THE ROTATION OF MERCURY EXPLAINED

Benoît Noyelles[1], Julien Frouard[2], Valeri Makarov[3] & Michael Efroimsky[3]
benoit.noyelles@unamur.be, frouard@imcce.fr, {valeri.makarov,michael.efroimsky}@usno.navy.mil
1: NAmur Center for Complex Systems (naXys), Department of Mathematics, University of Namur, Belgium
2: Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA), Northwestern University, Evanston, IL, USA
3: United States Naval Observatory, Washington, DC, USA

The rotation of Mercury is a unique case in the Solar System since this planet is locked into a 3:2 spin-orbit resonance, its rotational period being exactly two thirds of the orbital one. In this study, we simulate the despinning of Mercury, with or without a fluid core, and with a frequency-dependent tidal model employed. The tidal model is based on the Darwin-Kaula expansion for the torque, and incorporates the viscoelastic (Maxwell) rebound at low forcing frequencies and a predominantly inelastic (Andrade) creep of the mantle at higher frequencies. It is combined with a statistically relevant set of histories of Mercury's eccentricity. As was suggested by Makarov (2012), the tidal model has a dramatic influence on the behaviour of spin histories near spin-orbit resonances. Specifically, the probabilities of capture into high-order resonances are greatly enhanced, suggesting a swift entrapment within less than 20 Myr, which was well before differentiation. Exploring several possible scenarios, we arrive at a conclusion that, most probably, the present 3:2 spin state was achieved by entrapment of an initially prograde cold Mercury.

The rotation of Mercury

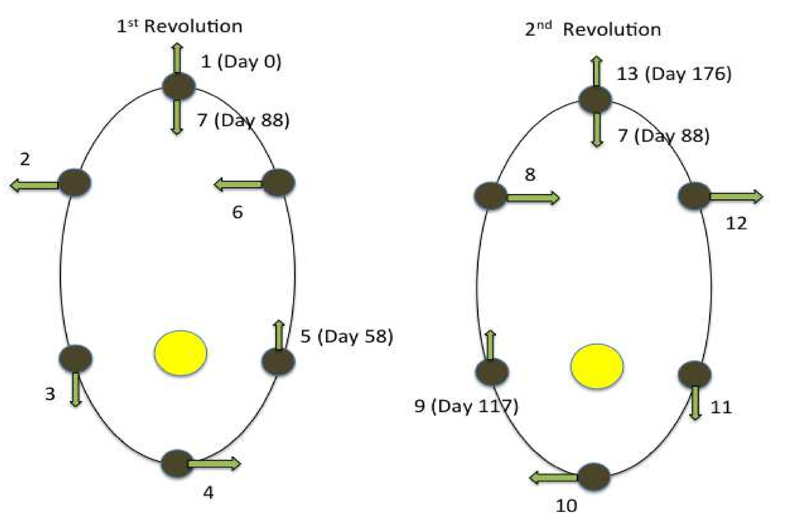

FIGURE 1: The resonant rotation of Mercury.

The existing literature: 3 scenarios

1. **A prograde rigid Mercury** Probability of capture into the 3:2 spin-orbit resonance is $\approx 7\%$ [4] with a constant eccentricity (≈ 0.206), $\approx 55\%$ if we consider the secular variations of eccentricities inducing multiple crossings [1]
2. **A prograde Mercury with a liquid core** Mercury likely to be trapped into the 2:1 resonance instead of the current 3:2 [8, 2]
3. **A Mercury once in synchronous rotation** [9] considered that the asymmetric distribution of impact craters was the signature of a past synchronous rotation, destabilized by an impact.

These scenarios use the Constant Time Lag (CTL) tidal model, which can not be applied to terrestrial planets of considerable viscosities. A mathematical consequence of that model is a *stable state of pseudosynchronous rotation*

$$\dot{\theta} = n + 6ne^2 + \frac{3}{8}ne^4 + \mathcal{O}(e^6),$$

on which the previous studies are based. We propose to revisit them in using a realistic tidal model.

The central point: a realistic tidal model

This tidal torque is a combination of the Maxwell model at low frequencies and Andrade at higher frequencies:

$$\mathcal{T}_{tide} \approx \frac{3}{2}\frac{GM_{☼}^2}{a}\left(\frac{R}{a}\right)^5 \sum_{j,q=-\infty}^{\infty} G_{20q}(e)G_{20j}(e)k_2\sin\epsilon_2\cos\left[(q-j)\mathcal{M}\right]$$

where $k_2\sin\epsilon_2$ depends on the tidal frequency $\chi_{2m0q} = |\omega_{2m0q}| \approx (2+q)n - m\dot{\theta}$ with

$$k_2\sin\epsilon_2 = \frac{3}{2}\frac{-A_2\mathcal{I}[\bar{J}(\chi)]}{\left(\mathcal{R}[\bar{J}(\chi)]+A_2\right)^2 + \left(\mathcal{I}[\bar{J}(\chi)]\right)^2}Sgn(\omega_{2m0q}),$$

$$A_2 = \frac{57\mu}{8\pi G\rho^2R^2},$$

$$\mathcal{R}[\bar{J}(\chi)] = 1 + (\chi\tau_A)^{-\alpha}\cos\left(\frac{\alpha\pi}{2}\right)\Gamma(\alpha+1),$$

$$\mathcal{I}[\bar{J}(\chi)] = -(\chi\tau_M) - (\chi\tau_A)^{-\alpha}\sin\left(\frac{\alpha\pi}{2}\right)\Gamma(\alpha+1),$$

and

- τ_A, τ_M: Andrade and Maxwell times,
- μ: unrelaxed rigidity,
- $[\bar{J}(\chi)]$: complex compliance,
- α: Andrade parameter (≈ 0.2).

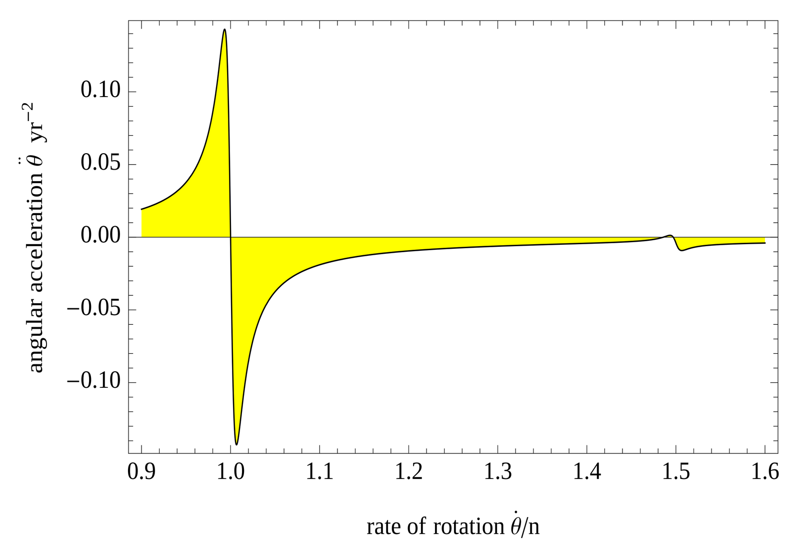

FIGURE 2: Frequency-dependence of the tidal torque. This kink shape strongly enhances the probabilities of capture.

Scenario 1: A prograde rigid Mercury

We revisit the despinning of Mercury in considering the secular eccentricity variations.

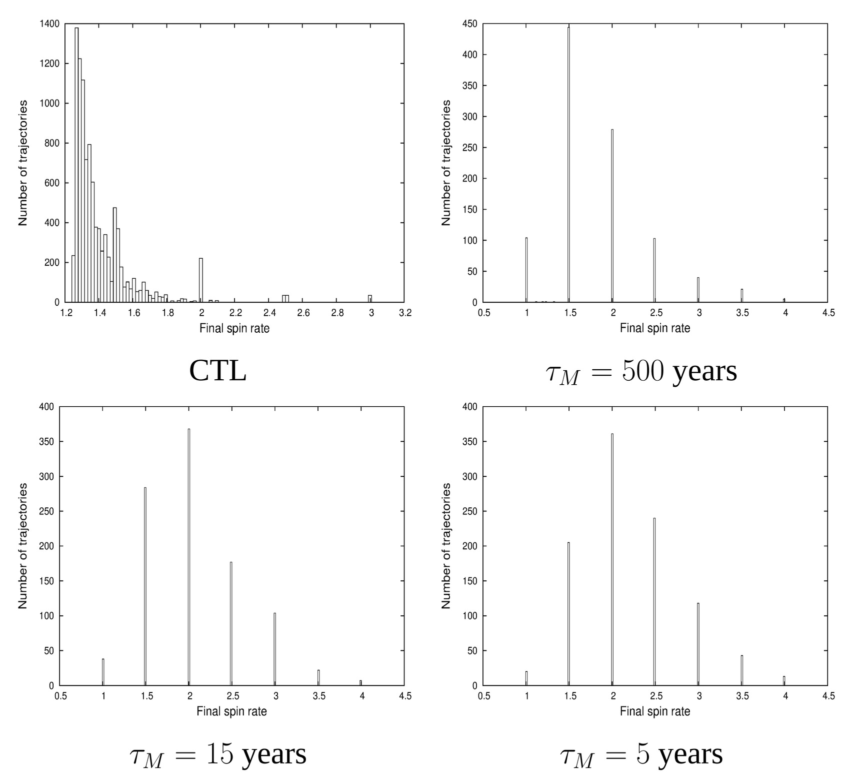

FIGURE 3: How the realistic tidal model and the Maxwell time τ_M affects the probability of capture. A long τ_M corresponds to a cold Mercury.

The consequence of our tidal model is that Mercury is usually trapped into the 3:2 resonance during its first crossing. Moreover, the absence of a stable pseudo-synchronous rotation makes several crossings impossible, and if Mercury is not trapped into the high order resonances, then it falls into the synchronous one. We also see that a pretty hot Mercury (short Maxwell time τ_M) is more likely to fall into the 2:1 resonance than into the current 3:2.

Scenario 2: A prograde Mercury with a core

We also considered a differentiated Mercury in including core-mantle friction following [5]:

$$\ddot{\gamma}_m = -\omega_0^2\,\sin 2\gamma_m + \frac{\langle\mathcal{T}_z^{(\mathrm{TIDE})}\rangle}{C_m} - \frac{k}{C_m}\left(\dot{\gamma}_m - \dot{\gamma}_c\right)\;,$$

$$\ddot{\gamma}_c = \frac{k}{C_c}\left(\dot{\gamma}_m - \dot{\gamma}_c\right)\;,$$

with

$$\gamma \equiv \theta - \left(1 + \frac{q'}{2}\right)\mathcal{M}.$$

We find that the 2:1 resonance is certain for the current eccentricity (0.206), so for the current configuration to be possible, the eccentricity of Mercury should have been pretty low.

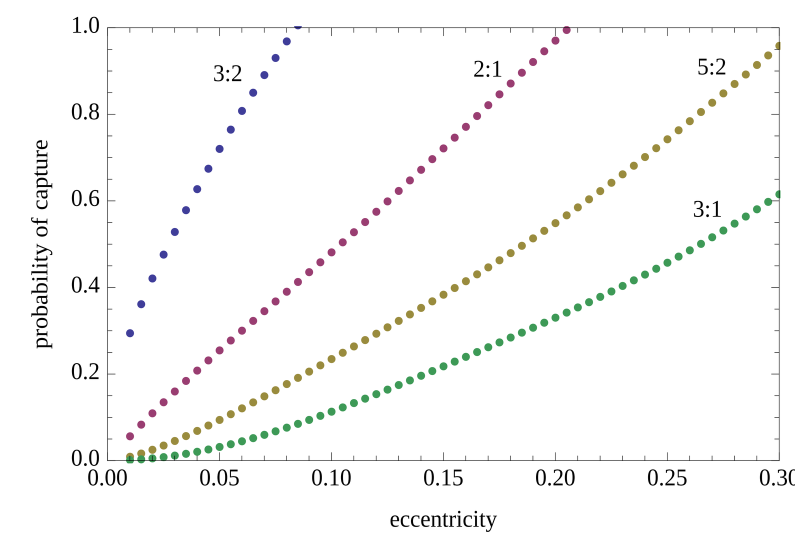

FIGURE 4: Probability of capture including core-mantle friction versus the eccentricity.

Scenario 3: If Mercury was synchronous

The distribution of craters, following MESSENGER data [3], suggests an East-West assymmetry, that could be consistent with a past synchronous rotation.

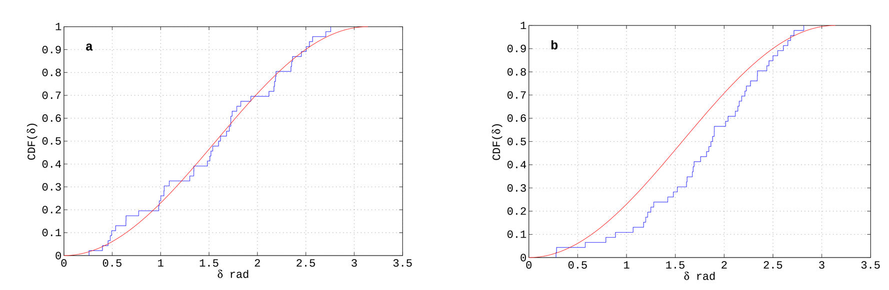

FIGURE 5: Sample CDF (broken line) and expected population CDF (smooth line) of angular distances of large and confidently detected impact craters on the surface of Mercury from (a) the presumably subsolar direction and (b) East direction.

However, the absence of pseudosynchronous stable rotation requires the impact to be energetic enough to make Mercury reach the 3:2 resonance. This implies a crater bigger than 600 km, while the use of the CTL model requires only a crater of 300 km.

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Conclusion

The Scenario 1 of an initially prograde and cold Mercury is the most likely to result in the current 3:2 spin-orbit resonance. The capture would have thus occured in less than 20 Myr.

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