GEOPHYSICAL CONSTRAINTS ON PHOBOS'S INTERIOR STRUCTURE.

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Introduction. Phobos is the innermost satellite of Mars and is locked in a 1:1 spin-orbit resonance. Its response to Martian tides is one of the principal sources of information about the interior of the satellite since the tidal response of a body is determined to first order by its internal properties (e.g., rigidity and density). In this study, we focus on the tidal bulge height as a possible means of determining the interior structure of Phobos. We compute the gravitational potential and tidal deformation of the satellite for a series of possible models of its interior structure with a focus on locating regions of maximum displacement so as to configure a potential orbiter-satellite system for optimal return. For this purpose, we solve, on the one hand, the full three-dimensional (3-D) elastostatic problem on the deformed body to determine the displacement field and, on the other hand, Poisson's equation for the gravitational potential. Our approach relies on the higher-order spectral-element method [1,2] and a recently developed extension to the waveform modelling package Salvus [3]. We investigate the possibility of distinguishing between first-order models in the form of homogeneous, ice-rock mixtures, and layered models using currently available observations that include the degree-2 gravitational coefficients and the libration in longitude in addition to the aforementioned tidal displacement field.

Models of Phobos's interior structure. Here, we focus on three models that encompass a large part of the models considered in previous research [4, 5] and that satisfy the basic constraints of mass and volume [6, 7]. The models include:

- a homogeneous model;
- ice-rock mixtures with ice fractions of 38% and 57%;
- layered models characterized by increasing density and elastic properties with depth.

For all these models, geophysical predictions of the longitudal libration magnitude, degree-2 gravity coefficients, and moment of inertia (MoIs) tensor were computed.

Results. Based on tens of simulations, the surface displacement patterns among the models belonging to the same class, i.e., ice-rock and layered, were found to be similar. Here we provide only the figures with results for a homogeneous Phobos (Fig.1).

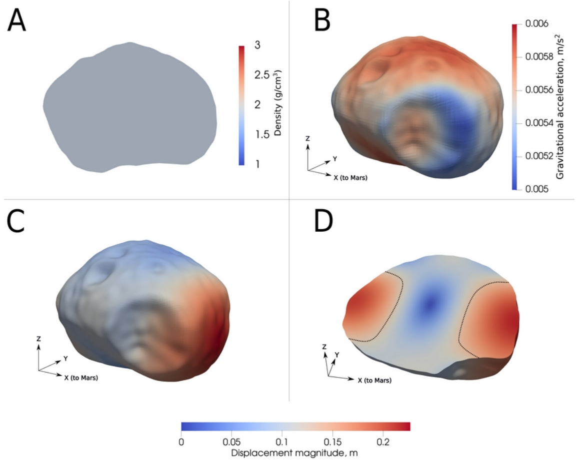

Figure 1: Three-dimensional modeling results for a homogeneous Phobos (A). (B) Surface gravity; (C) surface tidal displacement field; (D) interior tidal displacement field. Shear modulus is 0.01 Gpa.

Surface gravity: Computed surface gravity (**g**) across the body is shown in Fig. 1B and is seen to be relatively consistent across all models. The largest **g** occurs at the North and South poles, since the latter are closest to the center of the satellite, whereas the smallest **g** is located on the Eastern rim of Stickney crater (furthest from the center).

Tidal deformation: The surface tidal deformation is depicted in Fig.1C. The hemispheres opposite to and facing Mars experience, as expected, the largest radial deformation. The location of maximum radial deformation shifts from the center of the Mars-facing hemisphere (homogeneous and ice-rock) toward the rim of the Stickney crater closest to the sub-Mars point on Phobos for the layered model. To better understand the deformation behaviour for a wider range of μ (ρ has a smaller impact on the deformation and is ignored in the following), we varied μ for all models between 10^{-3} and 10 GPa and recomputed the tidal deformation for each of the "new" models. The results of this experiment are summarised in Fig. 2, which shows the maximum deformation experienced by the body as a function of effective μ. For comparison, we also plot the response of a spherically symmetric model of Phobos. The observations we can make from this figure are the following: maximum tidal deformation for all models increases exponentially with decreasing rigidity; the response of homogeneous Phobos (blue line), but including proper shape, is slightly larger than that of a homogeneous spherical model of Phobos. The other 3D models (stars and inverted triangles) are located around the response line of homogeneous Phobos and vary slightly with μ_{eff} because of the averaging scheme applied.

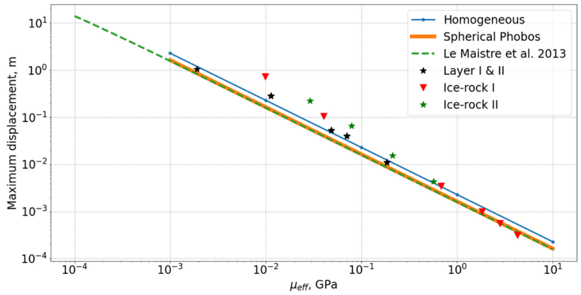

Figure 2: Relationship between rigidity of various one- and three-dimensional Phobos models and surface tidal deformation. For the one-dimensional and homogeneous Phobos models, μ_{eff} equals bulk μ.

Geophysical predictions: The computed libration magnitude, which ultimately depends on the principal MoIs and therefore density distribution, is similar for all considered models, and in good agreement with the observed values of [8, 9, 10]. This implies that from libration magnitude only, it is currently not possible to distinguish between the various interior structure models; yet other models with local density anomalies can result in larger variations of libration magnitude [5]. The 2-degree gravity coefficients reflect the radial distribution of mass in the interior of the satellite. The results for the models are mostly located outside of the error bounds of the current observations, which is probably caused by the value of the libration magnitude used for the numerical integration [11].

Conclusions. According to our results, the most promising means for inferring interior structure, in particular a solid core, is through measurements of the surface deformation, preferably along the equator. For this particular configuration, the largest deformation occurs toward the rim of the Stickney crater. This is a robust signal that is expected for a layered interior and in combination with the determination of the degree-2 gravity coefficients should provide a relatively reliable detection of a solid core. Failure to detect this Stickney crater-related signal would indicate either of two possibilities: 1) a more rigid satellite or 2) a porous or rubble aggregate moon.

Based on our modeling, we have seen that tidal surface deformation measurements on Phobos is an important source of information to constrain the effective shear modulus of the body. If we assume rigidities similar to those of Martian regolith simulants (0.01-0.1 GPa) [12], then the tidal deformation amplitude can be tens of centimeters to 1 m, if μ is an order of magnitude smaller (cf. Fig. 2).

Comparison of geophysical predictions with current observations have shown that it is generally difficult to discriminate between homogeneous models and ice-rock mixtures given current uncertainties. Degree-2 gravity coefficients and MoIs, on the other hand, appear to provide a first-order means of differentiating layered models from the other two families.

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