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Equipotential surfaces and geodetic implications on formation of Martian moons

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Abstract

We determine the *normal ellipsoids* for the Martian moons, Phobos and Deimos, that closely approximate the equipotential surfaces in the respective gravity fields. We compare the normal ellipsoids with the actual shapes of the moons and discuss the implications on their formation. In particular, we revisit and explore the plausibility that the moons were formed out of the debris disk around Mars by material accretion under self-gravity.

1. Introduction

The Martian moons, Phobos and Deimos, are in distinct, near-circular orbits around Mars [1]. Both are tidally locked and thus rotate synchronously in their respective orbits around Mars. There has been ongoing, vigorous discussion about the origins of the moons. They may have been extraneous objects captured by the martian gravitation during chance encounters [2]; alternatively, they may have accreted *in situ* out of debris disk after impacts or tidal break-ups of asteroids [3, 4], a process that might occur repeatedly [5]. Studying the origins and evolution of the moons could cast light on the formation of the entire Martian system or that of any planetary system in general.

2. Method for deriving normal ellipsoid

Phobos is subject to significant tidal forces comparable to gravitation and centrifugal forces in magnitude. Deimos' orbit is at a greater distance and not as strongly influenced by tidal forces as Phobos. We are interested in the equipotential surfaces of both irregular-shaped moons, where the gravity potential is constant. For instance, $W = W_0$ where W_0 corresponds to the average potential over the surface of the body. The equipotential surface indicates an idealized, equilibrium form that may or may not be close to the actual shape of the body. Specifically, we derive an ellipsoidal approximation of the equipotential surface, defined as the "normal ellipsoid" of the object. We split the gravity potential into a regular, dominant component, U, arising from the ellipsoidicity (e.g., polar and equatorial flattenings) of the attracting body, and small higher frequency disturbances, δW, such as

$$W = U + \delta W. \tag{1}$$

Thus, U is attributed to the gravity potential of the normal ellipsoid.

For Phobos and Deimos whose shapes are moderately irregular (e.g., overall convex without global concavities), it is reasonable and practical to model their gravitational fields by ellipsoidal harmonic series which yield reliable performance close to the surface [6, 7]. We apply an iterative approach to search for the normal ellipsoid such that the following conditions are satisfied: (A) $U = W_0$ and fully accounts for field variations up to degree two on the normal ellipsoid; (B) δW only appears from degree three or higher degrees [7].

3. Result

The method has been applied to deriving the normal ellipsoid of Phobos. Using the shape model presented in [8] and assuming homogeneous density for the body [9], the average gravity potential on the surface of Phobos is found as $W_0 = 67.57 \ \mathrm{m^2 s^{-2}}$. The normal ellipsoid of Phobos has three semi-axes of 14.70, 10.58, and 8.94 km, thus notably elongated from its actual shape. The elongation of the normal ellipsoid occurs in the direction towards Mars (which lies along the x axis, see Fig. 1), evidently due to tidal effects. Meanwhile, the elongation concurs with a contraction of the normal ellipsoid along the transverse plane from the actual shape of Phobos (near $x = 0$, Fig. 1c). We

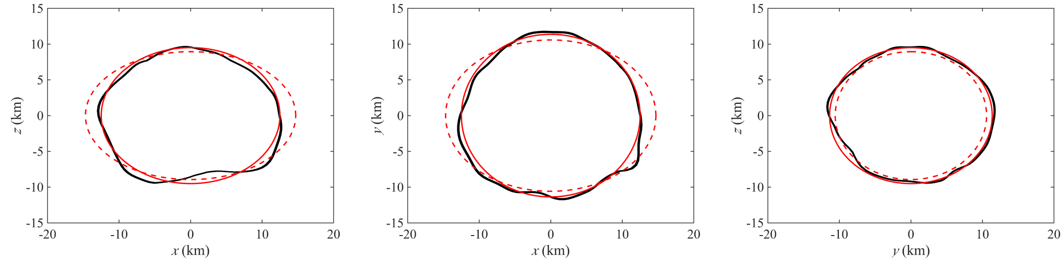

Figure 1: Projections of the normal ellipsoid in comparison with those of the actual shape of Phobos [8]. The shape of Phobos is indicated by the solid black lines. The normal ellipsoid is indicated by the red lines. The dashed and solid lines correspond to the tidally elongated and tide-free ellipsoids, respectively. This figure is adapted from Fig. 7 in [7].

also derived the normal ellipsoid of Phobos in a tide-free environment, with semi-axes of 12.49, 11.38, and 9.50 km, that corresponds to a slightly reduced surface potential of $66.48\ \mathrm{m^2s^{-2}}$. The shape of Phobos undulates more evenly about its equilibrium figure in the absence of tidal effects (Fig. 1).

4. Summary and outlook

That the current shape of Phobos differs notably from an equipotential surface corroborates that it is subject to tidal deformation in the future, the signs of which are perhaps already present [10, 11]. On the other hand, that Phobos would be close to equilibrium in an otherwise tide-free environment alludes to its formation dominated by gravitational aggregation [12], producing a porous rubble-piled structure with low bulk density [3, 4].

Work is being carried out to derive the normal ellipsoid of Deimos, which resides in a higher orbit of about 23500 km from (the center of) Mars and, thus, subject to less pronounced tidal effect.

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