ESAC Small Solar System bodies and Rosetta Group

The current focus of the group is the analysis of images from the OSIRIS scientific cameras of the Rosetta mission.

Research topics are:
- Surface features of the nucleus and their interrelation with comet activity
- Properties of individually observed dust particles and implied information about the formation of the comet
- Chemical homogeneity of the nucleus and processes in the innermost coma from analysis of gas emissions
- Analysis of large data sets to find statistical properties, trends, etc., with automated analysis.

Other research topics:
- Detection of volatiles on asteroids and dwarf planet Ceres and their interpretation
- Surface properties of asteroids and their evolution with time

Michael Küppers

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Sebastien Besse

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Fernando Pérez

Claudio Muñoz

https://www.cosmos.esa.int/web/esac-science-faculty/comet-rosetta-group

Individual particle studies in the determination of the understanding the physical and chemical processes in the coma and the imprint of primordial processes in cometary material

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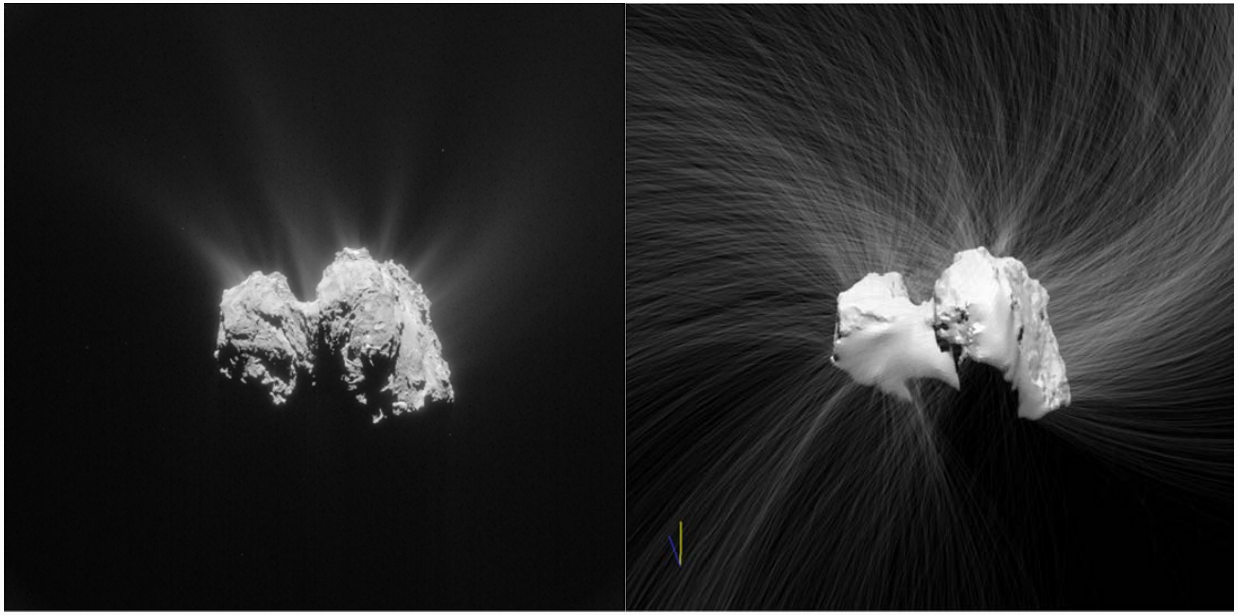
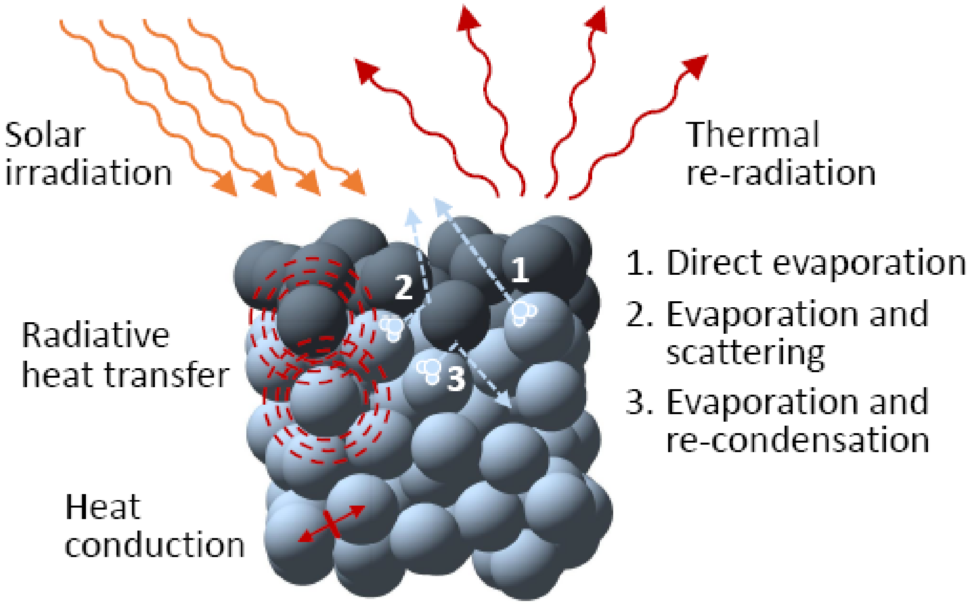
European Space Astronomy Center (ESAC), European Space Agency, Villanueva de la Cañada, Madrid, Spain



Why study dust in coma?

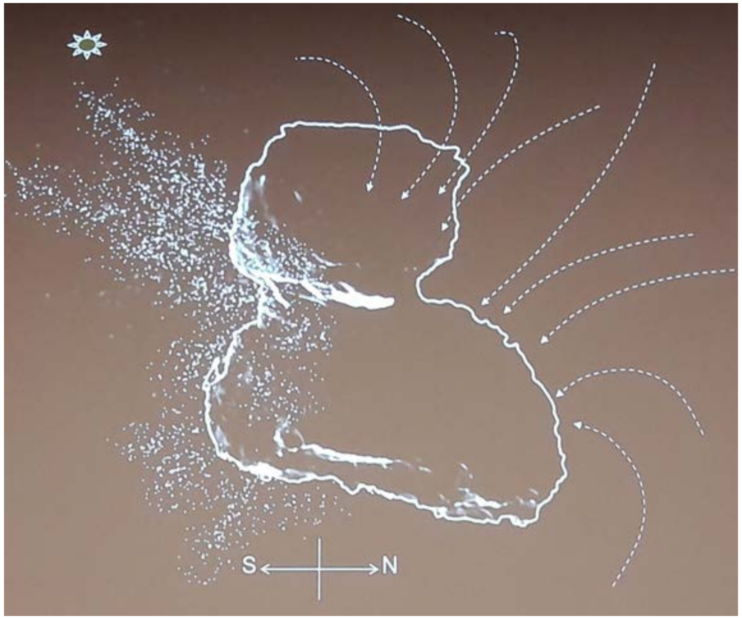
- Unresolved questions: cm-sized pebbles from streaming instability (Blum et al.2015) or larger blocks from hierarchical agglomeration (Davidsson et al.2016)?



Blum et al. 2015

Dust pebble formed with refractory material & ice if comet nuclei formed by gentle gravitational collapse of a bound clump of dust aggregates.

- Current size distribution may answer the question. Careful! Evolutional processes…



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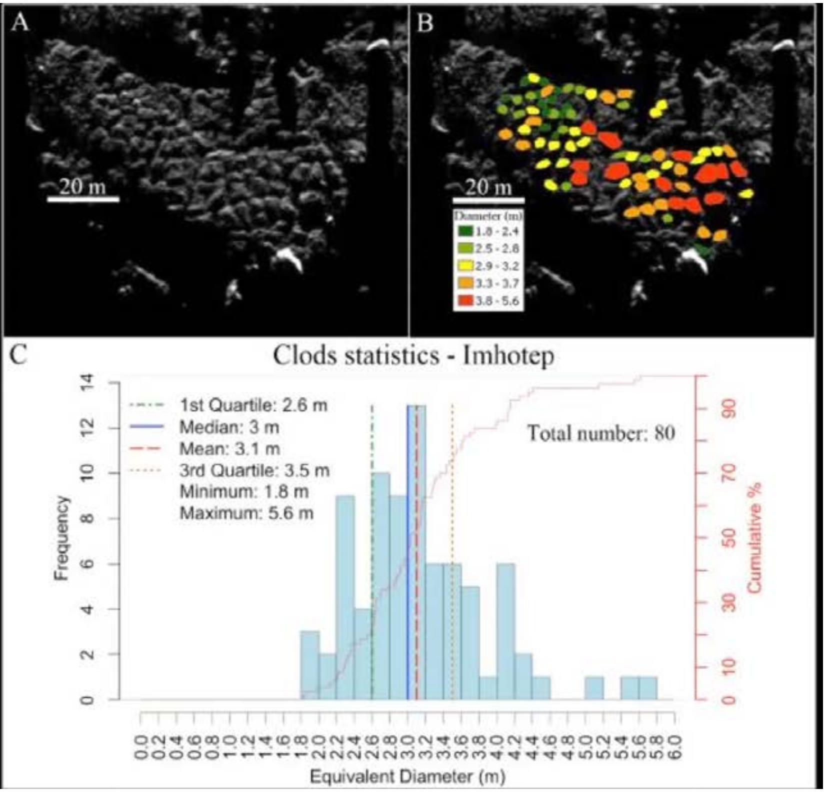
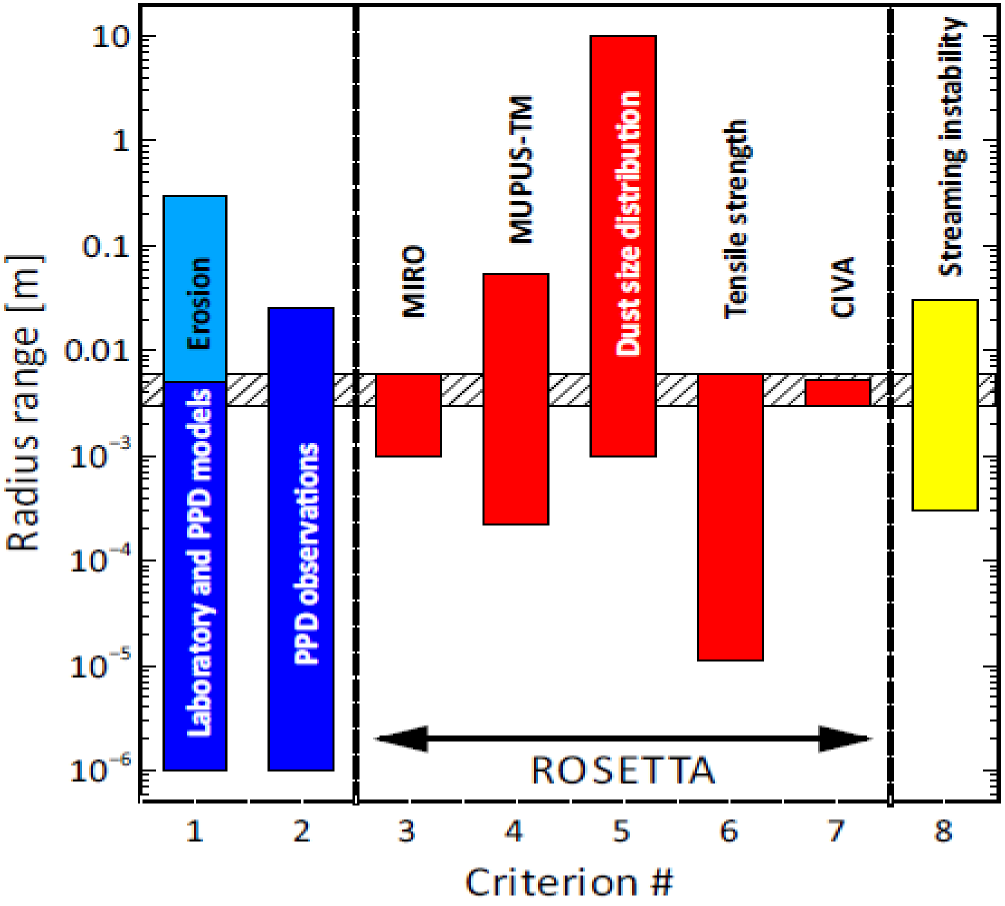


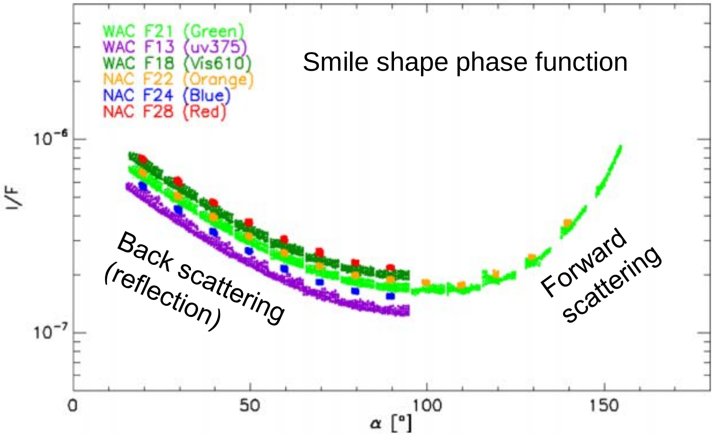
Davidsson et al. 2016

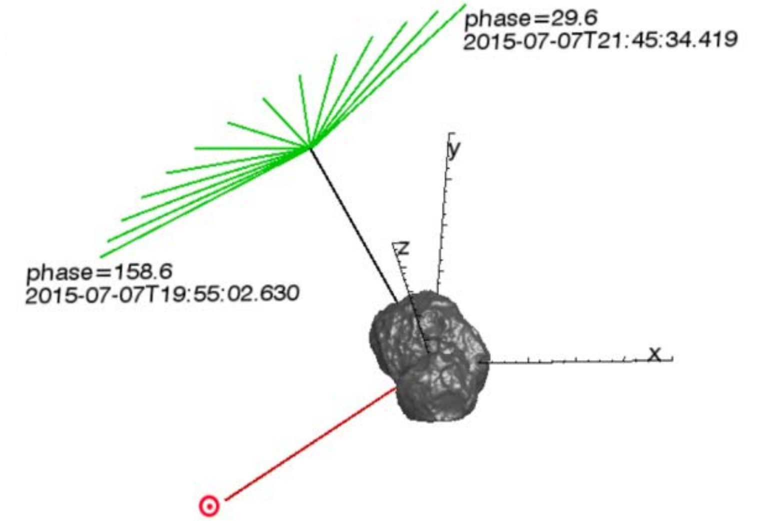


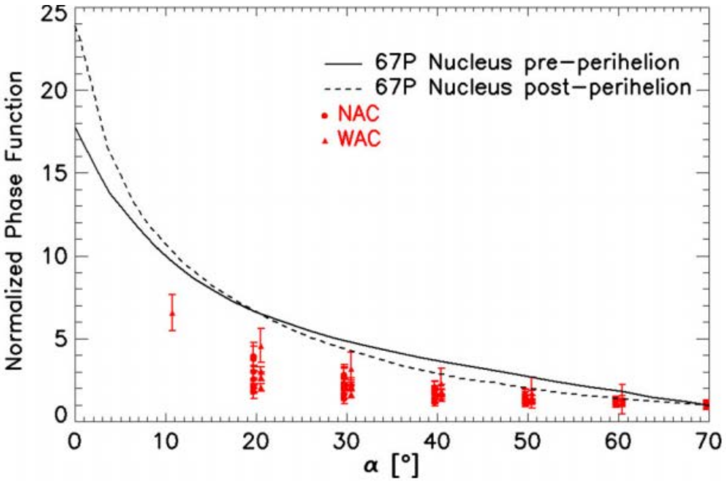
Blum et al. 2015

Dust size distribution

- Unresolved dust, phase function from small particles
  - overall phase function shape constant in time
  - Reflectance increases with phase angle
  - Consistent with other comets
  - Single scattering, the dominant, regardless of the distance from the nucleus
  - Background coma doesn't change its spectrum with time or distance from the comet
  - At angles < 30 nucleus redder than coma. Scattering modelling and laboratory measurements needed





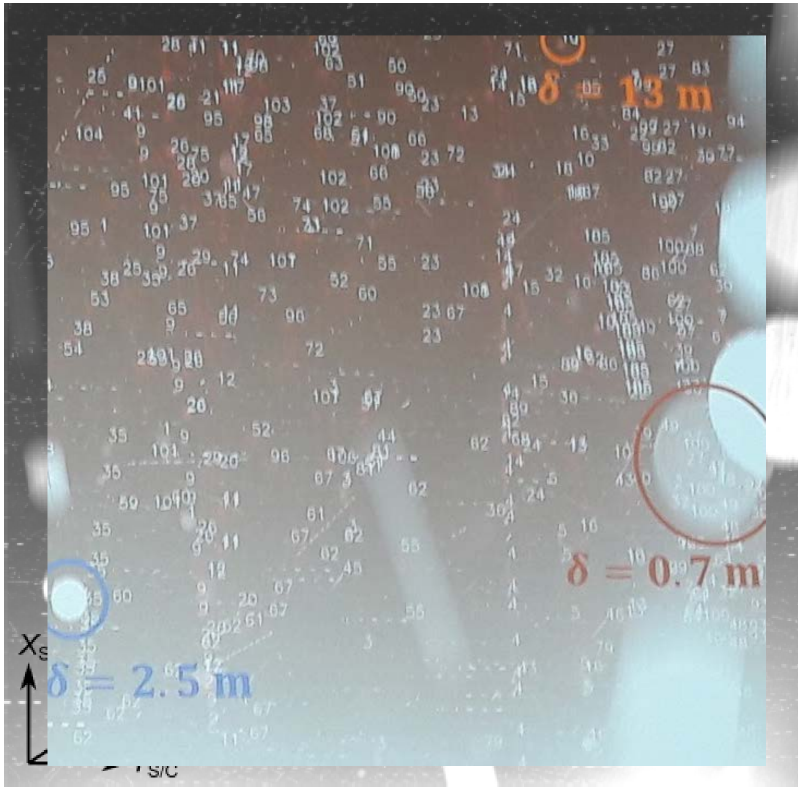


Bertini et al. 2017

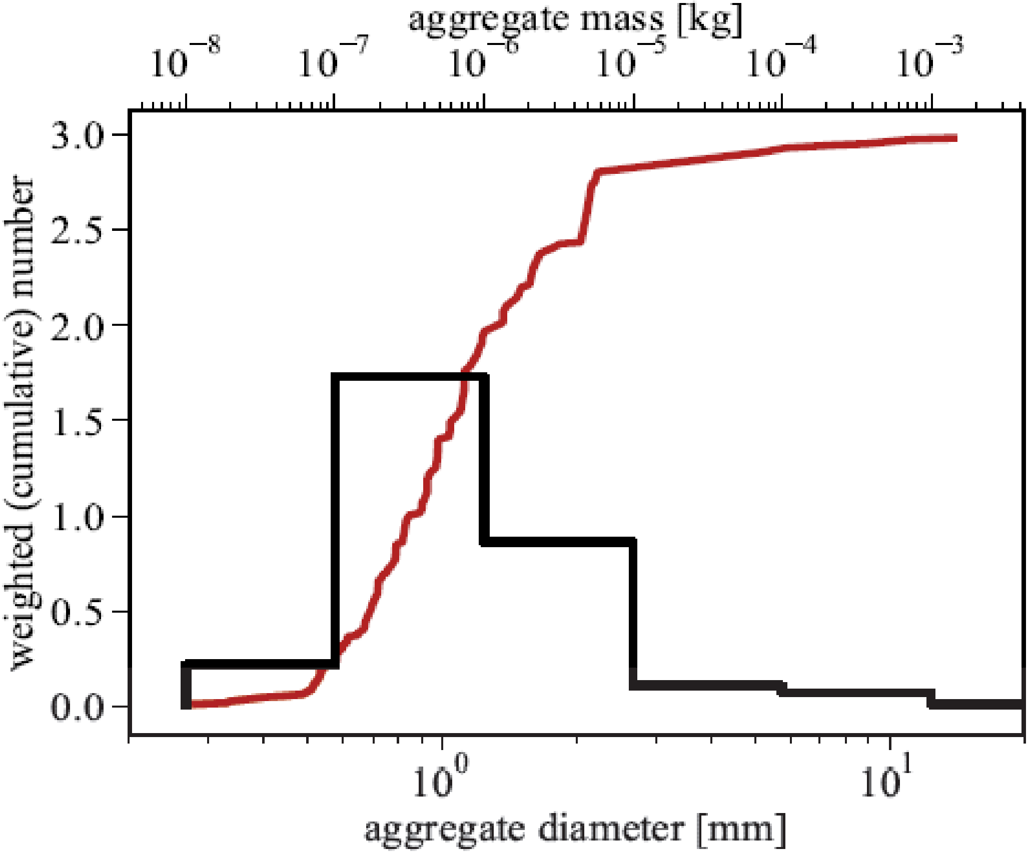
Dust size distribution

- Individual particles in different size ranges (<1mm up to >1m)

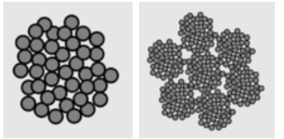
Which size ranges a



Güttler et al. 2016



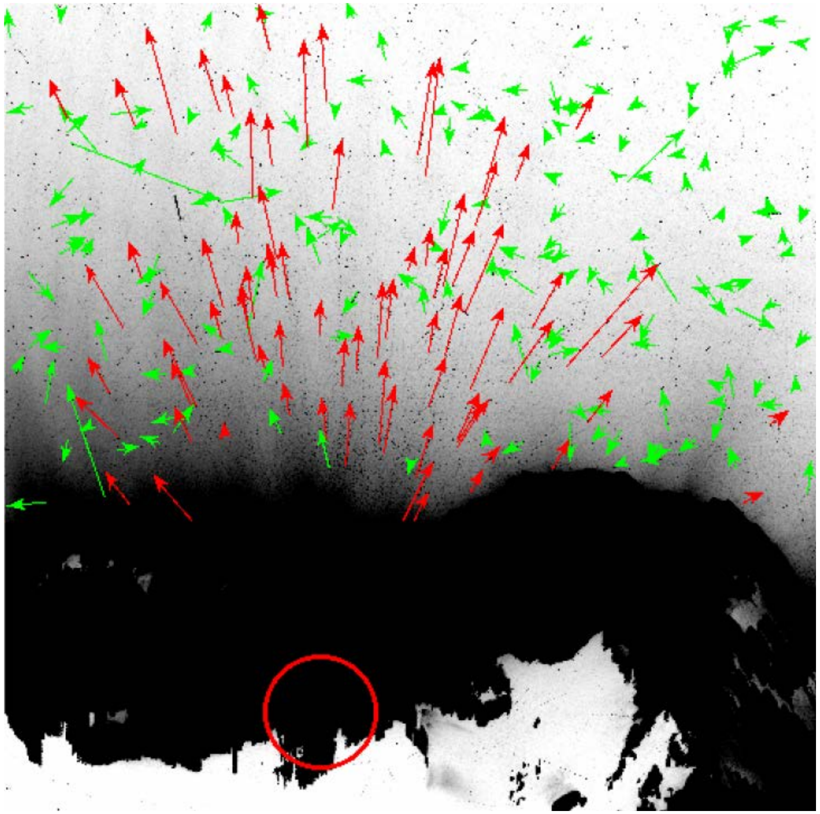
Distances 0.6 – 100 m from Rosetta



Dust size distribution

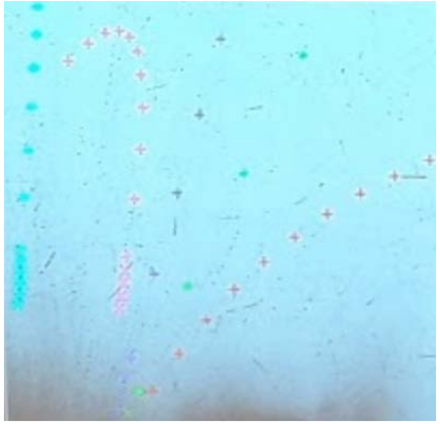
- Individual particles in different size ranges (<1mm up to >1m)

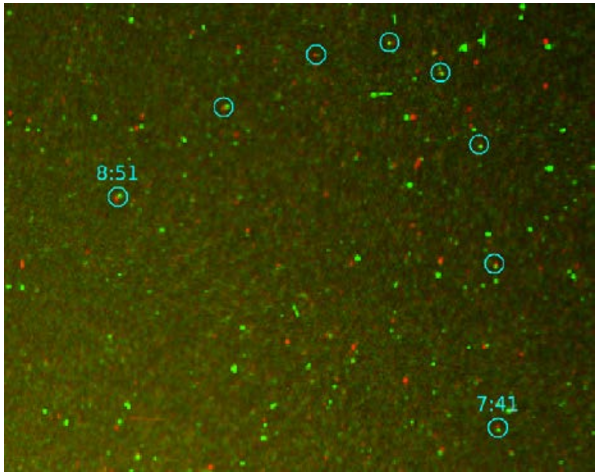
Which size ranges are dominant ? → Systematic study



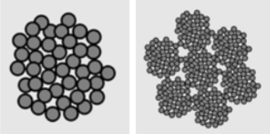
Agarwal et al. 2016

- First direct measurement of the acceleration of aggregates in the innermost coma.
- Combined forces of gravity, gas drag and rocket effect.
- Temporal brightness decreased cos ice sublimation?
- Accelerations up to 10 times larger than g
- Projected velocities of aggregates ≈ 1 m/s





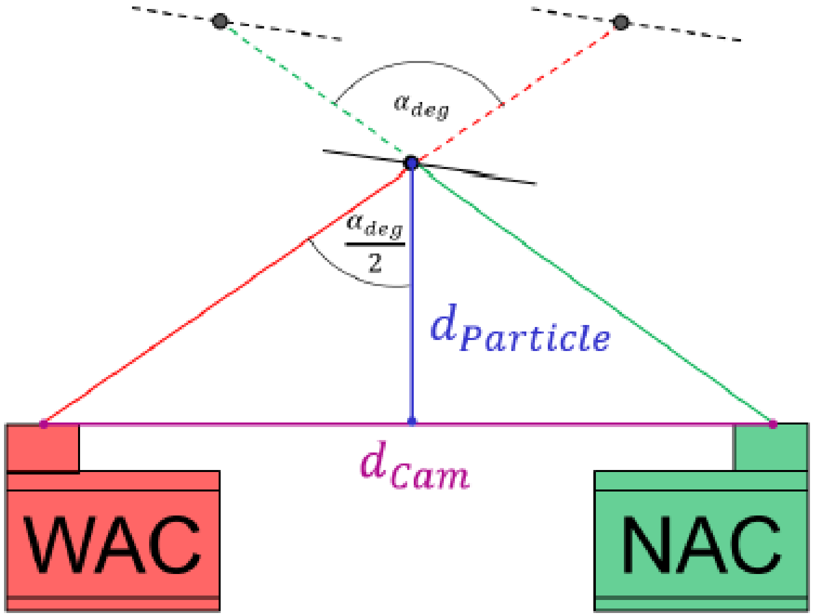
Distances 87 km from Rosetta



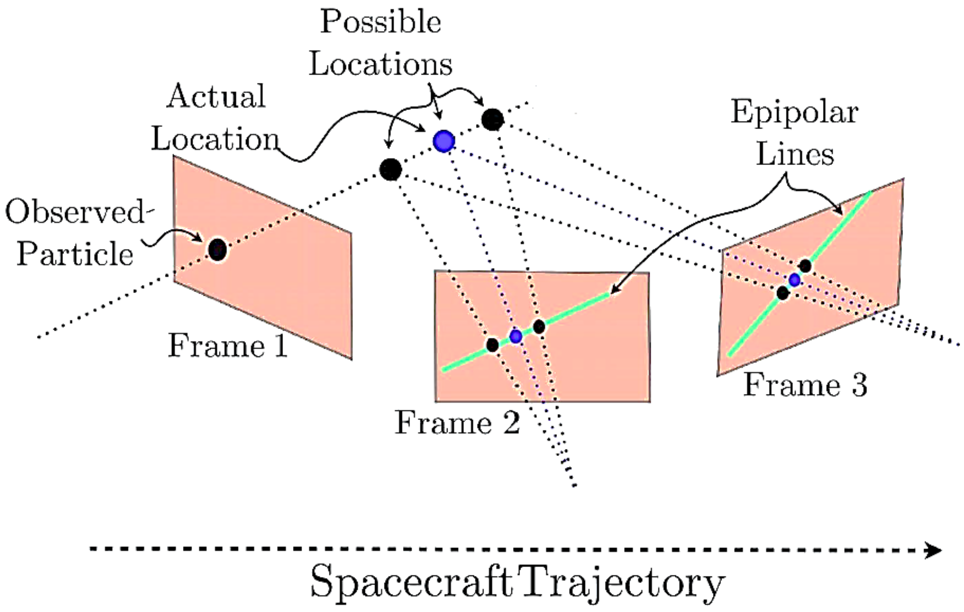
Dust size distribution

- Individual particles in different size ranges (<1mm up to >1m)

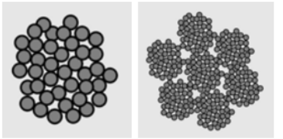
Which size ranges are dominant ? → Systematic study



Drolshagen & Ott et al. 2017



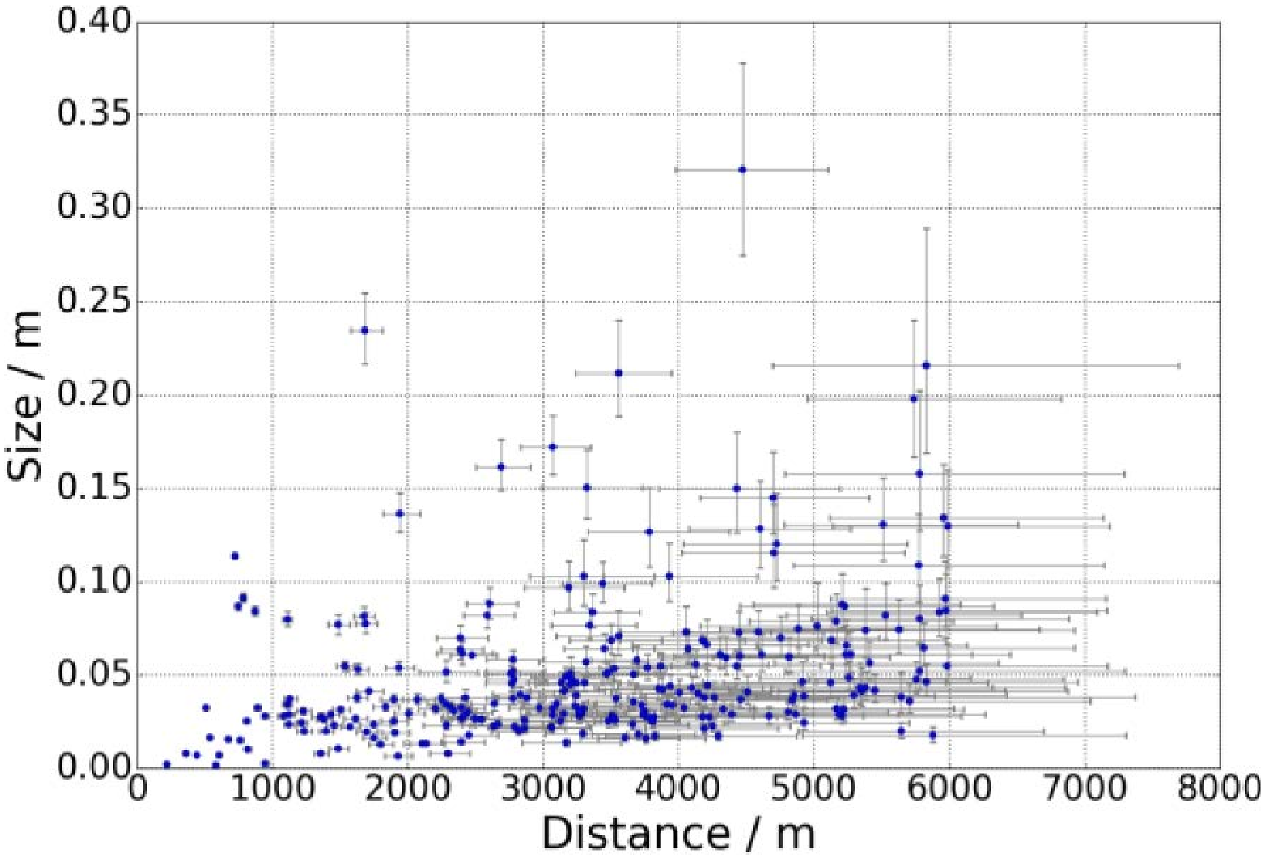
Distances 500 – 1600* m from Rosetta

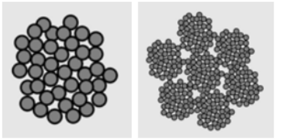


Dust size distribution

- Individual particles in different size ranges (<1mm up to >1m)

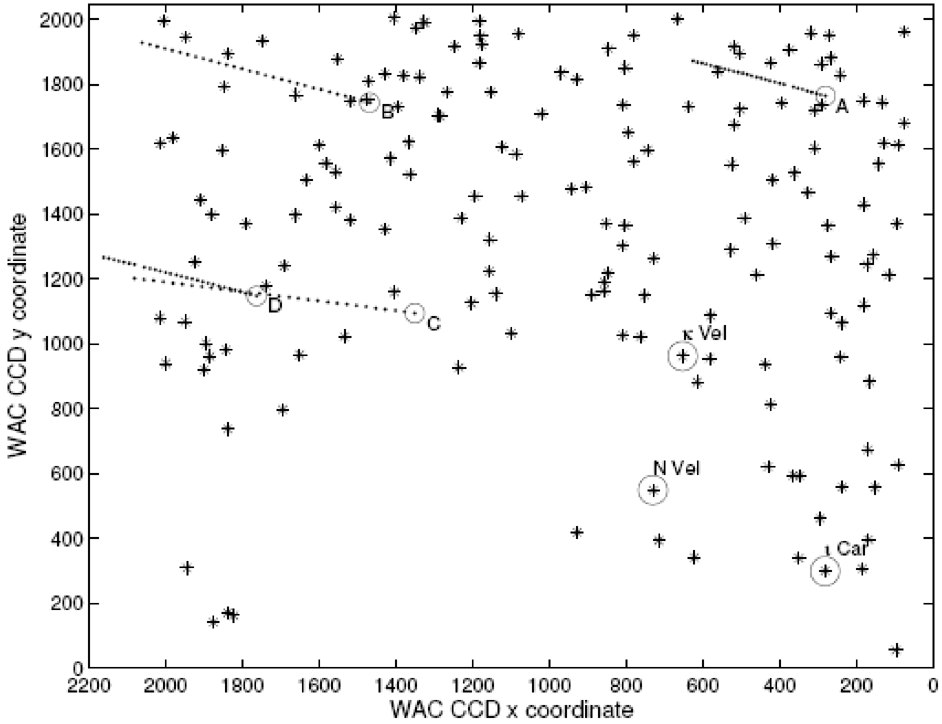
Which size ranges are dominant ? → Systematic study

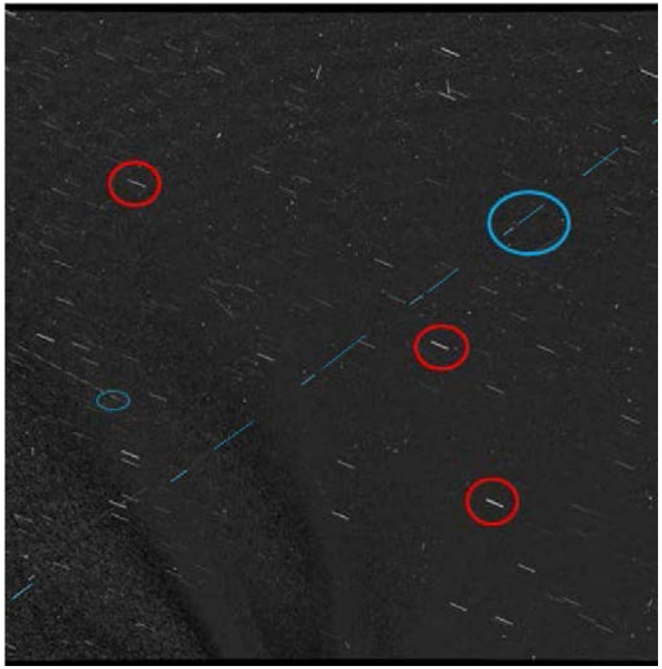




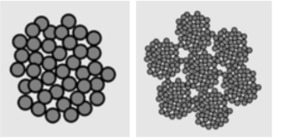
Particle trajectories: bound versus escape

- Lots of papers with assumptions, few with numerical trajectories.
- Davidsson et al.2015: Individual particle trajectories early in the mission → numerical trajectories, but limited observing time → inconclusive bound vs. escaping
- Research plan: to repeat study with particles observed later over a longer time scale



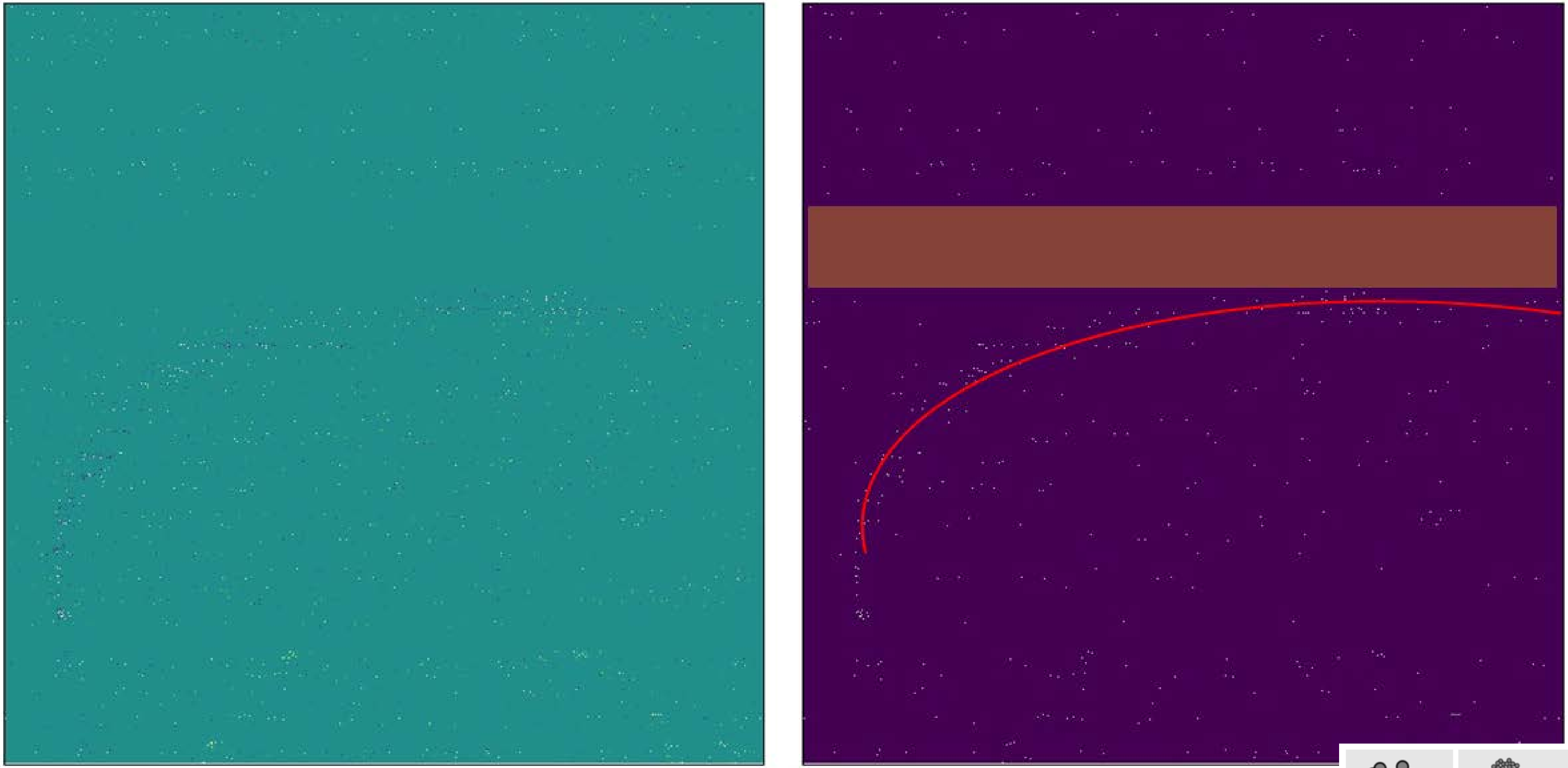


Davidsson et al. 2015



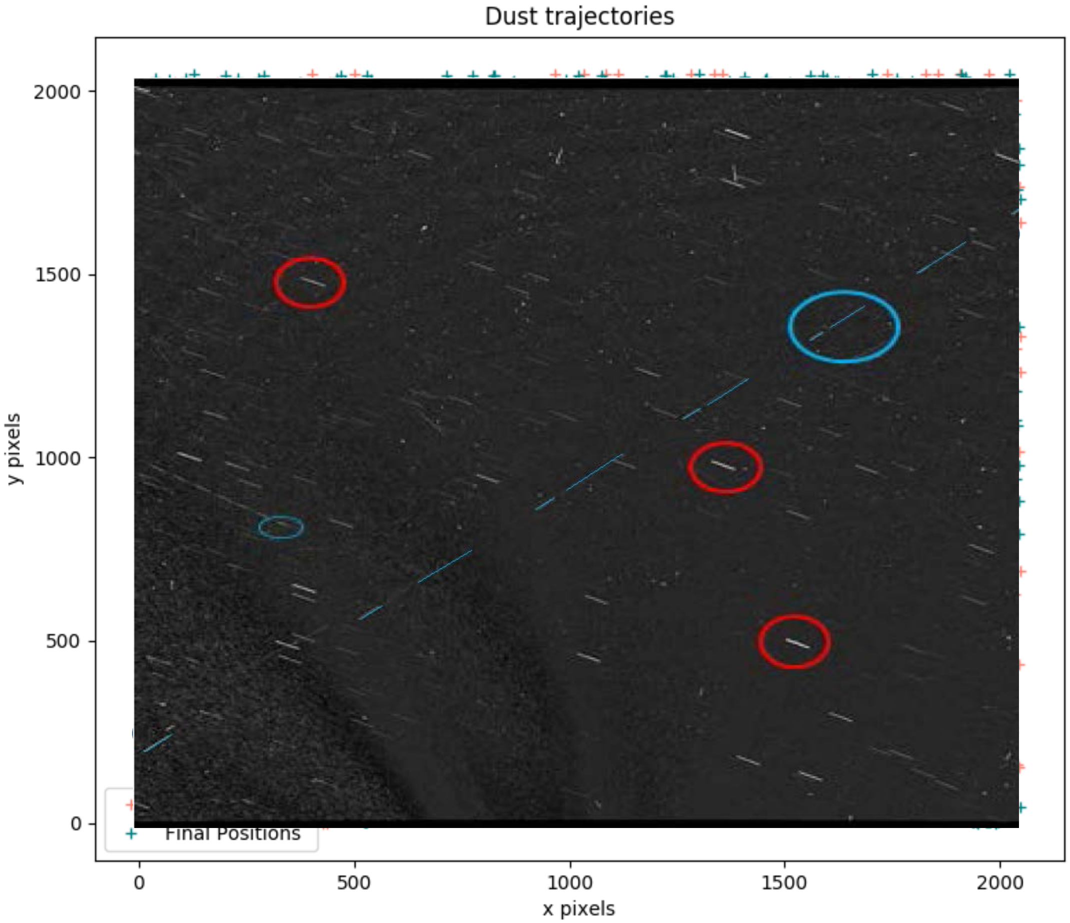
Particle trajectories: automatic processes

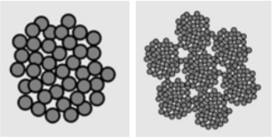
- Research plan: to repeat study with particles observed later over a longer time scale



Particle trajectories: automatic processes

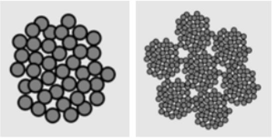
- **Research plan**: to repeat study with particles observed later over a longer time scale





Next Steps

- “Cluster” determinations (now it takes porous groups as points)
- Testing trends algorithms (differs stars from dust from “others”)
- Cleaning “noise” (limb, e.g.): the key for success is to reduce the number of false detections
- Run big sets of data (up to 100 images)
- Looking for individual segregating particles / rotating particles
- AI algorithms applied to calculation of trajectories
- Generating user friendly canvas -> PaDe SW idea
- Evaluating star trackers / other sources as sources of dust data



Physical processes in cometary atmospheres derived from narrowband imaging of gaseous fragment species

**Fernando Pérez-López, Julia Marín-Yaseli de la Parra, Michael Küppers,
the ESAC Small solar system bodies & Rosetta Group and the OSIRIS Team**

*Operations Department, Directorate of Science,
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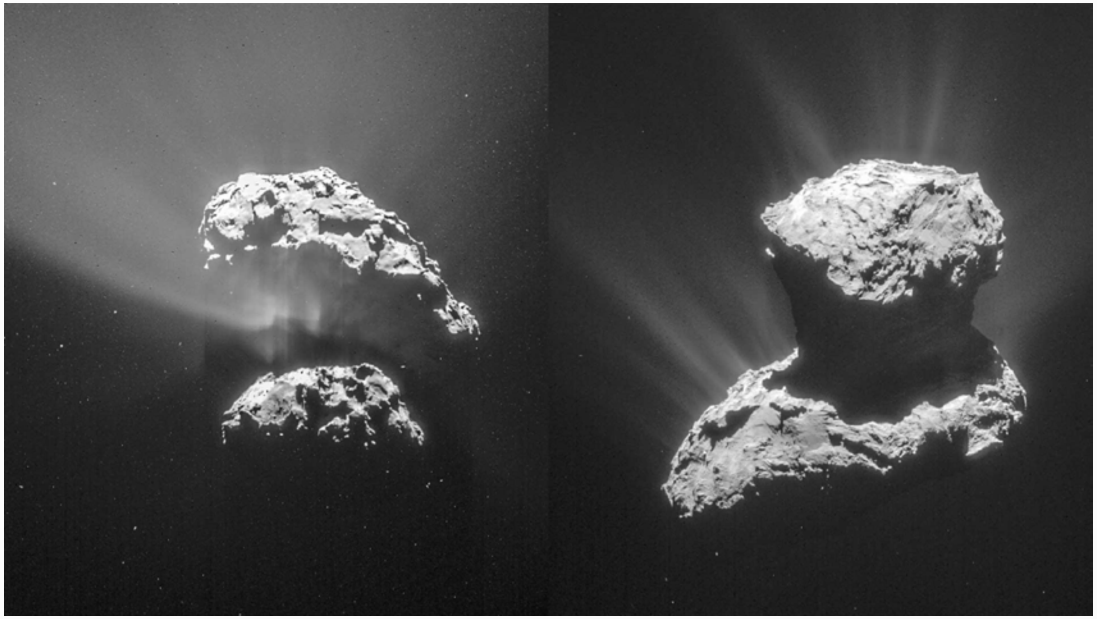
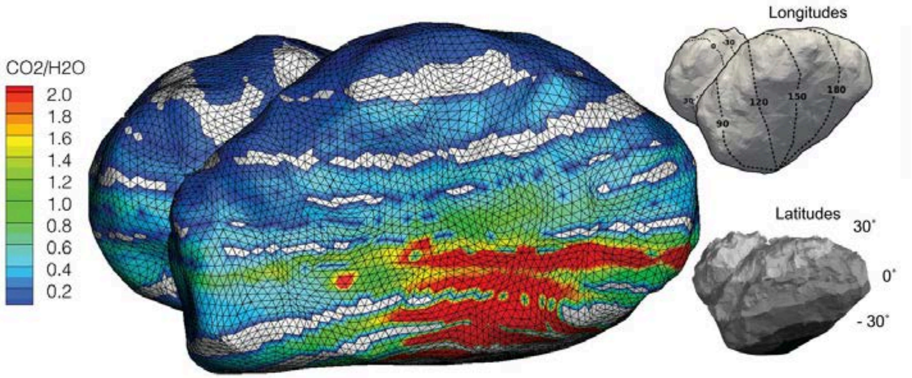


Why study gas in coma?

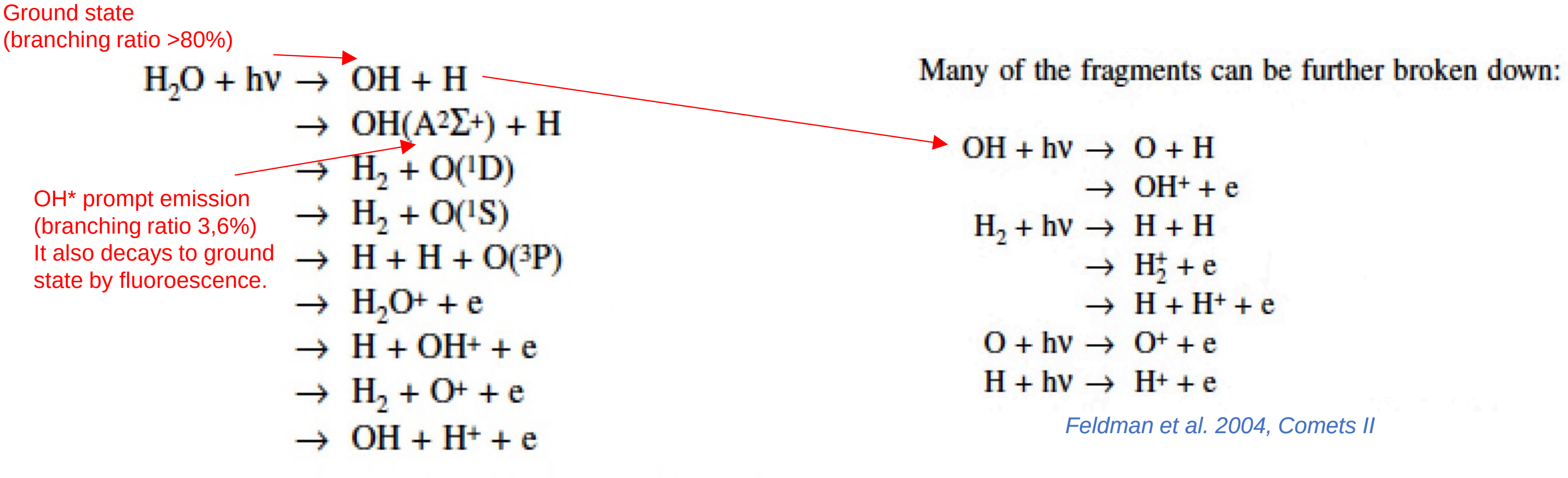


CO_2/H_2O density ratio from August 17 through September 22 mapped onto the shape model

- An important cosmogonical question about comets is whether they are heterogeneous on some spatial scale characteristic of the proto-cometesimal which accreted to form the nucleus.
- Central Question: Is heterogeneity primordial or evolutionary?
- Detailed comet nuclei close-up images suggested that heterogeneity in the coma of a comet may be related to heterogeneity of the nucleus.
- 67P Nuclei heterogeneity in terms of composition of outgassing material was found (*Hässig et al. 2015, Science 347, a0276*)
- The gases that come directly from the nucleus first flow through a region near the nucleus, where the gas densities are sufficiently high that collisions, and photochemical processes (photolysis of parent molecules, excitation mechanisms) change the composition of the gases.

Physical processes in coma

- Considering the OH observations as example:
  - **Photolysis** (or photodissociation**)** of parent molecules: Interaction of one or more photons with one target molecule.
  - **Resonance Fluorescence (RFE)**: An orbital electron of a molecule relaxes to its ground state by emitting a photon (e.g. OH*): $A^2\Sigma^+ - X^2\Pi$
  - **Prompt Emission:** Interaction of one or more photons with one target molecule could produce OH* in the first electronically excited state which by decays to the ground state.



Ground state
(branching ratio >80%)

OH* prompt emission
(branching ratio 3,6%)
It also decays to ground
state by fluoroescence.

$$\begin{aligned}
H_2O + h\nu &\rightarrow OH + H \\
&\rightarrow OH(A^2\Sigma^+) + H \\
&\rightarrow H_2 + O(^1D) \\
&\rightarrow H_2 + O(^1S) \\
&\rightarrow H + H + O(^3P) \\
&\rightarrow H_2O^+ + e \\
&\rightarrow H + OH^+ + e \\
&\rightarrow H_2 + O^+ + e \\
&\rightarrow OH + H^+ + e
\end{aligned}$$

Many of the fragments can be further broken down:

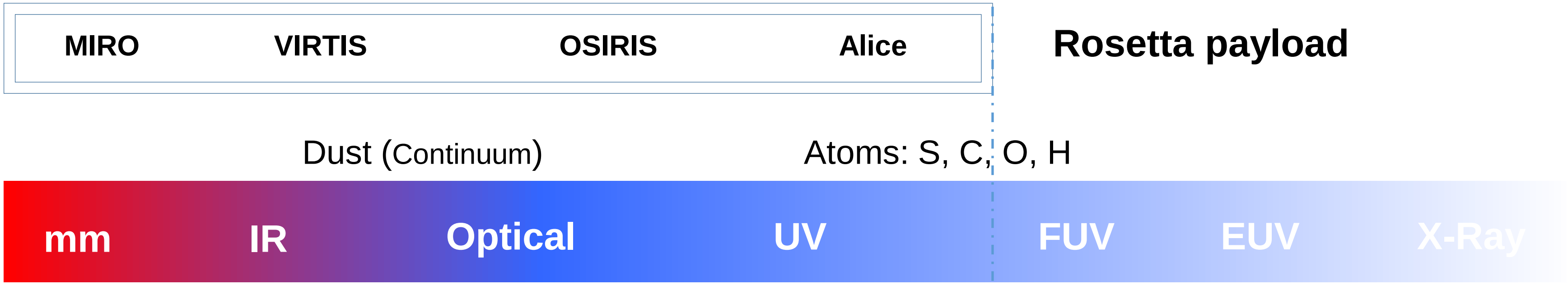
$$\begin{aligned}
OH + h\nu &\rightarrow O + H \\
&\rightarrow OH^+ + e \\
H_2 + h\nu &\rightarrow H + H \\
&\rightarrow H_2^+ + e \\
&\rightarrow H + H^+ + e \\
O + h\nu &\rightarrow O^+ + e \\
H + h\nu &\rightarrow H^+ + e
\end{aligned}$$

Feldman et al. 2004, Comets II

- **Dissociative Electron Impact excitation** (followed by prompt emission):

$$H_2O + e \rightarrow OH^* + H$$

Cometary Spectra



MIRO **VIRTIS** **OSIRIS** **Alice**

Rosetta payload

Dust (Continuum)

Atoms: S, C, O, H

mm **IR** **Optical** **UV** **FUV** **EUV** **X-Ray**

Parent molecules rovibrational
H_2O, CO, HCN, CH_4, CH_3OH

Fragment molecules electronic
CN, NH_2, C_3, C_2, NH, OH, CS, H_2

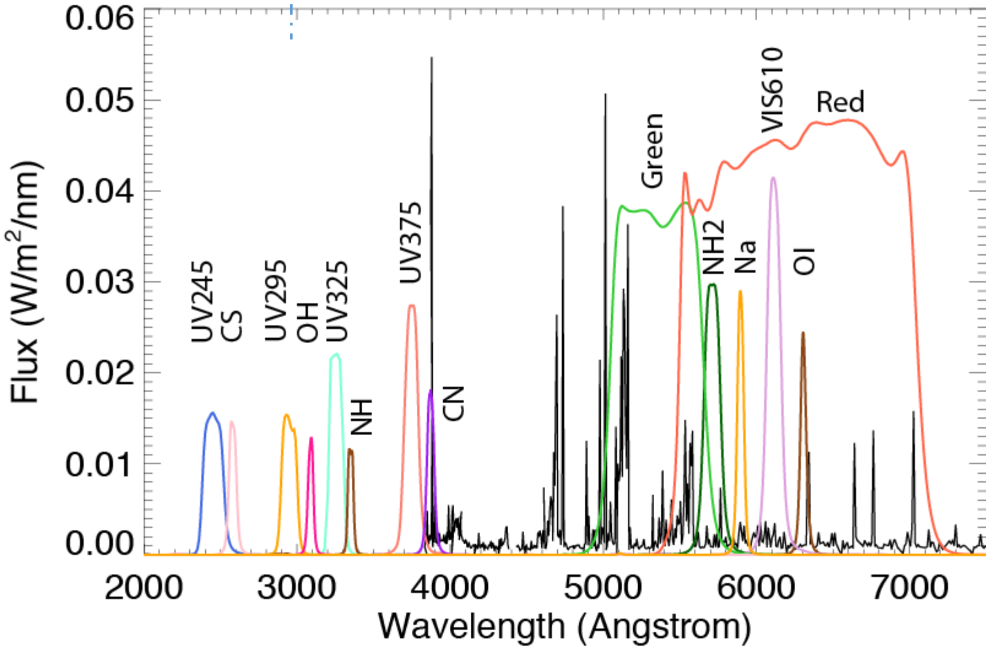
Molecular ions
CO^+, H_2O^+, CO^{2+},

- Analysing the evolution of the brightness and distribution of the gas emissions over time by using the OSIRIS WAC, through perihelion until the end of mission at 3.8 AU outbound, it will be possible to identify the physical processes involved.

- This has been following the same methodology followed by *Bodewits et al*.

  (Bodewits et al. 2016)

Rosetta-OSIRIS' WAC narrowband filters



Bodewits et al. 2016; Cochran 2002

Gas emissions vs. physical processes

Production Rates from photoprocesses

H_2O → OI

H_2O → OH

NH_3 → NH

HCN → CN

H_2O production rates based on MIRO measurements

expected NH_3 and HCN production rates

Emission	Known processes	New processes
CS 257 nm	F (CS_2, CS)	**-**
OH 308 nm	F (H_2O, OH) PD (H_2O,OH)?	EID (H_2O, OH)
NH 335 nm	F (NH_3, NH_2, NH)	EID (H_2O, OH^+)
CN 388 nm	F (HCN, CN)	EID (CO_2, CO_2^+)
NH_2 570 nm	F (NH_3, NH_2)	?
Na 589 nm	RS (dust or Na-bearing molecule, Na)	-
OI 630 nm	PD (H_2O, O)	EID (H_2O, O) EID (CO_2, O)

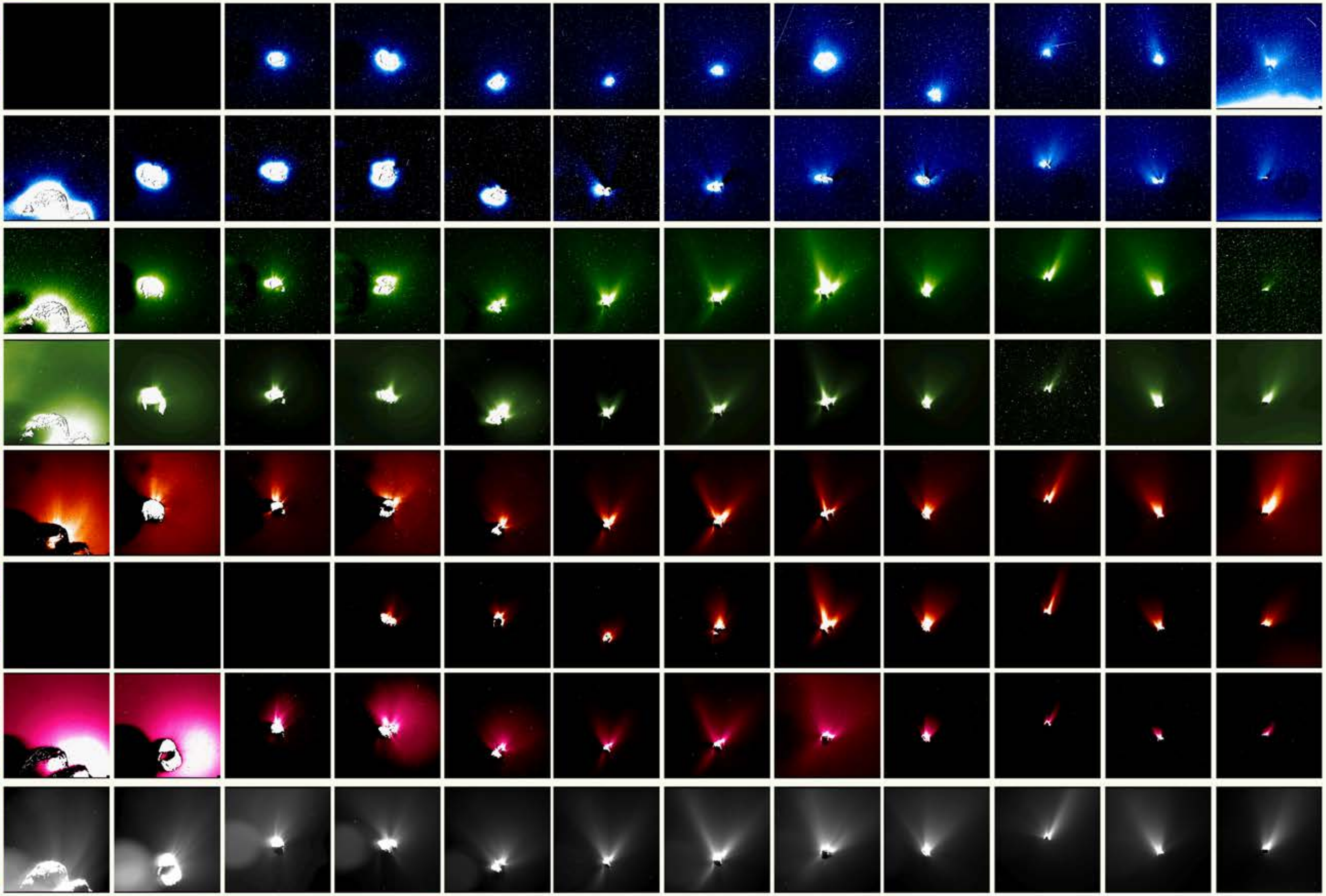
F = Fluorescence
PD = Photo-dissociation followed by prompt emission
EID = Electron Impact Dissociation followed by prompt emission
RS: Resonance Scattering

- Column densities and production rates, based on standard cometary models, derived from OSIRIS images are much higher than those measured by other Rosetta instruments (MIRO, VIRTIS and ROSINA).
- A new process acting in the inner coma had to be found to explain the observations. Electron Impact Dissociation.
- *Bodewits et al.* have been able to explain most of the emissions with electron impact excitation by low energy electrons in the inner coma. Closer to the sun, generally the known processes took over in dominating the observed emissions

So far only part of the data are analysed. More new processes are expected to be found.

Date (Year 2015)	Jan 24th	Mar 12th	Apr 12th	Apr 21st	May 13th	Jun 10th	Jun 29th	Jul 14th	Aug 4th	Aug 14th	Aug 24th	Sep 7th
Heliocentric Distance (AU)	~ 2,47	~ 2,12	~ 1,88	~ 1,81	~ 1,65	~ 1,46	~ 1,36	~ 1,30	~ 1,25	~ 1,24	~ 1,25	~ 1,28

Process *(Parent, Daughter)*	WAC Filter
F (CS_2, CS)	CS (259 nm)
F (H_2O, OH) **EID** (H_2O, OH)	OH (310 nm)
F (NH_3, NH_2, NH) **EID** (H_2O, OH^+)	NH (336 nm)
F (HCN, CN) **EID** (CO_2, CO_2^+)	CN (388 nm)
F (NH_3, NH_2) TBD	NH_2 (375 nm)
RS (dust or Na bearing molecule, Na)	Na (590,7 nm)
PD (H_2O, O) **EID** (H_2O, O) **EID** (CO_2, O)	O I (631 nm)
	UV (375 nm) dust

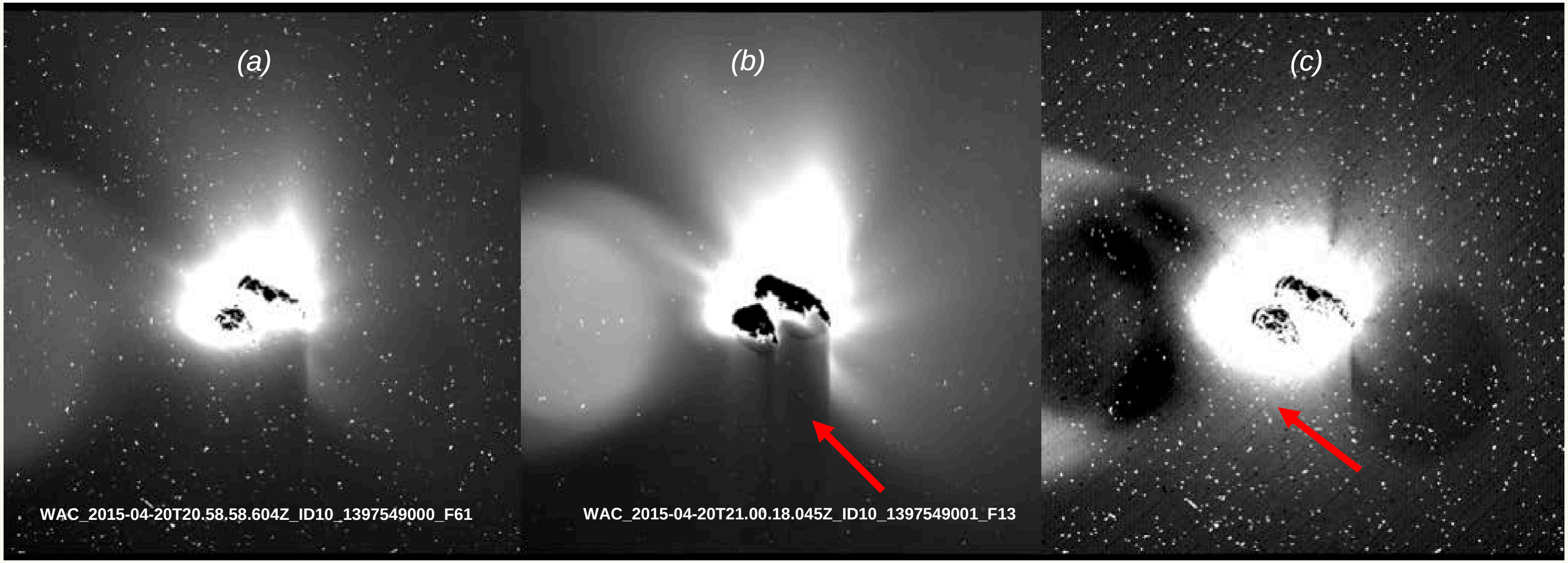


Known Processes based on ground based observations

Additional processes identified until now by OSIRIS in the very inner comma, (see reference [1])

F = Fluorescence
PD = Photo-dissociation followed by prompt emission
EID = Electron Impact Dissociation followed by prompt emission
RS: Resonance Scattering

Emissions at large heliocentric distances



(a) This shows the original *OH* emission images (level 3).

(b) This shows the dust emission and the jets using UV375 filter (level 3).

(c) This shows the gas subtracted from dust. It can be seen from *(b)*, see red arrow, the shadow of the nucleus clearly visible. This shadow is not seen in *(c)*; showing that the gas emission is not excited by the sun light. This demonstrates that the *OH* emission at large distances from the sun is excited by electron impact processes.

Next Steps

- Finalising qualitative analysis and starting quantitative processing of results:
    - We have found a similar behaviour to OH for NH (more production at large heliocentric distances) that needs to be evaluated
    - We are evaluating the surface brightness radial profiles in plume-ward and anti-sunward directions to analyse the surface where the electron impact excitation processes take place.
    - The continuum removal needs to be enhanced. We should check how far our continuum removal factors are from the theoretical ones according to OSIRIS gas group analysis (see *La Forgia F., et al.)*
    - We are working on the calculation of the water production rates for OH and OI for the data sets selected at different heliocentric distances. Based on the results, the objective would be to map and compare the distribution of H_2O and CO_2 considering the new identified processes and then the analysis their implications on the homogeneity/heterogeneity of the cometary nucleus.

Thank you!

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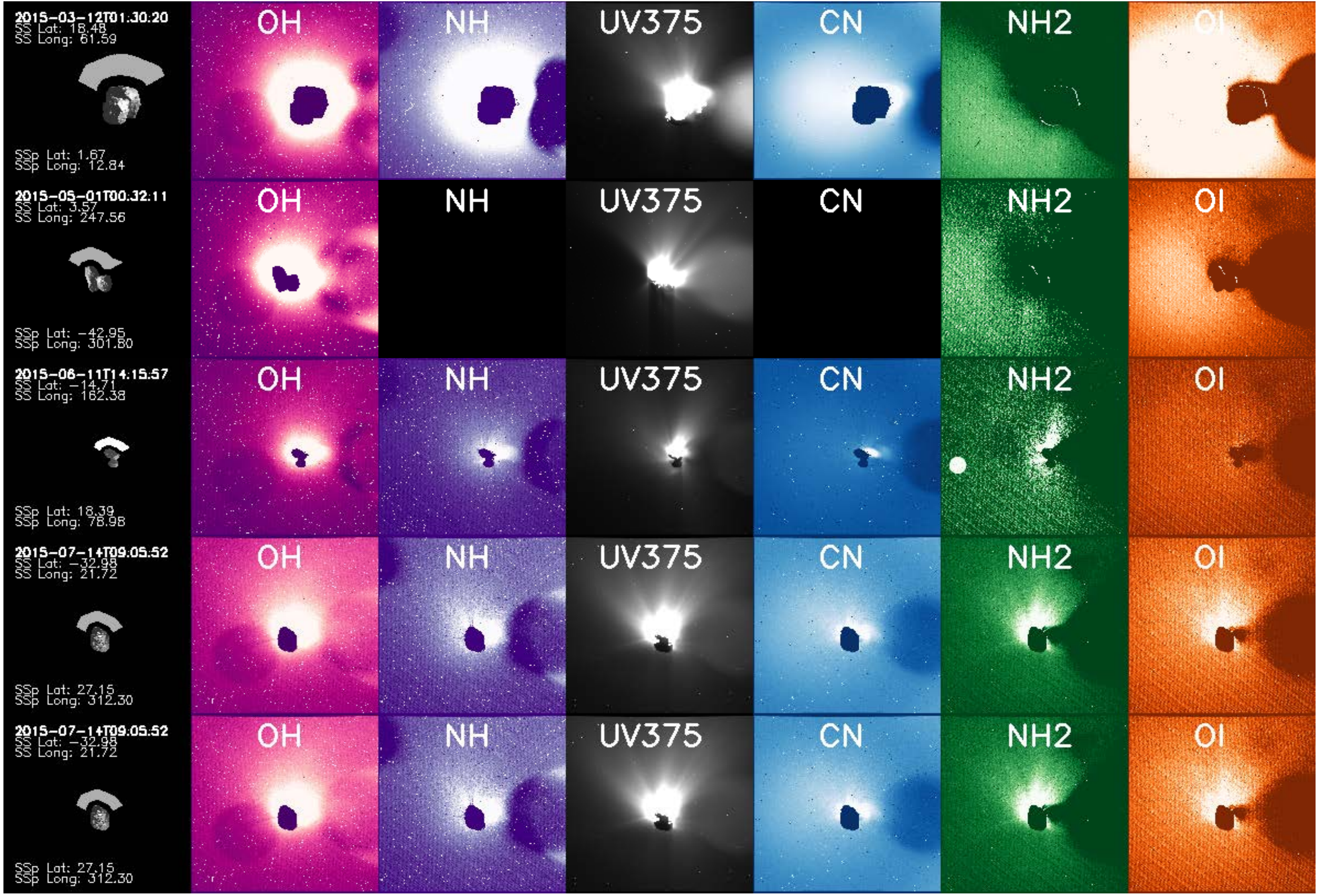
- *La Forgia F., et al., "Near-UV OH Prompt Emission in the Innermost Coma of 103P/Hartley 2", The Astronomical Journal, Volume 154, Number 5.*

EID visualisation



(*La Forgia, priv. comm*)

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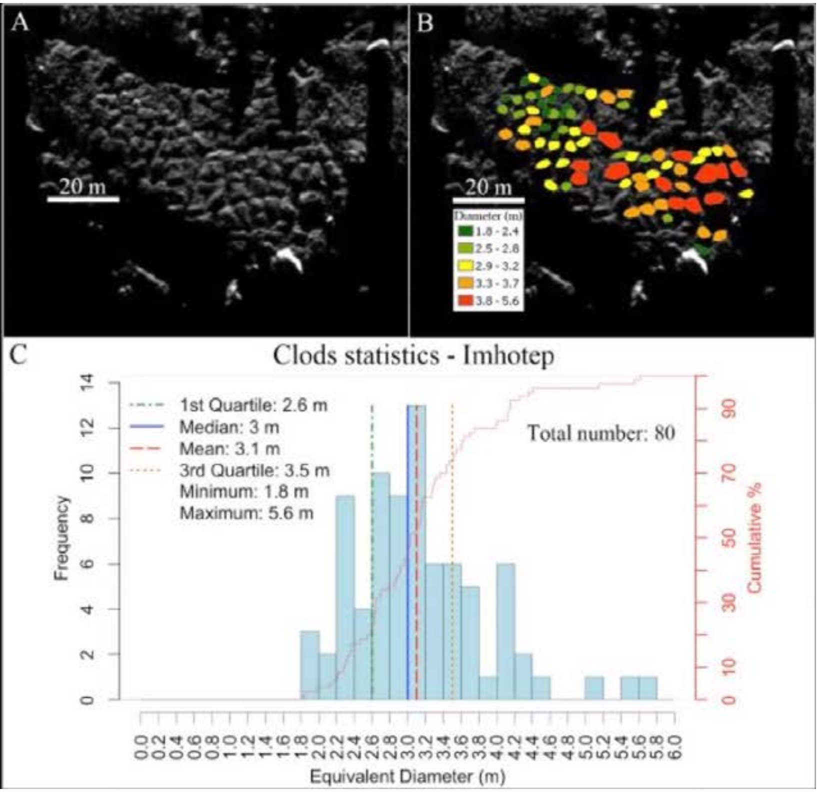
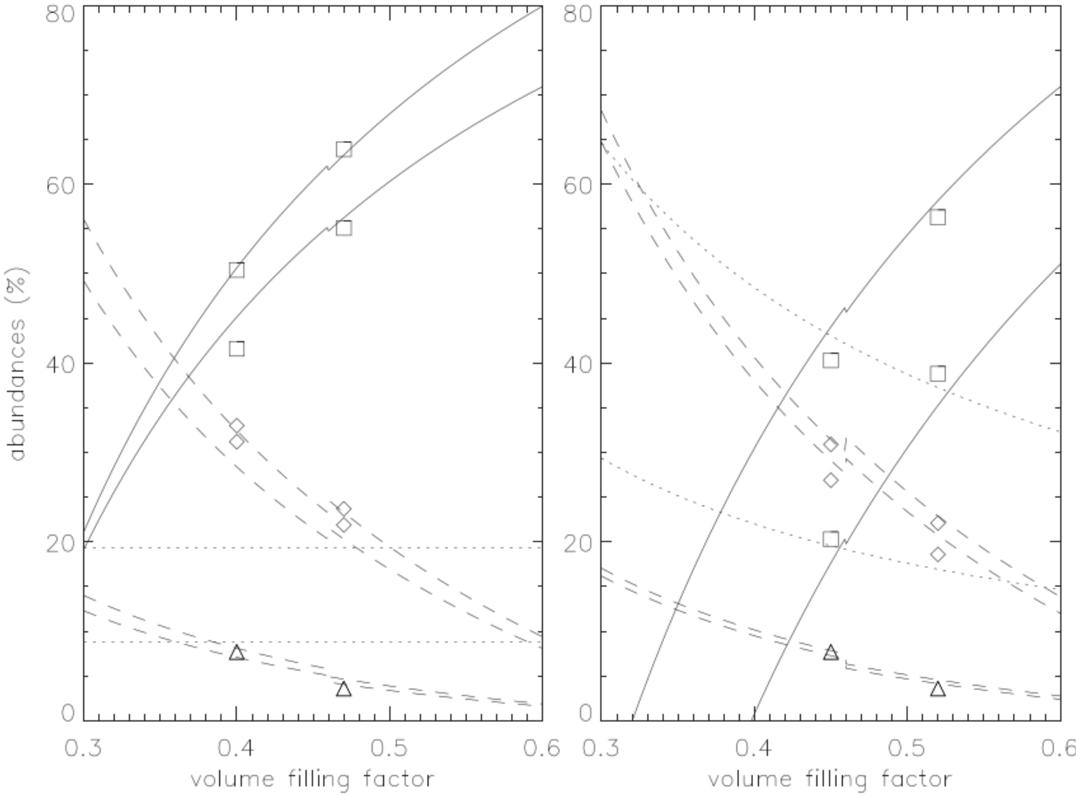
Fulle on going	*The phase function and density of cometary dust*
Hermalyn et al. 2013	*The detection, localization, and dynamics of large icy particles surrounding comet 103P/Hartley2*
Drolshagen et al. 2017	*Distance determination method of dust particles using Rosetta Osiris NAC and WAC data.*
Ott et al. 2017	*Dust mass distribution around the comet 67P/Churyumov-Gerasimenko determined via parallax measurements using Rosetta's Osiris cameras.*
Ott (IMC 2016)	*PaDe: The particle detection program*

Why study dust in coma?

- Unresolved questions: cm-sized pebbles from streaming instability (Blum et al.2015, Fulle et al.2016) or larger blocks from hierarchical agglomeration (Davidsson et al.2016)?



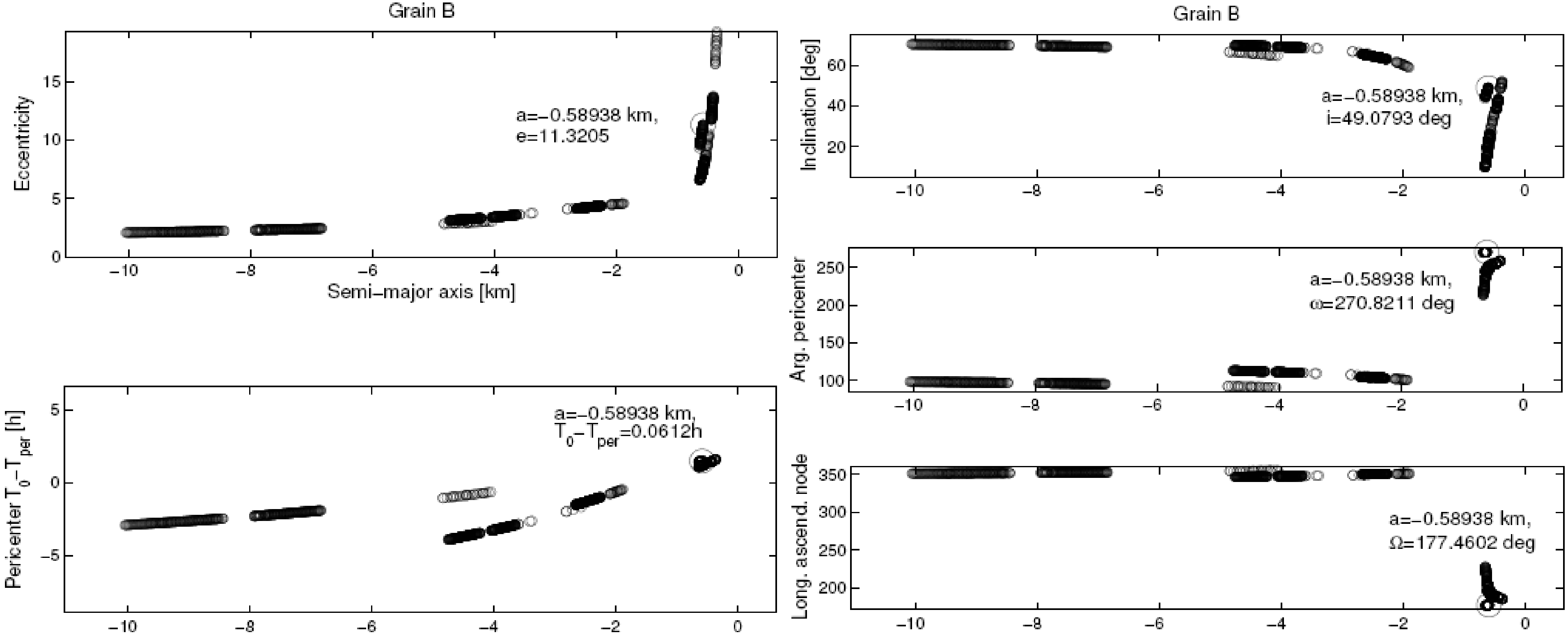
Davidsson et al. 2016



Fulle et al. 2016

Particle trajectories: bound versus escape

- Lots of papers with assumptions, few with numerical trajectories.
- Davidsson et al.2015: Individual particle trajectories early in the mission → numerical trajectories, but limited observing time → inconclusive bound vs. escaping
- Research plan: to repeat study with particles observed later over a longer time scale

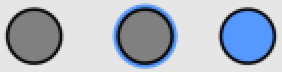


Davidsson et al. 2015

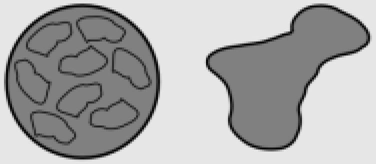
solid group

SOLID_1: irregular grain

SOLID_2: spherical monomer (e.g., in computer models)



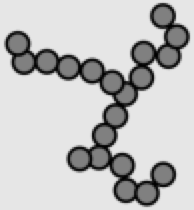
SOLID_3: chondrule and CAI



SOLID_4: dense aggregate of grains

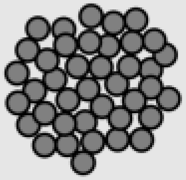
fluffy group

FLUFFY_1: fractal aggregate ($D_f < 3$)

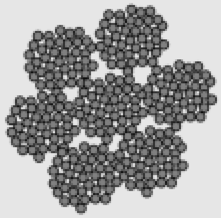


porous group

POROUS_1: porous aggregate, van-der-Waals aggregate



POROUS_2: aggregate from smaller aggregates



solid group

- < 10 %
- consolidated
- high strength

fluffy group

- > 95 %
- likely fractal
- very low strength

porous group

- 10 – 95 %
- aggregate
- low strength