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Reorientation Histories of Mercury, Venus, the Moon, and Mars

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Abstract

The spins of planets are not stagnant with time; they continuously evolve in response to both internal and external forces. One mechanism for changing the spin of a planet is true polar wander (TPW). TPW is the reorientation of the bulk planet due to some redistribution of mass on, or within, the planet. This processes can have important consequences for the climate, tectonics, and geophysics of the planet. Yet, despite its potential importance, it has been difficult to constrain the TPW histories of solar system worlds beyond the Earth. In this work, we present the first comprehensive, data-driven investigations into the reorientation histories of the terrestrial worlds: Mercury, Moon, Venus, and Mars. The technique utilizes the high resolution global gravity fields now available for these worlds. The methodology developed here is completely general, and can be applied to future investigations of other solar system worlds (e.g. ocean worlds).

1. Introduction

The dynamics of a planet's spin is controlled by the planet's inertia tensor. In a minimum energy rotation state, planets spin about the maximum principal axis of inertia. Yet, the magnitudes and orientation of these principal axes of inertia are not always constant with time. The redistribution of mass within the planet due to both interior processes (e.g. mantle convection) and surface processes (e.g. extrusive volcanism and impacts) can significantly alter the planet's inertia tensor, resulting in the reorientation of the planet with respect to its principal axes of inertia. This form of reorientation is known as true polar wander (TPW).

TPW can have dramatic implications for the geology of a planet. For example, TPW can change insolation geometry, altering climate and volatile stability; generate tectonic stresses; and modify the planet's magnetic field. Yet, despite its significance, the TPW histories of most solar objects are not well constrained. Here, we present the first systematic, data-driven investigation of TPW of the terrestrial worlds: Mercury, Venus, Moon, and Mars.

2. Methods

The orientation of a planet is controlled by the differences by the non-spherically symmetric component of the planet's inertia tensor. This non-spherically symmetric component can be directly related to a planet's spherical harmonic degree and order 2 gravity field (1). It is often assumed that the majority of a planet's degree-2 gravity field (and shape for that matter) arise from the combination of tidal and rotational deformation. This tidal and rotational deformation can have contributions both from the present-day tidal and rotational potential (often referred to as the "hydrostatic" figure), and from a past tidal and rotational potential that has been preserved by the presence of an elastic lithosphere (often referred to as the "fossil" or "remnant" figure). While tidal and rotational deformation often dominate the degree-2 gravity field of a planet, they are not the only important factor. Impact basins, volcanoes, and other smaller-scale geologic structures (henceforth, "mass anomalies") can contaminate the degree-2 gravity field—and thus the inertia tensor—of a planet.

We have developed a technique for using higher resolution gravity data to isolate the contribution of mass anomalies to the degree-2 gravity field of solar system objects (2). Most large mass anomalies (e.g. impact basins) are axisymmetric at long-wavelength. We model their gravity fields using a linear combination of concentric, uniform density spherical caps. The gravity anomaly of these caps scales linearly with the single (scalar) surface density of each cap. For each mass anomaly, we determine the best fitting linear combination of surface densities for each spherical cap. We perform these fits from spherical harmonic degree and order 3 and above, in order to prevent directly fitting any underlying tidal and rotational figure. Since the spherical harmonic gravity coefficients of a spherical cap scale linearly with the surface density of the cap, we can determine the degree-2 contribution by scaling the analytically-derived degree-2 gravity coefficients of the cap by the best-fit surface density determined from fitting higher degrees and orders. The inertia tensor perturbations arising from each mass anomaly can then be determined (1).

3. Results

Thanks to many robotic exploration missions, we now have sufficiently high resolution gravity data to perform this reorientation for a variety of solar system worlds, including Mercury, Venus, Moon, and Mars. Preliminary TPW chronologies for these terrestrial worlds are shown in Figure 1. In these chronologies, we use perform our mass anomaly fitting routine outlined above, and sequentially remove the inertia tensor perturbations of major mass anomalies from the present-day, non-hydrostatic inertia tensor of each planet. The chronologies are relative, and are not well constrained on many worlds. This technique is only capable of constraining reorientations driven by mass anomalies that are preserved in the present-day gravity fields of these worlds.

The reorientation histories for the Moon and Mercury are similar. The orientation of both planets is strongly controlled by the presence of a large remnant bulge. On the Moon, this bulge is predominantly a fossil tidal and rotational bulge; on Mercury, this bulge likely has a significant thermal component, arising from Mercury's proximity to the Sun and its unique spin-orbit resonance (3). Nonetheless, large impact basins and volcanic events have significantly altered the orientation of these worlds—resulting in 10-30° of total reorientation after their formation. The South Pole-Aitken impact basin on the Moon resulted in one of the single largest reorientation events on any planet studied here. Asymmetric thermal evolution may further alter the orientation of the Moon (4).

Mars has also experienced large reorientation events, but due primarily to the formation of the hemispheric dichotomy and Tharsis volcanic rise. Large impact basins contribute less to the planet's total inertia tensor than comparably sized impact basins on the Moon and Mercury.

Venus's slow rotation results in a very small tidal and rotational bulge, making it extremely prone to dramatic reorientation events (4). Our analysis of the inertia tensor perturbations of Venus's large volcanic provinces seems to agree with this notion. Individual, regional volcanic provinces can reorient Venus by as much as 60°. However, the exact reorientation chronology on Venus is by far the least well constrained.

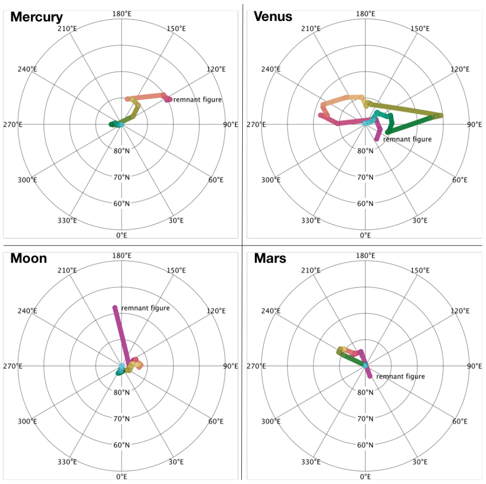
Mercury
Venus
Moon
Mars

Figure 1: Preliminary TPW chronologies for the terrestrial planets. Each point in these plots indicates the location of the spin pole after the formation of some large geologic feature, relative to the present-day coordinate system. TPW paths start at a presumed remnant figure (purple) and migrate to the present-day spin pole (blue).

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