Latitudinal Dependence of Asteroid Regolith Formation by Thermal Fatigue M. Hamm[1], H. Senshu[2], M. Grott[1], [1]German Aerospace Center, Insitute of Planetary Research, Berlin, Germany, Maximilian.hamm@dlr.de (include full mailing address and e-mail address if desired) for first author, [2]Chiba Institute of Technology, Planetary Exploration Research Center, Narashino, Japan

Introduction: The surface of asteroids is covered by a layer of broken up material called the regolith, which is formed by impacts and temperature induced rock breakdown. The latter is termed thermal fatigue and has been shown to be the dominating process for regolith generation [1]. Thermal fatigue describes the cracking, chipping or splitting of rocks due to temperature induced stresses and a multitude of studies investigated thermal stress in objects ranging from comets [2][3] to meteoroids [4] or boulders [5] as well as granular microstructures [6].

Thermal fatigue in rocks and boulders is generally parameterized in terms of the temperature gradient within the material [5], but it has been shown that in heterogeneous granular microstructures like chondrites the temperature gradients play a minor role [6]. Rather, the different thermo-elastic properties of the constituents drive thermal fatigue, and temperature excursions around the average, i.e., the amplitude of the diurnal temperature curve, is a better proxy for thermal fatigue in these materials.

In this work we investigate the spatial distribution of two proxies for thermal fatigue on asteroid surfaces: the vertical temperature gradient, representing the breakdown of boulders, and the amplitude of the diurnal temperature curve, relevant for the breakdown of chondritic matter. We search for the latitude at which each of these reach their maximum and study the dependency of these latitudes on thermal inertia and local solar declination. Actual stress models are not considered here, and we focus on the thermal forcing to learn about the spatial distribution of regolith generation on asteroid surfaces.

Methods: This study is based on a spherically symmetric thermal model of the Hayabusa2 [7] target asteroid (162173) Ryugu [8], but results are also applicable to other airless bodies of roughly spherical shape. The thermal model solves the one dimensional heat conduction equation using the surface energy balance as upper boundary condition. Insolation is given by the asteroid's rotation period, spin orientation, and orbital parameters, such that for a spherical shape the insolation I is given by the analytical expression

$$I(t) = \frac{I_0}{r_h^2}\,(\cos\phi\cos\delta\cos\psi(t) + \sin\phi\sin\delta)$$

where t is time, I_0 is insolation at 1 AU, and the asteroid is placed at a radial distance of r_h = 1.2 AU. The solar declination δ is changed between 0° and 85°, which is equivalent to tilting the rotation axis or changing the season on a circular orbit. The latitude ϕ is varied in steps of one degree as is the rotation phase $\psi(t)$. The temperature evolution is calculated until a stable solution is reached and temperature is calculated as a function of depth at 250 grid points. The vertical gradient is then defined as the temperature difference between the surface and the first sub-surface grid point, while the amplitude of the diurnal temperature curve is defined as half of the difference between maximum and minimum temperature.

Thermal models will be parameterized in terms of the surface thermal inertia, which is varied between 500 and 3000 J m^{-2} K^{-1} $s^{-1/2}$. This range corresponds to the thermal inertia of various meteorites, which range from 640 $\mathrm{J\,K^{-1}m^{-2}s^{-1/2}}$ for a CM2 chondrite to 3000 $\mathrm{J\,K^{-1}m^{-2}s^{-1/2}}$ for an E4 chondrite [9]. Non-chondritic materials like serpentine or enstatite also fall within this range.

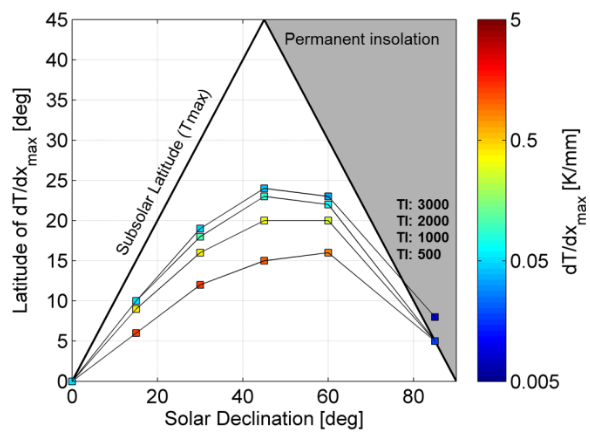

Figure 1: *Latitude of maximum vertical thermal gradient as a function of solar declination for four representative thermal inertias. Color indicates the amplitude of the gradient. Subsolar latitude and latitudes with permanent insolation are also indicated.*

Results: Fig. 1 shows the latitude of maximum thermal gradient as a function of solar declination for a set of thermal inertias between 500 and 3000 J m^{-2} K^{-1} $s^{-1/2}$. The magnitude of the thermal gradient is indicated by color and strongly depends on the thermal inertia where low values result in high gradients. Furthermore, low solar declination results in larger gradients and maximum gradients occur close to the equator.

An increase of solar declination increases the latitude of maximum thermal gradient until reaching its maximum for 45° to 60° solar declination, depending on thermal inertia. For the range of parameters investigated here, maximum latitudes reach 25° for high thermal inertia. Latitude then decreases for higher declination values following the boundary of permanent insolation. For a given solar declination the maximum thermal gradients occur closer to the equator with decreasing thermal inertia. Furthermore, the maximum latitudes in Fig. 1 are slightly shifted towards higher solar declination as thermal inertia decreases.

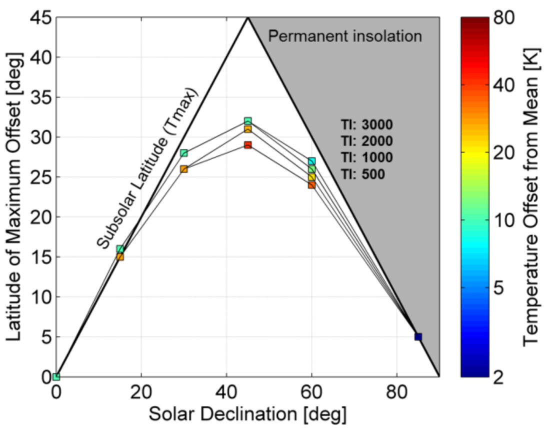

Figure 2: *Similar to Fig. 1, but for the amplitude of the diurnal curve.*

Fig. 2 is similar to Fig. 1, but shows the latitude of maximum amplitude of the diurnal temperature curve. This amplitude closely follows the subsolar latitude up to solar declinations of about 30°, from where the slope decreases. The highest latitude is reached for 45° solar declination, resulting in maximum amplitudes of the diurnal curve at a latitude of 30°. Higher declination decreases the latitude of maximum amplitude similar to the results shown in Fig. 1.

Unlike the latitude of the maximum gradient, the latitude of the maximum diurnal temperature amplitude is almost independent of thermal inertia. However, like the strength of the gradient, the amplitude also increases for decreasing thermal inertia and solar declination. Furthermore, for a given thermal inertia and solar declination, the amplitude reaches its maximum at higher latitudes compared to the maximum thermal gradients.

Discussion: Based on the assumption that either thermal gradients or the amplitude of the diurnal temperature curve cause thermal fatigue in the regolith, a band of finer material is predicted to form north and south of the equator. As the asteroid orbits the sun, solar declination will change from its maximum on one hemisphere to its minimum on the opposite hemisphere depending on the tilt of the rotation axis. This will cause the spot of maximum thermal forcing to oscillate around the equator, causing regolith erosion in this latitudinal band. The eccentricity of the orbit will break this symmetry, as the thermal forcing will be stronger at perihelion. In this case the regolith would be finer on one hemisphere than on the other.

Independent of the chosen proxy, the fine material will not form at the poles or sub-polar regions. Therefore, observations of a uniform, global fine regolith cover or fine regolith located at the poles (as observed, e.g., on asteroid Itokawa [10]) are strong indications for regolith migration or changes in the asteroid's rotation axis.

The results obtained here predict a difference between the regolith distribution for homogenous boulders on the one hand and chondritic material on the other hand. Boulders will break down fastest near the equator, thus reducing their thermal inertia. This results in a runaway effect that will cause fine regolith to be concentrated close to the equator, as subsequent orbits will cause even stronger gradients at these locations. In contrast, the diurnal temperature amplitude drives fatigue in chondritic material [6] and the fine regolith will be distributed more uniformly as the latitude of maximum amplitude is only slightly dependent on thermal inertia. Furthermore, this regolith band will be broader compared to non-chondritic asteroid surfaces, as the maximum amplitude occurs at larger latitudes compared to the thermal gradients.

The upcoming asteroid sample return missions Hayabusa2 (JAXA) and OSIRIS-REx (NASA) [11] will offer the unique opportunity to study the regolith of asteroids (162173) Ryugu and (101955) Bennu with their optical and thermal instruments ([12], [13], [14]). The combined study of the thermal environment and surface morphology will provide new insights into the process of regolith formation, and the results presented here will contribute to understanding the distribution of regolith observed on the respective asteroid surfaces.

References: [1] Delbo M. et al. (2014) Nature, 508, 233-236. [2] Kührt E. (1984) Icarus, 60, 512. [3] Auger N. et al. (2018) Icarus, 301,173-188. [4] Čapek D. and Vokrouhlický D. (2010) A&A, 519, A75. [5] Molaro J. et al. (2017) Icarus, 294, 247-261. [6] Molaro J. et al. (2015) JGR Planets, 120, 255-277. [7] Tsuda Y. et al. (2013), Acta Astronautica, 91, 356-362. [8] Takita et al. (2017) SSR, 208, 1-4, 287-315. [9] Opeil C.P. et al. (2010) Icarus, 208, 449-454 [10] Miyamoto H. et al. (2007) Science, 316, 1011-1014 [11] Lauretta DS. et al. (2015) Meteoritics & Planetary Science, 50, 834-849 [12] Okada T. et al. (2017), SSR, 208, 1-4, 255-286 [13] Grott M. et al. (2017), SSR, 208, 1-4, 413-431 [14] Hamilton V., (2014), EGU General Assembly, Vol. 16, EGU2014-4687-1