Morphological and compositional analysis of boulder distribution on comet 67P/Churyumov-Gerasimenko

PhD student
Pamela Cambianica

Admission to Third Year
13 September 2018

Supervisor: Giampiero Naletto
Co-supervisor: Gabriele Cremonese
Morphological and compositional analysis of boulder distribution on comet 67P/C-G

Aims:

- To define a method to analyze in a quantitative manner populations of boulders
Morphological and compositional analysis of boulder distribution on comet 67P/C-G

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- To define possible processes responsible for the boulder fragmentation through OSIRIS image analysis

Credits: ESA

NAC_2016-07-09T11.25.15.786Z_ID30_1397549000_F41
Morphological and compositional analysis of boulder distribution on comet 67P/C-G

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- To link the method with others described in literature
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- To understand the rule of thermal stress and fatigue in terms of propagation of cracks and fragmentation
Morphological and compositional analysis of boulder distribution on comet 67P/C-G

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• To link the method with others described in literature

• To define possible processes responsible for the boulder fragmentation through OSIRIS image analysis

• To understand the rule of thermal stress and fatigue in terms of propagation of cracks and fragmentation

• To develop a fragmentation model able to explain the presence of some features, like boulders, on the surface of comet 67P/C-G

Credits: ESA

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The Rosetta mission – OSIRIS instrument

Optical Spectroscopic Infrared Remote Imaging System (OSIRIS) (Keller et al. 2007)

NAC
Narrow Angle Camera
1.86 m/px at 100 km

WAC
Wide Angle Camera
10.1 m/px at km

"Morphological and compositional analysis of boulder distribution on comet 67P/C-G"

Credits: ESA

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Outline

Analysis of OSIRIS images
- Quantitative analysis of Imhotep, Hapi and Hatmehit boulder populations on comet 67P/Churyumov-Gerasimenko
- Measurements of erosion and dust deposits in the Hapi region

Thermal and stress analysis
- Thermal analysis of boulders of 67P/C-G comet
- Stress analysis of boulders of 67P/C-G comet

Future works
- Personal training plan
- List of publications

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Analysis of OSIRIS images

- Quantitative analysis of Imhotep, Hapi and Hatmehit boulder populations on comet 67P/Churyumov-Gerasimenko
- Measurements of erosion and dust deposits in the Hapi region
Analysis of OSIRIS images

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- Measurements of erosion and dust deposits in the Hapi region
Selection of surface images – Pre and post-perihelion

- **Imhotep**
  - NAC_2014-09-29T13.29.30.598Z_ID30_1397549600_F22
  - NAC_2016-07-09T11.25.15.786Z_ID30_1397549000_F41

- **Hapi**
  - NAC_2014-12-10T06.29.11.447Z_ID10_1397549002_F24
  - NAC_2016-07-20T08.02.48.392Z_ID30_1397549001_F22

- **Hatmehit**
  - NAC_2014-12-12T17.42.03.690Z_ID30_1397549500_F24
  - NAC_2016-07-23T17.54.43.732Z_ID30_1397549002_F41

Admission to third year – Pamela Cambianica
Selection of surface images – Pre and post-perihelion

Imhotep
NAC_2014-09-29T13.29.30.598Z_ID30_1397549600_F22
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Admission to third year – Pamela Cambianica
Cumulative size-frequency distribution

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

A power function can be used to fit data from every region to represent the general form of rock size distribution:

\[ N(\geq a) = k a^{-D} \]
Cumulative size-frequency distribution – Fractal theory

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

Empirical data have suggested that the size distribution of material expected from fractures and fragmentation would allow a fractal rule:

\[ N \left( \frac{1}{b_i} \right) = k \left( \frac{1}{b_i} \right)^r \]

\( k \) number of initiators of unit length

\( b \) scaling factor > 1

\( r \) fractal dimension

The SFD curve can be represented by a fractal theory, a power-law which appears as a straight line in a log-log plot.
Fractal theory – BoxCount (1/2)

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

\( n(r) \) = number of boxes needed to cover the set as a function of the size \( r \) of the boxes

**Solid line** = power-law \( N(r) = N_0 r^{D_f} \). 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 CFA covered by rocks vs diameter curve is represented in a log-log plot.

Usually, the distribution is fitted by an exponential or power-law equation:

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

- \( F(D) \) 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

Cumulative fractional area

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Boulders shape

The morphologies of rocks should provide records on rock surface processes if signature in their shape and surface texture can be identified and interpreted.

- Sphericity and elongation reflect the lithology of the mass itself
- Roundness describes transport or weathering history

The final shape is strongly influenced by the composition of particles
- Slate rocks tend to split into planar fragments
- Jointed rocks tend to split into cubic fragments
- Corners and edges are most vulnerable than faces

Shape factors
Dimensionless quantities calculated from measured dimension, such as diameter, area, perimeter, etc. The factors are normalized, that is the values range from 0-1 where 1 represents an ideal case of maximum symmetry.
Boulders shape – Source of errors

- To classify each area in terms of shape factors
- To compare pre and post perihelion shape factors

Elongation and azimuth

**Synthetic image test**

(A) Random
(B) azimuth = 120 elevation = 20
(C) azimuth = 55 elevation = 40
(D) azimuth = 120 elevation = 50

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Quantitative analysis of Imhotep, Hapi and Hatmehit boulder populations on comet 67P/Churyumov-Gerasimenko


(Affiliations can be found after the references)
Analysis of OSIRIS images

- Quantitative analysis of Imhotep, Hapi and Hatmehit boulder populations on comet 67P/Churyumov- Gerasimenko
- Measurements of erosion and dust deposits in the Hapi region
Measurements of erosion and dust deposits in the Hapi region

(Jshi et al, 2018)

JETS
22 AUG 2014 and 14 MARCH 2015

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Dust cover or poor spatial resolution?

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

MATLAB tool:
- Acquisition geometry
- Local surface
- Incidence angle

\[ H = l \tan(\pi - i) \]

Boulder definition

SPICE KERNELS

Height

Variation in height?

Measurements of erosion and deposit

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Data set

2014-08-21 19:42:54
2014-12-10 06:29:11
2015-01-22 23:29:54
2016-06-19 11:09:40
2016-07-20 08:02:36

22 August 2014
14 March 2015

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Matlab tool – Selection of an epoch

- We defined the boresight and the frame of instrument (NAC) by spice kernels
- We computed the boresight intercept of the projective ray of each pixel on the body shape (M0004 Vertices) at specific epoch.

10 December 2014 06:29:11
Matlab tool – Image alignment

- Define transformation (Bundle Adjustment) between the 3D model and the pinhole camera model (it describes the mathematical relationship between the coordinates of a point in three-dimensional space and its projection onto the image plane of an ideal pinhole camera).
- We applied a Laplacian filter to the height model in the camera frame to fixed tie points. The Laplacian of an image highlights regions of rapid intensity change and is therefore often used for edge detection.
Matlab tool – Local surface definition

Define surfaces around the boulders to define the mean surface reference system on which calculate the incidence angle
• To avoid the local granularity of the mesh
• To mediate the surface irregularities
Matlab tool – Incidence and emission angles

Incidence and emission angles are measured on the local surface avoiding the local granularity of the mesh.

Range from spacecraft to intercept point (km): 20.365
Intercept solar incidence angle (deg): 50.644176
Intercept emission angle (deg): 41.261912
Matlab tool – Selection of shadow’s peak

Select region for shadow peak

Select Shadow peak
Matlab tool – Shadow’s direction and length measurement
Preliminary results

- Tool capable of measuring heights of a target on 2-d images
- Estimate of the deposit thickness within the considered region

**Assumption**
We assume a variation not considering the erosion and activity of the boulder itself

Fragmentation model
Thermal and stress analysis
Thermal analysis of boulders on comet 67P/C-G

How was the boulder fragmented?

- Evidences for thermal fragmentation
- Far from landslides and niches

Good candidate for thermal cracking

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Thermal analysis of boulders on comet 67P/C-G - Aim

Perform theoretical studies of transient temperature and thermal stress on boulder of comet 67P

COMSOL Multiphysics Modeling Software – Finite Element Method (FEM)
Thermal analysis of boulders on comet 67P/C-G - FEM

Perform theoretical studies of transient temperature and thermal stress on boulder of comet 67P

**COMSOL** Multiphysics Modeling Software – Finite Element Method (FEM)

Geometry and mesh
Geometry and mesh (1/3) - Geometry

Model 1

Depth

Ice
Solid/ cometary material

Model 2

Depth

Solid/ cometary material + residual gases
Geometry and mesh (2/3) - Approximations

1° approximation
Shape of boulder: sphere

2° approximation
½ D just to compare results

3° approximation
No single point of contact

½ D

1/3 D

......

1/20 D
Sphere diameter (D): 40 m  
(Cambianica et al., in prep.)
Regolith depth: 0.1 < m < 2.0  
(Mottola et al., 2015)
Block size: 2D x 2D x 2D  
(Molaro et al., 2015 )

Mesh:
Tetrahedral elements
Controlled by physics + manually adjustment
Perform theoretical studies of transient temperature and thermal stress on boulder of comet 67P

**COMSOL** Multiphysics Modeling Software – Finite Element Method (FEM)

- Geometry and mesh
- Material selection and properties
Material selection (1/8) - VIRTIS

VIRTIS
Visible InfraRed Thermal Imaging Spectrometer
(Capaccioni et al., 2015)

67P composition
(Quirico et al., 2015)

- CH chemical groups
- OH chemical groups
- Refractory material
- Polyaromatic organics solid
- Sulfides
- Fe-Ni alloys

Credits: INAF-IAPS
Two-phase mixture

- \( K_c > K_d \)
  \[
  R_{e} = \frac{2}{\sqrt{-C(K_d - K_c)(K_e + B(K_d - K_c))}}
  \]
  \[
  \tan^{-1} \left( \frac{B}{2} \sqrt{-\frac{C(K_d - K_c)}{K_e + B(K_d - K_c)}} \right) + \frac{1 - B}{K_e}
  \]

- \( K_c < K_d \)
  \[
  R_{e} = \frac{1}{\sqrt{-C(K_d - K_c)(K_e + B(K_d - K_c))}}
  \]
  \[
  \ln \left( \frac{\sqrt{K_e + B(K_d - K_c)} + \frac{B}{2} \sqrt{-C(K_d - K_c)}}{\sqrt{K_e + B(K_d - K_c)} - \frac{B}{2} \sqrt{-C(K_d - K_c)}} \right) + \frac{1 - B}{K_e}
  \]

- \( B = \sqrt{3Pd/2} \)
- \( C = -4 \sqrt{\left( \frac{2}{3} \right) Pd} \)

**Kd** = thermal conductivity of the discontinuous phase

**Kc** = thermal conductivity of the continuous phase
Material selection (4/8) – Thermal conductivity of mixtures

Cheng and Vachon model, 1968

Three-phase mixture

\[ R_e = \int \frac{dx}{K_c + \left(\frac{K_{d1} - K_c}{K_c}\right)y_1 + \left(\frac{K_{d2} - K_c}{K_c}\right)y_2} \]

- \( \frac{K_{d1}}{K_c} > 100 \) and \( \frac{K_{d2}}{K_c} > 100 \)
- \( \frac{K_{d1}}{K_c} > 100 \) and \( 10 < \frac{K_{d2}}{K_c} < 100 \)
- \( 10 < \frac{K_{d1}}{K_c} < 100 \) and \( 10 < \frac{K_{d2}}{K_c} < 100 \)
- \( \frac{K_{d1}}{K_c} \sim 10 \) and \( \frac{K_{d2}}{K_c} \sim 10 \)
- \( \frac{K_{d1}}{K_c} \sim 10 \) and \( \frac{K_{d2}}{K_c} \sim 1 \)
- \( \frac{K_{d1}}{K_c} \sim 1 \) and \( \frac{K_{d2}}{K_c} \sim 1 \)
- \( \frac{K_{d1}}{K_c} < 1 \) and \( \frac{K_{d2}}{K_c} < 1 \)
Material selection (5/8) – Thermal conductivity – Model 1

Khader e Vachon model, 1973
Kumar et al. model, 1975

Model 1

Two-phase mixture

Model 1a
Model 1b

1a

Two-phase mixture

1b

Three-phase mixture

\[ R_e = \int \frac{dx}{K_c + (K_{d1} - K_c)y_1 + (K_{d2} - K_c)y_2} \]

- \( K_c > K_d \)
  \[
  R_e = \frac{1}{\sqrt{C(K_d - K_c)[K_c + B(K_d - K_c)]}} \left( -\frac{B}{2} \sqrt{\frac{-C(K_d - K_c)}{K_c + B(K_d - K_c)}} \right) + \frac{1 - B}{K_c}
  
- \( K_c < K_d \)
  \[
  R_e = \frac{1}{\sqrt{C(K_d - K_c)[K_c + B(K_d - K_c)]}} \left( -\frac{B}{2} \sqrt{\frac{-C(K_d - K_c)}{K_c + B(K_d - K_c)}} \right) + \frac{1 - B}{K_c}
  
1 solid material + ice
2 solid materials + ice

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Material selection (7/8) – Thermal conductivity – Model 2

Khader e Vachon model, 1973
Kumar et al. model, 1975

One-phase mixture

\[ K_{\text{eff}} = \frac{3(1 - P)(1 - C_1^2 Z^{2/3}) K_s}{(\pi/2)(\frac{3}{2C_1^2 Z^{17/3}} - 1) + (4 - 1.2C_1^2 Z^{2/3})} \]

\[ C_1 = \frac{2g \rho \pi (1 - \nu^2)^{1/3}}{16E(1 - P)} \]

P = porosity
Z = depth
Ks = thermal conductivity of the solid material
\( \rho \) = density
\( g \) = gravitational constant
E = modulus of elasticity
\( \nu \) = Poisson’s ratio

Two-phase mixture

\[ R_e = \frac{1}{\sqrt{\frac{K_s + B(K_d - K_s)}{K_s + B(K_d - K_s)}}} \]

\[ \tan^{-1} \left( \frac{B}{2} \right) \sqrt{-\frac{C(K_d - K_s)}{K_s + B(K_d - K_s)}} + \frac{1 - B}{K_s} \]

\[ \frac{2}{\sqrt{-C(K_d - K_s)(K_s + B(K_d - K_s))}} \]

\[ K_{\text{eff}} \]

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Perform theoretical studies of transient temperature and thermal stress on boulder of comet 67P

**COMSOL Multiphysics Modeling Software – Finite Element Method (FEM)**

- Geometry and mesh
- Material selection and properties
- Physics, boundary conditions and heat source

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Physics, boundary conditions and heat source (1/3)

NAIF SPICE

- Specific incidence angles at selected epoch and region (Imhotep in this case)
- X sun, Y sun, Z sun
- Comet 67P– Sun distance

\[ Q_{abs} = (1 - A) \frac{S_0}{R^2} \cos(i) \]

- A = albedo
- \( S_0 \) = solar constant
- \( R \) = comet 67P-Sun distance
- \( i \) = incidence angle
Physics, boundary conditions and heat source (2/3)

NAIF SPICE

- Specific incidence angles at selected epoch and region (Imhotep in this case)
- X sun, Y sun, Z sun
- Comet 67P– Sun distance

\[ Q = (1 - A) \frac{S_0}{R^2} \cos(i) \]

- \( A \) = albedo
- \( S_0 \) = solar constant
- \( R \) = comet 67P-Sun distance
- \( i \) = incidence angle

Input parameters

Comsol Multiphysics

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Heat transfer with surface-to-surface radiation

Model heat transfer by conduction, convection, and radiation

- Heat equation
  \[ \rho C_p \frac{\partial T}{\partial t} + \rho C_p u \nabla T + \nabla q = Q \]
- Fourier’s law of heat conduction
  \[ q = -k \nabla T \]

\( \rho \) = density [kg/m\(^3\)]
\( C_p \) = heat capacity at constant pressure [J/kgK]
\( K \) = solid thermal conductivity [W/mK]
\( u \) = velocity field if the parts of the model is moving
\( Q \) = heat source [W/m\(^3\)]

\( T_{abm} = 100 \text{ K} \)
\( P_{amb} = 0 \text{ Pa} \)

Solid Mechanics

Linear elastic material

\[ \nabla S + F_v = 0 \]

\( S \) = stress gradient
\( F_v \) = external force

Transient study

\[ \frac{\partial T}{\partial t} \]
Future works
Measurements of erosion and dust deposits in the Hapi region

- Extend the statistics by analyzing other images
- Discriminate between dust cover variation and boulder’s activity
- Apply this method to other regions and other objects
- Analyze possible volumetric variations of big boulders

Thermal and stress analysis

- Shape of boulder: different shapes, irregularities, edges, cavities
- Perform the analysis from different combinations of materials, geometry, etc...
- Correlate the Von Mises stress with the propagation of cracks

- Propagate cracks

Fragmentation model
### Personal training plan and Gantt bar chart

<table>
<thead>
<tr>
<th>Interdisciplinary Module/Activity</th>
<th>Expected ECTS</th>
<th>Attained ECTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>19.2</td>
<td>19.2</td>
</tr>
</tbody>
</table>

| Curriculum oriented activities    | 17.84        | 11.82        |

| Other educational activities      | 4.8          | 4.8          |

| TOT                               | 41.84        | 35.52        |

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**Gantt Bar Chart**

<table>
<thead>
<tr>
<th>LEVEL</th>
<th>ACTIVITY DESCRIPTION AND EVENTS</th>
<th>I YEAR</th>
<th>II YEAR</th>
<th>III YEAR</th>
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<tbody>
<tr>
<td>Event</td>
<td>Presentation for approval research</td>
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<td>WP100</td>
<td>OSIRIS and the Rosetta Mission</td>
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<td>WP110</td>
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<td>WP111</td>
<td>The ROSETTA mission</td>
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<td>WP112</td>
<td>The OSIRIS camera</td>
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<tr>
<td>WP200</td>
<td>Comets and the 67P/Churyumov-Gerasimenko comet</td>
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<td>WP211</td>
<td>Formation and evolution</td>
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<tr>
<td>WP212</td>
<td>Geomorphology</td>
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<td>WP213</td>
<td>Thermodynamics</td>
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<tr>
<td>WP300</td>
<td>Image analysis</td>
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<td>WP310</td>
<td>Study of the related literature</td>
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<td>WP320</td>
<td>OSIRIS archive and images</td>
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<td>Statistical analysis - size-frequency</td>
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<td>Fractal theory</td>
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<td>WP360</td>
<td>Boulders and fragments shape</td>
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<td>Thermodynamic and sublimation</td>
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**Admission to third year – Pamela Cambianica**
Publications

Papers

- Quantitative analysis of Imhotep, Hapi and Hatmehit boulder populations on comet 67P/Churyumov-Gerasimenko
  Cambianica, P. et al. (in prep)
- The backscattering enhancement of comet 67P/Churyumov-Gerasimenko dust coma as seen by OSIRIS onboard Rosetta
  Bertini, I. et al. 2018
- The big lobe of 67P/Churyumov-Gerasimenko comet: morphological and spectrophotometric evidences of layering as from OSIRIS data
  Ferrasi, S. et al. 2018
- Multidisciplinary analysis of the Hapi region located on Comet 67P/Churyumov-Gerasimenko

Abstracts, conference proceedings

- EPSC 2018 - Thermal analysis of boulders on the 67P/Churyumov-Gerasimenko comet
  Cambianica, P. et al.
- SAIT 2018 - Quantitative analysis of Imhotep, Hapi and Hatmehit boulder populations on comet 67P/Churyumov-Gerasimenko
  Cambianica, P. et al.
- EPSC 2018 - Geomorphological units of Khepry and Imhotep regions of comet 67P/Churyumov-Gerasimenko
  Ferrari, S. et al.
- EPSC 2018 - 3DPD application to the first CaSSIS DTMs
  Simioni, E. et al.
Thanks for the attention

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Credits: ESA