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 \(\approx 7\%\), with a constant eccentricity \(\approx 0.206\), see Goldreich & Peale (1966). The probability increases to \(\approx 55\%\) 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))

\[
T_{\text{tide}} \approx \frac{3}{2} \frac{GM^{2}}{a} \left( \frac{R}{a} \right)^{5} \sum_{j,q=-\infty}^{\infty} G_{20q}(e)G_{20j}(e)k_{2} \sin \epsilon_{2} \cos [(q-j)\mathcal{M}]. \tag{2.1}
\]
and \( M \) are the mean anomaly and mean motion; \( \theta \) and \( \dot{\theta} \) are the rotational angle and spin rate of the planet; \( k_2 \sin \epsilon_2 \) is a function the Fourier mode \( \omega_{2m_0q} \approx (2 + q)n - m\dot{\theta} \). 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 \( k_2(\omega_{2m_0q}) \sin \epsilon_2(\omega_{2m_0q}) \) goes continuously through zero in the resonance \( \omega_{2m_0q} = 0 \). 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 higher order resonance, it falls into the synchronous one. A hot Mercury (with a short Maxwell time \( \tau_M \)) 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.

References

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