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Thermally-driven Formation Mechanisms for Fractures on Comet 67P/Churymov-Gerasimenko

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Abstract

We investigate the role of thermally induced stresses in fracture propagation at the surface of comet 67P/Churymov-Gerasimenko by comparing images from the Rosetta spacecraft of fractures before and after perihelion passage. We then simulate the stress fields induced within the associated topography and relate the results to the observed fractures, providing insight into the efficacy and nature of this process.

1. Introduction

The Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS) [1] on board ESA's Rosetta spacecraft observed many fractures on the surface of comet 67P/Churymov-Gerasimenko [2]. These appear over many morphological regions at scales from sub-meter (fig 1a,b) to hundreds of meters (fig. 1c), and were initially assessed and classified by [3] based on their morphology and possible formation mechanisms. Evidence suggests that fracturing of consolidated material on the comet contributes to the development of unconsolidated regolith [4], thus investigating these formation mechanisms will provide insight into the recent history of the cometary surface. Here, we focus on testing the most likely mechanism for smaller scale fractures: thermally induced crack propagation, which is thought to operate on a variety of airless bodies [e.g., 5-8]. Recent work [5] has shown that spatially and temporally varying stress fields are induced in boulders undergoing diurnal thermal cycling on the Moon, which drive crack propagation in different directions and at different locations within their volume. While propagation rates and stress thresholds are not well constrained, OSIRIS images of fractures on comet 67P provide an unparalleled opportunity to study this process. Relating simulated stress fields to observed fractures will allow us to constrain these properties and provide insight into how these features develop over time. For this purpose, we will characterize and compare OSIRIS images of fractures before and after perihelion passage, and model the macroscopic stresses induced in the associated topographic features along the comet's orbital path.

2. Observations

The initial assessment of OSIRIS images from 2014 to 2016 showed evidence for fracturing during the mission timeline on the scale of <1-10s of meters [4, fig. 1]. This type of fracturing is not observed everywhere on the comet. Therefore, we suspect that their location is associated to specific conditions favouring this process. If thermal breakdown is a driving mechanism for these fractures and cliff failures, this suggests that the locations in which the cracks appear experience enhanced stresses (relative to other areas of the comet) due to differences in incident radiation and shadowing effects.

3. Modeling

Following the work of [5], we use COMSOL Multiphysics to perform 3D finite element simulations of the thermomechanical response of boulders on the surface of the comet to diurnal thermal cycling, allowing us to investigate the magnitude and distribution of resulting stresses. We model a spherical boulder embedded in a volume of regolith, impose incident solar radiation on the surface and solve the heat and displacement equations over one solar day. The model accounts for the radiative and conductive interaction between the boulder and surrounding regolith, as well as the size of the solar disk. We approximate the regolith as lunar regolith, with temperature and depth dependent material properties following [9], producing a temperature range and thermal inertia that are consistent with measurements taken by the MIRO instrument aboard Rosetta [10]. The boulder is composed of a mixture of water ice and basalt, which also have temperature dependent properties [5, 8]. Preliminary results suggest that stresses up to 6 MPa may be induced in consolidated objects at the comet's surface. Figure 2 shows an example of the stress induced along a 2D cross-section of a 1 m boulder (25% water ice by volume) at mid-morning. The boulder's temperature ranges from 251-277 K, suggesting that sublimation effects within pores may produce additional stresses that interact with the thermally induced stress field.

4. Future Work

The unique shape of comet 67P/Churymov-Gerasimenko suggests that certain locations will experience larger diurnal temperature ranges, and thus may be more susceptible to thermally induced fracturing. We will simulate the comet's global surface temperatures to identify these locations, and compare OSIRIS images of fractures before and after perihelion passage. We will then quantify the spatially and temporally varying macroscopic stress fields within the associated boulders and surface features to assess whether the observed fractures are thermally driven. We will constrain crack propagation rates, stress thresholds, and ice volume in the comet's consolidated material, providing valuable insight into the role of diurnal thermal cycling on the landscape evolution of comets.

References

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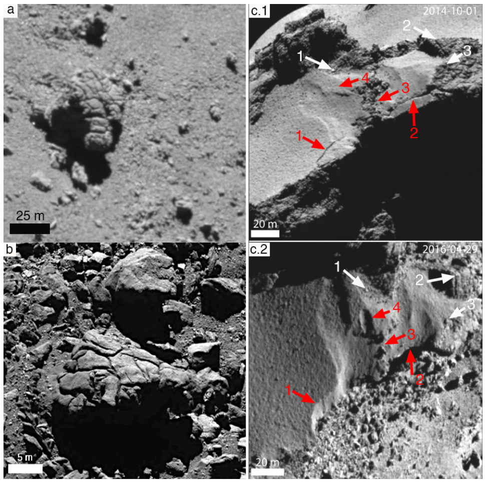

Figure 1: OSIRIS images of fractured boulders taken (a) before and (b) after perihelion. (c) Evolution of a cliff in the Ash region (c.1) before perihelion and (c.2) after perihelion [4]. Red arrows indicate morphological changes between images, and white arrows indicate reference points where no changes occur. Red arrows 1 and 2 point to meter-scale fractures in (c.1) that led to cliff collapse in (c.2). Red arrow 3 reveals rocky material in (c.1) that is covered by dust debris and/or eroded in (c.2). Red arrow 4 shows dry mass wasting feature associated to the destabilization of the terrain due to cliff collapse.

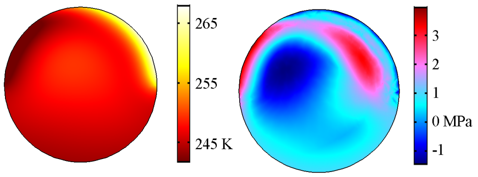

Figure 2. Snapshot of the temperature (left) and stress (right) in a 2D cross section through a 1m-diameter boulder (25% water ice) during mid-morning. We present the maximum principal stress (tensile stress is positive), which represents the idealized energy available for crack propagation at a given location.