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Spin–orbit evolution of Mercury revisited

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ABSTRACT

Although it is accepted that the significant eccentricity of Mercury (0.206) favours entrapment into the 3:2 spin–orbit resonance, open are the questions of how and when the capture took place. A recent work by Makarov (Makarov, V.V. [2012]. Astrophys. J., 752, 73) has proven that trapping into this state is certain for eccentricities larger than 0.2, provided we use a realistic tidal model based on the Darwin–Kaula expansion of the tidal torque.

While in Ibid. a Mercury-like planet had its eccentricity fixed, we take into account its evolution. To that end, a family of possible histories of the eccentricity is generated, based on synthetic time evolution consistent with the expected statistics of the distribution of eccentricity. We employ a model of tidal friction, which takes into account both the rheology and self-gravitation of the planet.

As opposed to the commonly used constant time lag (CTL) and constant phase lag (CPL) models, the physics-based tidal model changes dramatically the statistics of the possible final spin states. First, we discover that after only one encounter with the spin–orbit 3:2 resonance this resonance becomes the most probable end-state. Second, if a capture into this (or any other) resonance takes place, the capture becomes final, several crossings of the same state being forbidden by our model. Third, within our model the trapping of Mercury happens much faster than previously believed: for most histories, 10–20 Myr are sufficient. Fourth, even a weak laminar friction between the solid mantle and a molten core would most likely result in a capture in the 2:1 or even higher resonance, which is confirmed both semi-analytically and by limited numerical simulations.

So the principal novelty of our paper is that the 3:2 end-state is more ancient than the same end-state obtained when the constant time lag model is employed. The swift capture justifies our treatment of Mercury as a homogeneous, unstratified body whose liquid core had not yet formed by the time of trapping.

We also provide a critical analysis of the hypothesis by Wieczorek et al. (Wieczorek, M.A., Correia, A.C.M., Le Feuvre, M., Laskar, J., Rambaux, N. [2012]. Nat. Geosci., 5, 18–21) that the early Mercury might had been retrograde, whereafter it synchronised its spin and then accelerated it to the 3:2 resonance. Accurate processing of the available data on cratering does not support that hypothesis, while the employment of a realistic rheology invalidates a key element of the hypothesis, an intermediate pseudo-synchronous state needed to spin-up to the 3:2 resonance.

1. Motivation and plan

Half a century ago, radar observations determined the mercurian spin period to be $\approx$58 days (Pettengill and Dyce, 1965), which corresponds to a 3:2 spin–orbit resonance. A later study (Margot et al., 2007) revealed that the orientation of Mercury's spin axis is consistent with the Cassini State 1 (Colombo, 1965), the obliquity being $2.04 \pm 0.08'$ (Margot et al., 2012).

This raised the question: how had Mercury been trapped into this resonance? A consensus exists that the high eccentricity of Mercury (currently $e \approx 0.206$) favours the trapping by widening the resonance. At the same time, there is a cleavage in opinion on whether the 3:2 resonance was the most likely end-state of Mercury's spin–orbit evolution.

The first work on the despinning of Mercury was published by Goldreich and Peale (1966). They obtained a 7% probability for the capture into the 3:2 resonance, assuming that the eccentricity of Mercury has always had its present value, and that the tidal

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torque has obeyed the MacDonald (1964) model. Some 40 years later, Correia and Laskar (2004) explored a chaotic evolution of Mercury's eccentricity, showing that repetitive episodes of eccentricity increases could have boosted the probability of entrapment in the 3:2 resonance to 55%.

A more complete study, though, should include a large fluid core. Keeping the eccentricity constant, Peale and Boss (1977a) explained that the core–mantle friction could have significantly enhanced the 3:2 capture probability, provided that Mercury had not been trapped into the 2:1 resonance prior to that. Correia and Laskar (2009) revisited the problem, with the core included, and suggested that the eccentricity of Mercury might have been very low in the past, lowering drastically the probability of an early capture into the 2:1 resonance, and making a later trapping into the 3:2 spin state almost certain. Both works by Correia and Laskar (2004, 2009) were based on the CTL (constant time lag) tidal model.

Wieczorek et al. (2012) hypothesised that Mercury had initially been retrograde, evolving later to synchronism. Correia and Laskar (2012) achieved the synchronism from an initially prograde rotation. Then this resonance could have been destabilised by a huge impact driving Mercury into a state of stable pseudosynchronous rotation maintained by a significant eccentricity, before falling into the 3:2 resonance. The stability of pseudosynchronous spin depends on the applicability of the CTL model.

Unfortunately, neither the MacDonald nor the CTL models are compatible with the properties of telluric bodies (Efroimsky, 2012a).[1] A study based on a more realistic tidal response was undertaken recently by Makarov (2012) for a uniform Mercury analogue. The study demonstrated that entrapment in the 3:2 resonance is inevitable at eccentricities between 0.2 and 0.41, without invoking a core–mantle friction or eccentricity variation.

We continue this line of research, for realistic histories of the eccentricity. In Section 2, we overview the preceding studies. Section 3 deals with the triaxiality-generated torque. Section 4 presents an expression for the tidal torque, with a special emphasis on how an essentially arbitrary rheology should enter that expression. Section 5 addresses the despinning timescale. In Section 6, we compute histories of Mercury's eccentricity. Section 7 describes our numerical method. We test it by reproducing the results by Correia and Laskar (2004).

In Section 8, we apply our method to a homogeneous, originally prograde Mercury, and demonstrate that its likeliest end-state is 3:2. For a cold early Mercury (with the Maxwell time $\tau_M = 500\,\mathrm{yr}$), it is reached in less than 20 Myr. For a warmer Mercury (with lower values of τ_M), it is reached in less than 10 Myr. This justifies the homogeneity assumption, because heating-up and differentiation takes up to a billion of years (see Appendix A). Despite this, to make our study complete, in Section 9 we explore the despinning of an initially prograde Mercury with a liquid core. In this case, even a moderate friction in the core–mantle boundary boosts the probabilities of capture into the 3:2 and higher resonances. For example, with the present value of Mercury's eccentricity, entrapment into the 2:1 resonance becomes certain (while trapping in the 5:2 resonance becomes more probable than traversing it). Therefore, had Mercury been hot and differentiated soon after its creation, its despinning all the way to the 3:2 state would be highly unlikely. In Section 10, we provide a critical analysis of the hypothesis by Wieczorek et al. (2012) that the early Mercury might had been retrograde, whereafter it synchronised and then accelerated its spin to the 3:2 resonance. Accurate processing of the available data on cratering does not support that hypothesis; while the employment of a realistic rheology invalidates a key element of that hypothesis, an intermediate pseudosynchronous state needed to spin-up to the 3:2 resonance. So that hypothesis has to be abandoned. Finally, in Section 10 we draw conclusions.

This paper is an extremely squeezed version of a more comprehensive work (Noyelles et al., 2013) to which we refer here and there for details and derivations.

[1] Besides this, the MacDonald model is inherently inconsistent (Williams and Efroimsky, 2012; Efroimsky and Makarov, 2013) and cannot be used even in theoretical studies.

2. Scenarios of Mercury's spin–orbit evolution. An overview

Consider a planet of a mean radius R, mass M_{planet} and the principal moments of inertia $A < B < C$. Assume that the spin of the planet is directed along its major-inertia axis z, the one related to the maximal moment of inertia C. The sidereal angle θ of the planet can be reckoned from the line of apsides to the largest-elongation axis x, the one related to the minimal moment of inertia A, as in Fig. 1. The star exerts two torques on the planet. One, $\vec{\mathcal{T}}^{(TRI)}$, is due to the planet's permanent triaxiality. Another, $\vec{\mathcal{T}}^{(TIDE)}$, is caused by the tidal deformation of the planet. Rotation of the planet about its major-inertia axis z is then governed by the torques' polar components. Expressing the maximal moment of inertia as $C = \xi M_{planet} R^2$, we write the equation of motion as

$$\ddot{\theta} = \frac{\mathcal{T}_z^{(\mathrm{TRI})} + \mathcal{T}_z^{(\mathrm{TIDE})}}{C} = \frac{\mathcal{T}_z^{(\mathrm{TRI})} + \mathcal{T}_z^{(\mathrm{TIDE})}}{\xi M_{planet} R^2}. \quad (1)$$

The value of ξ reflects the degree of inhomogeneity. While for a homogeneous sphere $\xi = 0.4$, for Mercury it is known to be 0.346 ± 0.014 (Margot et al., 2012; Noyelles and Lhotka, 2013). The fact that $\xi < 0.4$ indicates that the inner part of Mercury is denser than its outer part.

This equation governs the spin history. The outcome also depends on the initial conditions and on disruptive events. Three options have been discussed in the literature hitherto.

2.1. Option 1: Spin-down of a homogeneous Mercury

Suppose Mercury was captured when it was yet homogeneous, and its liquid core was formed afterwards. Simplistic, this approach is convenient mathematically, wherefore it was used in the pioneer works. The first such investigation was undertaken by Goldreich and Peale (1966) who assumed that the initially spin was prograde

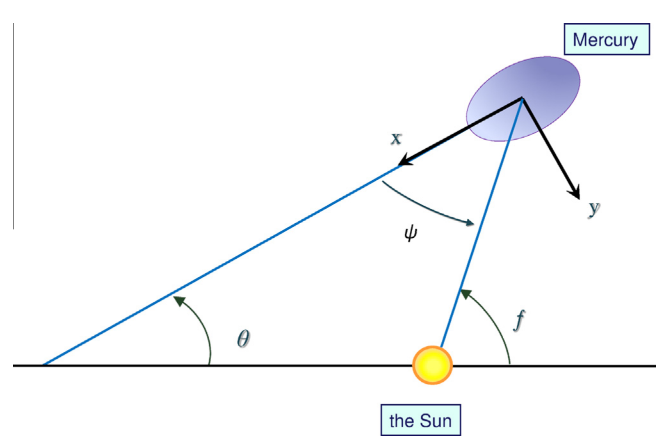

Fig. 1. The principal axes x and y of the planet correspond to the minimal and middle moments of inertia, respectively. The horizontal line is that of apsides, so f is the true anomaly. In neglect of the apsidal precession, θ is the sidereal angle of the planet. The angle $\psi = f - \theta$ renders the separation between the planetocentric direction towards the star and the minimal-inertia axis x.