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Tidal Disruption of Phobos as Cause of Surface Fractures

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Abstract

Phobos displays an extensive system of grooves that are mostly symmetric about its sub-Mars point. The ~20 km diameter satellite is spiraling in due to the tides it raises. It will undergo tidal disruption [1, 2] before crashing into Mars in tens of millions of years [3]. We compute the tidal evolution of the de-orbiting satellite and show that most of its prominent grooves have excellent correlation with the resulting stress in a thin elastic shell. The model requires a very weak interior (rubble pile) overlain by a somewhat cohesive exterior (~1 MPa), similar to interpretations [4] of comet 67P/C-G and consistent with the predicted behavior of microgravity regolith [5, 6, 7].

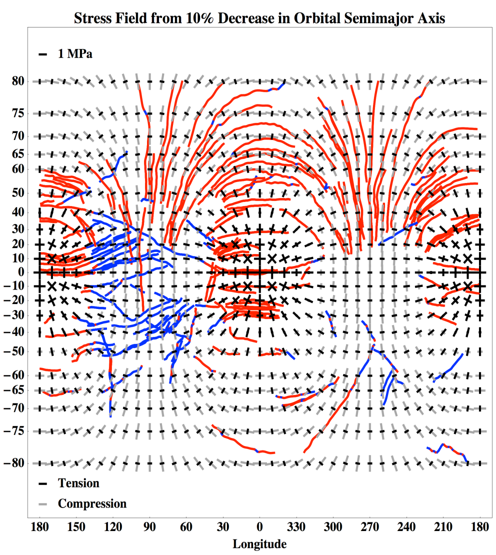

Figure 1. Stresses in a 10 m elastic shell computed for the last 10% of orbital decay (Fig. 2) for a spherical Phobos with much weaker interior. Stresses are in tension radial to the tidal bulge (0° and 180°) and in compression concentric to it; both axes are in tension near the bulge. Most observed grooves experience tensile stress across their strike (red); anomalous grooves (blue; mostly in leading hemisphere) require a different mode or time of origin.

Methods

Shortly after Viking obtained the first geomorphic images of Phobos, it was proposed [8] that stresses from orbital decay cause grooves. The idea proved unworkable in the context of a homogeneous spheroid. We apply a two-layer stress model [9] with ρ_{av}=1.88 g/cm^3, inner rigidity $\mu=10^6$ Pa, and outer rigidity $\mu=10^{10}$ Pa in a 10 m thick shell. As the satellite de-orbits, the tidal deformation increases, resulting in a growing surface stress that we compute using a spherical thin shell approximation [10, 11].

We then mapped ~200 of the most prominent linear features on Phobos. Using the latitude, longitude and strike for multiple points along these fractures, we calculated: the principal tidal stress experienced along their tracks, the orbital decay stress parallel and perpendicular to each fracture, and the shear stress across each fracture. The magnitudes of the computed stresses, and the correlation between principal stress orientations and the azimuths of observed fractures, provide the critical tests of the tidal fracturing model.

For a range of parameters where a weak Phobos is overlain by a more rigid surface layer, we obtain (Figure 1) a strong correlation between the surface stress field due to orbital decay and the geometry of grooves. Orbital decay from 3.04 to 2.77 R_{mars} can produce >1 MPa of surface tensile stress (Figure 2). The majority of grooves (red) align with the local tensile stress, indicating that they could have formed (or are forming) by tensile failure of the surface.

Tidally-aligned grooves are absent S/SE of the sub-Mars point. This might be attributed to the absence of a cohesive surface layer in this location (nothing to record the strain), or to structural collapse or impact reverberation. In our model, fracture walls are weak (~1 MPa) and only strong in comparison to the rubble pile interior. Non-aligned grooves (blue) require an alternative explanation. They could have formed earlier when Phobos was in a different tidally locked orientation [12]. The are found predominately in the leading hemisphere, perhaps consistent with the idea that Phobos swept up co-orbiting debris [e.g., 13]. By quantifying the grooves according to their goodness of fit to the tidal stress, we set the stage for comparative geomorphic analysis, that awaits higher definition imaging of Phobos.

A weak interior with an elastic shell is more commonly associated with terrestrial planets and icy moons than with small bodies. But another such body is the Jupiter family comet 67P/C-G, which has regional-scale strength of tens of Pa based on cliff heights [4], and a surface strength >4 MPa based on Philae lander operations [14]. For a presumably refractory body like Phobos, instead of considering surface ice we note that a thin outer layer of powdery regolith may be more coherent than a blocky interior due to intergranular forces [5, 6, 7]. Our calculations, taken alongside surface observations, support the hypothesis that Phobos has a weak interior (rubble pile) overlain by meters of fine regolith, and that the regolith is developing fissures as the global body deforms due to increasing tides. This is consistent with thermal inertia [15] that indicates the surface or Phobos is fine powder to >~0.1-1 m depth.

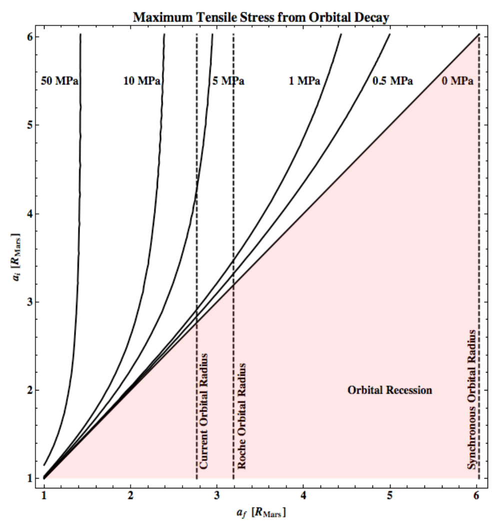

Figure 2. The maximum tensile stress experienced on Phobos for various amounts of orbital decay, from an orbital distance a_i to a_f. Significant stresses could be generated early in Phobos' history, allowing for several generations of surface fractures to evolve.

Discussion

Just because Phobos is fracturing in a thin surface layer does not mean its catastrophic disruption is imminent. A friction angle ~3° is sufficient to prevent downslope movement even in the absence of cohesion [2]. It just means that the interior is weak enough to permit tidal deformation and build up fracture stresses in an outer shell. The deformation computed from Phobos' orbital decay leads to a surface stress field closely aligned with most of the observed grooves. More detailed study by an orbiter or lander will provide better constraints on the satellite's past and near-term geologic evolution, and its suitability for human exploration given what may be an active and evolving surface.

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