**EVOLUTION OF MERCURY'S OBLIQUITY.** Marie Yseboodt, Jean-Luc Margot, Cornell University, Department of Astronomy, Cornell University, Ithaca, NY 14853, (mariey@astro.cornell.edu).

**State of Mercury's Core and Peale's experiment:** Mercury is in a 3:2 spin-orbit resonance between the rotation period and the revolution period. With the assumption of a Cassini state, Peale (1976, 2002) has shown that the knowledge of the second degree coefficients of the gravity field, the 88-day libration amplitude, and the obliquity can be used to determine the size and state of the Hermean core. While the 88-day libration amplitude and $C_{22}$ gravitational harmonic are sufficient to distinguish a molten core from a solid core, the combination of all four quantities above is needed to evaluate the moment of inertia factor $C/MR^2$ and the ratio between the mantle moment of inertia and the total moment of inertia $C_m/C$. The latter quantity with assumptions on mantle and core densities can be used to constrain the size of the core. Therefore knowing the obliquity is important to infer the radius of Mercury's core. We investigate the value of the obliquity and its time evolution with a combination of analytical and numerical work.

One of the goals of both the Messenger and Bepi-Colombo missions is to determine these quantities (gravity field, libration, obliquity) for Mercury. Earth-based radar data can also be useful to determine the libration amplitude and the instantaneous spin orientation.

**Rotational motions:** If Mercury is in a Cassini state, its spin axis, orbit normal and normal to the Laplacian plane will be coplanar.

If for some reason, Mercury is displaced slightly from the Cassini equilibrium, the planet will oscillate around it and some free motions will appear (Peale 2004). These free modes can be a libration in longitude (period of about 16 years) and a precession of the spin about the Cassini state (about 1066 year period, D'Hoedt and Lemaitre 2004, Rambaux and Bois 2004). A free libration in longitude would not affect the obliquity nor the ability to distinguish a molten from a solid core. But a free precession would change the obliquity value and therefore the ability to determine the radius of the core using Peale's experiment.

Peale (2004) examined the free rotational motions of Mercury and derived damping timescales that are much shorter than the age of the solar system. Therefore any deviation from the Cassini state would imply a recent excitation mechanism. Rambaux and Bois (2004) have suggested the possibility that planetary perturbations cause obliquity variations.

**The Hamiltonian method:** One can study Mercury's spin-orbit motion using an Hamiltonian approach. D'Hoedt and Lemaitre (2004) obtain Hamilton's equations using canonical transformations and Andoyer's and Delaunay's variables which represent the rotation and revolution variables, respectively. The main hypotheses involved are principal axis rotation, a gravity field with only second degree terms, and no planetary perturbations. An asymmetrical planet is considered, all the perturbations with period equal or smaller to the revolution period (88 days) are neglected, and there are neither tides nor damping. For this problem with two degrees of freedom, D'Hoedt and Lemaitre (2004) have shown that the analytical method gives values of two proper frequencies that are in agreement with the numerical results of Rambaux and Bois (2004).

**The obliquity and the effect of the planetary perturbations on Mercury's orbit:** The generalized Cassini laws apply to the case where Mercury's orbit is not fixed in space but is rotating with a constant velocity and a constant inclination around the invariable plane. According to those laws, the obliquity between the spin axis and the orbit normal must remain constant. But due to the perturbations from the other planets, Mercury's orbit has a complex motion with a superposition of different frequencies.

Rambaux and Bois (2004) find through numerical integrations that include the effects of the planets that Mercury's obliquity is not constant with time. The authors find variations of a few arcminutes around a mean value of about 1.6 amin at a proper frequency of 1066 years.

In order to test the effects of the planets, we have included in the previous Hamiltonian formulation the perturbations of the 8 planets on Mercury's orbit with a simplified form (secular potential, see for example Murray and Dermott 2000). The time evolution of the spin-orbit variables can be found by numerically integrating the equations of motion.

**The evolution of the rotation variables:** In the simplest case involving no planetary perturbations, the equilibrium values found with the Hamiltonian formalism correspond to the Cassini states with a fixed obliquity as already shown by D'Hoedt and Lemaitre

(2004). We also reproduce the values of the two proper frequencies for similar assumptions on the moments of inertia.

When planetary perturbations are introduced, our results show oscillations in obliquity at the 1000-year proper frequency. The mean obliquity and the amplitude of the oscillations are sensitive to initial conditions and are on the order of a minute of arc.

A poor choice of initial conditions or sudden onset of perturbations could result in the inadvertent introduction of obliquity variations, e.g. in the form of a free precession. In order to rule out this possibility, we investigated different sets of initial conditions and turned on planetary perturbations smoothly by gradually increasing the masses of the perturbers. We find that obliquity variations are present in every case. Moreover, the amplitude of the oscillations depends on the perturber masses.

We also turned off planetary perturbations by reducing the perturber masses to zero and found that the obliquity variations disappear. As there is no mechanism for damping free motions in our formalism, this suggests that the oscillations in obliquity are forced by the external perturbers.

A varying obliquity impacts the determination of Mercury's internal structure. Future work will include the determination of the set of initial conditions that are compatible with existing obliquity measurements, and the study of obliquity time variations with those initial conditions.

**References:**

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