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Thermal Fracturing on Comet 67P/Churyumov-Gerasimenko

Nicholas Attree (1), Olivier Groussin (1), Laurent Jorda (1), Anne-Thérèse Auger (1), David Nébouy (1), Nicolas Thomas (2), Yann Brouet (2), Olivier Poch (2), Ekkehard Kührt (3), Frank Preusker (3), Frank Scholten (3), Jörg Knollenberg (3), Stubbe Hviid (3), Paul Hartogh (4)

(1) Aix Marseille Univ, CNRS, LAM, Laboratoire d'Astrophysique de Marseille, Marseille, France (nicholas.attree@lam.fr), (2) Physikalisches Institut, Universität Bern, Sidlerstrasse 5, 3012 Berne, Switzerland, (3) Deutsches Zentrum für Luft-und Raumfahrt (DLR), Institut für Planetenforschung, Rutherfordstraße 2, 12489 Berlin, Germany, (4) Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany

Abstract

We simulate the stresses induced by seasonal temperature changes in a putative hard layer near the surface of comet 67P/Churyumov-Gerasimenko with a thermo-viscoelastic model. We show that a hard, icy layer will experience large stresses, of up to tens of mega pascals, which far exceed its material strength down to depths of tens of centimetres to several metres (0.5 m in our nominal case of thermal inertia I = 50 J m^{-2} K^{-1} s$^{-1/2}$). This result is constant across all cometary latitudes and consistent with the detection of meter-scale thermal fracturing all over the comet. Thermal fracturing may be an important erosion process on cometary surfaces.

1. Motivation

Fracturing is prevalent at many scales on the consolidated terrains, boulders and cliffs of comet 67P/Churyumov-Gerasimenko, when observed by Rosetta's OSIRIS instrument [2]. Polygonal networks of intersecting fractures have been likened to thermal contraction crack polygons, also seen on Earth and Mars [2, 1]. Such features form when thermal stresses exceed material strengths over large, uniform areas, leading to fracture networks of a size related to the material and thermal environment in the subsurface. [1] suggest that the observed polygons, of a few metres in size, are consistent with a hard layer within a few centimetres of the surface. Such a layer would explain the high material strength encountered by the MUPUS instrument on the Philae lander, and could be formed by the recondensation or sintering of water-ice and dust grains, as suggested by laboratory experiments and computer simulations.

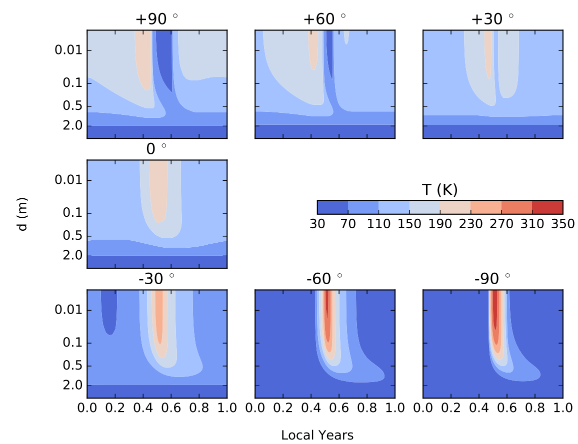

Figure 1: Temperature maps with depth and time for each of the labelled latitudes on comet 67P, produced by our 1-D thermal model with a thermal inertia of I = 50 J m^{-2} K^{-1} s$^{-1/2}$.

2. Modelling

2.1. Temperatures

We used a spherical shape model for the nucleus, orientated accordingly to its pole, to compute the temperature inside the nucleus as a function of time to derive the seasonal temperature trends. Our thermal model takes into account the solar insolation, the nucleus surface thermal emission and heat conductivity. The average diurnal temperature at each depth interval, i.e. the seasonal trend, is then computed.

The seasonal thermal wave can be seen (Fig.1) propagating downwards from the surface to some depth. The phasing of the seasonal change varies between the northern and southern hemispheres because of the comet's obliquity.

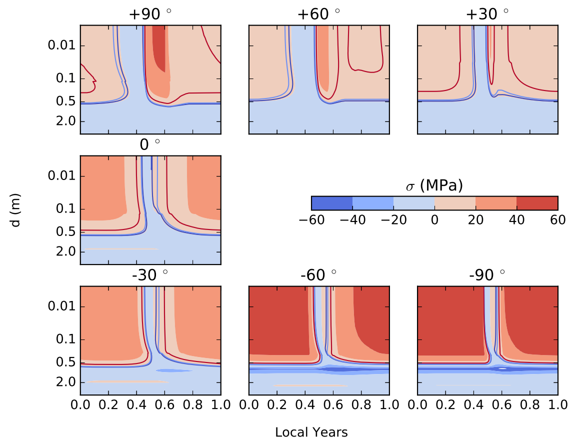

Figure 2: Thermal stresses with depth and time for each of the labelled latitudes on comet 67P, with I = 50 J m^{-2} K^{-1} $s^{-1/2}$. Highlighted contours are likely material strengths, from [3], of $1, 2.5$ and 10 MPa.

2.2. Thermal Stresses

Following the method of [4], we use a Maxwellian thermo-viscoelastic description of an ice-rock mixture. We solve the equations numerically for stress (σ) at each time- and depth-step of the temperature profiles from above. For our baseline mode, we use a thermal inertia of I = 50 J m^{-2} K^{-1} $s^{-1/2}$ and adopt the Martian permafrost material properties for a linear mixture of 45% ice and rock [4]. Ice, snow and ice-bonded soils all have similar rheologies so any hard layer, containing significant amounts of ice, should therefore exhibit the same type of viscoelastic behaviour.

As shown in Fig. 2, compressive (negative) stresses follow the thermal wave, followed by tensile (positive) stresses as the material cools. Tensile stresses remain large for much of the cycle, particularly in the cold southern hemisphere, and the maximum depth of the transition from tension to compression is roughly the same in all cases at ~ 0.5 m. The highlighted contours show various values for the tensile strength of a water-ice and rock-ice mixtures [3].

3. Summary and Conclusions

Thermal stresses are easily large enough to exceed the tensile strength of water-ice and ice-rock mixtures down to ~ 0.5 m, depending on thermal inertia. Fracturing can therefore be expected to at least this depth at all latitudes on the comet. These results are nearly independent of latitude but do vary with ice content, Young's modulus and thermal expansion coefficient. Stress decreases with decreasing ice-content and at zero ice-fraction the unconsolidated material probably cannot support fractures.

Polygons on Earth and Mars are typically a few times their fracture depth, entirely consistent with these results for polygons of mean size 3 m [1], measured on 67P. This agreement is suggestive of an ice-rich hard layer within about half a metre of the cometary surface. Because of the polygons' uniformity, little variation in the depth or mechanical properties of this hard layer is suggested

Thermal fracturing on the metre-scale may be an important erosion mechanism. Gradual weakening of material by thermal fatigue will break down boulders and weaken cliff walls, making collapse more likely. Debris fields at the bottom of many cliffs suggest this is a common process, while individual collapses have been linked with outburst activity. This kind of process could be occurring all over the comet, leading to the gradual retreat of cliffs and removal of material across the surface. Other Jupiter-family comets undergo comparable seasonal temperature changes and the presence of hard, ice layers and thermal fracturing is therefore also expected on them.

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