The Rosetta mission: Clues on the origin of comet nuclei

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Overview

- Rosetta+Philae observations of 67P holding clues to comet origin
- Formation mechanisms
  - Hierarchical agglomeration: primarily sticking
  - Streaming instabilities (+ eddies, pressure bumps, vortices): primarily gravity
- Post-formation collisional processing

Bulk density and porosity

Nucleus mass and bulk density

Non-grav from ground: $M=(1.06\text{-}1.13)\cdot 10^{13}$ kg
(Davidsson & Gutiérrez 2015, *Icarus* **176**, 453)

In situ (RSI): $M=0.9982\cdot 10^{13}$ kg
(Pätzold *et al.* 2016, *Nature* **530**, 63)

OSIRIS: $\rho_{bulk}=535 \pm 35$ kg m^{-3}
(Preusker *et al.* 2015 *A&A* **583**, A33)

$\rho_{bulk}=532 \pm 7$ kg m^{-3}
(Jorda *et al.* 2016 *Icarus* **277**, 257)

Nucleus: deep interior

CONSERT:

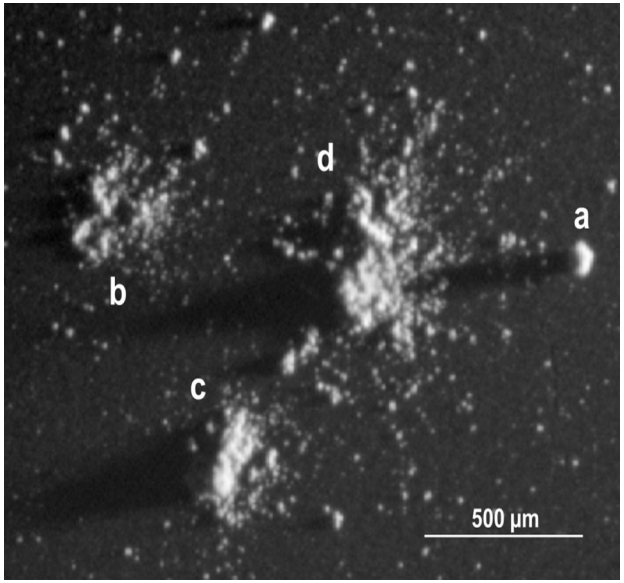
Dielectric constant $\varepsilon=1.27$, porosity $\psi=75\text{-}85\%$
(Kofman *et al.* 2015, *Science* **349**, aab0639)

Nucleus: shallow depth (upper 2.5m)

Groundbased radar: $\varepsilon=1.9\text{-}2.1$, $\psi=70\%$
(Kamoun *et al.* 2014, *A&A* **568**, A21)

Nucleus: surface (upper 1m)

SESAME/MUPUS: $\varepsilon=2.45$, $\psi=40\text{-}55\%$
(Lethuillier *et al.* 2016, *A&A* **591**, A32,
Spohn *et al.* 2015, *Science* **349**, aab0464)



Credit: ESA/Rosetta/MPS for COSIMA Team MPS/CSNSM/UNIBW/TUORLA/IWF /IAS/ESA/BUW/MPE/LPC2E/LCM/FMI/UTU/LISA/UOFC/vH&S/ Langevin et al (2016)

Coma aggregates

GIADA: $\rho_{bulk}=795$ kg m^{-3}

$\Psi=52 \pm 8$ %
(Fulle *et al.* 2016, *Mon. Not. R. Ast. Soc.*
doi: 10.1093/mnras/stw2299)

Conclusions:

Upmost surface compacted! Interior?

a) E.g., $\psi_{micro}=76\%$, $\psi_{macro}=0\%$?

b) E.g., $\psi_{micro}=60\%$, $\psi_{macro}=40\%$?

Strength and macro-porosity

<u>Aggregates of μm-sized silica:</u>

ψ_{micro}=75-85% ⇒ tensile strength S_t=1-1.5 kPa

ψ_{micro}=60%, ⇒ S_t=2.5 kPa

(Güttler *et al.* 2009, *Astrophys. J.* **701**, 130)

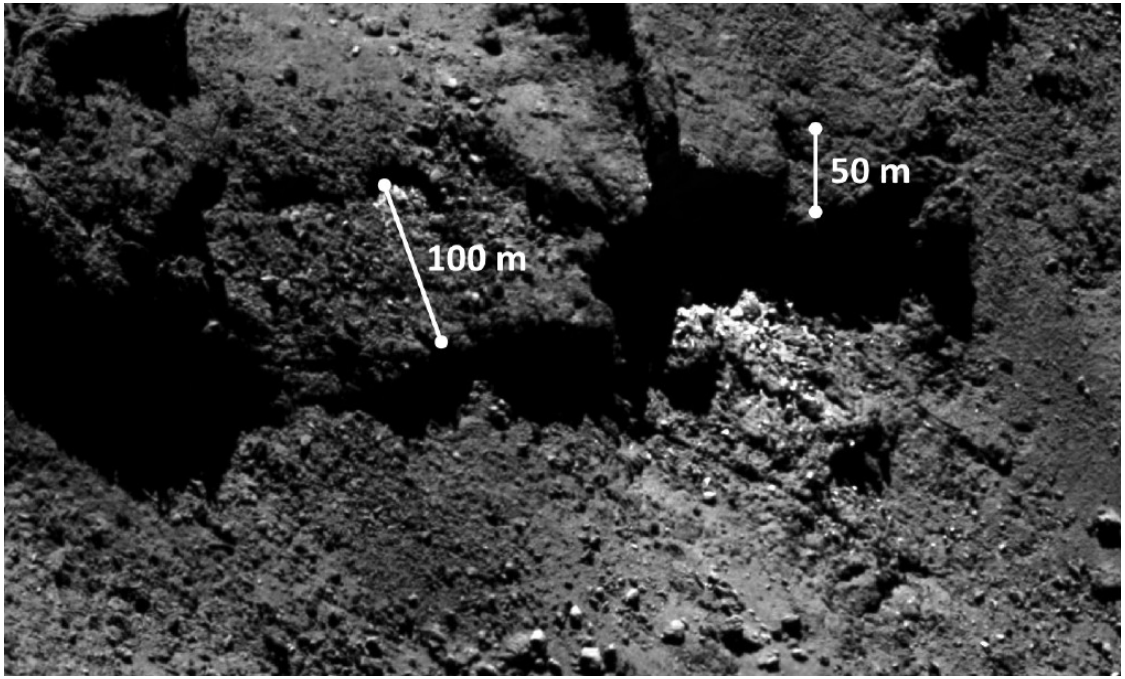
Macro-porosity lowers effective strength:

ψ_{macro}=40% ⇒ S_t=500 Pa

ψ_{macro}=50% ⇒ S_t=130 Pa

ψ_{macro}=63% ⇒ S_t= 3 Pa

(Shoshany *et al.* 2002, *Icarus* **157**, 219)



Credit: Groussin *et al.* 2015, *A&A* **583**, A32

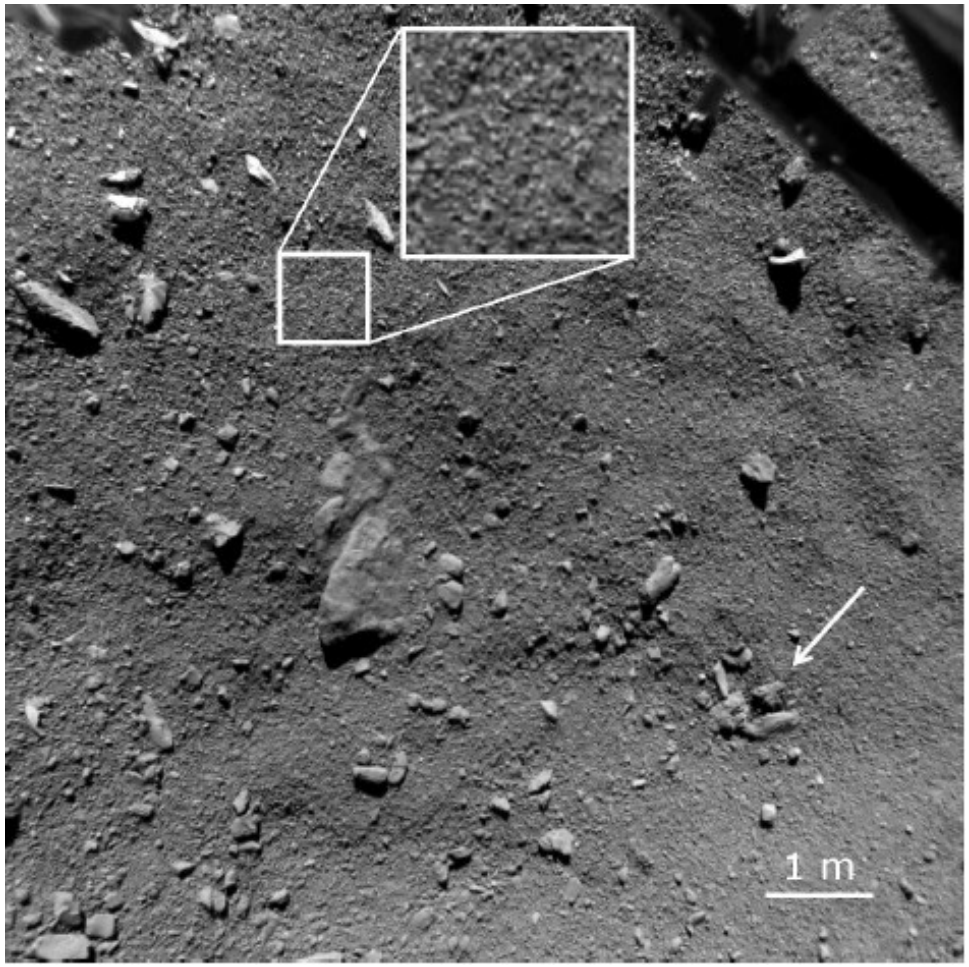
~100 m structures collapsed ⇒
S_t < 90 Pa, suggesting $\psi_{macro} \gtrsim 50\%$

~10 m structures still standing ⇒
S_t > 3-15 Pa, suggesting $\psi_{macro} \lesssim 63\%$

(Groussin *et al.* 2015, *A&A* **583**, A32)

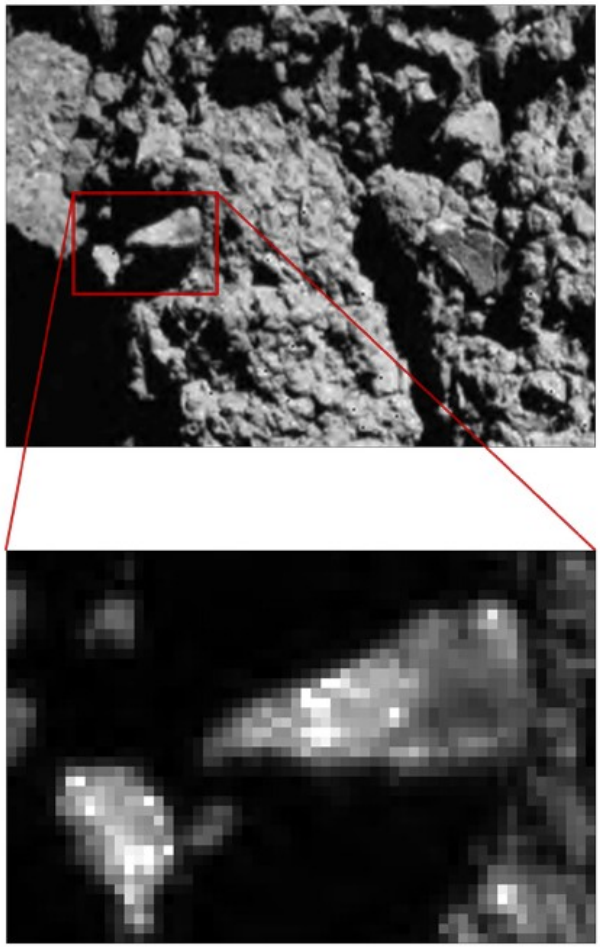
Size of macroscopic voids I

Philae/ROLIS



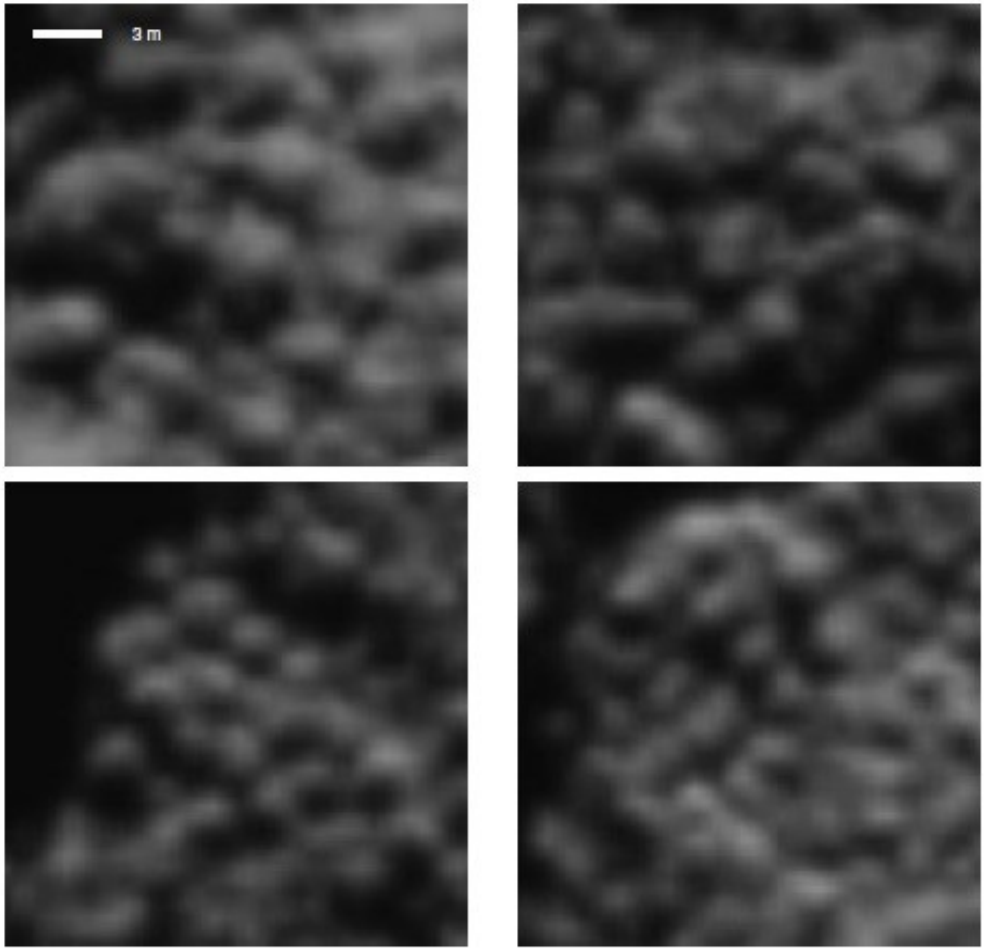
Credit: Mottola *et al.* 2015, *Science* **349**, aab0232

Philae/CIVA



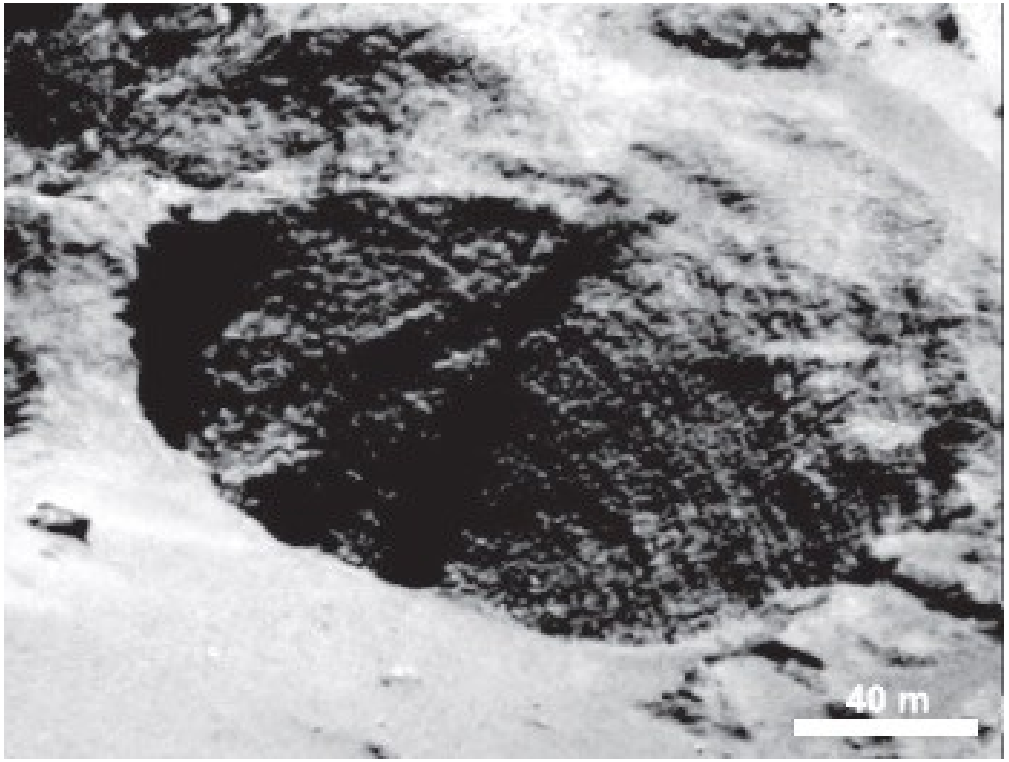
Credit: Bibring *et al.* 2015, *Science* **349**, aab0671

Size of macroscopic voids II



Credit: Davidsson *et al.* 2016, *A&A* **592**, A63

OSIRIS: Goosebumps & pits
Goosebumps suggest cavities on dm-m scale



Credit: Sierks *et al.* 2015, *Science* **347**, aaa1044

CONSERT & RSI: cavities < 10m
(Kofman *et al.* 2015, *Science* **349**, aab0639)
(Pätzold *et al.* 2016, *Nature* **530**, 63)

Pits: few cavities on 100m scale?
(Vincent *et al.* 2015, *Nature* **523**, 63)

Internal mass distribution

Complex rotation

Periodogram of spin {α,δ}: strong periodicity $P_c \approx 270$h when rotation period P=12.4h was fixed.

Rigid, torque-free Euler solution:

Spin period P_ψ=13h
Precession period P_φ=6.35h
Nutation period P_θ=6.5h

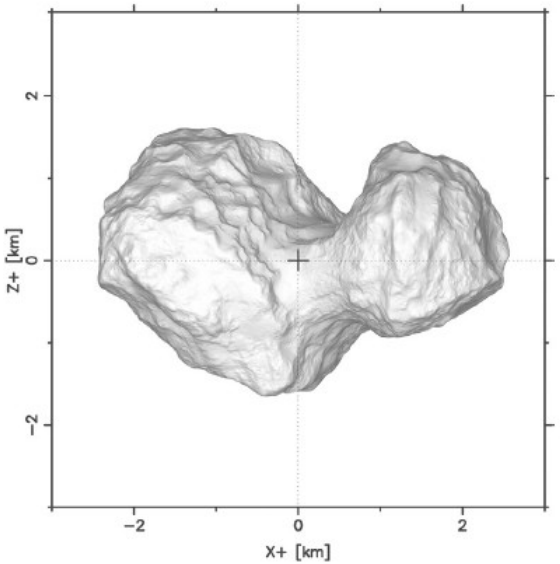
with $P_c^{-1} = P_\varphi^{-1} - P_\theta^{-1}$

Implies moments of inertia I_z-I_y=0.96.
Mass concentrated to equatorial plane *and* surface (homogeneous: I_z-I_y=0.14)

(Gutiérrez *et al.* 2016, *A&A* **590**, A46)

Density gradient
CONSERT: porosity increase by ~10-20% in upper 150m. Shallow regions denser than interior by a factor 1.2-2.0.
(Ciarletti *et al.* 2015, *A&A* **583**, A40
Brouet *et al.* 2016, *MNRAS,* doi:10.1093/mnras/stw2151)

Lobes have different densities?
COM/COF off-set {18,-32,16} meters
Principal axis tilts 4.0° ± 1.9° wrt z-axis
(Jorda *et al.* 2016, *Icarus* **277**, 257)



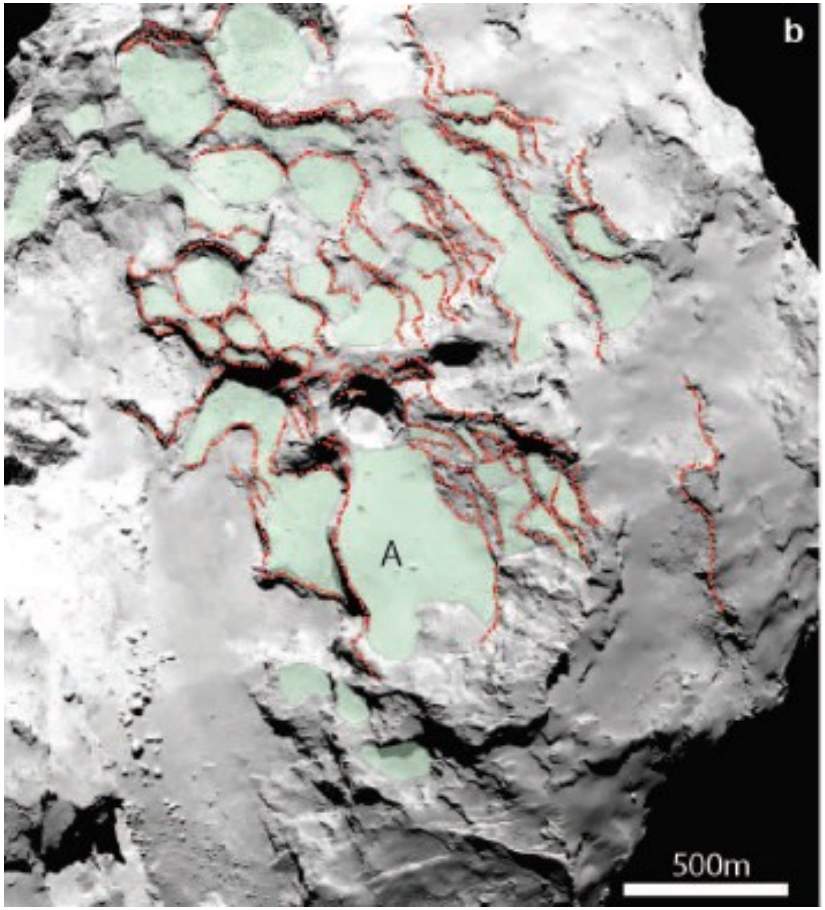
ρ_{big}=540-570 kg m^{-3}?

ρ_{small}=445-515 kg m^{-3}?

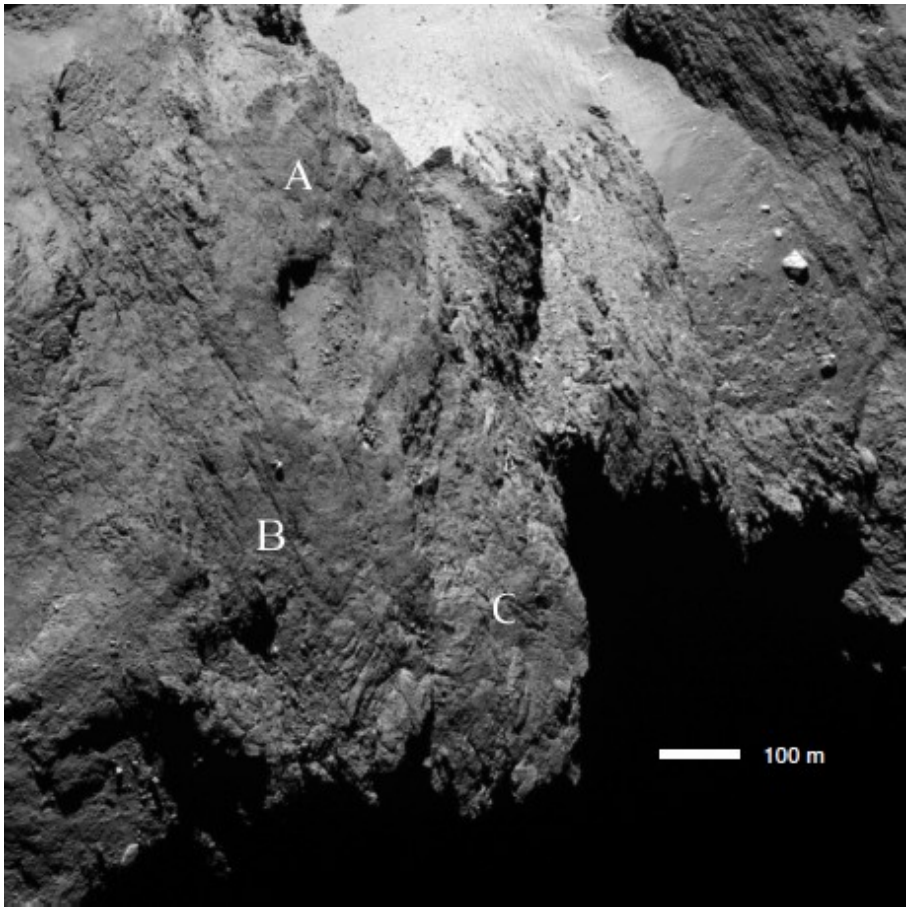
Credit: Jorda *et al.* 2016, *Icarus* **277**, 257

Morphological & structural features

- 600m-thick onion-shell layering, encapsulating the lobes individually
- 400m diameter positive relief features (PRFs): spherical caps, proposed building-blocks
- Bi-lobed shape from merger of two individual objects

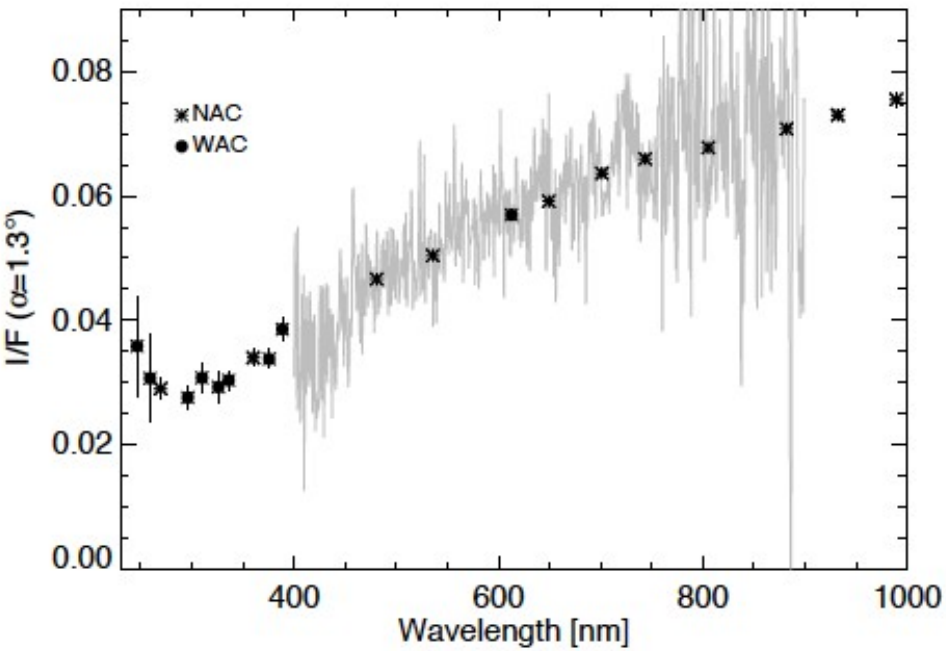


Credit: Massironi *et al.* 2015, *Nature* **526**, 402

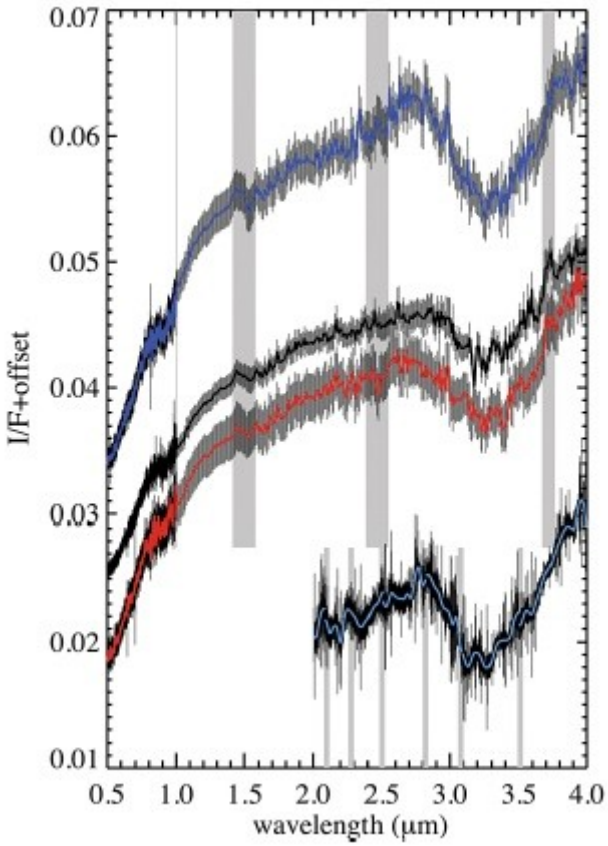


Credit: Davidsson *et al.* 2016, *A&A* **592**, A63

Spectrophotometry



Credit: Fornasier *et al.* 2015, *A&A* **583**, A30



Credit: Capaccioni *et al.* 2015, *Science,* **347**, aaa0628

OSIRIS photometry and VIRTIS spectroscopy does not show the 0.7 μm absorption feature.

Phyllosilicates rare or absent; radiogenic heating and water liquefaction did not take place.
Consistent with absence of phyllosilicates and presence of cristobalite in Stardust samples.
(e.g., Brownlee *et al.* 2012, *Meteo. Planet. Sci.*, **47**, 453; Roskosz & Leroux 2015, *Astrophys. J.*, **801**, L7)

Volatiles

<u>High abundances of supervolatiles:</u>

$CO/H_2O = 0.13 \pm 0.07$

$CO_2/H_2O = 0.08 \pm 0.05$

$O_2/H_2O = 0.0380 \pm 0.0085$

(Hässig *et al.* 2015 *Science* **347**, 276
Bieler *et al.* 2015, *Nature* **526**, 678)

<u>Some ices are *presolar*</u>

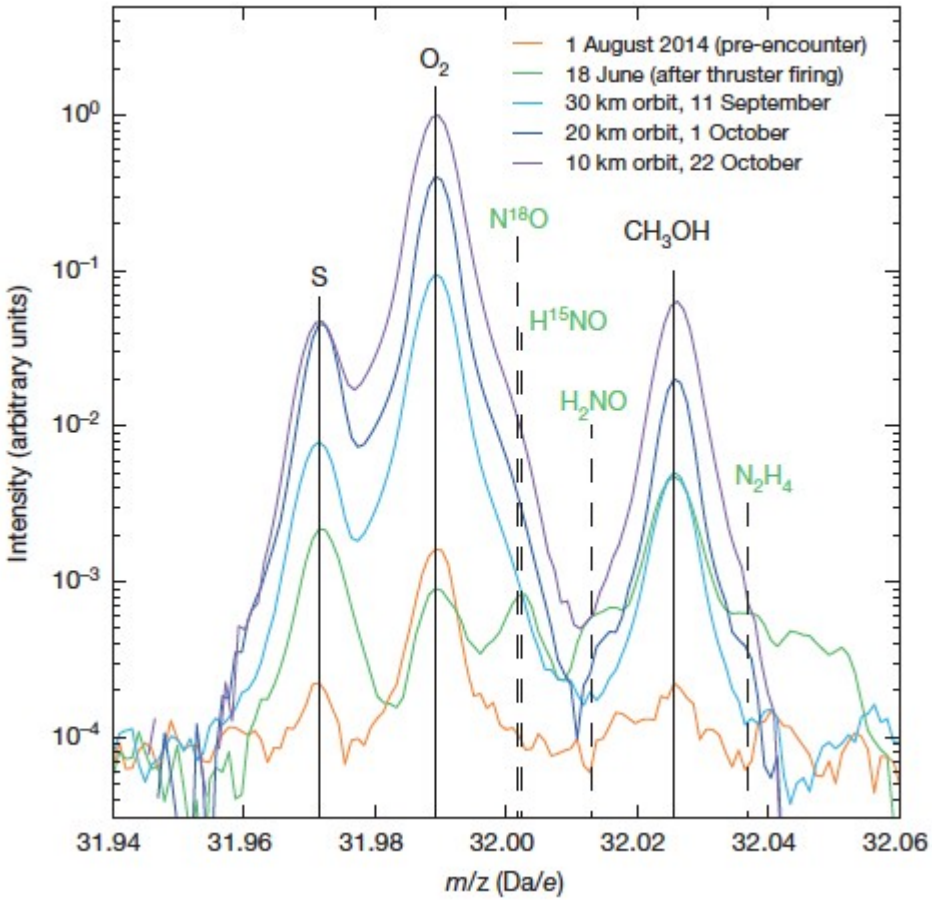
O_2, S_2, S_3, S_4 detected; S_2 has extremely short photolysis time

<u>Highest D/H thus far in comets</u>

Earth a factor f=7.1 above solar
103P: f=7.8
67P: f=25.2
(Altwegg *et al.* 2015, *Science* **347**, 1261952)

Comets have always been extremely cold. Preservation of a high D/H diversity among comets necessary.

ROSINA



Credit: Bieler *et al.* 2015, *Nature* **526**, 678

A comet formation scenario

A&A 592, A63 (2016)
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Astronomy & Astrophysics

The primordial nucleus of comet 67P/Churyumov-Gerasimenko

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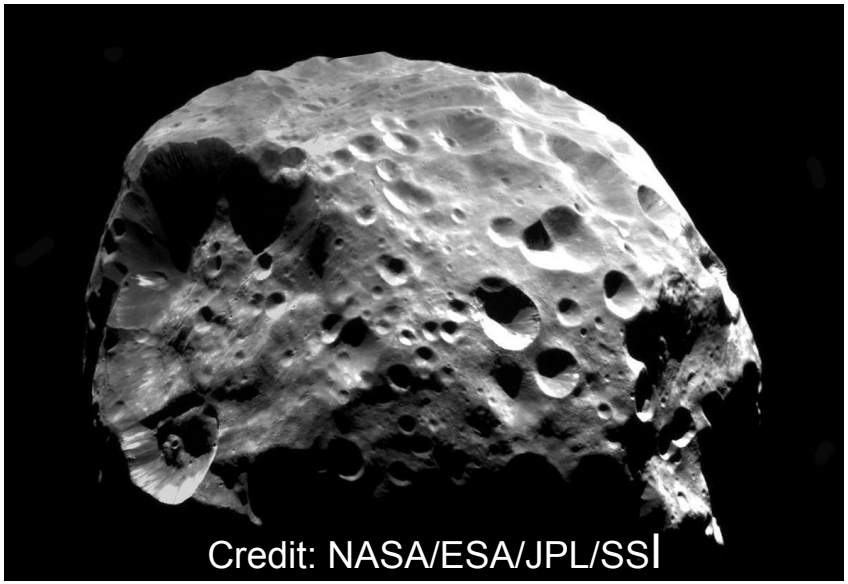
<u>In the *solar nebula* (0-3 Myr after CAI)</u>

- 13 $M_\oplus$ cm-sized pebbles form 50-400km "TNOs" in *streaming instabilities*
- ^{26}Al causes severe thermal processing, densification, aqueous alteration
- Remaining 2 $M_\oplus$ cm-sized pebbles form 0.1-1km cometesimals through *hierarchical agglomeration*. ^{26}Al heat dissipates; porosity, m-sized ψ_{macro},supervolatiles, mineralogy preserved.

<u>In the *primordial disk* (3-400 Myr after CAI)</u>

- "TNO" runaway growth to ≲ Triton-size. Gradually stir the disk.
- Comet accretion: layering and few PRFs
- No gas drag: bi-lobe nucleus formation
- D≳50km comets form (Hale-Bopp)
- Low collision frequencies; *primordial rubble-pile nuclei survive.*

No large-scale collisional cascade



Captured Saturn satellite Phoebe

Overdense for its size (D=218km). Irregular ρ<500-1000 kg m^{-3} expected; oblate ρ=1634 kg m^{-3} measured.

Phyllosilicate absorption features in Phoebe, numerous Jovian irregulars, Uranus irregular Caliban, Centaurs (Chariklo, 1999 DE_9)
Plutinos (2000 GN_{171}, 2000 EB_{173}, 2003 AZ_{84})

Collisional rubble-piles from early 50km-class parents have $\psi_{micro} \lesssim 0.1$, $\psi_{macro} \lesssim 0.4$, $\rho_{bulk} \gtrsim 1000$ kg m^{-3}, $\gtrsim$0.1-1 MPa strength, 100m-size voids, lack of supervolatiles, presence of phyllosilicats.

TNOs are exceptionally "bad parents" of comets!

We need formation and post-formation processing environments where material from large TNOs (50km and up) does not mix efficiently with the comet population.

No extensive collisional grinding in the primordial disk!

Davidsson et al. *(2016) see the primordial disk as being low-mass and dynamically cold, with rather few comets.*

Alternative mechanism for late comet formation

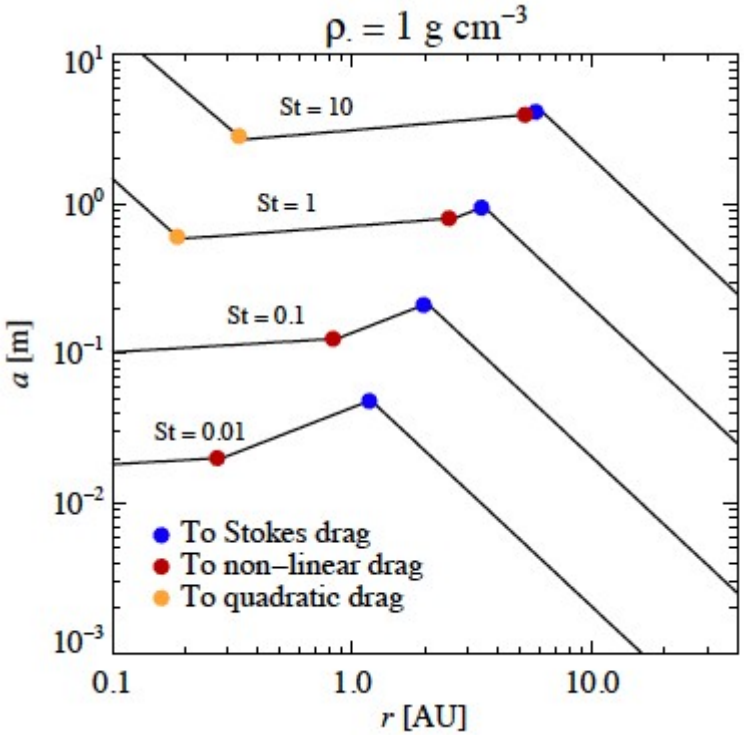
Streaming instabilities effective at high metallicities.
(Thus switch-off when 2 $M_\oplus$ cm-sized pebbles remains).

Second late epoch of streaming instabilities when solar nebula disperses?
(Johansen *et al.* 2009, *Astrophys. J.* **704,** L75)

Streaming instabilities may form comet-sized objects.
(Wahlberg Jansson & Johansen 2014, *A&A* **570**, A47)

If so, mm-cm pebbles must avoid growth and drift for up to 3 Myr. Can they?

Radial drift peaks for ~1m at 1 AU, ~1cm at 30 AU, ~1mm at 100 AU. But 5-10 Myr systems are rich in mm-size grains at 100 AU. Do we understand radial drift?
(Brauer *et al.* 2007, *A&A* **469**, 1169)



Credit: Johansen *et al.* 2014, *Protostars and Planets VI*

Does the bouncing barrier exist for ice/organic-rich material?
0.1-1 Myr old HL Tau as *decimeter-sized* boulders at 13-63 AU.
(Zhang *et al.* 2015, *Astrophys. J. Lett.* **806**, L7)

How to distinguish formation through streaming instabilities vs. hierarchical agglomeration? Comet macro-porosity, layering, density gradients, bilobe shapes?

Post-formation collisional processing?

<u>Current baseline Nice model</u>
35 $M_\oplus$ primordial disk with $2 \cdot 10^{11}$ D>2.3km comets ⇒ scattered disk with $6 \cdot 10^{8}$ D>1.4km comets ⇒ 500 JFCs of which ~ 108 are active.
Primordial disk comets dynamically excited ($\Delta v \approx 0.6$ km s^{-1}); diff. size distr. (q=3.0-3.5)

Number of catastrophic impacts on 67P: 58 at 15-20 AU, 12 at 25-30 AU.
If so, 67P created by disruption of a larger body. Many sub-catastrophic impacts.
(Morbidelli & Rickman 2015, *A&A* **583**, A43; Rickman *et al.* 2015, *A&A* **583**, A44)

<u>Alternative model (still consistent with overall Nice scenario!)</u>
15 $M_\oplus$ primordial disk with 70 times less comets ⇒ scattered disk with 14 times less ⇒ up to 270 JFCs of which ~ 108 are active.
Primordial disk comets dynamically cooler ($\Delta v \approx 0.2$ km s^{-1}); diff. size distr. (q=2.4) and dearth of 100m-sized objects.

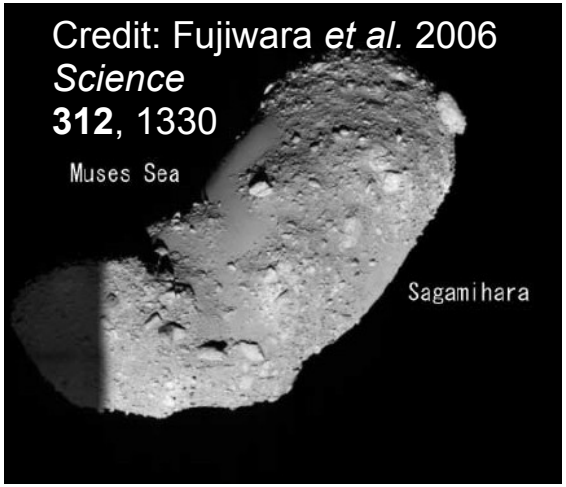
About ~ 5% risk that 67P would have experienced a catastrophic collision.
If so, 67P most likely primordial.
(Davidsson *et al.* 2016, *A&A* **592**, A63)

Questions to address

- Does the baseline Nice model avoid disruption of 50km-class objects?

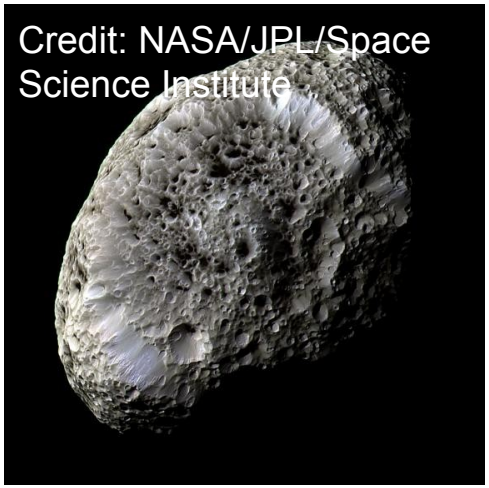
- It is inevitable that material with ~ 100 kPa compressive strength is compacted by $v \gtrsim 50$ m s^{-1} impacts. Can ~75% porosity be maintained without
  a) introducing macro-porosity above the ~ 10m scale (block-rich surface like Itokawa)?
  b) introducing ejecta-free compaction craters (Mathilde & Hyperion)?
  (Housen *et al.* 1999 *Nature* **402**, 155; Housen & Holsapple 2012 *Icarus* **219**, 297)

- 10-100 catastrophic impacts means orders of magnitude more smaller impacts. How to maintain the wide diversity of comet D/H ratios in surface material?



Credit: Fujiwara *et al.* 2006 *Science* **312**, 1330

Credit: NASA/JPL/JHUAPL


Credit: NASA/JPL/Space Science Institute

Summary

- Rosetta+Philae has provided the most detailed characterization of a comet nucleus thus far
  - *Invaluable information about Solar Nebula and presolar chemistry and mineralogy*
- We must reach consensus regarding the degree of (violent) collisional processing
  - *Invaluable information about primordial disk physics*
- We must reach consensus regarding the mechanism by which comets grew (the role of sticking versus gravity)
  - *Invaluable information about Solar Nebula physics*