Introduction: Thermal stress weathering (thermal fracture) is the mechanical breakdown of a rock from expansion and contraction caused by changes in temperature. Together with aeolian, fluvial, and chemical weathering, it plays a role in the evolution of Earth’s landscapes, breaking down boulders, changing rock surfaces, and generating sediment. In most Earth environments, processes such as freeze-thaw and salt weathering dominate rock breakdown [15, 2, 7]. However, in environments that lack significant amounts of water, thermal fracture plays the key role in processes such as exfoliation, large crack formation, and granular disintegration [5, 6, 11, 3, 4, 9].

The amount of damage done by thermal stress is proportional to the rate of temperature change, thus on bodies lacking atmospheres, thermal stress weathering is likely to be even more effective. The presence of an atmosphere dampens both heating and cooling rates experienced by a rock surface through both sensible heat exchange and radiative effects. During heating, the atmosphere’s optical depth limits the amount of solar flux available at ground level to heat the rock’s surface. During cooling, the atmosphere emits long wavelength radiation, providing a source of heat even while the rock is shaded. Bodies that lack atmospheres, however, experience greater rates of heating and cooling, and thus greater thermal stresses than otherwise. On bodies whose surfaces reach very high temperatures, it is possible that sudden shadowing or sudden illumination of a rock surface could yield thermal stresses great enough to cause permanent damage.

Thermal stress is typically divided into two broad categories: thermal fatigue and thermal shock. Thermal fatigue is progressive structural damage caused by thermal cycling, usually the diurnal cycle of the sun. Microscopic cracks are formed each cycle in localized regions of the rock, which over time accumulate to cause catastrophic failure [10]. Thermal shock is the formation of macroscopic cracks due to rapid changes in temperature. When temperature changes rapidly, a thermal gradient with depth is formed and different parts of the rock expand or contract by different amounts, causing immediate catastrophic failure [8]. In reality, there is a continuum of processes between these two regimes, operating at a variety of temporal and spatial scales. In addition to fatigue, thermal weathering on airless bodies likely also operates at some intermediate scale. Our model results (discussed below) suggest that thermal stresses from sudden shadowing or lighting are likely not great enough to cause immediate catastrophic failure, but enough to cause microfractures to form. Damage would be slow and progressive, leading to failure over time, and contribute to dust and regolith production, boulder breakdown, and, on a larger scale, crater degradation. Even if only a small amount of damage is incurred on a rock each day, over long periods of time this damage will accumulate. Over geologic time scales, thermal weathering could play a profound role in landscape evolution. In this study, we will examine and compare the strengths of thermal stresses caused by shadowing on airless, inner solar system bodies.

Model: High thermal stresses are not caused by large changes in temperature, but rather by rapid changes in temperature. The rate of temperature change, dT/dt, determines whether or not damage can occur. Typically (in terrestrial studies), a value of 2 °C/min is used as the threshold, above which damage is assumed to occur and below which damage is assumed not to occur [12, 4, 11, 13, 9]. While this threshold value is not well constrained and likely varies depending on rock size and properties [1, 14], it will still act as a useful approximation in order to determine whether or not thermal stress weathering is occurring on various solar system bodies.

The maximum dT/dt values for these bodies can be calculated by modeling surface temperature changes using the heat conduction equation. We built a one-dimensional heat conduction model of a single surface, with variable latitude, slope, and aspect (measured in degrees east of north-facing) angle. The surface is considered to be bare rock, free of regolith, with properties typical of basalt. We used a density of ρ=2600 kg/m^3, heat capacity of c_p= 840 J/kg, and thermal conductivity of k=2.5 W/K m. Mercury is ideal for the initial test body, due to its extremely high temperatures. Using the NAIF SPICE Toolkit [16], we calculated the solar flux over one complete insolation cycle at latitudes of 0, 45, and 85 degrees. The longitude was set so that the surface is directly facing the sun at perihelion (a “hot spot”). To simulate a sudden shadowing event, the surface was artificially shadowed for a brief period in the afternoon. The temperature was then calculated with slopes varying from 0 to 90 degrees, and aspect angles from 0 to 360 degrees. The maximum dT/dt values calculated for a complete insolation cycle, with a given set of parameters, were recorded and plotted, examples of which are shown in Figure 1. These plots allowed us to identify the optimal parameter values to cause large thermal stress shocks, ideally with dT/dt values near or greater than 2 °C/min. The shocks were separated into cold (tensional) shocks, where the temperature decreased (dT/dt<0), and hot (compressional) shocks, where the temperature increased (dT/dt>0).
**Initial Results:** The “observations” resulting from initial model runs yield a set of trends that indicate where we should expect thermal stress weathering to be most effective. Shocks near or greater than 2 °C/min were found at the equator and midlatitudes, but not at the poles. Figure 1B (midlatitude) shows a significant number of shocks greater than the threshold value, particularly for south-facing surfaces with slopes between 20 and 50 degrees. Thermal weathering is unlikely to be significant in the polar regions due to an overall low solar flux. At each latitude, cold shocks were found to be stronger than hot shocks. This is significant, as the tensile strength of a material is typically lower than the compressional strength and thus cold shocks are more effective at causing damage than hot shocks. Optimal rock slopes for non-equatorial cases were centered at ~40–50 degrees. Optimal aspect angles for cold shocks were those for which the rock was warmest when the shadowing occurred. This is intuitive, as the rock will radiate heat away most quickly the hotter it is. Optimal aspect angles for hot shocks were those for which the rock was facing the sun when the rockface emerged from shadow, thus absorbing the most amount of sunlight when lit again.

The trends resulting from the model yield a set of guidelines to begin looking for physical evidence of thermal weathering, such as differences in crater slopes, regolith depth, or boulder size on different bodies. In addition to Mercury, this process may also be occurring and relevant on the Moon and NEOs.

We will report on our findings for Mercury and other inner-solar-system bodies and discuss optimal parameters for thermal weathering, and a relative sense of efficacy and importance of this process for each body.


**Figure 1:** Contour plots of dT/dt in °C/min for the strongest cold (tensile) shocks as a function of rockface slope and aspect, at latitudes (A) 0°N with contour lines 0.1 °C/min apart, (B) 45°N with contour lines 0.3 °C/min apart, and (C) 85°N with contour lines 0.02 °C/min apart. The white dotted line corresponds to the damage threshold of -2 °C/min.