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Long-term rotational stability of terrestrial planets with viscoelastic lithospheres: Theory and application to Martian True Polar Wander (TPW)

Kimberly Moore (1), Ngai-Ham Chan (2), Amy Daradich (3), and Jerry Mitrovica (1)

(1) Department of Earth & Planetary Sciences, Harvard University, Cambridge, United States (kimberlymoore@g.harvard.edu), (2) Department of Earth & Planetary Sciences, McGill University, Montreal, PQ, Canada , (3) Department of Earth Sciences, University of Ottawa, Ottawa, ON, Canada

The long-term rotational stability of terrestrial planets is a classic problem in geophysics and planetary science. Modern theoretical treatments date to Gold (1955) and Goldreich & Toomre (1969), who argued that the rotation axis orientation of terrestrial planets is inherently unstable since any stabilization due to the rotational bulge is transient. Willemann (1984) and Matsuyama et al. (2006) extended this work, showing that an elastic lithosphere acts to resist TPW through stresses induced in the lithosphere by reorientation. Thus the presence of an elastic lithosphere can strongly dampen the magnitude of load-induced TPW. The above studies were based on equilibrium stability theories that describe only the final state of the rotation axis. Other studies (e.g., Ricard et al., 1993; Tsai & Stevenson, 2007; Harada, 2012; Chan et al., 2014) have developed methods for modeling the time dependence of TPW.

We build on this earlier work to derive a new theory for time-dependent TPW on terrestrial planets with viscoelastic lithospheres. In this case, on short timescales, polar motion is resisted by a strong lithosphere (the Willemann and Matsuyama case); but on long time scales, the lithosphere relaxes and the rotation axis becomes unstable (the Gold case). We highlight our theory by applying it to load-induced TPW on Mars. First, we demonstrate, in contrast to previous arguments, that an equilibrium theory is inaccurate when considering load-induced TPW on Mars. Indeed, for sufficiently high, but plausible values of lithospheric viscosity, surface loading can induce TPW that persists for billions of years. Second, we consider the possible range of TPW driven by the development of the massive Tharsis volcanic province that does not violate constraints imposed by the present day figure of Mars. We show, once again in contrast to some previous arguments, that this range permits the large angle (> 50 degrees) TPW inferred in previous studies on the basis of Martian surface features.