Vieillissement thermique des matériaux à la surface des astéroïdes et des comètes

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Asteroids are covered by regolith (this is the moon)
Classically it is thought that regolith is formed by impact debris (and by the comminution of boulders by micrometeorite impacts)

Ejecta exceed the gravitational escape velocity of small asteroids (km-sized and smaller)
Thermal fatigue cracking on asteroids?

Day/night temperature variations causes differential expansions/contractions of rocks i.e. mechanical stress.

Cyclic stress $\rightarrow$ MATERIAL FATIGUE

from [McFadden et al., 2005]
Laboratory Experiments

Meteorite samples as asteroid analogues

Murchison; CM2 Carbonaceous chondrite (C-type asteroid)
Laboratory Experiments

Meteorite samples as asteroid analogues

Sahara 97210; LL3.2

Ordinary chondrite (S-type asteroid)
Laboratory temperature cycles of asteroid analogs

- We exposed meteorites temperature variations similar to those of the day/night cycle of NEAs.
- We performed about 407 temperature cycles.
- Dynamical life of an NEA 1-10 My → (0.5 – 30) × 10$^9$ cycles given a rotation period of 2.5-10 hours.

For an albedo=0.2, P=2.5h, thermal inertia = 300 J m$^{-2}$ s$^{-0.5}$ K$^{-1}$

Experiments by Guy Libourel (at GRPG Nancy)
Protocol of the thermal fatigue laboratory experiments

407 temperature cycles

76 temperature cycles

331 temperature cycles

meteorites in the climatic chamber for temperature cycling.
meteorites in the computer tomographic (CT) scanner for crack imaging.
meteorites transported from the CT scanner to the climatic chamber.
meteorites transported from the climatic chamber to the CT scanner.

this and following slides from [Delbo et al., 2014]
Visual crack growth (cycles=0)
Visual crack growth (#cycles=76)
Visual crack growth (#cycles=407)
Average crack growth in Murchison and Sahara 97210

Murchison: mean change of crack length relative to N # = #0

Sahara 97210: mean change of crack length relative to N # = #0
Thermo-mechanical model

![Graph showing crack size vs. thermal cycles for Murchison and Sahara 97210 samples.](image-url)
Comparison of theoretical and measured crack growth

Extended Data Figure 6 | Schematics of our micromechanical model.

a, Flow chart; b, schematic of the two-scale representation (Methods). \( \partial V \) is the surface of a body of volume \( V \). A microscopic spherical inclusion, centred at the macroscopic point \( x \) is embedded in an infinite, effectively homogenized matrix. A general microscopic material point is located at a distance \( y \) measured from the centre of its nearest spherical inclusion located at \( x \). The spherical inclusions of radius \( r_c \) are located at the vertices of a cubic lattice with lattice parameter \( 2\ell \).
Thermo-mechanical model application to asteroids

![Diagram showing the application of a thermo-mechanical model to asteroids. The diagram includes a table indicating initial cracks through the bedrock and temperature scales with limits from $T_{max}$ to $T_{min}$. The bedrock is shown in blue with varying colors indicating temperature variations.](image-url)
Thermo-mechanical model application to asteroids

Energy balance at the surface: 
\[(1 - A)S_\odot r^{-2} \mu = \epsilon \sigma T^4 - \kappa \frac{\partial T}{\partial z}\]

Heat conduction in the subsurface: 
\[\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} (\kappa \frac{\partial T}{\partial z})\]
Energy balance at the surface: \[(1 - A) S_\odot r^{-2} \mu = \epsilon \sigma T^4 - \kappa \frac{\partial T}{\partial z}\]

Heat conduction in the subsurface: \[\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \kappa \frac{\partial T}{\partial z}\]

Time to breakdown is between $10^3$–$10^6$ years in near-Earth space, and $10^5$–$10^9$ years in the Main Asteroid Belt. Time to breakdown strongly depends on composition and size [Delbo et al., 2014].
Regolith formation from Murchison in the laboratory

Tomographic slices of regions of the same sample of Murchison before and after temperature cycling. The arrows indicate fragments that broke off from Murchison. From [Delbo et al., 2014].
Regolith formation by impacts on the Moon

see [Hoerz et al., 1975, Hörz and Cintala, 1997].
Efficiency of regolith production on the Moon by impacts

Monte Carlo simulation of surface residence time of Lunar rocks against meteoroid impacts by [Hoerz et al., 1975, Hörz and Cintala, 1997]
Dust particles spiral in, towards the sun, due to the PR drag. Orbital inclination is conserved. Higher particle density at 1 AU than at 2.5 AU.
Dust particles spiral in, towards the sun, due to the PR drag. Orbital inclination is conserved. Higher particle density at 1 AU than at 2.5 AU.
Efficiency of regolith production on Asteroids

Near-Earth Asteroids and Main-Belt Asteroids by micro-meteoroid impacts

see [Delbo et al., 2014].
Time required to break rocks on asteroids by thermal fatigue

from [Delbo et al., 2014].
The doom of low-perihelion asteroids

- at 0.3 AU the solar radiation pressure can remove grains with radii of the order of millimetres from the surface of an asteroid with a radius of 100 m [Jewitt, 2012]
- mm-sized grains these can be produced in $\lesssim 200$ yr.
- low-perihelion NEAs loose regolith at a rate of $5 \times 10^{-5}$ m/yr
- implying that an object with a radius of 100 m would be completely eroded in about 2 Myr.
- We found observational evidence that asteroids are indeed destroyed as their orbits approach the sun [Granvik et al., 2016]
Asteroid regoliths: (4) Vesta
Asteroid regoliths: (433) Eros and (25143) Itokawa

Same spectral class. Same albedo. Different size.

(433) Eros

(25143) Itokawa
Asteroid regoliths: (433) Eros
Asteroid regoliths: (25143) Itokawa
The size of the regolith depends on the size of the body

From [Gundlach and Blum, 2013].
Asteroids, parents of chondrites, delivered water to Earth

From [Altwegg et al., 2015].
Allende CV3 Carbonaceous Chondrite
Asteroid distribution
Other minor planets: Comets, Centaurs and TNOs
Comets and 67/P Churyumov–Gerasimenko
Complex geology of 67/P Churyumov–Gerasimenko
Fractures on 67/P Churyumov–Gerasimenko

From [El Maarry et al., 2015]
Fractures on 67/P Churyumov–Gerasimenko

From [El Maarry et al., 2015]
Rapid temperature variation on 67/P C–G

Comparison between $\left(\Delta T/dt\right)_{\text{max}}$ map for epoch 2 and an image of 67P taken in 2014 September 2 (image credit ESA/Rosetta/Navcam/). From [Alí-Lagoa et al., 2015]
Small fracture on Philae landing Site on 67/P C–G

Close-up from CIVA no. 1 showing the fractured block. The left image was stretched to emphasize the fractures. The two reds arrow indicate the limit of the fracture having the maximum length (537.6 mm at 1 mm/pix resolution or 752.6 mm at 1.4 mm/pix resolution). From [Poulet et al., 2016].
Observations of thermal fatigue cracking on other bodies by day/night temperature variations

Earth: dry deserts (McFadden et al. 2005, Keil, 2005);
From lab experiments, rocks crack if $\frac{dT}{dt} > 2 ^\circ C/min$

Boulder on (433) Eros erode on place and create characteristic deposits in ponds (Dombard et al. 2010)
An eroding boulder in a pond on Eros

From [Dombard et al., 2010]
Thermal Moonquakes

Figure 4. Nonlocal events observed per day (averaged over 11 lunarions) recorded by the station 14 short-period component (blocked line) and lunar surface temperature (smooth line) versus time of lunarion. A reasonably good correlation between event activity and temperature is seen with an onset about 48 hours after sunrise. The temperature curve is from a10 [1968].

During periods when the event detection program was not used or the events were missed by the program during periods when analog records were available, 91 additional thermal moonquake signals were found.

Figure 5 shows the occurrence of all identified thermal moonquakes at station 14. Thermal moonquake activity starts abruptly about 48 hours after sunrise and continues at a level of about five events per day until sunset, when the level drops to about three events per day and then decreases further. The larger number of occurrences during the final two lunations is due to a programmed increase in the sensitivity of the event detection program for this time period, not to increased lunar activity. That individual types of thermal moonquakes tend to occur at specific times of a lunation can be seen from Figure 6, showing the occurrence times of four types of thermal moonquakes. Type 300 events tend to occur many times per lunarion during an 11-day period beginning near lunar noon and ending about 3 days after lunar sunset, whereas the other three types usually occur only once per lunarion. Type 300 thermal moonquakes are of particular interest and will be discussed later in this paper.

Wave forms. The signal from each type of thermal moonquake has a unique wave form. Figures 7a and 7b show examples of the wave forms. Note that the events of Figure 7a are almost identical. By the criteria mentioned earlier this identity among events implies that the source of type 330 thermal moonquakes did not change appreciably throughout the period of observation. Figure 7b shows a similar plot for type 340 thermal moonquakes. Note that the wave form changes slightly from one lunarion to the next, the implication being that the source is changing. The relative change in amplitude of individual peaks from one event to the next suggests that the source is changing.

Figure 5. Occurrence calendar of all thermal moonquakes observed at station 14. This figure is read like a calendar; each line represents one lunarion. Each lunarion is broken into terrestrial days, starting at sunrise. Dots represent the number of thermal moonquakes occurring in each 6-hour period. Note that activity drops off after sunset and that no thermal moonquakes are observed during the latter part of the lunarion. Solid horizontal lines show periods when the event detection program was not run. Dotted horizontal lines show periods when analog records are available. Sensitivity of detection program was higher during lunations 11 and 12. The recording period starts on February 11, 1971, and ends on January 10, 1972.

Duennebier and Sutton, 1974
Cracked Rock on Mars – from MER Spirit PANCAM
Cracked Rock on Mars – from MER Spirit PANCAM

Crack direction is predominantly N-N-E, likewise to those of Earth’s rocks in mid-latitude deserts. This is consistent with stresses from diurnal solar heating.

From [Eppes et al., 2015]
Cracked Rock on Mars – from MER Spirit PANCAM

Crack direction is predominantly N-N-E, likewise to those of on Earth’s rocks in mid-latitude deserts. This is consistent with stresses from diurnal solar heating.

From [Eppes et al., 2015] Laboratory experiments produce thermal fatigue-related fracturing when subjecting basalts to thermal cycling replicating Mars temperature extremes; [Viles et al., 2010]
Rockfall triggering by cyclic thermal stressing of exfoliation fractures

From [Collins and Stock, 2016]
Rockfall triggering by cyclic thermal stressing of exfoliation fractures – From [Collins and Stock, 2016]

![Graph showing crack aperture and temperature changes over time with shaded areas indicating cyclic thermal stressing.](image)

<table>
<thead>
<tr>
<th>Date</th>
<th>Light intensity (klx)</th>
<th>Crack aperture (cm)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
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<td>12.5</td>
</tr>
<tr>
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<td>11.5</td>
<td>12.0</td>
</tr>
<tr>
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<td>11.0</td>
<td>11.5</td>
</tr>
<tr>
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<td>10.5</td>
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<tr>
<td>13 June 2011</td>
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<td>10.0</td>
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</table>

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\[ \begin{align*}
\Psi & = \frac{\sigma_{nl}}{K_I} \\
K_I & > K_{IC} \\
\Delta T & = \frac{R \cdot L}{2 \cdot \kappa} \\
\end{align*} \]
Conclusions

Moon

Mars
[Viles et al., 2010, Eppes et al., 2015]

Asteroids
[Delbo et al., 2014, Dombard et al., 2010, Molaro et al., 2015]

Comets
[Vincent et al., 2016, El Maarry et al., 2015, Alí-Lagoa et al., 2015, Poulet et al., 2016]
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