# THERMAL CYCLING ON SURFACES OF SMALL ASTEROIDS: A LAYER-TO-GRAIN APPROACH

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How “weathered”” is the surface material exposed on an asteroid’s surface? Weathering in this sense is the difference in strength properties between the outer few centimeters and sub-surface grain layers. Thermal shock may be the dominant contributor to boulder erosion and regolith development on small near-Earth asteroids (NEAs) [1]. This process may be particularly effective on small carbonaceous NEAs because of relatively rapid rotation with numerous diurnal cycles, low albedo of volatile-rich carbonaceous chondrites and differences in thermal expansion of the minerals assemblages.

Thermal peak and gradient variations are strongest at the exposed free surfaces of the asteroid’s regolith, but may significantly weaken the outer few centimeters of the grain layers in the sub-surface. We discuss our modeling of a nominal case here that addresses both the evolving properties of the surface layers and the effects of grain heating and mobility.

We consider rubble-piles with appreciable voids (including the surface, with coarse to fine regolith material, in terms of grain size distribution. This porosity affects the skin depth, through a model-derived thermal conductivity. Different models we implement approximate different medium realizations ranging from large coherent voids (2-phase plane) to randomly packed granular material (Maxwell continuous mixing). In an NEA-like orbit, the thermal skin depth determines whether deeper buried sub-surface material can experience further alteration. We look into the local thermal skin depth in the near sub-surface of an object. The orbital and physical properties of the body considered correspond to OSIRIS-Rex’s mission target 101955 Bennu [1] and the now-deceased ARM mission target, 2008 EV5 [2].

The two simulation modes are: “meso-scale”, where we model the thermal fluxes between the surface boundary conditions and the sub-surface layers with a complete thermo-physical code (solution of heat/mass transfer in a porous medium); “micro-scale”, where we model particle-particle effects in fine adjacent layers, via a DEM MD style code, which includes heat transfer and stress/strain calculations over pairwise interactions.

For the “meso-scale” approach we use our *COMET* code [3, 4]. It is a thermal-physical evolution code, with a detailed model of coupled heat and gas diffusion, through a porous matrix. We track the thermal cycles that the surface and sub-surface experience, as a function of the location on the surface, following a quasi-3D scheme. This means that we produce a latitude-longitude grid for the surface boundary conditions and calculate the radial thermal evolution of each section.

For the “micro-scale” approach we use the well-es-DEM package *LIGGGHTS* [5]. This approach treats the granular material as groupings of many discrete solid particles dispersed over a domain and interacting with each other through collisions and heat transfer.

We implemented new material definitions in the LIGGGHTS code, which represent measured physical and thermal properties of CM/CK chondritic types. We ran a suite of low-resolution cases, to examine the interplay between the shear movement, packing level and heat flux in short durations. The integration times are relatively short, representing physical time on the order of minutes, and the number of particles is small (a few 1000s). High-resolution simulations or complex geometries require a more substantial amount of CPU hours.

**Results:** As motivation for our modeling approach, we begin by considering a basic relation of thermo-elastic theory [6] - $\varepsilon \approx (\alpha/k) Q\delta$ (derived from the definition of local strain and the application of Fourier's law). $Q$ is the local heat flux, $k$ is the thermal conductivity and, $\delta \approx \Delta X$ is the length scale of the temperature gradient assuming that the thermal skin depth ($\delta$) covers the scale of the variation, $\delta \approx \Delta X$. The constitutive relation includes measured material properties (e.g., for meteorites or minerals) and factors derived from analytical or numerical calculations and depend on the environment and evolution of a given object's surface and sub-surface.

Fig. 1 shows the above relation, where the thermal strain is shown as a function of time and skin depth range. The orbital time variable determines the heliocentric distance (through the eccentric anomaly) and through that the heat flux $Q$ is determined. The skin depth variable is taken to cover the range from diurnal to orbital variations, as a function of porosity and granular packing. Sthermal strain effects would be experienced around perihelion and where the heat wave reaches deeper into the sub-surface

Our initial 2008 EV5 model includes: perihelion and aphelion distances of 0.878 and 1.038 AU, respectively, mean radius of 200 m, albedo of 0.095, rotation period of 3.725 hrs and composition analogues to C-chondrites. For the unknown (or poorly-determined) physical properties, we take nominal values and vary it within a reasonable range. For example, the nominal bulk density is taken as 1.3 g/cc (like that determined for Bennu), but varied in a range of 1.0 – 2.3 g/cc, in order to cover the range expected for small C-type asteroids and CI/CR meteorite types. We restricted our consideration to the spin pole direction referred in the ARRM BARD document, namely ecliptic long./lat. [180, -84] degrees.

Fig. 2 shows the interpolated (and smoothed) results for the thermal cycling, at a depth of 1 cm, for the considered range of densities (1.0 – 2.3 g/cc) and rock grain sizes (5 micron to 0.1 mm). The latter affects the Hertz factor (contact area between material grains relative to the cross-sectional area), which depends on the structure of the medium (assumed spherical packing). As a general trend from these results, we can say that the leading hemisphere, where higher temperatures are reached at perihelion and aphelion, experience a smaller temperature differential throughout a single orbit.

From our low-resolution and several high-resolution cases of the "micro-scale" modeling, we can conclude that a stable heat flux gradient is established quickly within unperturbed particle beds. This was found to be ~0.1 of the thermal relaxation time. For representative CM/CK meteorites, at a temperature of 200 K and a layer thickness of 10 cm, this timescale is 3-7 hours.

Movements of particle groups, which create shear strains between adjacent layers, as well as changes in the packing of particle groups, which changes the thermal conductivity, disrupt the locally-relaxed state described above. This affects also the mechanical response of these particle layers.

Thermal cycling of the bulk layer of granular material will not be disturbed on an orbital timescale (~1 year, for near-Earth asteroids). Locations the surface and the shallow sub-surface of the body, which are sensitive to diurnal effects will experience disruptions in the thermal cycling, which may increase the cracking and reduce the cohesion of the material.

**Acknowledgements:** GS thanks FSI for continued support, through SRI awards and discretionary funds.

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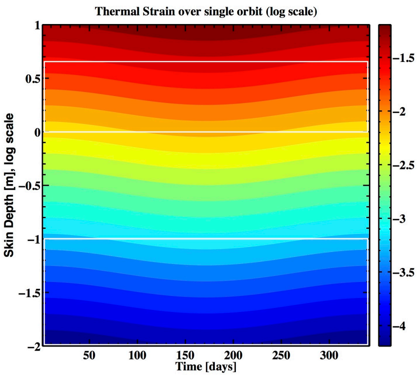

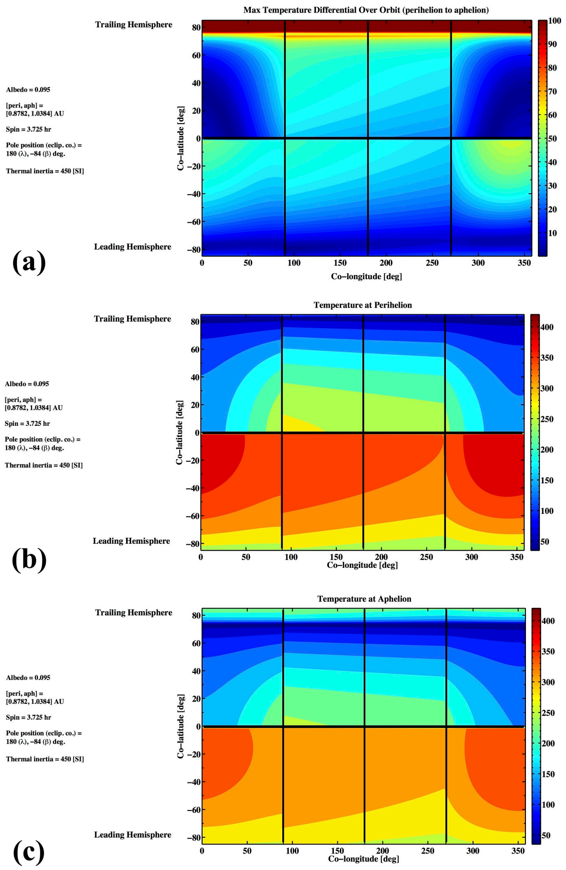

**Figure 2 :** Temperature distribution at 1 cm depth in the orbit of 2008 EV5, from an interpolation of a suite of thermal evolution models. Co-latitude/longitude define surface locations, relative to the spin pole position. We show temperature variations for both hemispheres and 4 quadrants. Note that the object has appreciable obliquity, hence the asymmetric behavior between hemispheres. **(a)** Maximal T differences a proxy for the thermal cycling strength. **(b)** T amplitude at perihelion. **(c)** T amplitude at aphelion.

**Figure 1 :** Thermal strain relation (see text), as a function of time through a single orbit, starting from perihelion. The two white rectangles encompass the expected ranges of skin depths for orbital (top) and diurnal (bottom) variations.