Morphological and compositional analysis of boulders distributions on comet 67P/Churyumov-Gerasimenko

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Admission to the final exam
13 September 2019
Centro di Ateneo di Studi e Attività Spaziali "Giuseppe Colombo" - CISAS
Outline

- Origin of Comets
  - Overview
  - The Rosetta Mission
  - Comet 67P/Churyumov-Gerasimenko

- Fragmentation and Fractals. The case of isolated boulder fields on comet 67P
- Time Evolution of Dust in the Hapi Region
- Thermal and Stress Analysis in Boulders of Comet 67P

- Conclusions
- Future Works
- List of Publications
Overview - Origin of Comets

Why are comets and asteroids so important for the understanding of the Solar System formation?

Comets and asteroids are leftovers of the Solar System formation.
Overview - The Rosetta Mission

The first mission designed to orbit and land on a comet

2 March 2004
Launch

10-years journey
towards comet 67P

2867 Steins (2008)
21 Lutetia (2010)

June 2011
Hybernation mode

6 August 2014
Arrival of comet

12 November 2014
Philae landing

30 September 2016
End of the mission

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Overview - OSIRIS

Optical, Spectroscopic and Infrared Remote Imaging System (OSIRIS)

<table>
<thead>
<tr>
<th></th>
<th>NAC</th>
<th>WAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical design</td>
<td>3-mirror off-axis</td>
<td>2-mirror off-axis</td>
</tr>
<tr>
<td>Angular resolution [μrad px-1]</td>
<td>18.6</td>
<td>101</td>
</tr>
<tr>
<td>Focal length [mm]</td>
<td>717.4</td>
<td>140 (sag)/131 (tan)</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>13.2</td>
<td>9.48</td>
</tr>
<tr>
<td>Field of view [°]</td>
<td>2.20 - 2.22</td>
<td>11.35 - 12.11</td>
</tr>
<tr>
<td>F-number</td>
<td>8</td>
<td>5.6</td>
</tr>
<tr>
<td>Spatial scale from 100 km [m px-1]</td>
<td>1.86</td>
<td>10.1</td>
</tr>
<tr>
<td>Typical filter bandpass [nm]</td>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td>Wavelength range [nm]</td>
<td>250 - 1000</td>
<td>240 - 720</td>
</tr>
<tr>
<td>Number of filters</td>
<td>12</td>
<td>14</td>
</tr>
</tbody>
</table>

Mission
To image the comet's nucleus and its gas and dust coma
Overview - Comet 67P/Churyumov-Gerasimenko

- **Volume**: 21.4 km$^3$
- **Mass**: $1.0 \times 10^{13}$ kg
- **Density**: 470 kg/m$^3$
- **Porosity**: 70–80%

Rotation period: 12.4043 hours
Spin axis:
- 69.3° Right Ascension
- 64.1° Declination
Obliquity of the comet’s rotational axis: 52°

- **Dust/gas ratio**: 4
- **D/H ratio**: $5.3 \times 10^{-4}$
- **Average water vapour production**:
  - 300 ml/s → June 2014
  - 600 ml/s → July 2014
  - 1200 ml/s → August 2014

Surface temperature:
- $-93°C$ to $-43°C$
- $-243°C$ to $-113°C$

Average albedo: 6%
Overview - Comet 67P/Churyumov-Gerasimenko

Huge variety of terrains
- Smooth
- Hummocky
- Partially or entirely covered by dust

Morphological dicothomy

Huge variety of landforms and features
- Smooth flat planes
- Vertical cliffs
- Talus aprons
- Pits
- Boulders
Objectives

Boulders

Opportunity to study the physical properties and the evolution of the comet

Imprints of geological and erosional processes that affected the surface

To study phenomena responsible for the \textit{fragmentation} of the surface

- Thermal stress weathering
- Gravitational phenomena
- Activity
Fragmentation and Fractals. The case of isolated boulder fields on comet 67P
Quantitative analysis of isolated boulder fields on comet 67P/Churyumov-Gerasimenko


(Affiliations can be found after the references)

Received 4 December 2018 / Accepted 7 June 2019

To characterize isolated boulder populations unrelated to specific niches or detachment scarps
Data Selection

Hatmehit

Hapi

Imhotep

NAC-23:19:15 UT

NAC-03:19:25 UT

NAC-06:19:26 UT

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Data Selection

Pre-perihelion

Post-perihelion

Hatmehit Hapi Imhotep

11811 boulders

Size-frequency distribution

Cumulative fractional area

Fractal theory

Shape factors

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**Method**

**SIZE-FREQUENCY DISTRIBUTION**

The SFD of rocks on surfaces can supply geological information related to the body’s origin and evolution.

\[ N(\geq r) = kr^{-D} \]

-6.5 < D < -5
Collapses and pit formation
-4.5 < D < -3.5
Gravitational events
due to thermal fragmentation
-2.0 < D < -1.0
Gravitational events + sublimation and in-situ fragmentation

**CUMULATIVE FRACTIONAL AREA**

The CFA covered by rocks vs diameter curve is represented in a log-log plot.

Usually, the distribution is fitted by an exponential equation.

\[ F(\geq D) = ke^{-q(x)D} \]

\( F(D) \) is the CFA covered by rocks of diameter D or larger.
\( k \) is the total area covered by all rocks.
\( q(x) \) governs how abruptly the area covered by rocks decreases with increasing diameter.
Method - Results

SIZE-FREQUENCY DISTRIBUTION

<table>
<thead>
<tr>
<th>Region</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hatmehit pre</td>
<td>-2.7</td>
</tr>
<tr>
<td>Hatmehit post</td>
<td>-2.8</td>
</tr>
<tr>
<td>Hapi pre</td>
<td>-1.7</td>
</tr>
<tr>
<td>Hapi post</td>
<td>-1.2</td>
</tr>
<tr>
<td>Imhotep pre</td>
<td>-2.4</td>
</tr>
<tr>
<td>Imhotep post</td>
<td>-2.4</td>
</tr>
</tbody>
</table>

-6.5 < D < -5
Collapses and pit formation

-4.5 < D < -3.5
Gravitational events due to thermal fragmentation

-2.0 < D < -1.0
Gravitational events + sublimation and in-situ fragmentation

CUMULATIVE FRACTIONAL AREA

<table>
<thead>
<tr>
<th>Region</th>
<th>Trend line</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hatmehit pre</td>
<td>$y=0.0632x^{-0.792}$</td>
<td>0.9942</td>
</tr>
<tr>
<td>Hatmehit post</td>
<td>$y=0.0594x^{-0.639}$</td>
<td>0.9875</td>
</tr>
<tr>
<td>Hapi pre</td>
<td>$y=0.0648x^{-0.179}$</td>
<td>0.9120</td>
</tr>
<tr>
<td>Hapi post</td>
<td>$y=0.0556x^{-0.150}$</td>
<td>0.8545</td>
</tr>
<tr>
<td>Imhotep pre</td>
<td>$y=0.0697x^{-0.364}$</td>
<td>0.9945</td>
</tr>
<tr>
<td>Imhotep post</td>
<td>$y=0.0548x^{-0.378}$</td>
<td>0.9910</td>
</tr>
</tbody>
</table>
The size distribution of material expected from fractures and fragmentation would allow a fractal rule

(Mandelbrot, 1982)

**BOXCOUNT METHOD**

Analysis of a complex 2D pattern by breaking an image into smaller pieces, and analyzing the pieces at each smaller scale

How many boxes are required to cover the image?

Calculation of the Minkowski-Bouligand dimension seeing how this number changes as the grid became finer

\[
D_f = \lim_{r \to 0} \frac{\log(N(r))}{\log(1/r)}
\]
Fractal Theory - Results

\[ n(r) = \text{number of boxes needed to cover the set as a function of the size } r \text{ of the boxes} \]

**Solid line** = power-law \( N(r) = N_o r^{-D_f} \). It should appear if the set is fractal

**Dotted line** = it appears showing the scaling \( N(r) = r^{-2} \) for comparison, expected for a space-filling 2D image

The discrepancy between the two curves indicates a possible fractal behavior of the image
Boulders Shape

Morphologies of rocks → Records on rock surface processes → Shape factors

• Lithology of the mass
• Transport mechanisms
• Weathering history

Shape factors
Dimensionless quantities calculated from measured dimension, such as diameter, area, perimeter, etc.

<table>
<thead>
<tr>
<th>Aspect Ratio</th>
<th>Circularity</th>
<th>Roundness</th>
<th>Compactness</th>
<th>Elongation</th>
<th>Solidity</th>
<th>Complexity</th>
<th>Convexity</th>
<th>Feret’s diameter</th>
</tr>
</thead>
</table>

2D-test

3D-test

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Boulders Shape - Results
Conclusions

- We propose techniques to analyse populations of boulders
- No differences before and after the perihelion
- Anomalies

**Hapi area**

- Boulders are collapsed during gravitational events and their fragmentation in-situ is controlled by thermal fatigue
- These boulders would represent the tops of outcrops, immersed in a deposit of back fall material several tens of meters thick

(Keller et al. 2017)

- The heat flux density received during the perihelion passage is not enough to change the examined populations
- There could have been changes, but the erosion was uniform and the shape parameters can only distinguish differential erosion.
Time Evolution of Dust in the Hapi Region
Time Evolution of Dust in the Hapi Region

22 August 2014
and
14 March 2015

(Shi et al. 2018)
Comet 67P experiences strong seasons, resulting in significant differences in insolation between the northern and southern hemispheres. This strong dichotomy is reflected in the morphology between the two hemispheres.

**Northern regions**
- Minimal amount of insolation and erosion
- FULLY COVERED OF DUST

**Southern regions**
- Southern summer = perihelion
- Strong insolation
- Strong erosion
- CONSOLIDATED AND COARSE TERRAINS
The dust cover in the northern regions can be the result of transport mechanisms of particles from the southern hemisphere during the southern summer.

The erosion of the southern hemisphere, the subsequent transport of material, and then its fallout on the nucleus, are fundamental to investigate the pristine water ice abundance comet 67P, assuming that 67P's ice content is representative of the average value of all comets.

(Keller et al. 2015)
Dust Erosion and Deposit

MATLAB Software

Height of boulders through the length of shadows can improve the knowledge of the erosion and deposit variation of the dust on the comet surface.

\[ H = L \tan\left(\frac{\pi}{2} - i\right) \]
MATLAB Software

Selection of the image

10 December 2014 06:29:11

To obtain the correct projection of the OSIRIS images on the 3D shape model

Image alignment

Local Surface Definition

To avoid the local granularity
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Thermal and Stress Analysis in Boulders of Comet 67P
Thermal Stress Weathering

“Rock breakdown due to the expansion and contraction of a rock induced by heating and/or cooling” (Lamp+2016)

**Thermal shock**
Rapid failure in the material as a result of a sudden $\Delta T$

**Thermal fatigue**
Cyclic thermal expansion and contraction of the material

“Photographic atlas of rock breakdown” Burne and Viles (2007)

(Eppes+2015)
Data Selection

1+ 350 fragments
Spatial scale: 0.28 m/px
Diameters: 0.3 - 8.3 m
Power-law: -2.7 +0.1/-0.2
Average: 1.4 m
(Cambianica et al., 2019)

Average spacing: 0.98 m
Length: 3.8 < m < 26.6
Preferred cracks orientation

• Non-random
• Strong north-south orientation

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Workflow

Solar irradiance (W/m²)

(Keller+2015)

Boundary conditions

FEM Software

- Temperature variation within a boulder
- Maximum tensile stress (MPa)

Whether the modeled maximum tensile thermal stresses are sufficient to cause crack propagation
Geometry and Mesh

- Geodesic polyhedron (40 m size boulder)
- Cubic volume (1 km x 1 km x 1 km)
- z-axis // rotating axis of the comet
- Two different meshes
- Thermal contact
- Controlled by the physics
Material Selection

Nucleus
organic components + minerals + water ice

- COOH- and OH groups
- polycyclic aromatic hydrocarbons
- refractory macromolecular material (CH$_2$ and CH$_3$)

Carbon

Graphite

Thermal inertia 10-50 K m$^{-2}$ s$^{-0.5}$

(From Gulkis+ 2015)
Conclusions

- Method to analyze isolated boulder fields on comet 67P/Churyumov-Gerasimenko
- New tool to measure and monitor the erosion and fallout on comet 67P/Churyumov-Gerasimenko
- Thermomechanical model to simulate thermal stresses of boulders on comet 67P/Churyumov-Gerasimenko

- Shape factors
- Pristine 67P's ice content
- Sunrise and sunset are responsible for thermal fragmentation
Future Works

Global map of dust erosion/accretion - Application of the method in other regions

Thermomechanical model

- We will model temperature and stresses including a regolith layer with variable thickness to understand the rule of this layer in terms of thermal conduction and cracks propagation.

- We will apply the Cheng and Vachon theory (1968) to calculate the thermal conductivity of two- and three-phase solid heterogeneous mixtures.

- We will perform the simulation over the entire orbit of the comet to include in our study the thermal fatigue, and to determine the number of orbits necessary for the fragmentation of the surface.
List of Publications

First-authored peer reviewed papers
“Quantitative analysis of isolated boulders fields on comet 67P/Churyumov-Gerasimenko”, A&A Rosetta 2 special issue, June 2019
“Comets and carbonaceous chondrites share a similar water content”, Science Advances, Submitted

Co-authored peer reviewed papers
List of Publications

Conferences

“Bouncing boulders on comet 67P”, Vincent J-B et al. 2019, EPSC/DPS
“Sample return from a relic ocean world: The CALATHUS mission to Occator Crater, Ceres”, IPPW 2019
”Geomorphological units of Khepry and Imhotep regions of comet 67P/Churyumov-Gerasimenko”, Ferrari S. et al. 2018, EPSC
“3DPD application to the first CaSSIS DTMs”, Simioni, E. et al. 2018, EPSC
“Thermal analysis of boulders on comet 67P/Churyumov-Gerasimenko”, Cambianica et al. 2018, EPSC
“Quantitative analysis of Imhotep, Hapi and Hatmehit boulder populations on comet 67P/Churyumov-Gerasimenko”, Cambianica et al. 2019, Congresso Nazionale di Scienze Planetarie
“Fragmentation processes on the 67P/Churyumov-Gerasimenko surface from the OSIRIS images” Cambianica et al. 2016, From Giotto to Rosetta
Thanks for the attention

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