The effect of rotation rate and semi-major axis on the efficacy of thermal stress weathering.
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Introduction: Terrestrial geomorphologists have debated the importance of thermal stress weathering, the mechanical breakdown of rock from changes in temperature, for decades. In a famous review paper, [1] concluded that there was insufficient evidence to determine if the process operated at all. Another oft-cited study [2] found that cracks could only be induced through thermal cycling if the heated samples were cooled with water. Thus the idea that thermally induced cracks could form without the presence of water was abandoned for some time. Thermal cycling was still pursued, however, by the materials science community. Richter and Simmons [3] found experimentally that heating igneous rocks to temperatures >620 K or at rates >2 K/min generated immediate macroscopic cracks. A series of field studies [e.g. 4, 5, 6] recorded rates of temperature change of rock surfaces in hyper-arid environments far in excess of 2 K/min, and suggest that thermal stress weathering could play a key role in processes such as exfoliation, large crack formation, and granular disintegration. Though it is not well constrained, this threshold is now typically quoted as a requirement for thermally-induced damage.

On a microphysical, level cracks caused by thermal stresses form both due to thermal gradients and mismatches in the thermal expansion coefficient in adjacent mineral grains. The adoption of the 2K/min threshold presumes that the required spatial temperature gradients caused by these rapid changes in surface temperature are large enough to form a crack. In reality, this threshold is not well understood or constrained and will vary with rock type, size, and amount of pre-existing damage [7]. Many studies argue that the conditions necessary for this process to operate without water simply do not exist on Earth [e.g. 8]. Bodies with little or no atmosphere, however, provide perhaps the environment most conducive to thermal weathering as surface rocks can heat and cool at greater rates and over a greater temperature range than on Earth. Bodies such as asteroids also have very fast spin rates, making their surfaces even more susceptible to high rates of temperature change, as well as increasing the frequency of thermal cycling. Dombard et al. [9] attributed smooth ponds of material found on the asteroid Eros to breakdown of boulders by thermal fatigue (Fig 1), and Viles et al. [10] showed that only modest temperature cycles are required to cause fatigue on Mars.

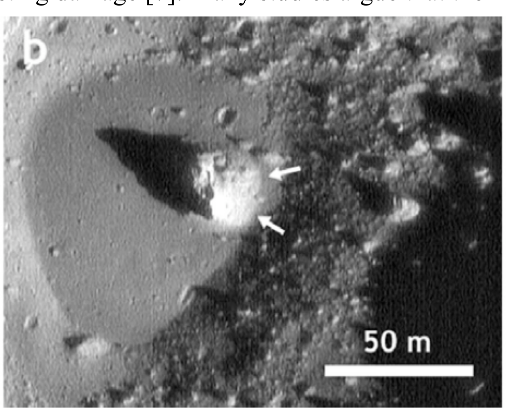

Figure 1. Ponds of smooth material on Eros are found in topographic lows. Boulders, often with surrounding debris aprons (arrows) are commonly embedded in this smooth material (from Dombard et al. 2010).

Thermal Model: While no studies have been done that attempt to actually quantify how much damage may be caused as a result of sudden temperature changes, looking at rates of temperature change on these bodies will indicate how susceptible to this process they may be. Using a 1-D heat conduction model [11], we have shown that, for a range of rock face slopes, aspect angles and latitudes, surfaces on Mercury and the Moon attain only modest rates of temperature change during sunrise and sunset. Maximum values of dT/dt for both bodies were ~0.5 K/min, on highly sloped surfaces facing east or west (Fig 2). Rates of surface temperature change are highest at the equator and decrease with increasing latitude.

We have also shown that sudden shadowing and illumination on some rock faces on Mercury and the Moon can yield rates of temperature change on the order of 50 K/min and 10 K/min, respectively, assuming the sun acts as a point source (Fig 3D). The same tests, but including the effect of the size of the solar disk, predict dT/dt values on the order of 1 K/min (Fig 3C) indicating that a body's rotation rate and distance from the sun will likely play a large role in the effectiveness of thermal weathering on its surface. Comparing these two parameters (Fig 4) shows that many bodies that are within ~0.6 AU of the sun and that have a day length of less than ~10 Earth days have rock surfaces that experience dT/dt values larger than the 2 K/min threshold.

Conclusions and Future Work: Our preliminary model results indicate east and west facing, steeply sloped surfaces are most susceptible to high rates of temperature change on Mercury and the Moon, and that thermal shocks from sudden shadowing increases these rates. Shocks experienced during sunrise and sunset were comparable on both bodies, but higher temperatures mean that shocks from daytime shadowing were much more dramatic on Mercury than the Moon. In this study we will use the model described above to explore how rates of temperature change vary with body rotation rate, semi-major axis, and obliquity by modeling surface temperatures of several near earth asteroids. A study of the sensitivity of temperature change to a wide range of parameters will allow us to explore which inner solar system bodies are likely to be most susceptible to thermal stress weathering.

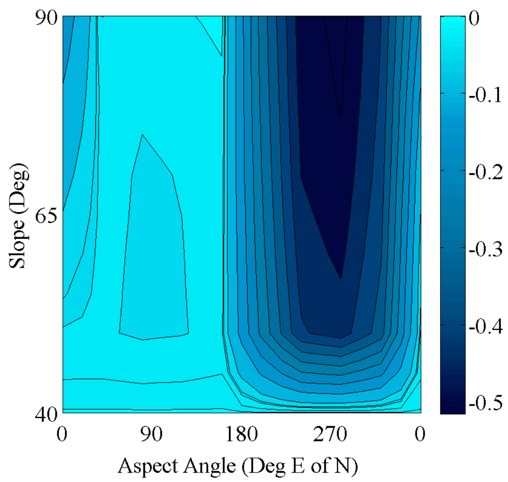

Figure 2. Contour plot of minimum calculated dT/dt values experienced by rock surfaces at the equator of Mercury with a range of slopes (y-axis) and aspect angles (x-axis). The colorbar has units of K/min.

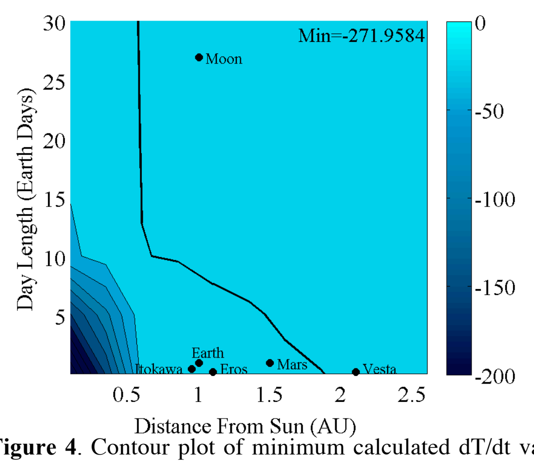

Figure 4. Contour plot of minimum calculated dT/dt values experienced by a West-facing rock surface with a slope of 90 degrees at the equator of a bodies with varying distance from the sun (x-axis) and day length (y-axis). The colorbar has units of K/min. The bold line corresponds to -2 K/min, and the other contour lines are at intervals of -20 K/min. Several solar system bodies are shown on the plot according to their day lengths and semi-major axes.

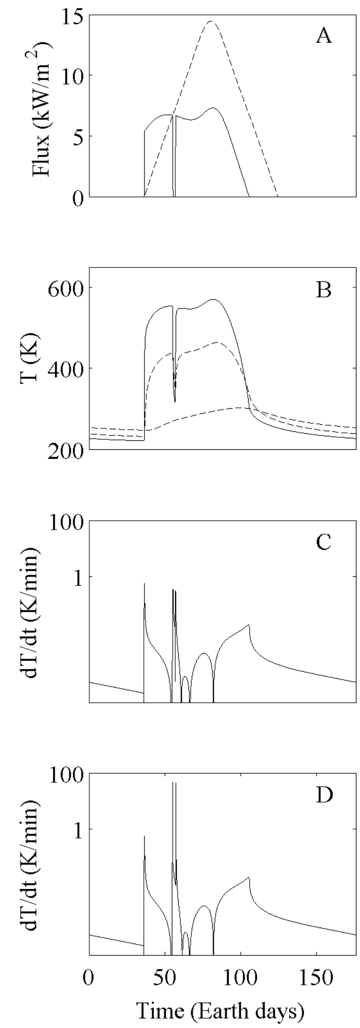

Figure 3. A) The solar flux incident upon a surface at the equator on Mercury (at a hot pole) with a slope of 60 deg and an aspect of 80 deg (E of N), with corresponding B) surface temperature and rate of change in temperature caused by a C) soft-edged and D) hard-edged shadow. Both (C) and (D) are semi-log plots. The dashed lines are (A) the solar flux that would be incident on flat ground and (B) the temperature at 0.25 and 2 m depth. In this test, an artificial shadow was introduced in the morning (at t~60 Earth Days).

References: [1] Griggs D. T. (1936) *J. Geology, 44,* 783-796. [2] Blackwelder E. (1933) *Am. J. Sci., 26,* 97-113. [3] Rickter D. and Simmons G. (1974) *Int. J. Rock Mechanics, 11,* 403-411. [4] Hall K. (1999) *Geomorph., 31,* 47-63. [5] Hall K. and Andre M. F. (2010) *Geomorph., 41,* 23-35. [6] Molaro J. L. and McKay C. P. (2010) *Earth Surf. Proc. Landforms, 35,* 501-507. [7] Bahr H. A. et al. (1986) *J. of Mat. Sci., 21, 2716-2720.* [8] Moores J. E. et al. (2008) *Geomorph., 102,* 472-481. [9] Dombard A. J. et al. (2010) *Icarus, 210,* 713-721. [10] Viles H. et al. (2010) *Geoph. Res. Letters, 37,* L18201. [11] Molaro J. L. and Byrne S. (2010) *EPSC-DPS2011,* Abstract #560.