TIDAL DISSIPATION FOR NON-SYNCHRONOUSLY ROTATING, BINARY SYSTEMS: APPLIED TO PLUTO-CHARON AND EXOPLANETS. Joe P. Renaud[1,2,*], Wade G. Henning[3,2], Prabal Saxena[3,2], Terry Hurford[2], and Avi Mandell[2]. [1]Universities Space Research Association ([*]joseph.p.renaud@nasa.gov), [2]NASA Goddard Space Flight Center, [3]University of Maryland College Park.

Introduction: Tides provide a conduit to extract energy stored in a planet or moon's orbit or rotation and transform it into internal heat via friction. Thus, the long-term thermal, orbital, and rotational evolution of a world orbiting a nearby massive host will be, in part, controlled by tides. In this study, we apply a model of tidal dissipation that simultaneously tracks the tidal heating and torques within both a host and its companion. This model includes effects due to: an eccentric and/or inclined orbit, the obliquity of either the host or companion and any non-synchronous rotation (NSR) of either world. Our goal is to categorize when this dual dissipation model is necessary compared to traditional methods.

Here we also present the application of this model to the early evolution of binary Trans-Neptunian Objects (TNOs), such as Pluto-Charon, as well as tidally active exoplanets. Since some formation models of TNO binaries suggest high initial spin-rates and eccentricities [1], it is important to understanding how non-synchronous spin affects their thermal-orbital evolution. Likewise, exoplanets which are in mean-motion resonances (MMR) with sibling planets may have forced eccentricities much like Io and the Galilean Moons. These can enable spin-orbit resonance trapping which is generally not considered by traditional models.

Methods: *Dissipation Efficiency*. Prior work has investigated the long-term tidal evolution undergoing NSR [2] as well as dual-body dissipation [3, 4]. Yet, these and similar studies estimate the efficiency of a world's tidal dissipation by using either the Constant Time Lag (CTL) or Constant Phase Lag (CPL) models (this is generally done by use of a constant *quality factor*, *Q*). But, observations on how real rocks and ices respond to tidal forces have found complex relationships – requiring additional dependencies on pressure, temperature, and frequency [eg., 5, 6]. The CTL method does provide an extra dependence on frequency when compared to CPL, but it still falls short in describing the nuances of real-world materials [7, 5]. Many recent studies have replaced the CPL and CTL methods with more realistic rheological responses [8, 9, 10, 11]. Even more recently, realistic rheologies have been applied to the dual dissipation of Mars and its moons [12]. But to the best of our knowledge, these models have not been extensively studied in the context of icy worlds nor exoplanets.

Orbital and Rotational Model. To study the impact of realistic rheologies, we use the Darwin-Kaula theory of viscoelastic tides [13, 14]. The generalized theory allows for arbitrary rheologies that use tidal modes as their frequency input [15]. The tidal modes are linear combinations of orbital motion and spin rate and can be different for each world. They allow a planet to fall into various spin-orbit resonances depending upon the orbital eccentricity and the world's obliquity. An additional goal of this study is to quantify the impact that rheologies have on spin-orbit resonance trapping for various TNO and exoplanet scenarios. For the rheological model, we choose the Sundberg-Cooper rheology which has been found to better model both rocks and ices [11]. The time evolution of eccentricity, semi-major axis, obliquity, and rotation rates are tracked using methods developed to work with the generalized Darwin-Kaula theory of tides [16]. These evolutions have been truncated to order-6 in eccentricity and obliquity angles.

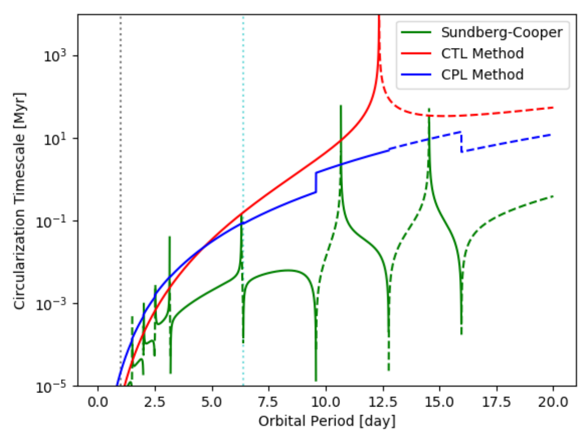

Figure 1: Circularization timescales (estimated by utilizing the change in eccentricity: $\tau \sim -e/\dot{e}$) for the post capture Pluto-Charon system are calculated for the Sundberg-Cooper rheology alongside two comparison models (CTL, CPL). Pluto's rotation period is fixed at 1 day (black-dotted line) while Charon's rotation is fixed at its modern value of 6.39 days (cyan-dotted line). An eccentricity of 0.3 is used. For the Sundberg-Cooper rheology, material parameters suitable for dissipation within pure water-ice were used.

Initial Results and Discussion: In Figure 1, we calculate the circularization timescale of a post-captured Pluto-Charon system using the CTL, CPL, and the Sundberg-Cooper rheology. The latter model shows distinct spikes and dips in the circularization time at spin-orbit resonances for both objects. These features are largely lost when using the CTL and CPL methods. We have found that these differences are significant enough to alter time simulations of this and similar systems. Perhaps more importantly, Sundberg-Cooper generates more dissipation, especially at low frequencies, leading to faster circularization times.

Exoplanets with sufficiently high eccentricity can become trapped in higher-order spin-orbit resonances for as long as that eccentricity remains. We demonstrate this phenomenon in Figure 2 where the rotation rate and eccentricity are varied for the exoplanet TRAPPIST-1e. The contours indicate rotational acceleration, red is positive acceleration and blue is negative. Locations where these colors meet are regions of constant rotation rate. For example, there is a horizontal meeting line at the 3:2 spin-orbit resonance that appears for an eccentricity greater than approx. 0.1, in comparison to the 5:2 which requires an eccentricity of at least 0.3. As eccentricity tends towards zero the only remaining spin-orbit resonance is the 1:1, which is the ultimate end state for tidal evolution. Loosening the truncations on eccentricity, and allowing for a non-zero inclination, will further modify these resonances as well as activating new ones.

The importance of these corrections depends upon the longevity of the forced eccentricity. However, if these super-synchronous spin-rates *are* long-lasting for certain worlds, then studies have shown that NSR can greatly alter those world's climates [17]. Determining the duration that an exoplanet is trapped in a higher-order spin-orbit resonance is complicated by eccentricity's derivative being coupled to the change in spin-rate for both the host and companion (see Figure 1). Furthermore, both the changes in spin-rate and eccentricity depend upon the thermal state of the world's interior. The next step of this project will be to examine a fully coupled thermal-orbital model that simulates the orbital and thermal evolution. Preliminary results have shown that binary TNOs can have complex spin evolutions for the first ~500 Myr after a capture event [18]. The tidal heating from those evolutions only modestly enhance liquid water within those worlds.

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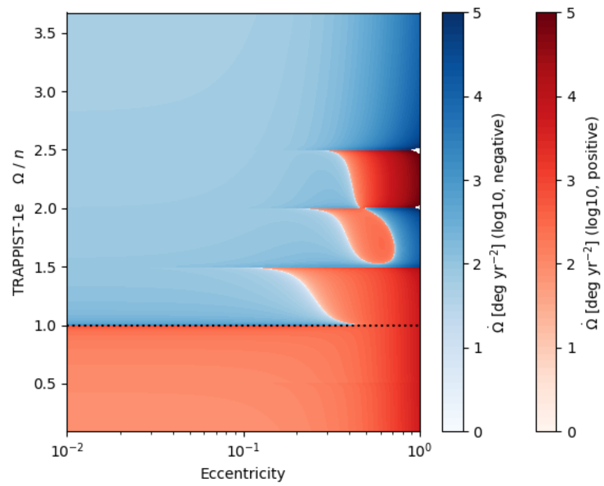

Figure 2: Spin-rate derivatives are shown in log-scale for the exoplanet TRAPPIST-1e subjected to an eccentric orbit (varying across x-axis) and non-synchronous spin-rate (y-axis). The blue contours indicate a negative, or slowing, spin-rate, while the red shows accelerating rotation. Regions of transition between colors indicate a parameter space where the exoplanet could become trapped at a consistent spin-rate if other orbital and thermal parameters stay constant.

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