Long Period Non-Synchronous Rotation of Io J. N. H. Abrahams[1] (abrahams@ucsc.edu), F. Nimmo[1], I. Garrick-Bethell[1,2], B. G. Bills [3], C. J. Bierson[4], [1]Department of Earth & Planetary Science, University of California Santa Cruz, Santa Cruz, CA, [2]Kyung Hee University, Republic of Korea, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, [4]Arizona State University, Tempe, Arizona

Summary: We investigate whether Io may be undergoing very long period faster-than-synchronous rotation, where every time it orbits Jupiter it experiences slightly more than one rotation on its axis. This is a result of nonzero average tidal torques on Io's figure [1] and the period is set by the timescale on which Io's mantle behaves like a fluid.

Non-Synchronous Rotation Background: All major satellites in the solar system are tidally locked, presenting the same face to their planet every periapse. This is because planets tidally torque satellites' nonspherical shapes toward synchronicity. However, for fluid satellites on eccentric orbits, the equilibrium state is somewhat faster than synchronous [2]. In this abstract when we refer to long period non-synchronous rotation, we are referring the the perturbation on a mostly-synchronous rotation rate, so "long period" refers to the extra rotation taking place, and we will use the acronym "NSR". Searches for imaging evidence of NSR have been unsuccessful, indicating that NSR periods are of order 10^4 yr or more [3]. Theoretical arguments show that only a small amount of permanent ("frozen in") topography is required to overcome the torques on the tidal bulge and ensure exactly synchronous rotation; [2] estimate a 10 km tall, 100 km radius mountain would synchronize Io, but in reality Io has many volcanoes which will partially cancel each other out, so it is not clear whether Io's topography alone is enough to synchronize it. On the other hand, the lack of a pronounced apex-antapex asymmetry in crater distributions has been used to argue that NSR does happen [4]. Despite the lack of clear evidence of NSR up to ~kyr timescales, materials will behave more viscously at longer timescales, so it is worth exploring on what timescale (if any) bodies like Io will experience NSR.

Io Background: We are interested in exploring the potential for NSR on Io for two reasons. First, Io is at least partially molten, making it likely that it has a fairly low mantle viscosity compared to other satellites. Second, observations of Io's volcanoes [5] have found them offset from where they are expected to form in canonical solid body tidal heating models [see discussion in 5]. NSR could explain this by constantly shifting volcanoes away from where they are forming. Previous searches have not found any deviation from synchronous rotation and constrain any Io NSR to have a period longer than about 4 kyr [3].

Methods: Broadly, figuring out how quickly a body rotates (above synchronous) requires figuring out its very low frequency tidal response. We explore this in two steps: First, we analytically solve equations for tidal evolution to determine how the low frequency tidal response determines the rate of NSR. Then, we use numerical codes to determine that tidal response for a suite of potential Io structures and rheologies.

Tidal Calculations: We begin with a general formula for the orbitally averaged tidal torque on a body [6] as a function its response to tides (k_2) and how dissipative it is (Q), which are both functions of frequency:

$$\langle T\rangle_{orb} = -\frac{3Gm_0^2R^5}{2Ca^6}\sum_{k=-\infty}^{\infty}\left(X_k^{-3,2}\right)^2\frac{k_2}{Q}\Big(2\Omega-kn\Big) \tag{1}$$

where Ω is the satellite's rotational frequency, n is the satellite's orbital frequency, and $X_k^{-3,2}$ are analytically known Hansen Coefficients [see 6]. G is the gravitational constant, m_0 the central body mass, R the satellite radius, C the satellite's maximum moment of intertia, and a the satellite's orbital semi major axis, so the term in front of the sum is easily measured. The NSR frequency, which we call ω_{nsr}, is given by $\omega_{nsr} = \Omega - n$, the difference between the rotational and the orbital frequencies. Note that this equation is similar to eq 212 in [7].

Observing Equation 1, we note that for an approximately synchronous body, $\Omega \approx n$ (i.e. $\omega_{NSR} \ll \Omega$) so for $k \neq 2$, the term in the sum is just k_2/Q evaluated at multiples of the orbital frequency. We know Io's k_2/Q at its orbital frequency from watching the secular evolution of its orbit and inferring the energy dissipation which must be taking place [8]. At $k = 2$ we have k_2/Q at (twice) the NSR period, which is of order millions of years if it explains the volcano offset. Taking advantage of knowing $\frac{k_2}{Q}(n)$, we find that to a very good approximation (because e is small), the equilibrium rotation state ($\langle T\rangle_{orb} = 0$) has

$$\frac{k_2}{Q}(2\omega_{nsr}) = 12e^2\frac{k_2}{Q}(n) \tag{2}$$

What this equation says is that a body will experience NSR at whatever frequency makes its tidal dissipation equal to its orbital frequency tidal dissipation times $12e^2$. This is fully general and applies to any body that is nearly synchronous and has a small eccentricity. In the case of Io, $e = 0.0041$ and $\frac{k_2}{Q}(n) \approx 0.015$, so Io will non-synchronously rotate at the frequency where $\frac{k_2}{Q} \approx 3 \times 10^{-6}$.

Numerical Models: The inverse problem, of finding a planetary structure with a particular tidal response, is very nonunique, so instead we forward model different structures in order to compute their tidal response.

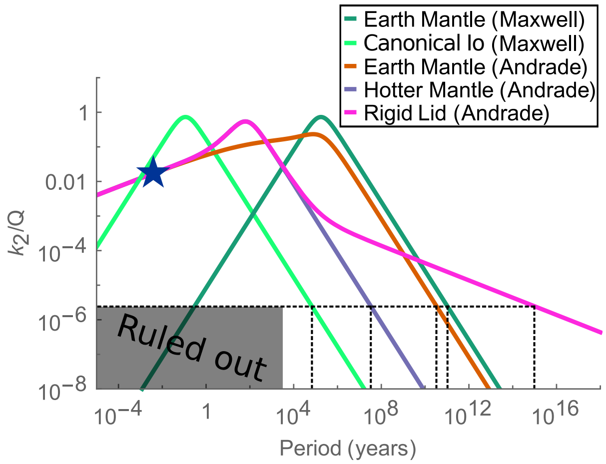

Figure 1: k_2/Q as a function of period for a few simple models. Light green is a Maxwell model for a canonical Io viscosity of 10^{15} Pa·s [9,10], dark green is a Maxwell model for a uniform Io made of Earth's upper mantle ($\eta = 10^{21}$ Pa·s), orange is an Andrade rheology for the green body (using Andrade parameters from [11]), purple is the same as the orange model but with a viscosity of 10^{18} Pa·s, and pink is the purple body with a 10 km rigid crust. The star shows Io's inferred k_2/Q at its orbital frequency [8], which the real Io must pass through, hence Io needing to either be very low viscosity or not a Maxwell material. The dotted lines highlight the period over which each body would undergo an extra rotation – for example the hot Andrade mantle model would undergo one extra rotation roughly every 30 Myr. The gray box indicates NSR periods which are ruled out by observations.

We use numerical codes based on the "propagator matrix" technique [12], which allows us to compute exact tidal parameters for arbitrary bodies as long as they are made of finite thickness spherical shells.

Because we are specifically interested in viscoelastic behavior (rather than purely elastic or purely viscous), we also need to choose a rheology. We primarily use an Andrade rheology as our main rheology because it appears to be a better fit to observations [11], although we also sometimes include the simpler Maxwell rheology for comparison.

Figure 1 shows k_2/Q for a few very simple models, and the dotted lines indicate the frequency at which each model has $k_2/Q = 3 \times 10^{-6}$. Although those models are very simple, with just one or two layers and no melt, they already illustrate the fact that NSR can happen at a variety of timescales and depends strongly on Io's internal structure. In addition, it illustrates why an Andrade rheology is likely closer to reality than a Maxwell rheology – Andrade models' shallower slope at high frequencies allows much less exotic structures to fit Io's observed orbital evolution ([11] explore this more).

If a magma ocean is present that can decouple the shell from the interior, which is plausible for Io, the situation will likely be very different. We intend to explore models that include a magma ocean, and anticipate they will sample a very different range of timescales for NSR. The degree to which elastic deformation of the lid (assuming it is unfractured) reduces the NSR rate [13] will also be examined.

Comparison to Io: If the offset of Io's volcanoes from their expected location is caused by NSR, the NSR timescale must be similar to the volcano building timescale. The volcano building timescale is a major unknown that will require substantial work, but a first approximation is to compare the system to Hawaii, another place where silicate volcanoes are being offset from their source region. Simple physical models and ages from drill cores suggest Hawaiian volcanoes have a lifetime on the order of 1 Myr [14], so we take that very approximate timescale to be the timescale of interest for Io. This is also comparable to the estimated surface age of Io, which is ∼1 Myr [15].

We plan to run a suite of models in order to determine which potential Io structures would give rise to 1 Myr NSR. In particular, the Keck Institute for Space Studies report on Io [16] identified four major potential Io interiors, and we will determine the implications for NSR for each model. For instance, the lower bound on NSR period of 4 kyr [3] may allow us to rule some models out.

Conclusions: Despite the slow pace of NSR, it can have important effects: producing large stresses at the surface [17]; disrupting expected crater spatial distributions [4]; and displacing tidal heating and melt production from their expected locations. By comparing future spacecraft (e.g. IVO) observations with Galileo images, it may be possible to determine Io's NSR rate. By understanding the rotational history of Io, we can better understand its interior and its behavior. In addition, there are other bodies which could experience important NSR, including Europa [3] and highly irradiated exoplanets. A better understanding of planetary NSR will allow us to better understand these bodies and their pasts.

References : [1] Goldreich, 1966, *AJ* [2] Greenberg & Weidenschilling, 1984, *Icarus* [3] Hoppa et al., 1999, *Icarus* [4] Zahnle et al., 2001, *Icarus* [5] Hamilton et al., 2013, *EPSL* [6] Correia et al., 2014, *A&A* [7] Wisdom & Meyer, 2016, *Cel. Mech. & Dyn. Astr.* [8] Lainey et al., 2009, *Nature* [9] Moore, 2003, *JGR:P* [10] Tyler et al., 2015, *ApJ* [11] Bierson & Nimmo, 2016, *JGR:P* [12] Sabadini & Vermeersen, 2004, *Springer* [13] Goldreich & Mitchell, 2010, *Icarus* [14] DePaolo & Stolper, 1996, *JGR:SE* [15] Schenk et al., 2004, *Jupiter: The Planet, Satellites and Magnetosphere* [16] de Kleer et al., 2019, *Keck Inst. for Space Stud.* [17] Wahr et al., 2006, *JGR:P*.