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Revisiting the capture of Mercury into its 3:2 spin-orbit resonance

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Abstract. We simulate the despinning of Mercury, with or without a fluid core, and with a frequency-dependent tidal model employed. The tidal model incorporates the viscoelastic (Maxwell) rebound at low frequencies and a predominantly inelastic (Andrade) creep at higher frequencies. It is combined with a statistically relevant set of histories of Mercury's eccentricity. The tidal model has a dramatic influence on the behaviour of spin histories near spin-orbit resonances. The probabilities of capture into high-order resonances are greatly enhanced. Exploring several scenarios, we conclude that the present 3:2 spin state was achieved by entrapment of an initially prograde cold Mercury when its age was less than 20 Myr, i.e., well before differentiation.

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1. Previous studies

In the literature hitherto, three scenarios of Mercury's entrapment have been discussed.

(*a*) *A prograde rigid Mercury.* The probability of capture into the 3:2 spin-orbit state is ≈ 7%, with a constant eccentricity ≈ 0.206, see Goldreich & Peale (1966). The probability increases to ≈ 55% due to multiple crossings induced by secular variations of the eccentricity, see Correia & Laskar (2004).

(*b*) *A prograde Mercury with a liquid core.* Within this scenario, Mercury was more likely to be trapped into the 2:1 resonance than into the 3:2 one, as demonstrated by Peale & Boss (1977), Correia & Laskar (2009).

(*c*) *A Mercury once synchronised.* Wieczorek *et al.* (2012) argued that the allegedly asymmetric distribution of impact craters was the signature of a past synchronous rotation destabilised later by an impact.

All these scenarios rely on the CTL (*Constant Time Lag*) tidal model, which cannot be applied to terrestrial planets of considerable viscosities. Among the mathematical consequences of that model is a *stable state of pseudosynchronous rotation* on which the previous studies are based. We revisit these scenarios, using a physics-based tidal model.

2. A more realistic tidal model

At low obliquities, the polar tidal torque reads as (Noyelles *et al.* (2014))

$$\mathcal{T}_{tide} \approx \frac{3}{2}\frac{GM_{\odot}^2}{a}\left(\frac{R}{a}\right)^5 \sum_{j,q=-\infty}^{\infty} G_{20q}(e)G_{20j}(e)k_2 \sin\epsilon_2 \cos\left[(q-j)\mathcal{M}\right]. \qquad (2.1)$$

$\mathcal{M}$ and $n \equiv \dot{\mathcal{M}}$ are the mean anomaly and mean motion; θ and $\dot{\theta}$ are the rotational angle and spin rate of the planet; $k_2 \sin\epsilon_2$ is a function the Fourier mode $\omega_{2m0q} \approx (2+q)n - m\dot{\theta}$. Its shape is determined by the planet's self-gravitation and rheology. Viscoelastic (Maxwell) at low frequencies, the rheology comprises both viscoelastic and inelastic reaction (Andrade creep) at higher frequencies (Efroimsky(2012)).

Kink-shaped, the quality function $k_2(\omega_{2m0q}) \sin\epsilon_2(\omega_{2m0q})$ goes continuously through zero in the resonance $\omega_{2m0q} = 0$. With all terms expressed as functions of $\dot{\theta}$, the series (2.1) is a superposition of kinks. Employment of this torque radically changes the entrapment probabilities and excludes pseudosynchronism, see Makarov & Efroimsky(2013).

3. Scenario 1: A prograde rigid Mercury

As soon as our tidal model is used, Mercury almost always gets trapped into the 3:2 resonance *on the first crossing*. Moreover, the absence of a stable pseudosynchronous rotation makes several crossings impossible. So, if Mercury is not trapped into a high-order resonance, it falls into the synchronous one. A hot Mercury (with a short Maxwell time τ_M) is more likely to fall into the 2:1 resonance than into the current 3:2.

4. Scenario 2: A prograde Mercury with a core

We also considered a differentiated Mercury with core-mantle friction, following Goldreich & Peale (1967). When our tidal model is used, the 2:1 resonance is certain for the current eccentricity (0.206). Only a past low eccentricity or a collision disrupting the 2:1 resonance (Correia & Laskar (2012)) could have made the current configuration possible.

5. Scenario 3: A once synchronous Mercury

The distribution of craters, according to the MESSENGER data (Fassett *et al.* (2012)), suggests an East-West asymmetry consistent with a past synchronous rotation. However, the absence of pseudosynchronous stable rotation requires the impact to be energetic enough to make Mercury reach the 3:2 resonance. This would leave a crater larger than 600 km, while the use of the CTL model would require only a crater of 300 km. For a detailed critical analysis of this scenario, see Noyelles *et al.* (2014).

6. Conclusion

Within the Scenario 1 of an initially prograde cold Mercury, the 3:2 resonance is the likeliest end state. The capture takes place in less than 20 Myr, well before differentiation.

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