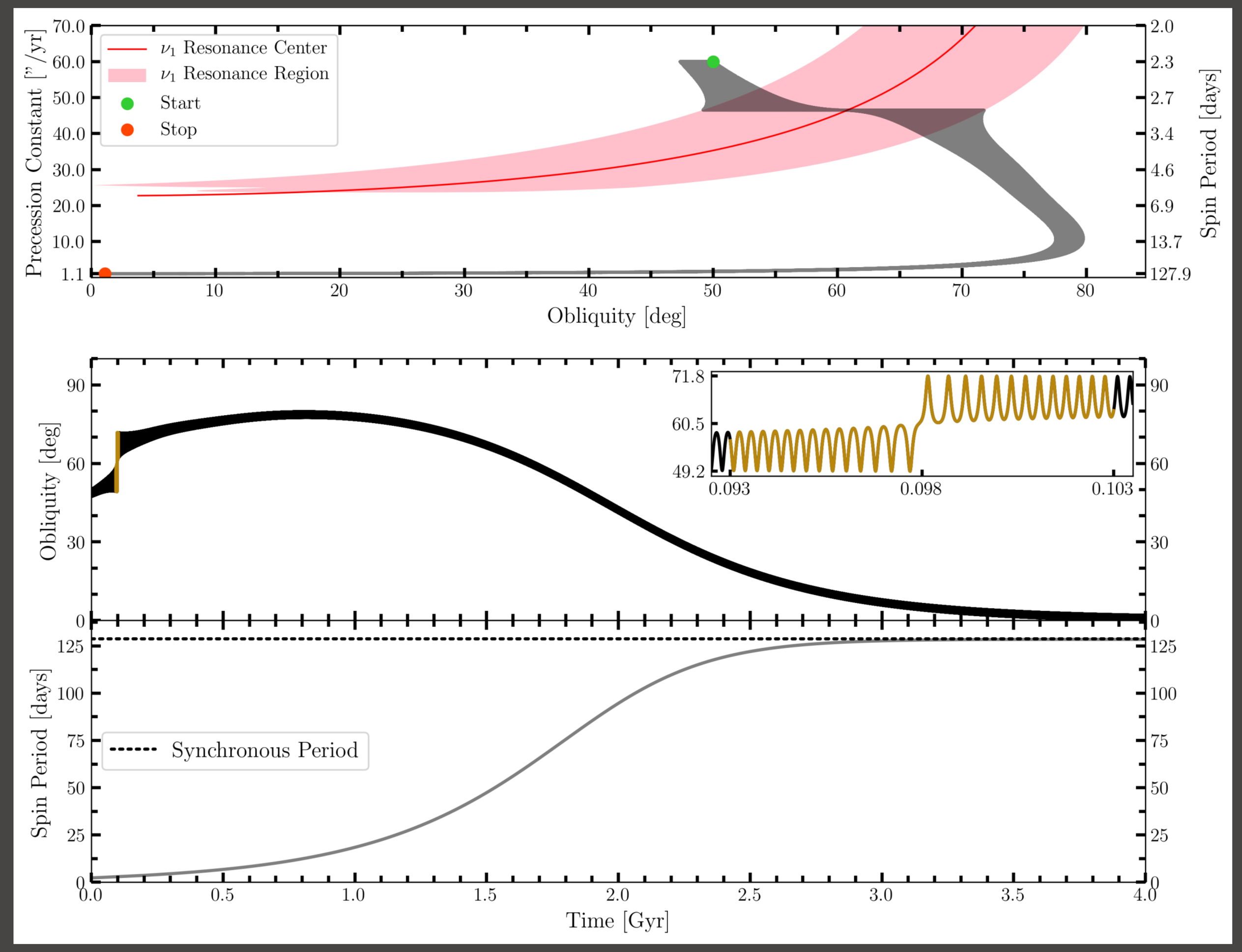
$$J_2 = \frac{\omega_p^2 R^3}{3Gm_p}\left(\frac{5}{D} - 1\right)$$

Our implementation agrees with the time lag model of Leconte et al. (2011), by comparing the tidal evolution of an eccentric moonless Earth at 0.2 AU.



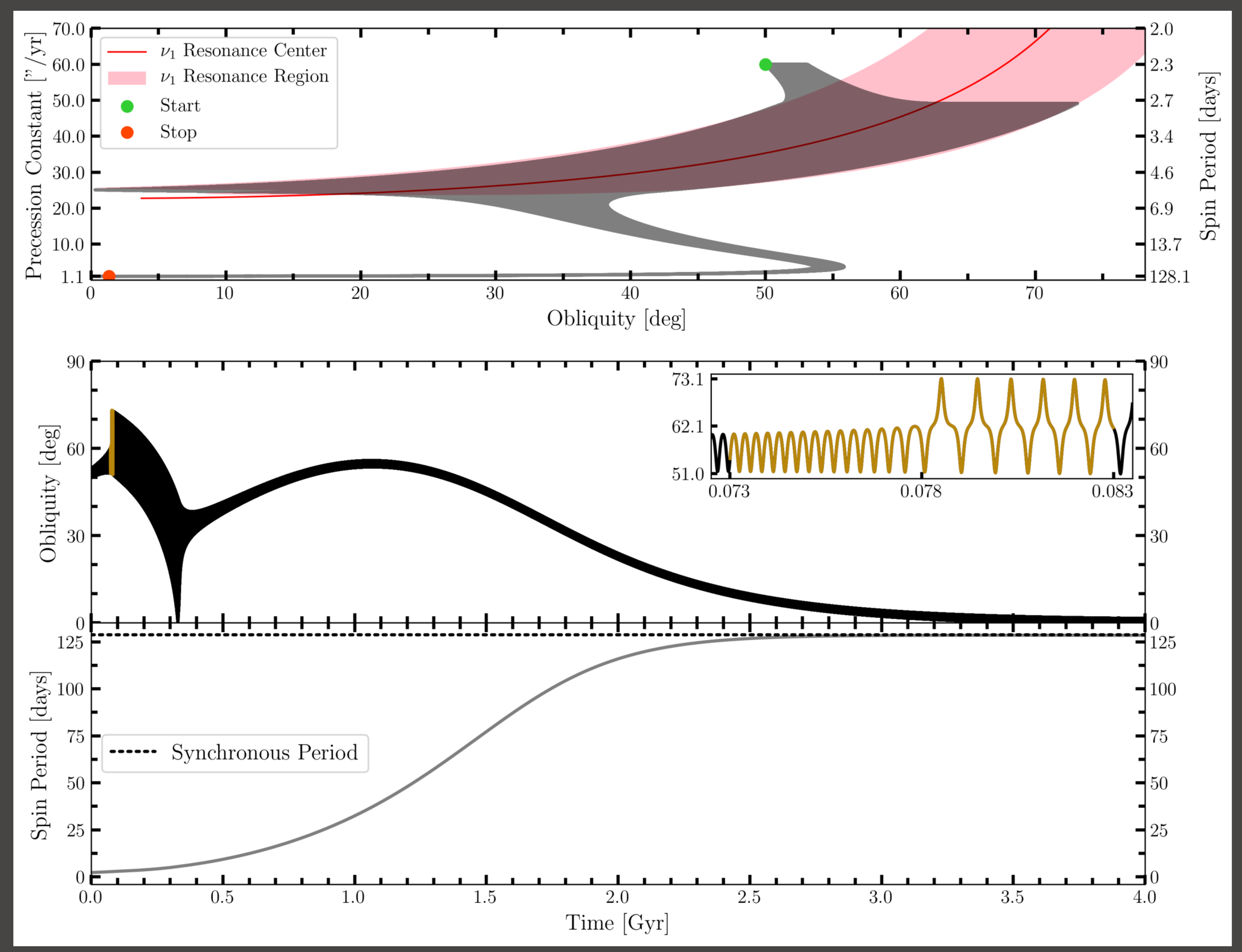
Experiments

We use SMERCURY-T to perform a few simulations that demonstrate its capability to study interesting phenomena that can occur under when a planet's spin state is under the influence of the tidal force. From left to right, here are results that showcase a spin-orbit resonance crossing, capture into a spin-orbit resonance, and finally a crossing of a chaotic zone that exists as the overlap of two spin-orbit resonances. Video links are included below each figure.



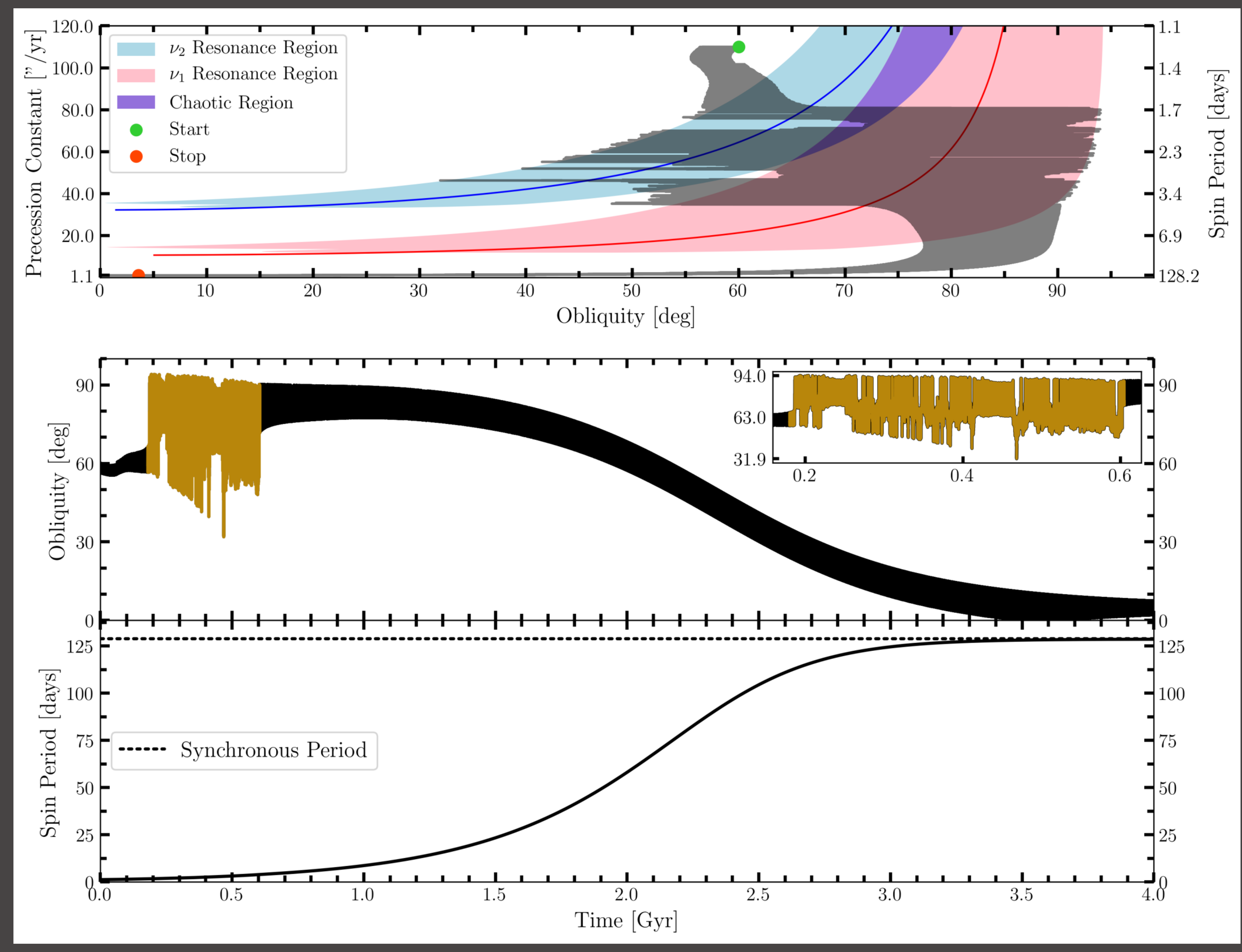
Spin evolution of an Earth-mass planet in a toy system consisting of the Sun with a mutually inclined moonless Earth and Jupiter at 0.5 AU and 2.5 AU, respectively.

Click here for video



Same as the figure to the left, but the initial azimuthal precession angle of the Earth-mass planet was shifted 180°, causing resonance capture instead.

Click here for video



Chaotic spin evolution of an Earth-mass planet at 0.5 AU in a toy system consisting of the Sun, two Earth-mass planets at 0.5 and 0.7 AU, and Jupiter at 3.5 AU.

Click here for video

Future Work

The spin-orbit resonance encounter phenomena that we demonstrated are important to the past, present, and future spin evolution of a variety of astrophysical bodies. With the completion of SMERCURY-T, we look forward to applying this code to study new and interesting problems. We offer this code publicly for anyone to access and use:

Click here for a link to SMERCURY-T'S GitHub repository.

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