IMPACT OF ANELASTICITY ON MARS' DISSIPATIVE PROPERTIES – APPLICATION TO THE *INSIGHT* MISSION.
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Introduction: We revisit the interpretation of Mars' dissipation factor inferred from the secular acceleration of Phobos. The low value of that parameter has been interpreted as evidence for the existence of a highly dissipative region within Mars' mantle or crust.

While previous approaches have relied on the assumption that Mars' mantle behavior can be described by a viscoelastic model (Maxwell body), experimental data indicate that the anelastic motion of defects is the major mechanism driving dissipation in silicates at the 5.5 hr period of the forcing exerted by Phobos. We demonstrate that material anelasticity is likely responsible for the observed dissipation factor and deemphasize the need for a highly dissipation region proposed for explaining the observed dissipation. We extend this analysis to a broad frequency range relevant to the RISE and SEIS experiments planned as part of the *InSight* mission.

Background: Constraints on planetary interiors can be inferred from their response to tidal stress through the tidal Love number k_2 and dissipation factor Q, both of which are functions of the tidal forcing period. Mars is one of the very few objects whose tidal response has been determined at different periods. Measurement of the Solar tides on Mars from Mars Global Surveyor has led to the discovery of a large liquid iron core in the planet [1]. The secular acceleration of Phobos has been attributed to dissipation within Mars in response to the tide raised by its moon. Different methods used for tracking that secular acceleration have led to an accurate estimate of Mars' k_2/Q at the forcing period of 5.5 hrs (see [2] for a review). We denote that property as k_2^{pho}/Q^{pho}. The dissipation factor inferred from that measurement is relativey small, about 80 if one takes k_2^{pho} ~0.152 [e.g., 3]. That small dissipation factor value has been interpreted as the signature of partial melt in the Martian mantle, or of an enrichment in volatiles [e.g., 4, 5]. However, an anomalously low mantle viscosity and/or the presence of partial melt in the mantle are not supported by thermal models [6-8]. In fact, these models [4, 5] are based on the assumption that Mars behaves as a Maxwell body, a theoretical model that is not supported by laboratory measurements [e.g., 9, 10].

On the other hand, several studies [7, 11] considered alternative approaches (constant frequency band and Burgers) that yield mean mantle viscosities at least two orders of magnitude greater than the value yielded by the Maxwell model. Building on these pioneering studies, we implement an experimentally constrained model that accounts for the anelasticity of silicate material. That property is found a major contribution to dissipation at the period of the forcing exerted by Phobos. This problem bears important implications because, as illustrated above, a weak zone may be diagnostic of increased water content or of anomalous heating. Better constraining the source of the dissipation would also help to understand its frequency-dependence and predict the long-term evolution of Phobos.

Attenuation Models: Material attenuation is a complex phenomenon determined by the density, geometry, and mobility of defects in the material [e.g., 10]. The most commonly reported model fitting microcreep and forced oscillations experiments of silicates is the the Andrade model [12-14]. Per analogy with Earth, Mars' mantle deformation is believed to deform in the dislocation creep regime, and this even at the low stress exerted by Phobos. Attenuation measurements of silicate materials deformed in that regime at a forcing period of a few hours [e.g., 15] are consistent with the general description of the Andrade model. That model associates a Maxwell element representing material viscoelasticity and a term describing the complexity of the relaxation spectrum when the material is deforming in the anelastic regime:

$$J(\chi)=\frac{1}{\mu}-\frac{i}{\eta\chi}+\beta(i\chi)^{-\alpha}\Gamma(1+\alpha)$$

where χ is the angular forcing frequency, μ the material unrelaxed shear modulus, η its steady-state creep, and Γ is the Gamma function. The anelastic response is described by a parameter α that represents the degree of heterogeneity of the material [16] but remains to be parameterized, and β, a function of the density of defects, is related to the viscoelastic properties of the material [9].

Modeling Approach: We model the interior of Mars following the approach considered in previous studies [4, 11] assuming that the primary source of dissipation stems from the mantle. The liquid core is not considered a major source of dissipation, at first order. The contribution of the elastic crust to the global dissipation budget of the planet is negligible.

As a first step to approaching the problem, we have computed Mars' k_2^{pho}/Q^{pho} with the Andrade model for a structure including a solid inner core, a liquid core layer, a mantle, and crust (consistent with the observed moment of inertia, and Mars' k_2 measured at the orbital period. We range the viscosity in the mantle over a relevant range from 10^{12} to 10^{22} Pa s and searched for the range of mantle viscosities that can explain the observed k_2^{pho}/Q^{pho} (Figure 1).

The response of the interior structure to an external potential is computed from the numerical integration of spherical oscillations over a multilayered structure following the approach introduced by [18]. Stresses and strains are functions of radial equations that represent the transfer functions of stress within the object as a function of the complex compliance of each layer.

Results and Discussion: In the case of the Maxwell model, the observed k_2^{pho}/Q^{pho} can be fitted by a mantle viscosity of ~2×10^{16} Pa s (Fig. 1). If one accounts for the attenuation due to anelasticity, then the average mantle viscosity required to explain k_2^{pho}/Q^{pho} is now between 10^{18} and 10^{22} Pa s. The uncertainty is due to the broad range of values for the parameter α considered in this study. Indirect constraints on the value of that parameter suggest it is to 0.15-0.2 [19, 20]. Further study is needed in order to better understand the dependence of α on the intrinsic properties of silicate material. However, we note that that lower bound corresponds to a mean mantle viscosity of 10^{22} Pa s, which in turn suggests an average mantle temperature of ~1700 K, assuming dry olivine [21] and is consistent with geophysical evolution models [e.g., 8].

In summary, although our results support the idea that Mars' mantle is relatively cold, consistently with geological observations. In the continuation of this work we will compute the attenuation spectrum of Mars for a broad range of input parameters and in the prospect of the SEIS and RISE experiments proposed as part of the *InSight* mission (under review).

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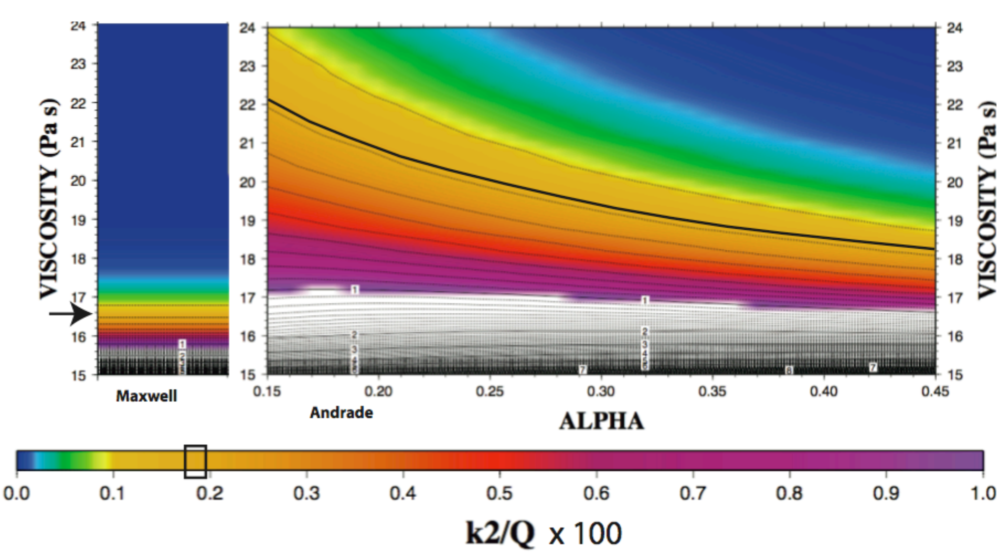

Figure 1. k_2^{pho}/Q^{pho} for two different dissipation models, Maxwell and Andrade, as a function of the viscosity assumed for Mars' mantle and the Andrade parameter α. This model includes a core radius of 1700 km, an inner solid core of 1100 km, and a crust thickness of 50 km, consistent with the observed moment of inertia [7].