



Séminaire CEA 29-01-2019



# The Rosetta Space mission at 67P/Churyumov-Gerasimenko



**J. Lasue**

IRAP-OMP, CNRS-UPS, Toulouse,  
France ([jlasue@irap.omp.eu](mailto:jlasue@irap.omp.eu))



# Highlights

## 1. Why do we study comets?

1. Comet properties
2. Solar system formation, LHB and Nice model
3. Transitional link with asteroids ?

## 2. The Rosetta mission

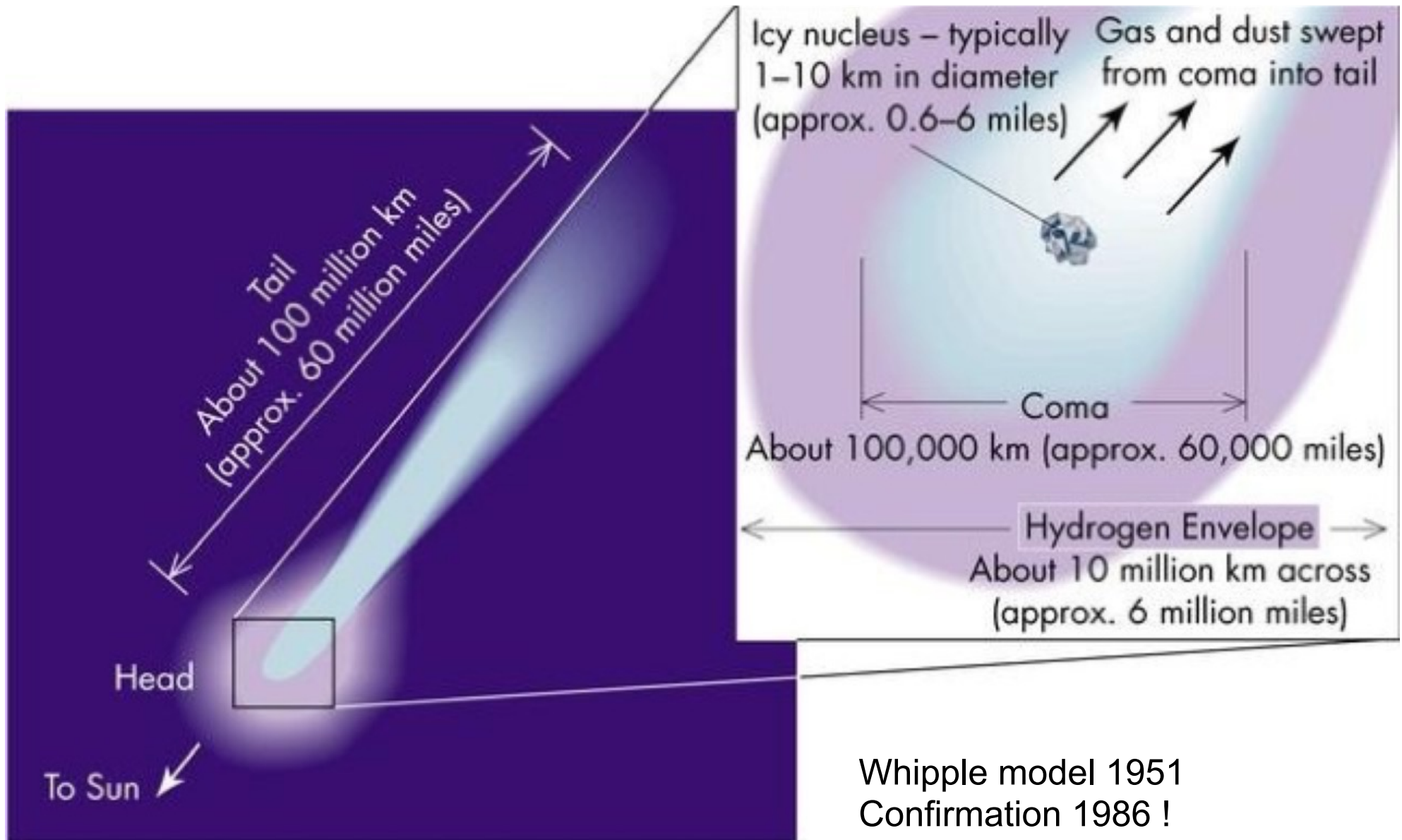
1. Description of the mission
2. 2 years of 67P exploration

## 3. What's next?

1. The Kuiper Belt and beyond

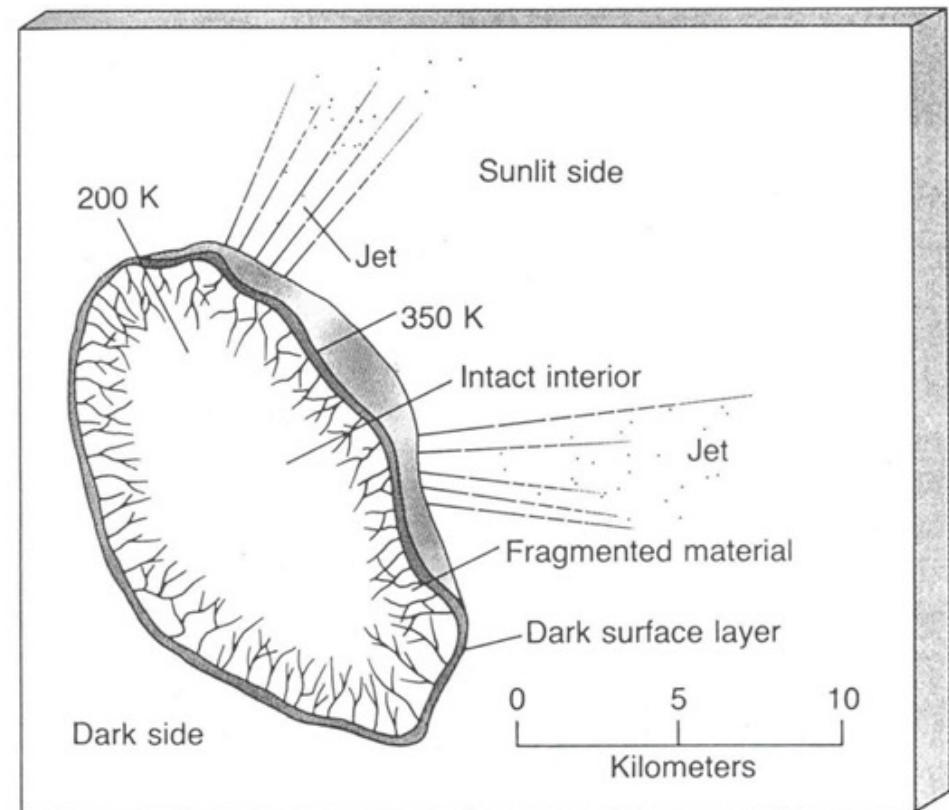
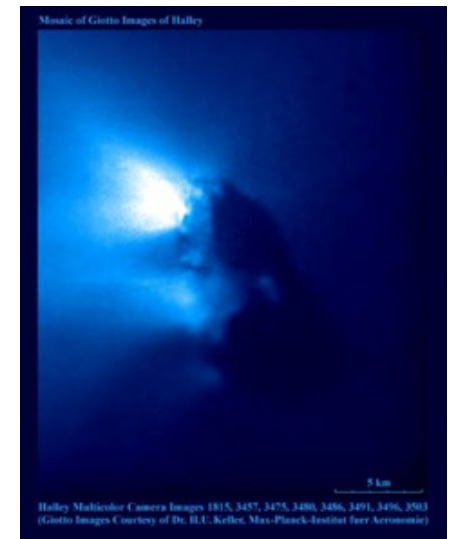


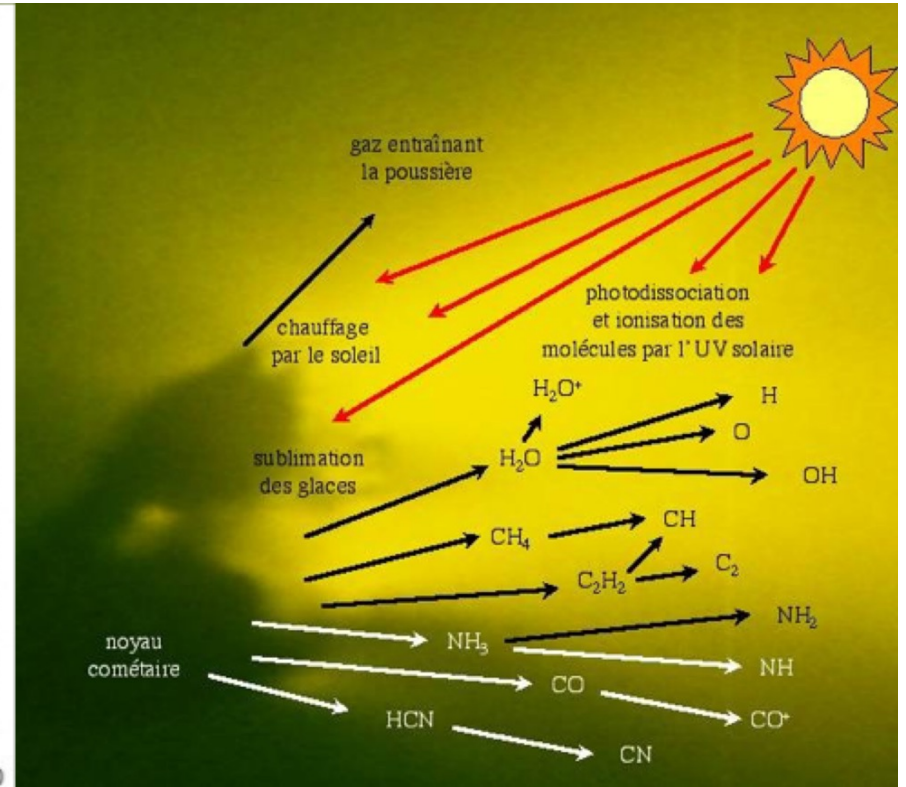
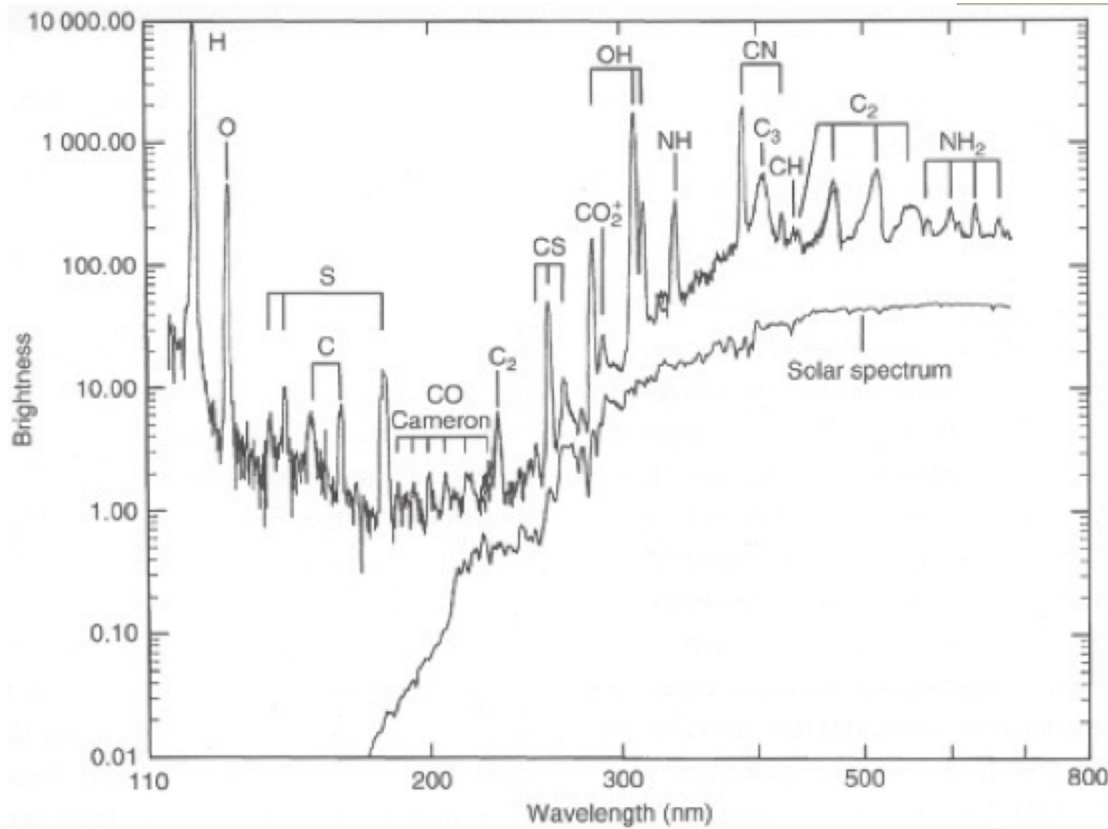
# Comet properties



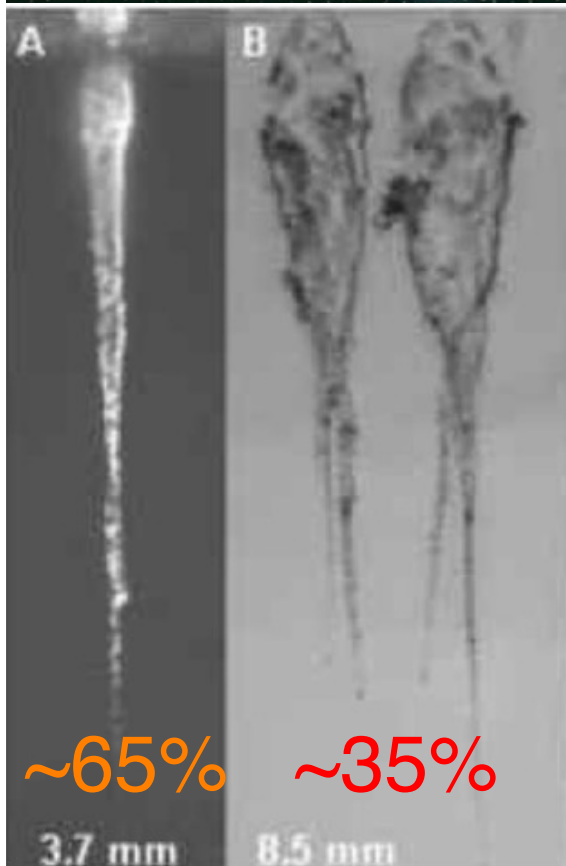
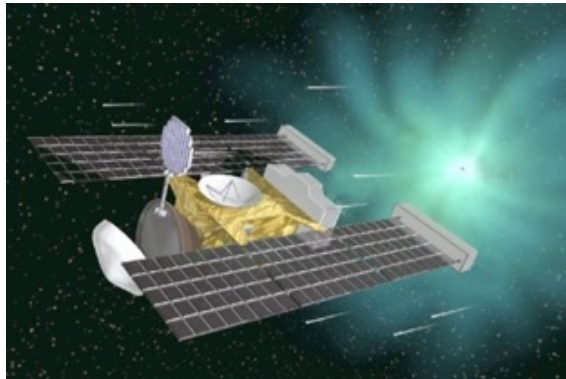
- Irregular object: 15 x 7 x 10 km.  
Dark color, neutral spectrum without features, reddish.  
Albedo ~4%.
- Similar to very dark asteroids, rich in volatiles and organic compounds from the external Main Belt (types P, D)
- Composition (number of molecules):
 

water ice	80%
Carbon monoxide	10%
Carbon dioxide	3.5%
Organic compounds (CHON)	1-2%
- slowly rotating, periods of many days, and usually present a nutation movement.





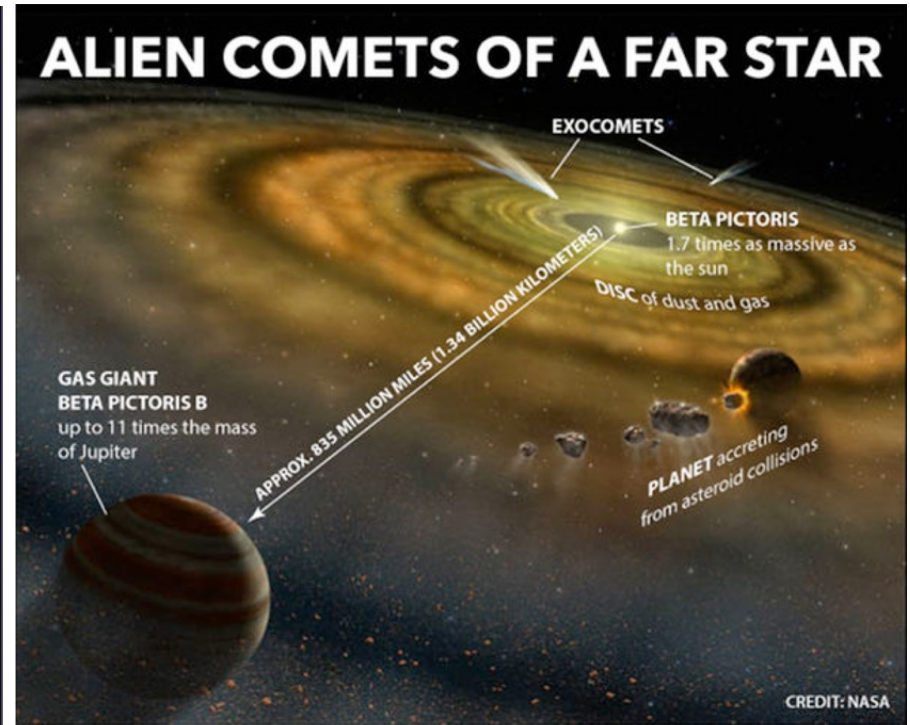
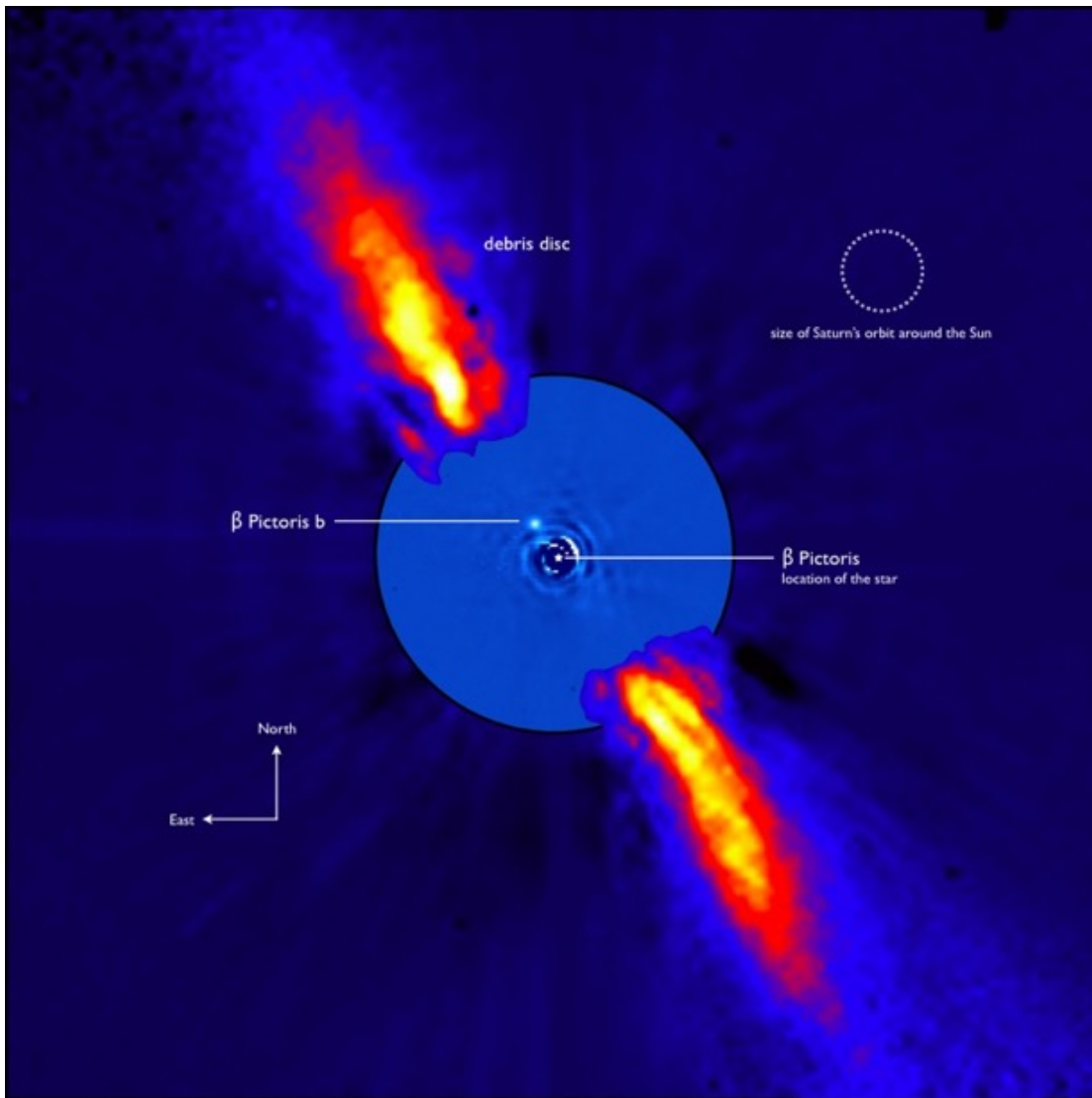
103P/Hartley 2 (EPOXI target;  
Weaver et al. 1992)



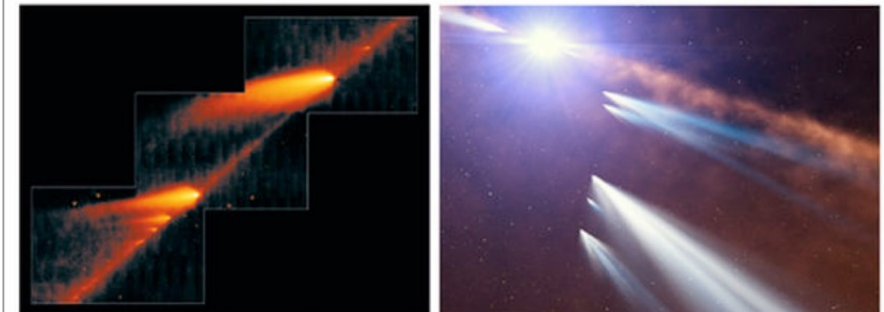
## Cometary samples returned in 2006:

- Abundances similar to carbonaceous IDPs and CI chondrites (Flynn et al., 2006)
- Mineralogical variety with crystalline silicates (1500K) indicates large scale mixing in the primordial nebula (Zolensky et al., 2006; Keller et al., 2006)
- Some peculiar compositions : particles rich in Na, Cr, K (Joswiak et al., 2007; 2008)
- Glycine (amino-acid) discovered (Elsila et al., 2009)

Stardust (2004): 81P/Wild 2



At only 23 million years old, the Beta Pictoris star system is very young compared to Earth's solar system. Beta Pictoris is still undergoing the initial condensation of its planets from smaller bodies, a process called accretion. The system is 63.4 light-years away from Earth.



LEFT: The spectral signatures of exocomets (comets of another solar system) have been seen approaching Beta Pictoris and disintegrating as their water ice and other volatiles evaporate into space. The breakup would appear similar to that of comet 73p/Schwassmann-Wachmann in Earth's solar system (CREDIT: NASA/JPL-Caltech/W. Reach). RIGHT: Artist's rendering of swarms of comets in the Beta Pictoris solar system (CREDIT: European Southern Observatory).

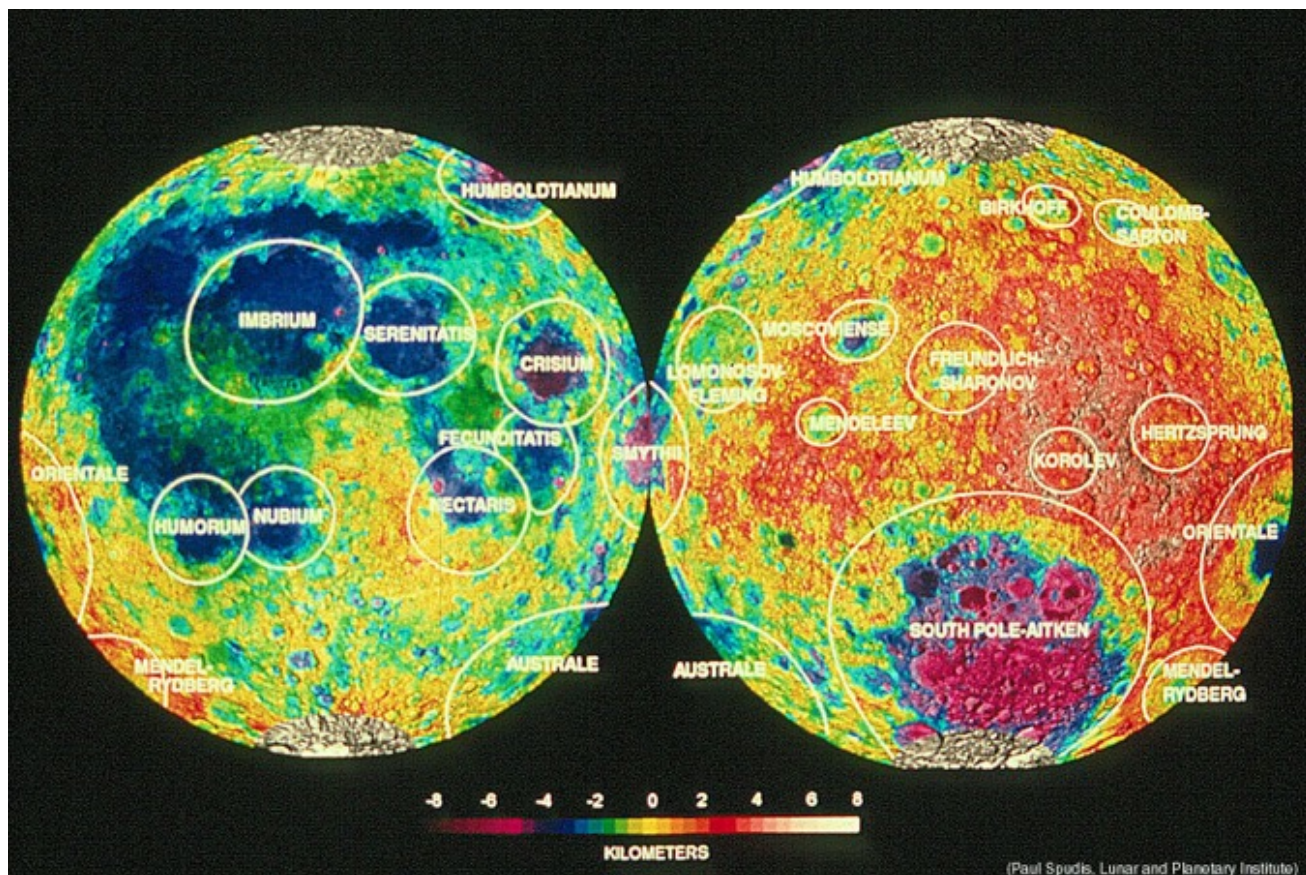
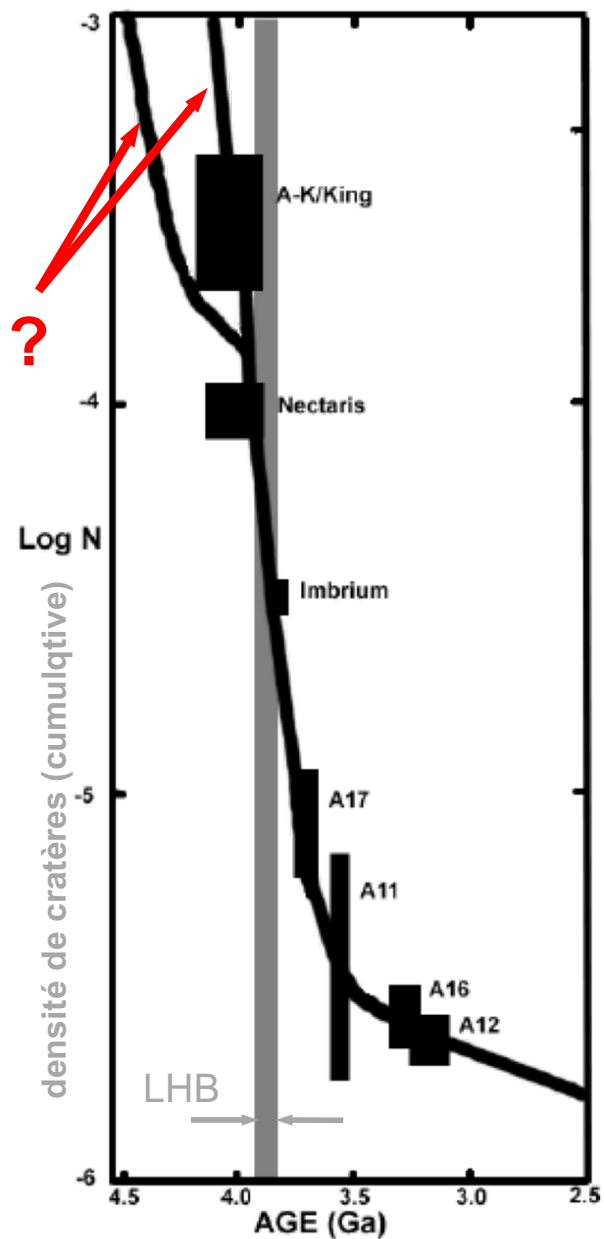
SOURCES: NASA, ESO

SPACE.COM

KARL TATE / © Space.com

Lagrange et al. 2008 A&A Let.

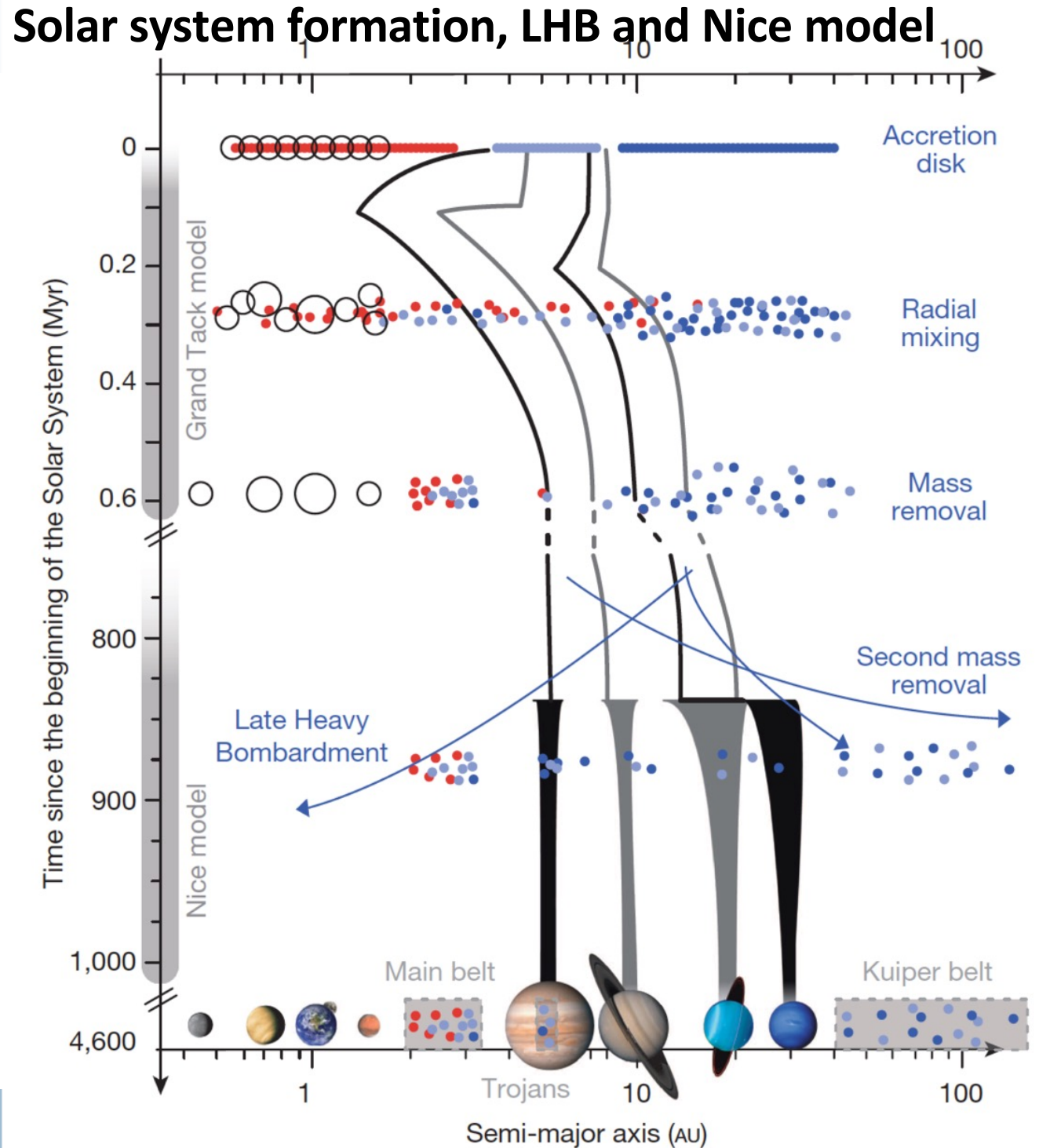


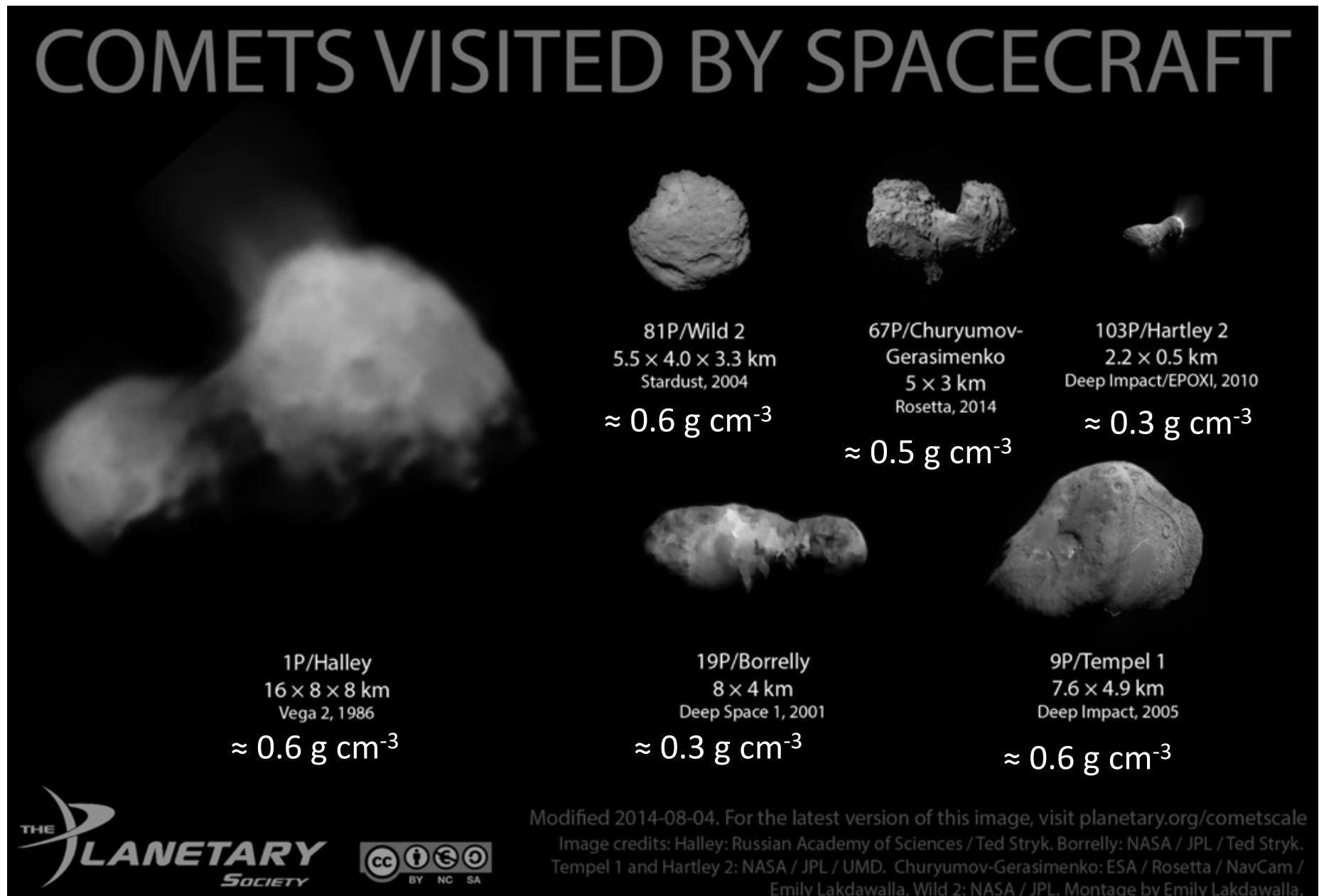


*Implies:* short cataclysmic bombardment (50-100 Ma) with formation of impact basins between 4 and 3.8 Ga: Late Heavy Bombardment (LHB)

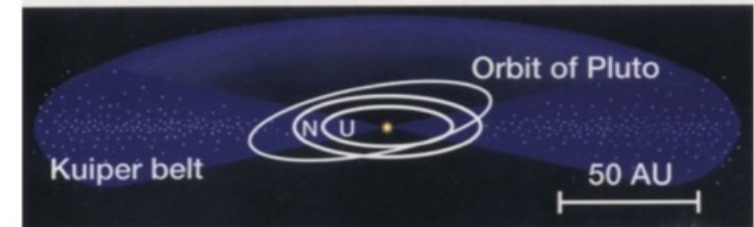
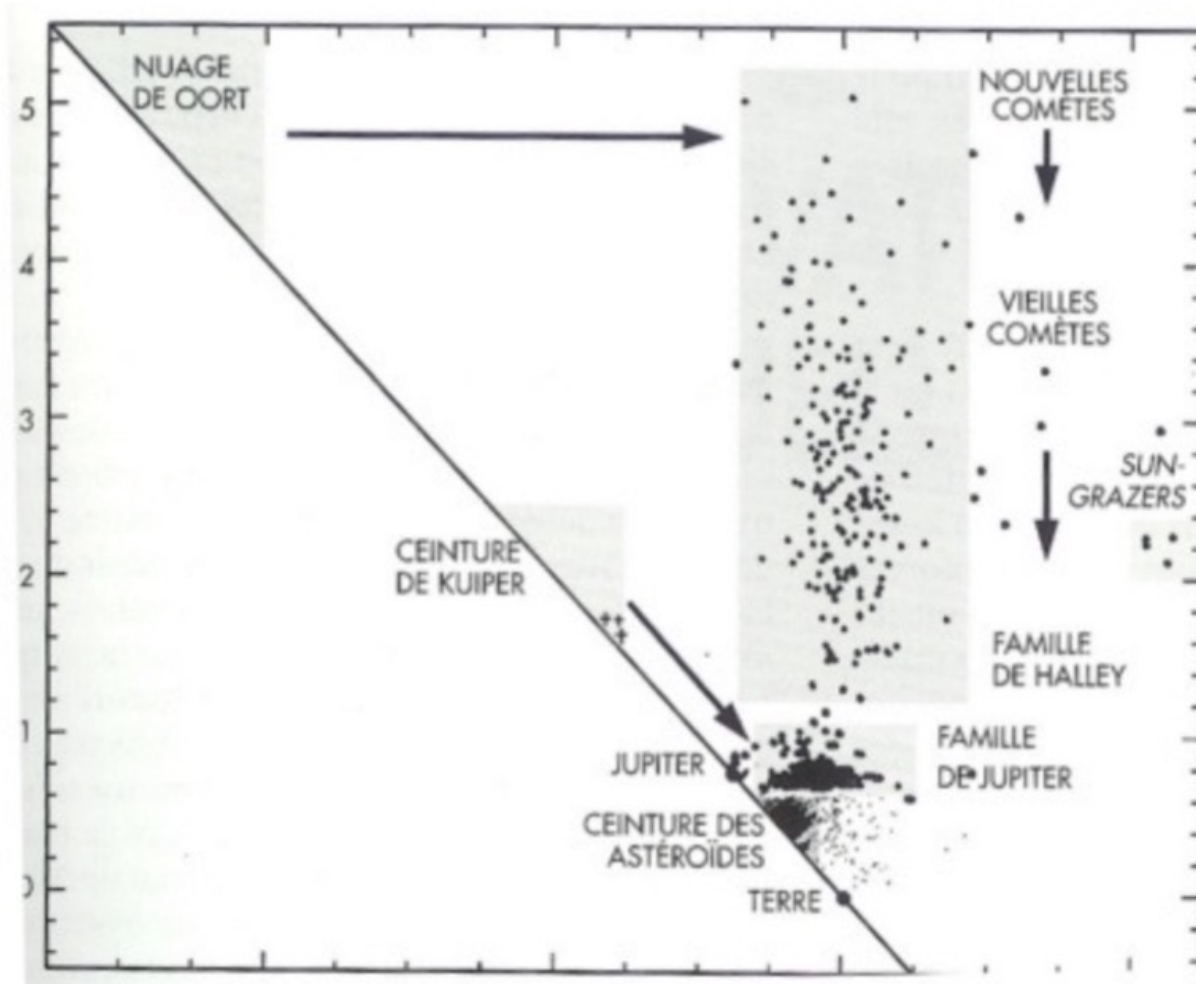
# Why study comets ?

De Meo & Carry Nat 2014





### Comet reservoirs

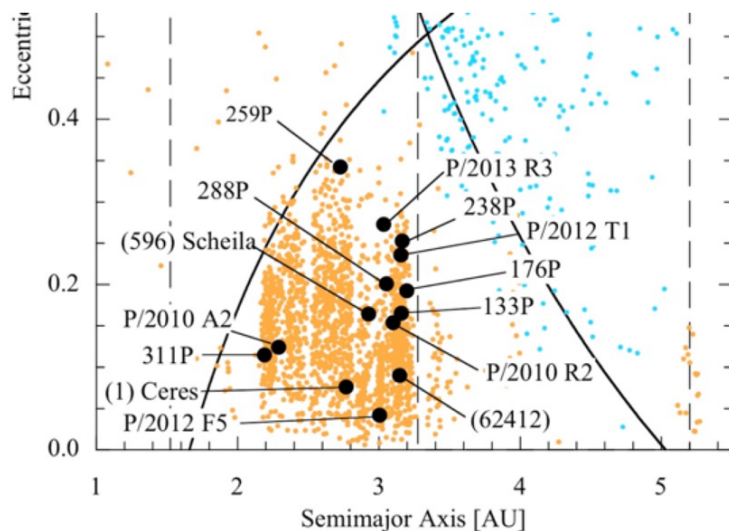
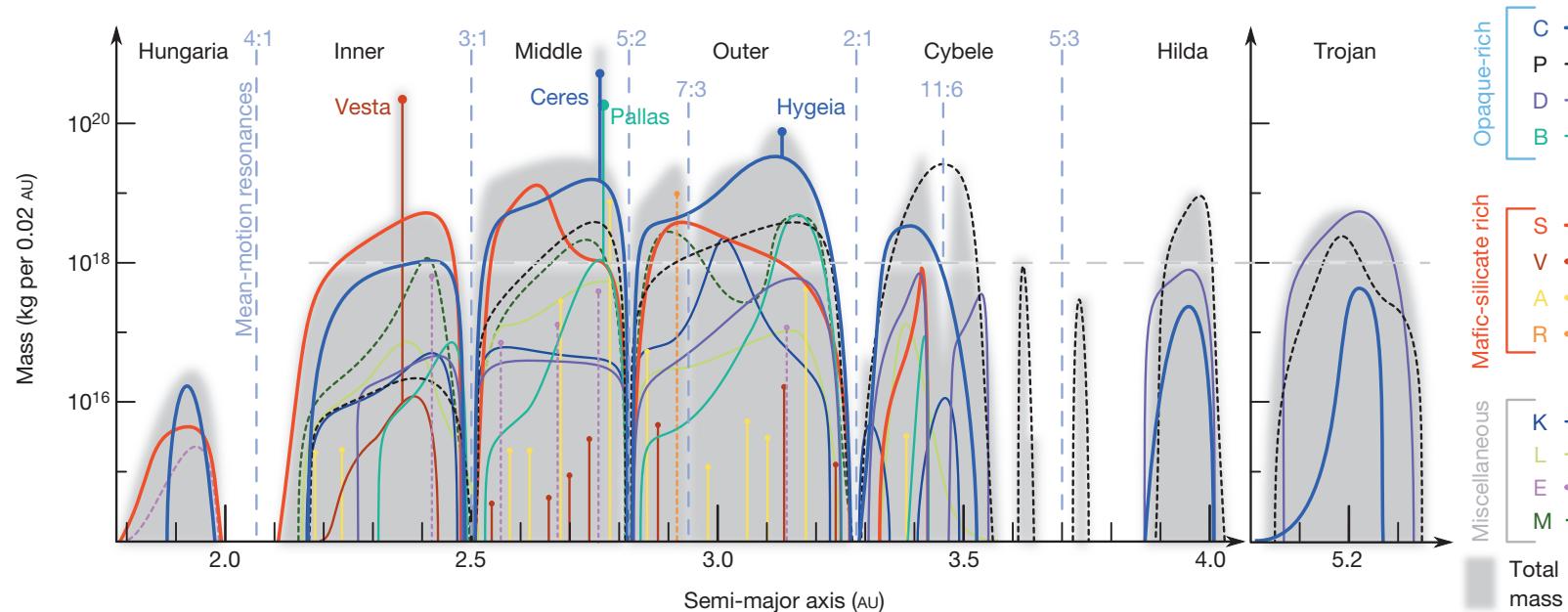


Log(a) vs Log(p)

Crovisier and Encrenaz 1995

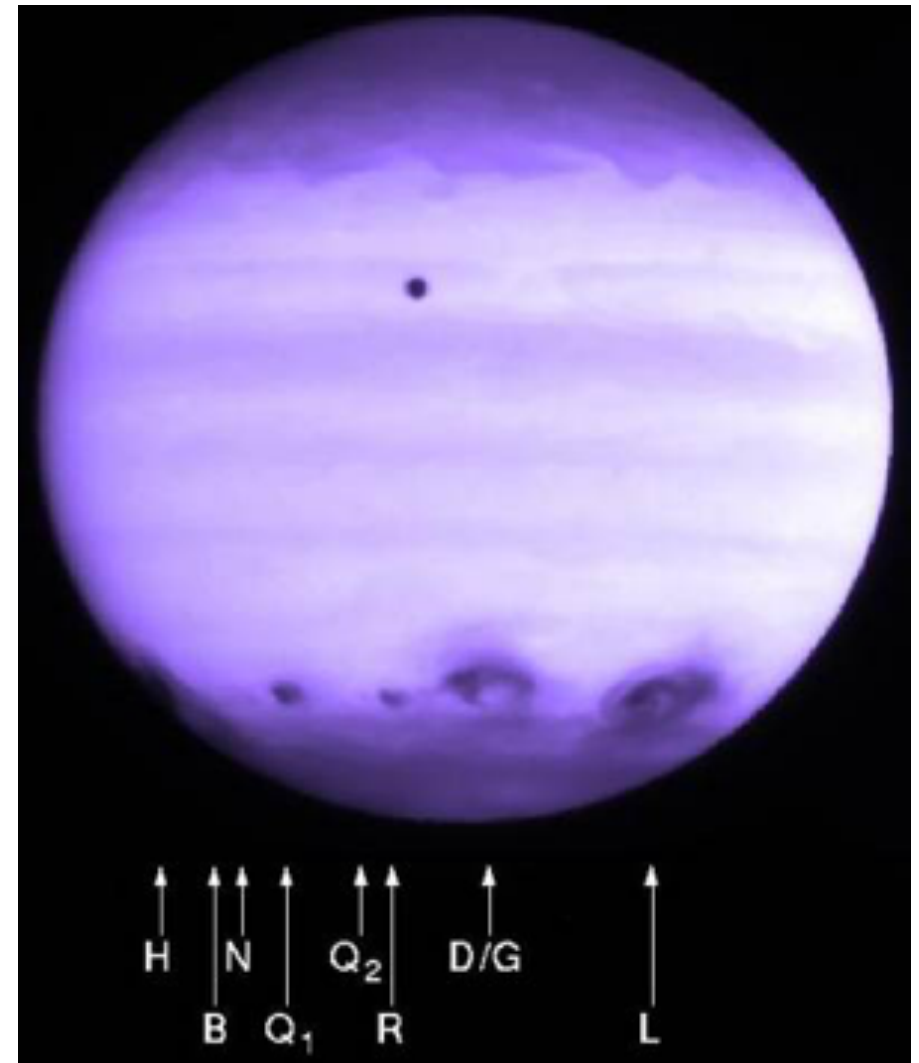
# Distribution in the solar system

DeMeo and Carry, Nature 2014



Main belt comets distribution, updated from Jewitt, AJ 2012

Possible activity mechanisms include: **sublimation**, impacts, electrostatics, rotational bursting, thermal effects, radiation pressure sweeping



## The Rosetta mission



Rosetta main goals include : understand the formation of comets, determine their composition, analyze the surface and the interior, determine what role they played for Earth's evolution.

### 11 instruments :

**ALICE** UV, vis & IR spectroscopy  
**VIRTIS**

**OSIRIS** vis, near IR&UV camera

**CONSERT** bistatic radar

**COSIMA**  
**ROSINA** Mass spectrometry

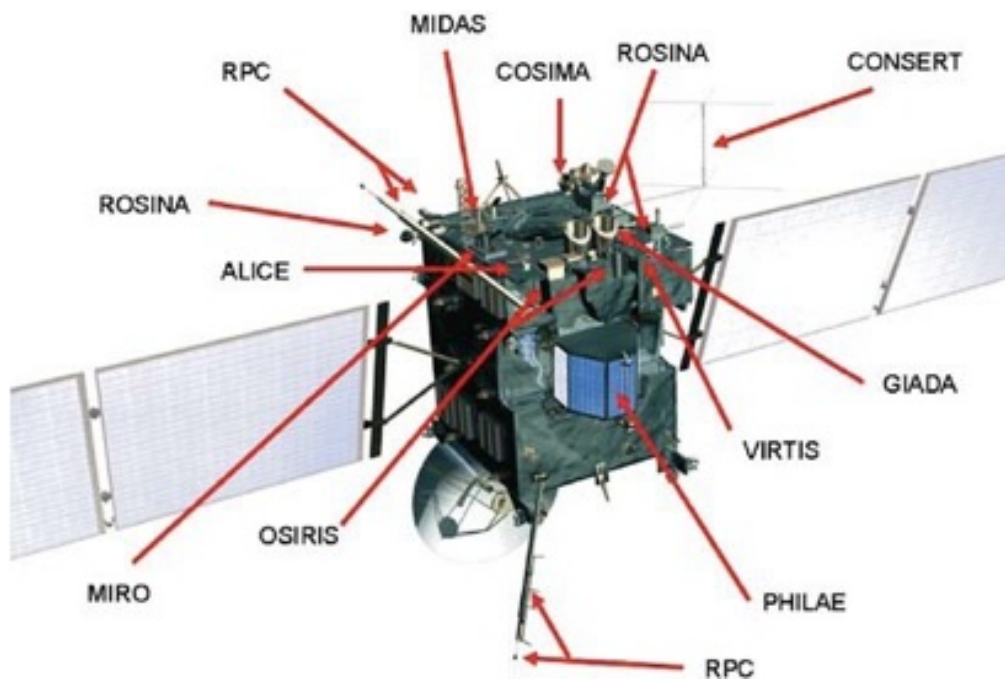
**MIRO** microwave detection

**GIADA** dust dynamics detection

**MIDAS** dust grains microscope

**RPC** plasma measurements

**RSI** Radio science





$\mu$ wave MIRO (~ cm)

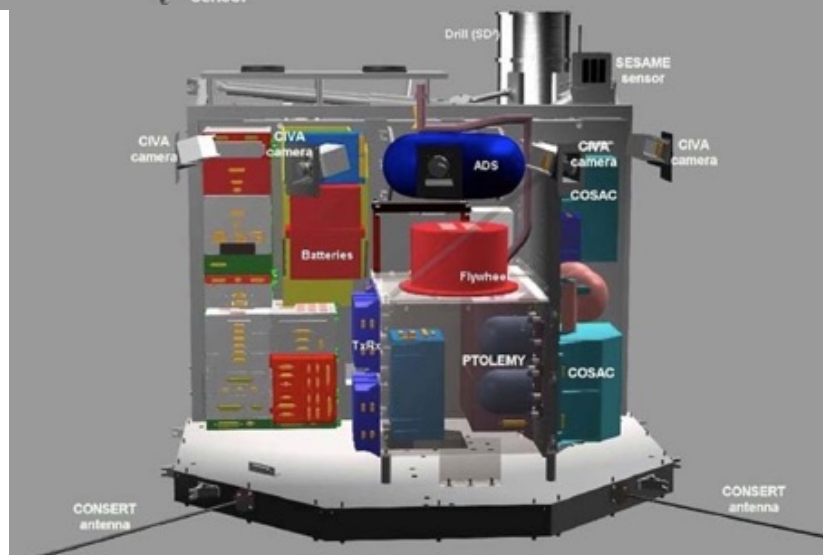
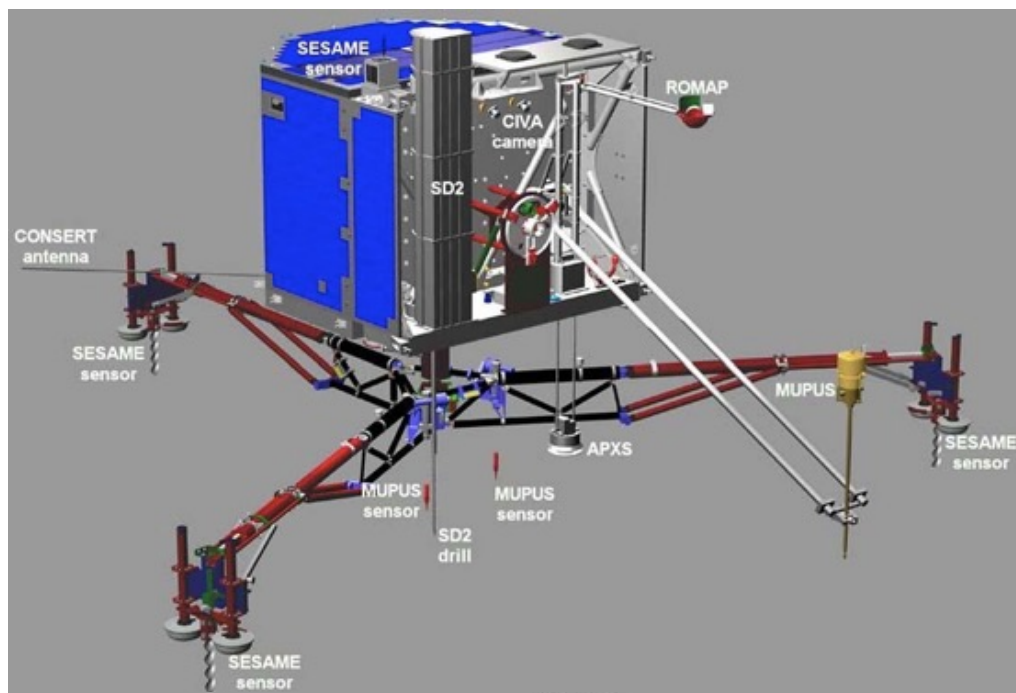
MUPUS (10 cm)

Drill S2D (few 10 cm)

SESAME/PP (~ 1 m)

**Radar CONSERT (100 m)**

RSI (whole nucleus)



## 9 instruments :

**COSAC** complex molecules analysis

**MODULUS-Ptolemy** isotopes

**CONSERT** bistatic radar

**APXS** composition

**MUPUS** penetrating sensors

**ROMAP** magnetometer and plasma

**SESAME** surface physical properties

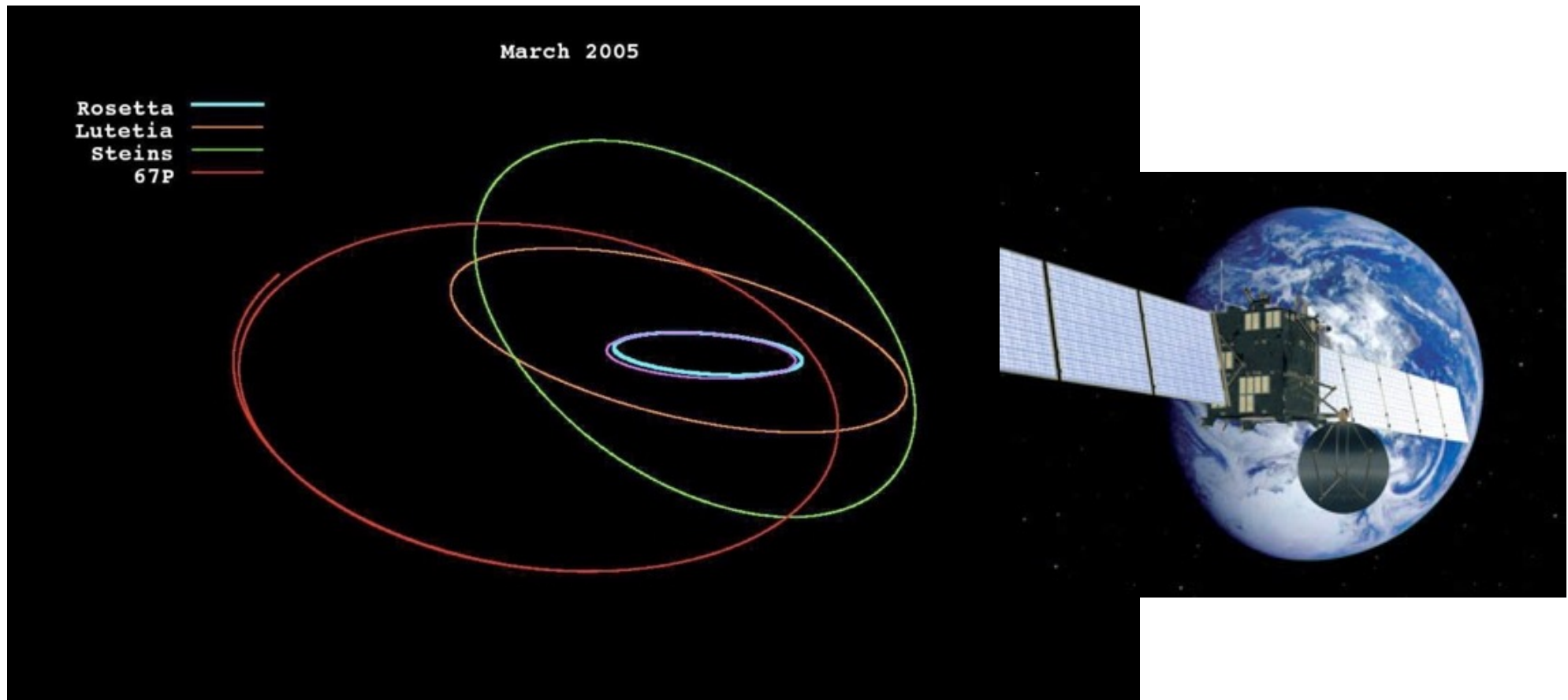
**CIVA** VIS and IR camera

**ROLIS** CCD camera

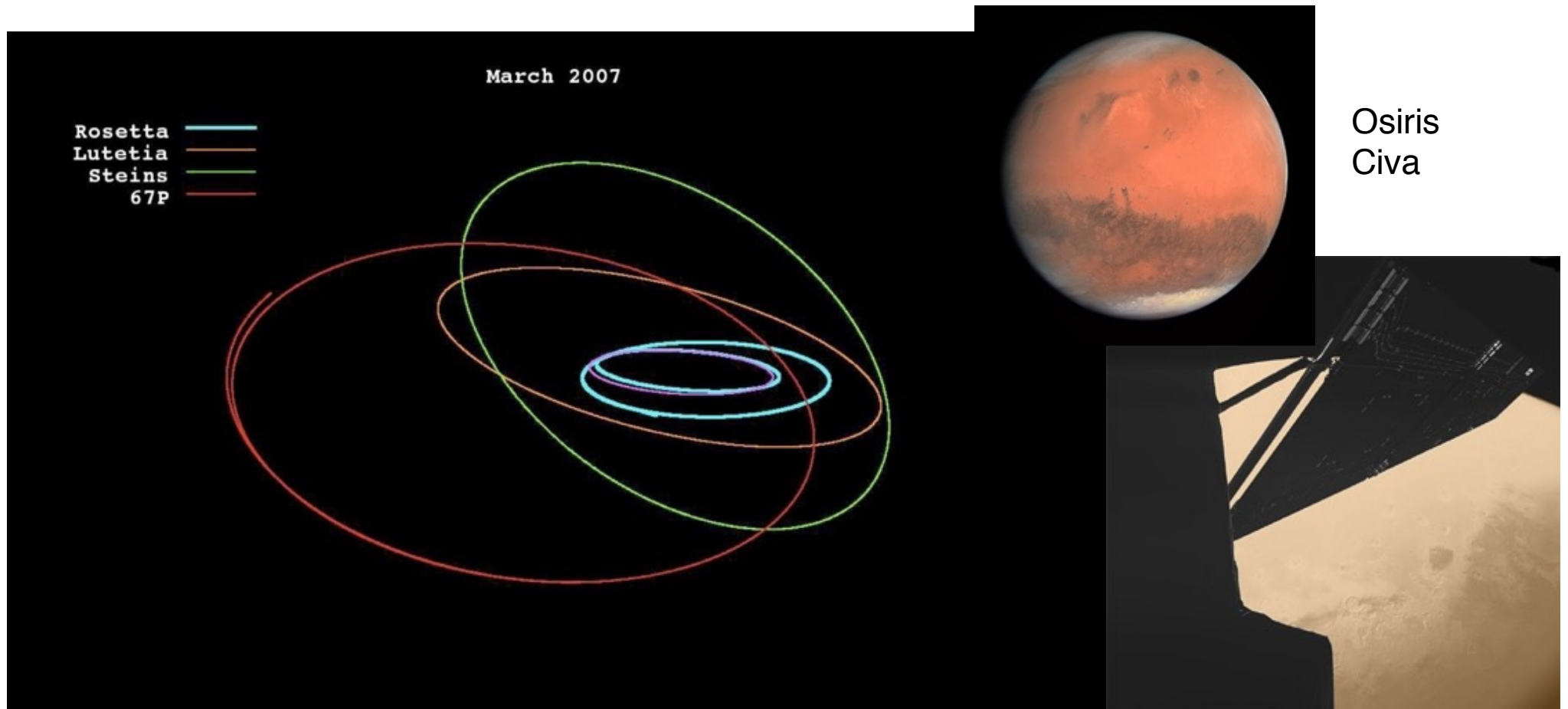
Mission phases. **March 2004: launch from Kourou**  
Initially scheduled for Jan 2003 for 46P/Wirtanen in 2011



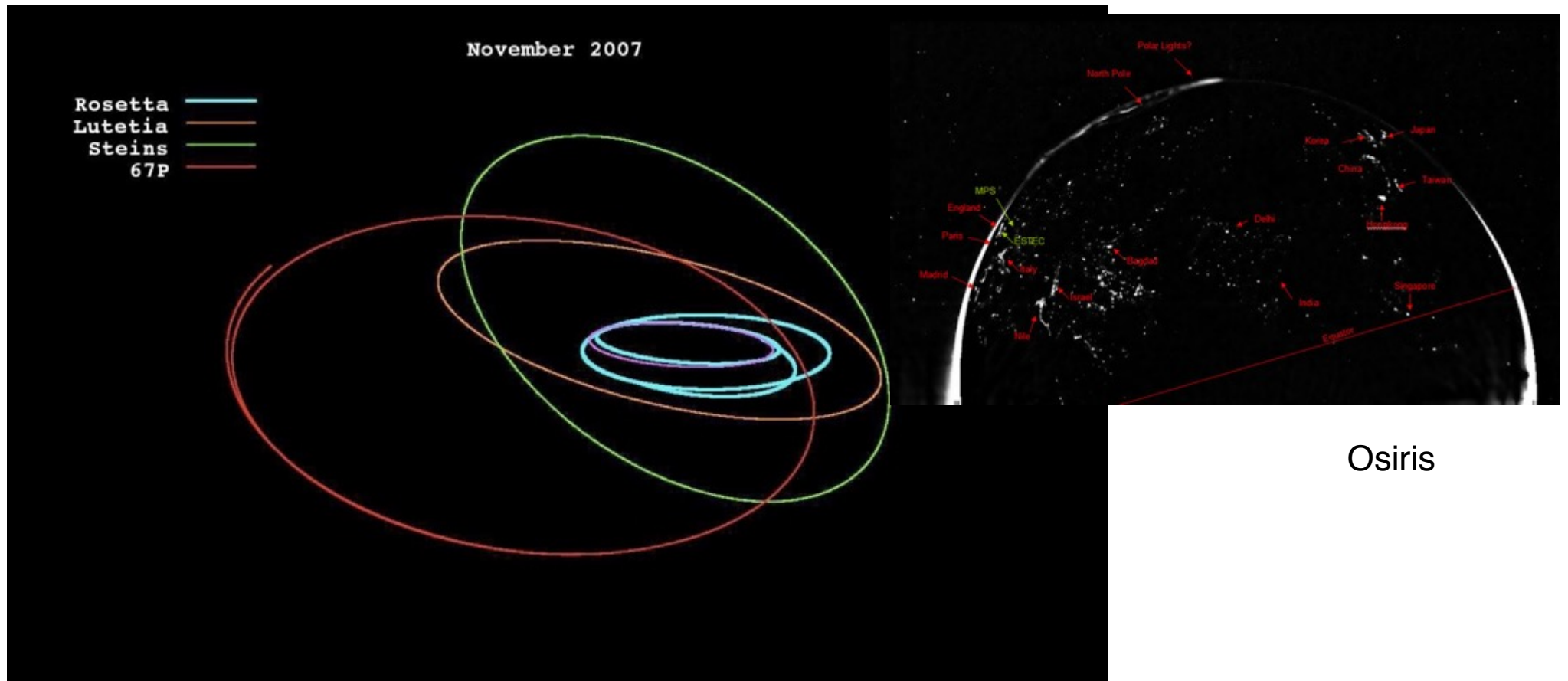
Mission phases. **March 2005: gravity assist by Earth 1**



Mission phases. **March 2007: gravity assist by Mars**

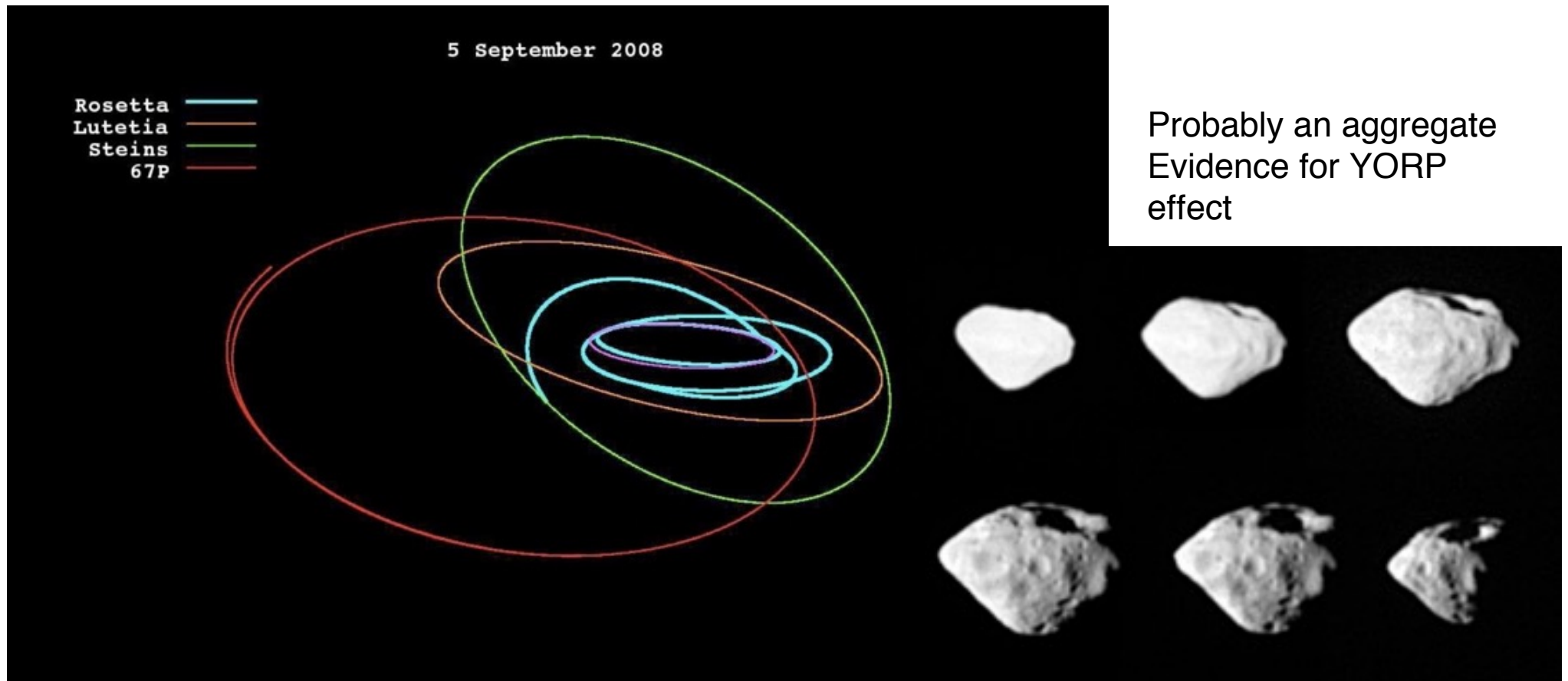


Mission phases. **Nov 2007: Gravity assist Earth 2**

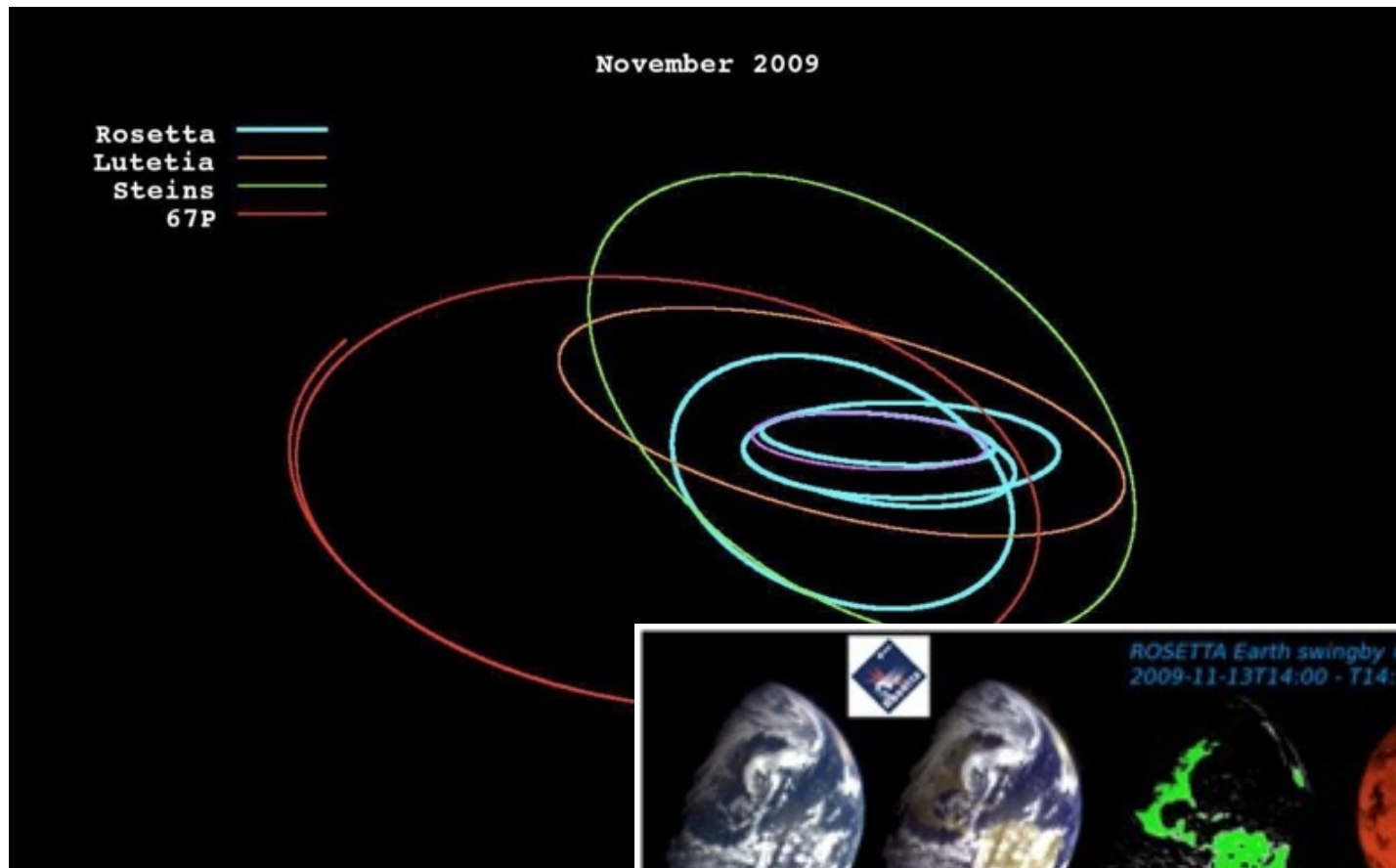


Osiris

Mission phases. **Sept 2008: 2867 Steins fly-by at 800km**



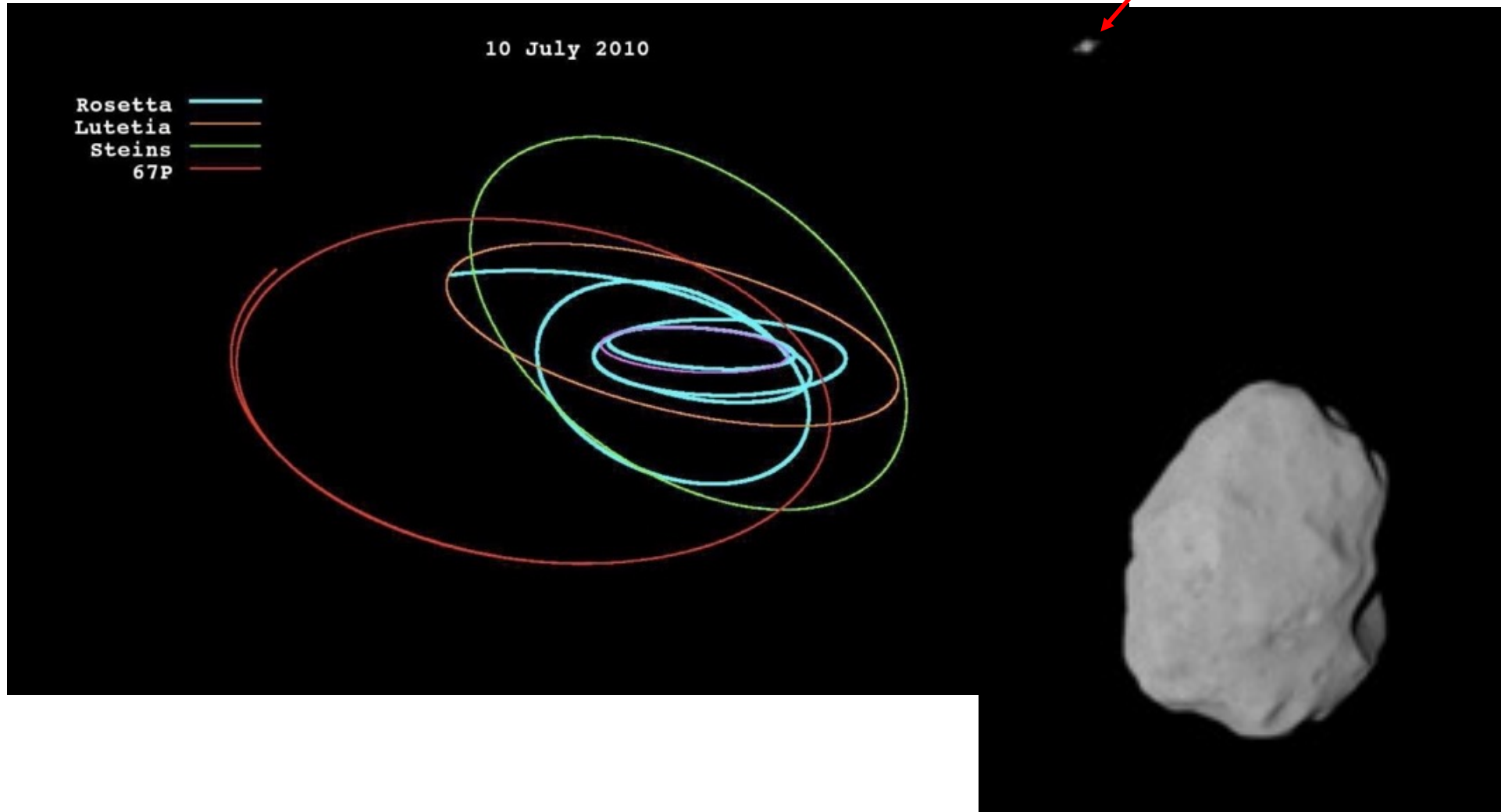
Mission phases. **Nov 2009: Gravity assist Earth 3**



Virtis

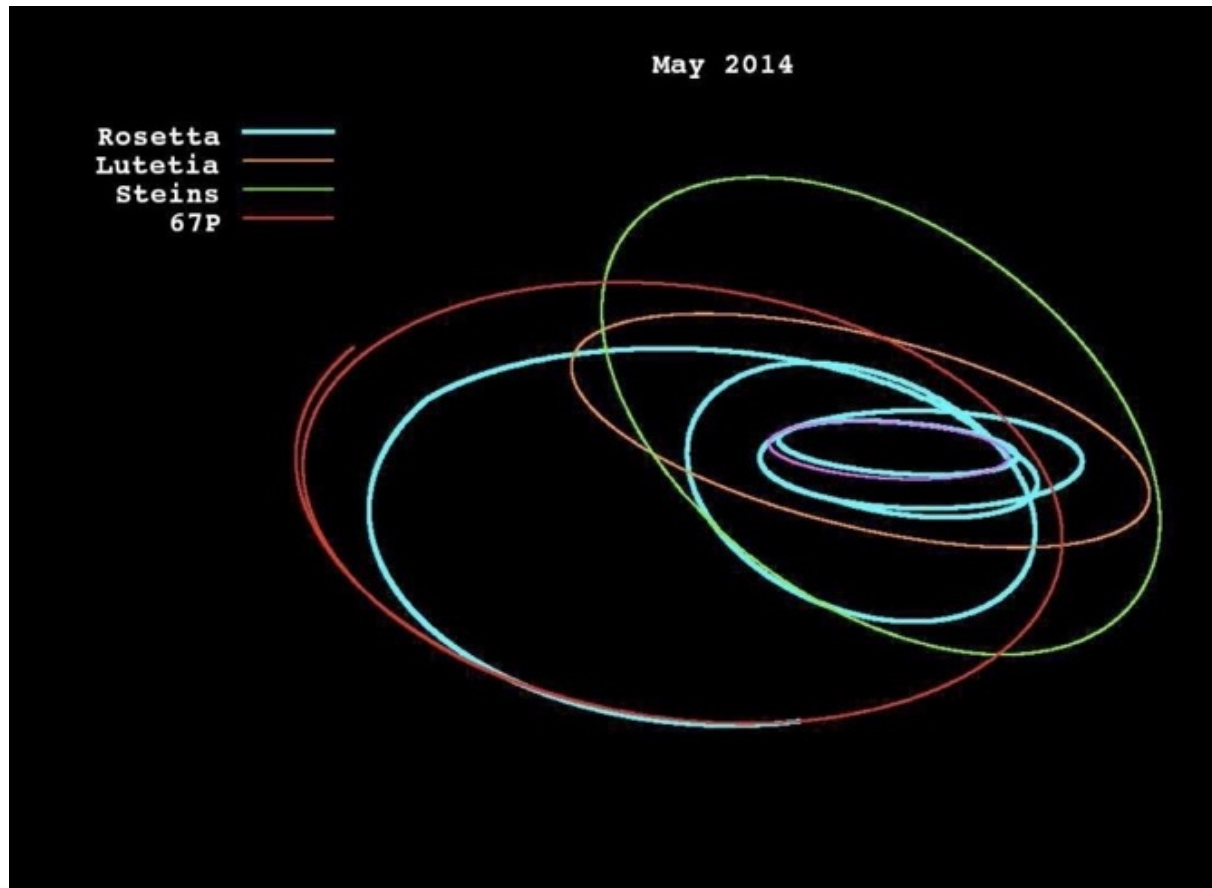


Mission phases. Jul 2010: 21 Lutetia fly-by at 3160 km

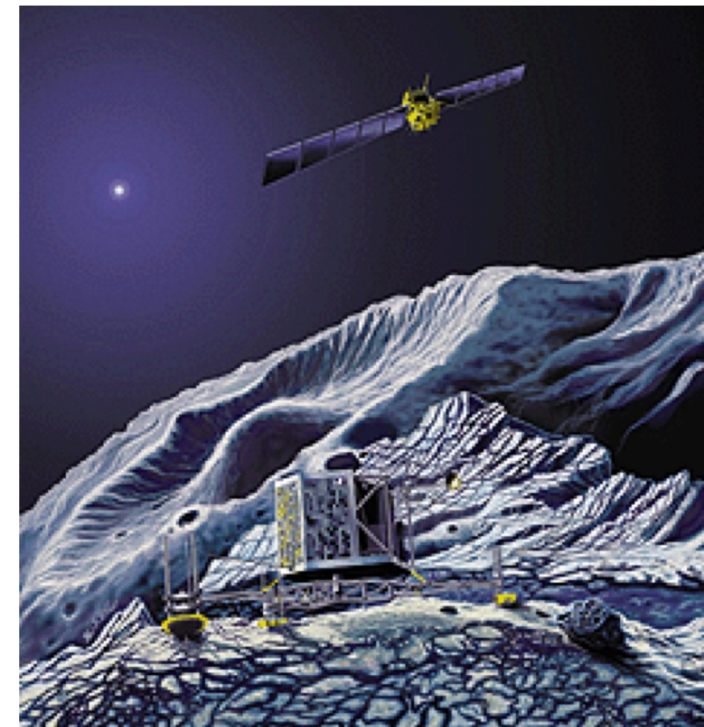




Mission phases. **May 2014: rendez-vous maneuver**

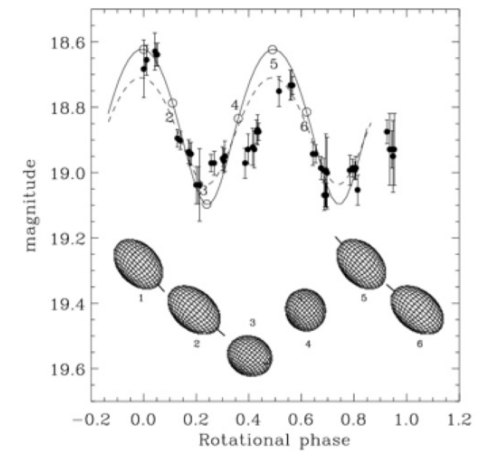


**Aug 2014: nucleus close-in**  
**Nov 2014: landing**  
**Aug 2015: perihelion passage**  
**Sept 2016: end of mission**



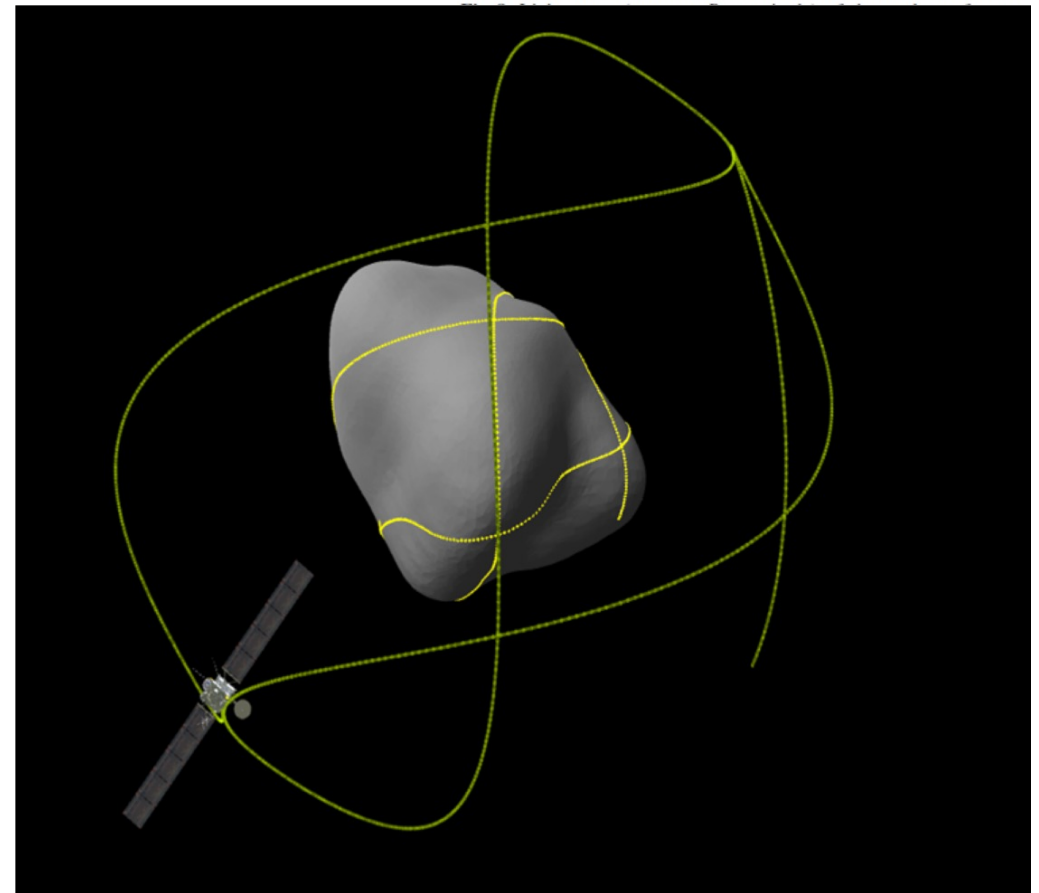
Lamy et al.,  
A&A 2006

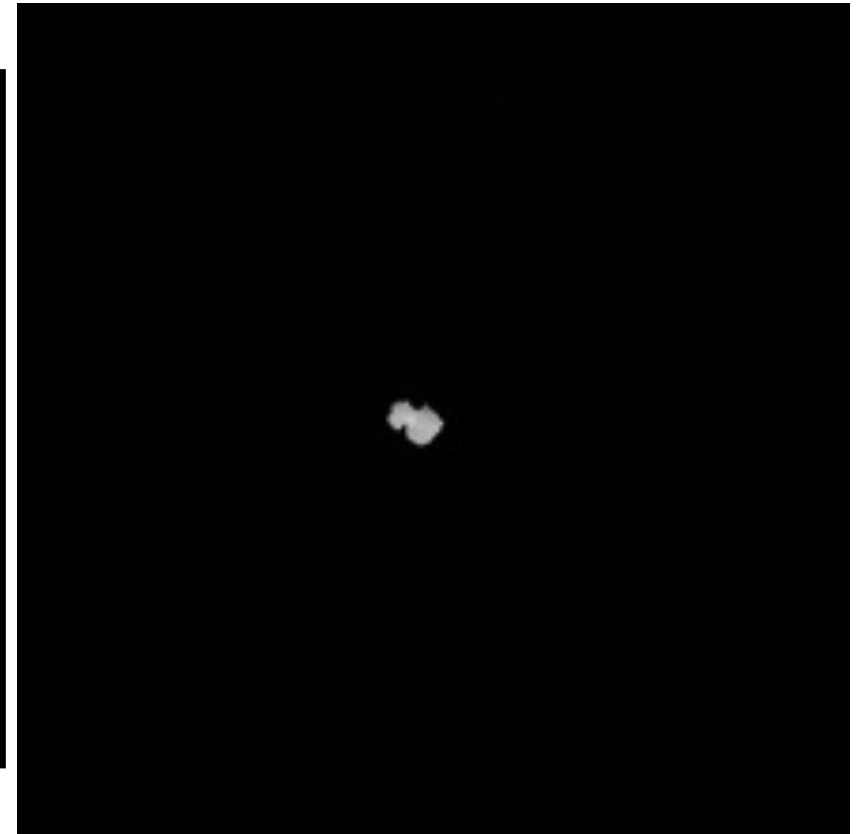
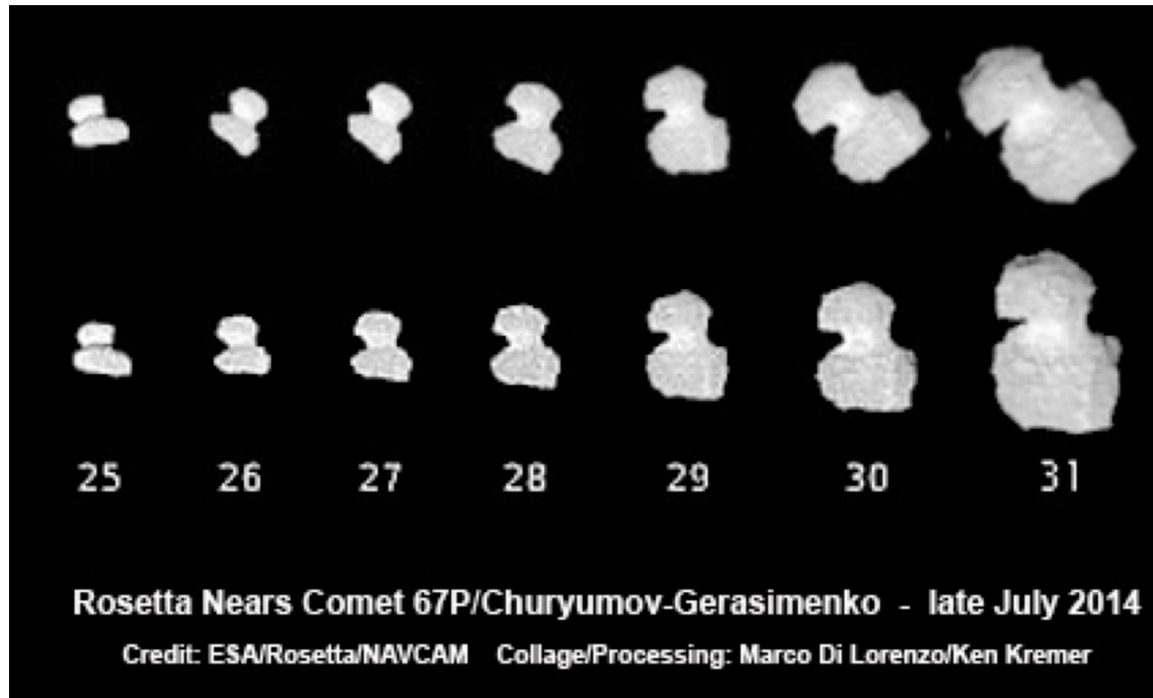
Mission phases. **2014-15: rendez-vous and landing**

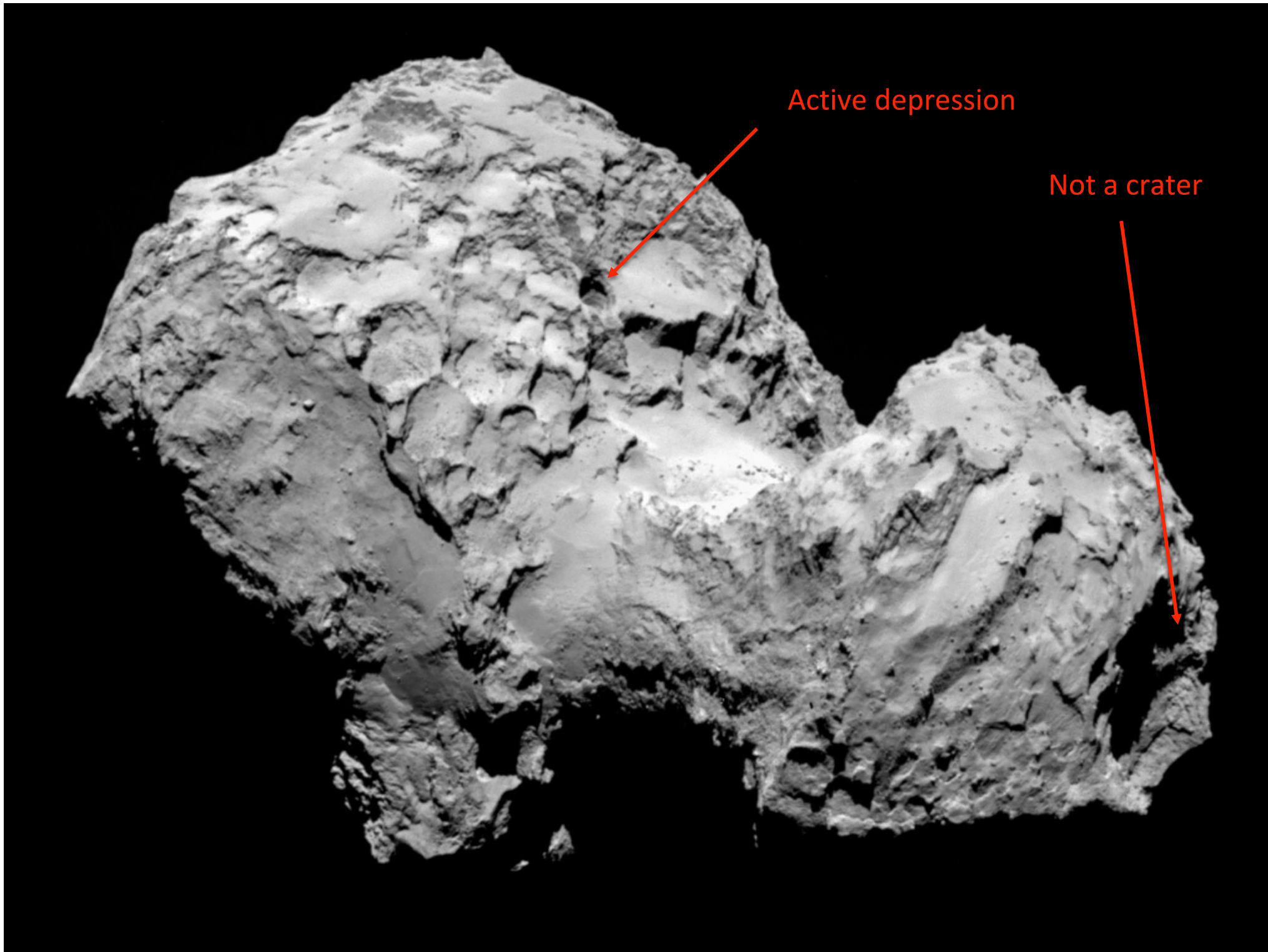


Mission issues:

- distance => communication ~50min
- **Low gravity** =>  
Gas drag force  $> g$  ( $5 \cdot 10^{-4} \text{ ms}^{-2}$ )
- Rotation 12.55 h ~ orbital period
- **Unknown environment** => dust
- **Extremely porous body**





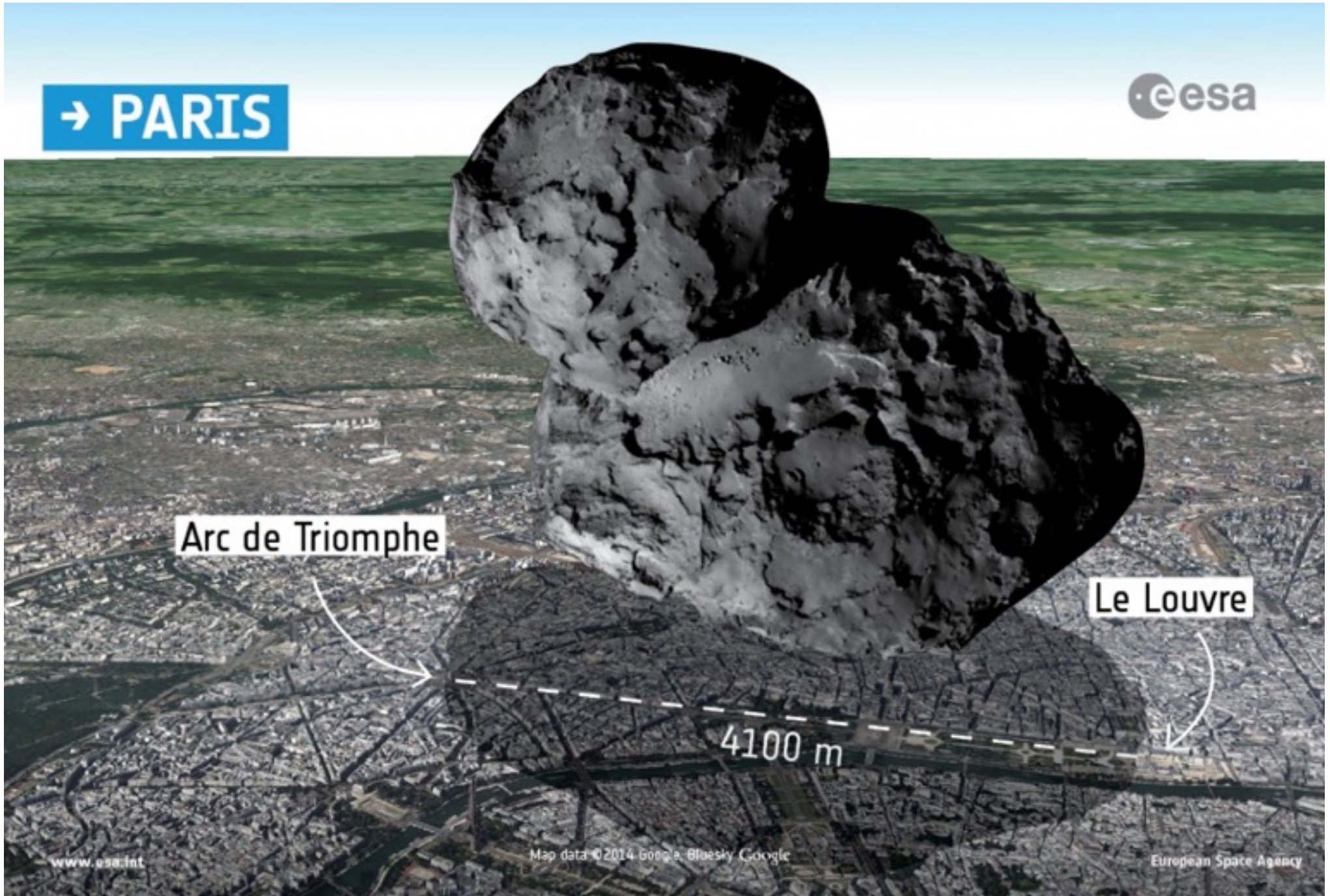


Active depression

Not a crater



→ PARIS

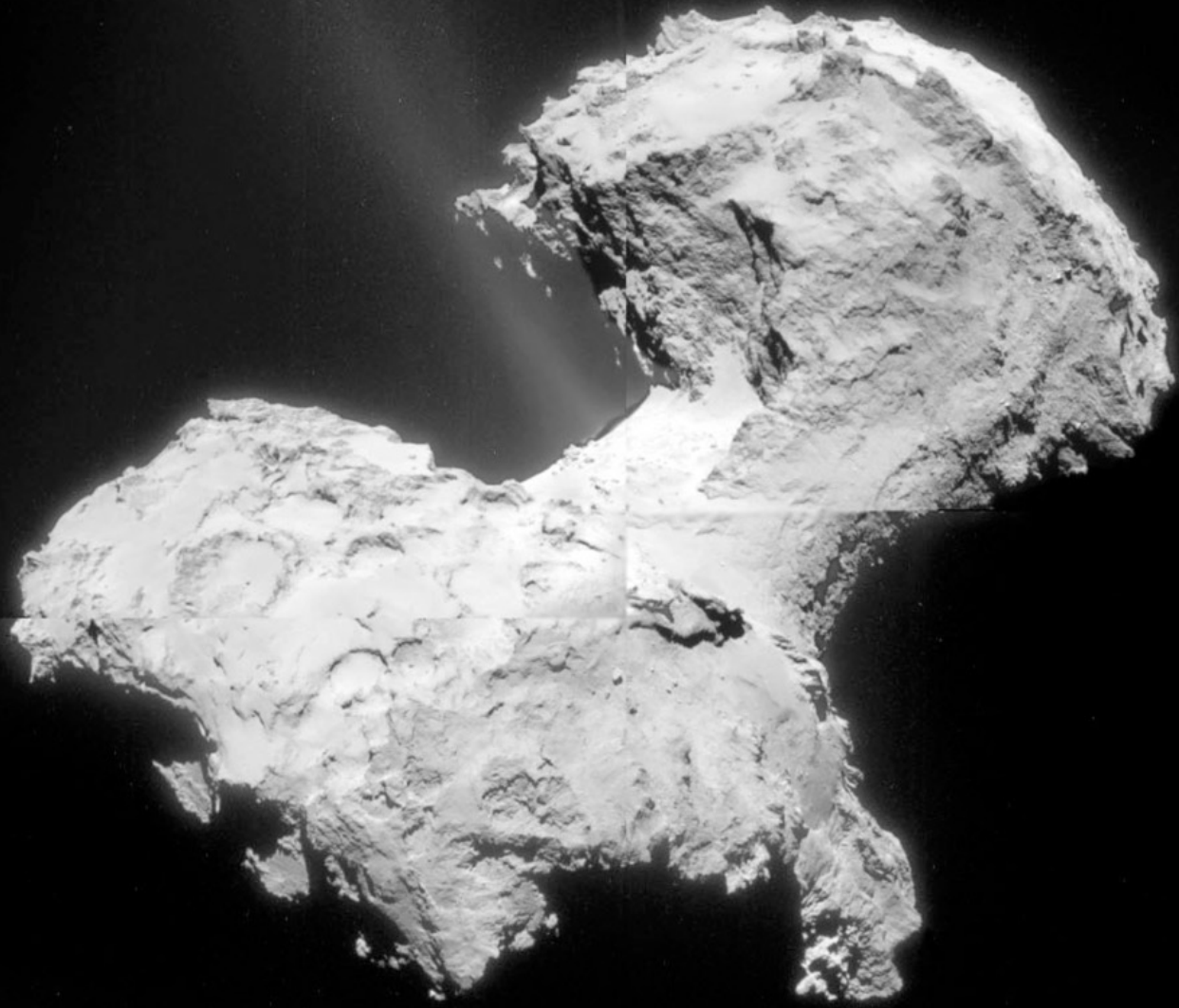


Arc de Triomphe

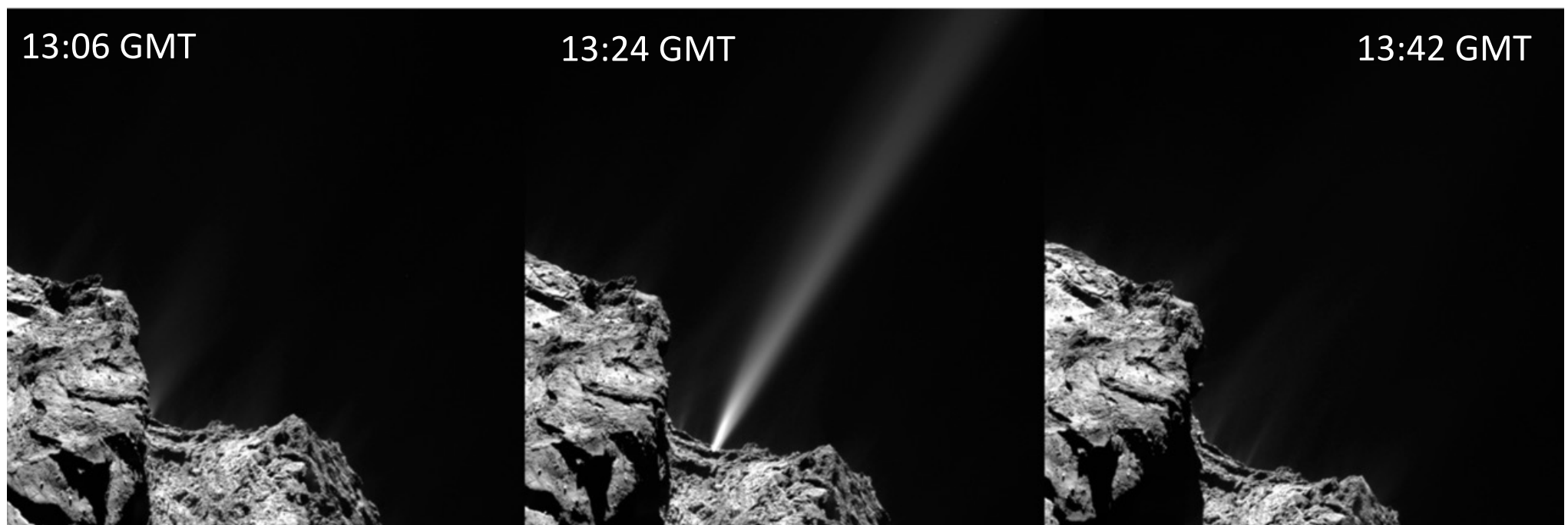
Le Louvre

4100 m

Th

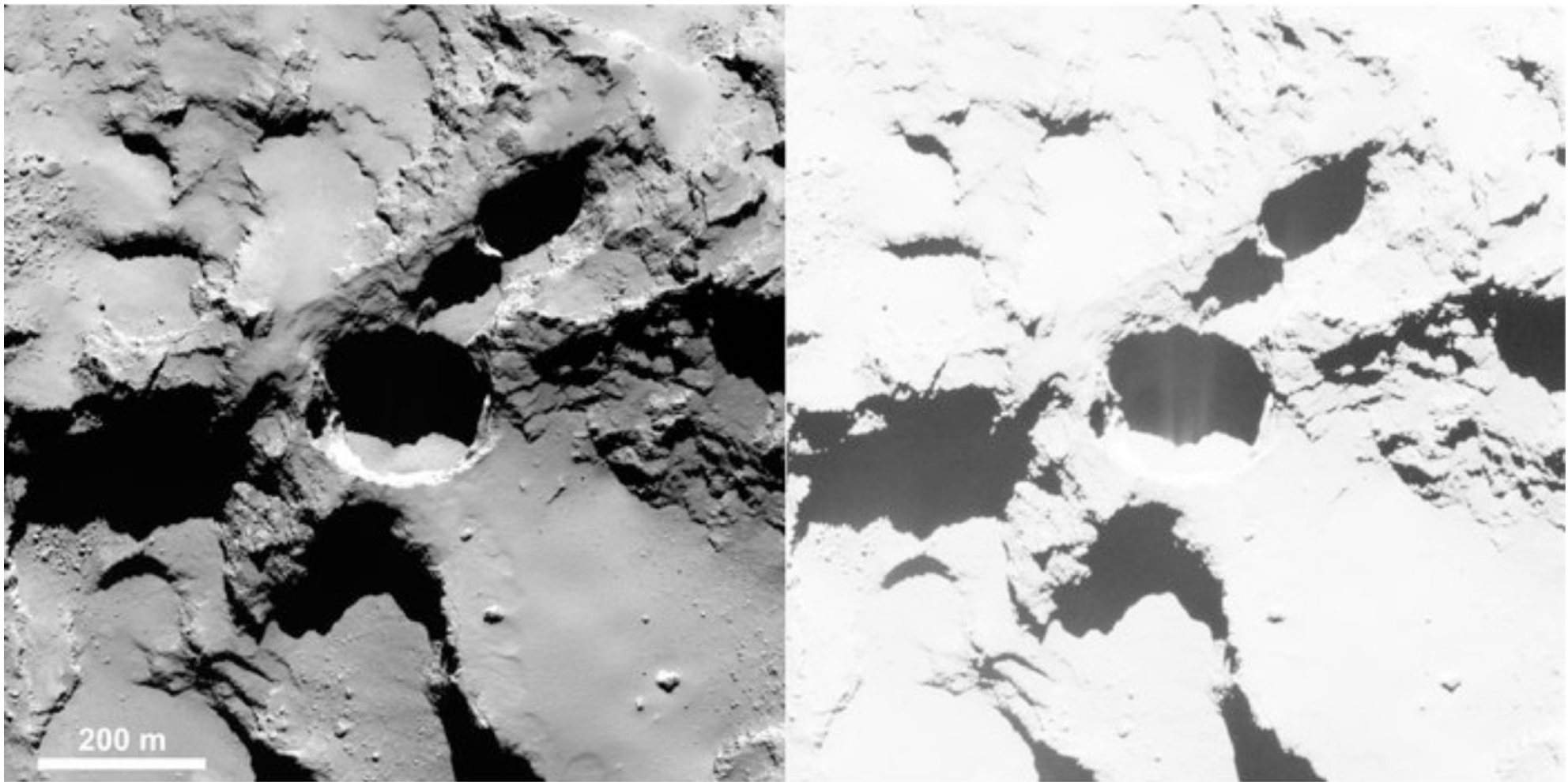


- A short-lived outburst from Comet 67P/Churyumov–Gerasimenko was captured by Rosetta's OSIRIS narrow-angle camera on 29 July 2015.
- The jet is estimated to have a minimum speed of 10 m/s and originates from a location on the comet's neck, in the rugged Anuket region.



Credit: ESA/Rosetta/OSIRIS Team

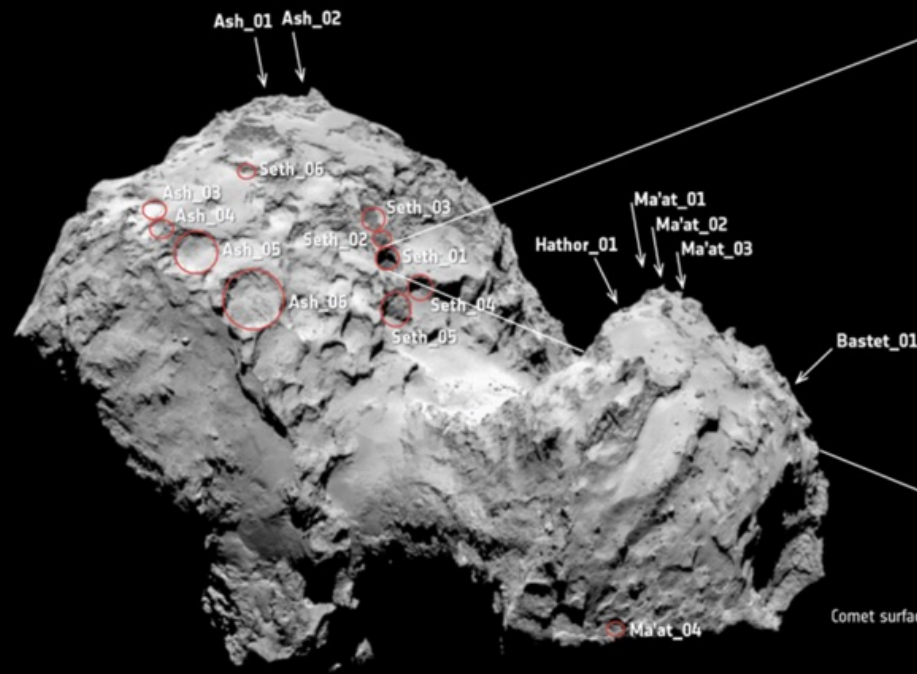
Sierks et al., Science 2015





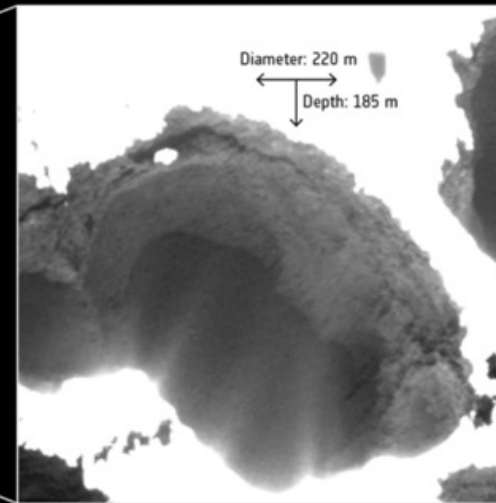


## → ACTIVE PITS ON COMET 67P/CHURYUMOV–GERASIMENKO



The pits were identified in OSIRIS images taken August–October 2014.

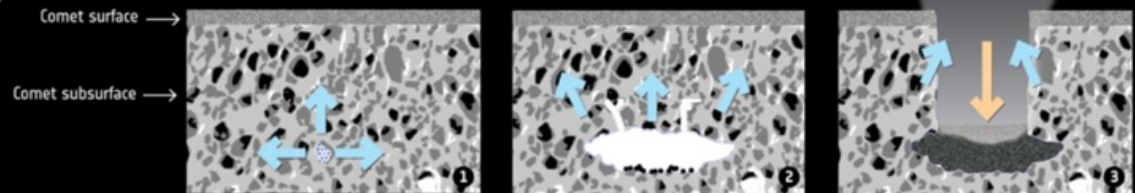
→ Close-up of Seth\_01 shows jets emanating from the pit walls



→ Active pits contribute to the comet's overall activity seen from afar.



→ Pit formation via sinkhole collapse

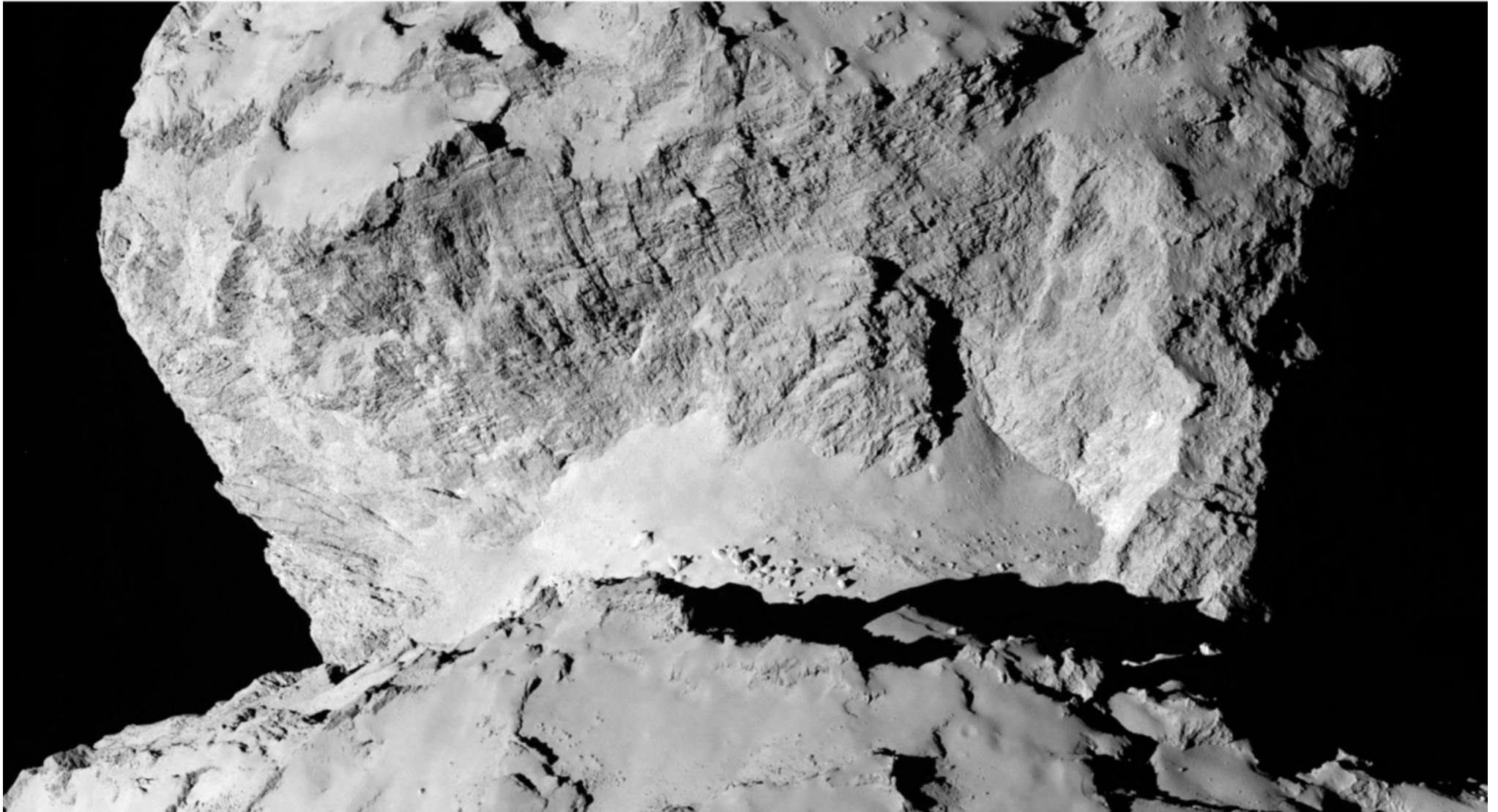


1. Heat causes subsurface ices to sublimate (blue arrows), forming a cavity (2). When the ceiling becomes too weak to support its own weight, it collapses, creating a deep, circular pit (3, orange arrow). Newly exposed material in the pit walls sublimates, accounting for the observed activity (3, blue arrows).

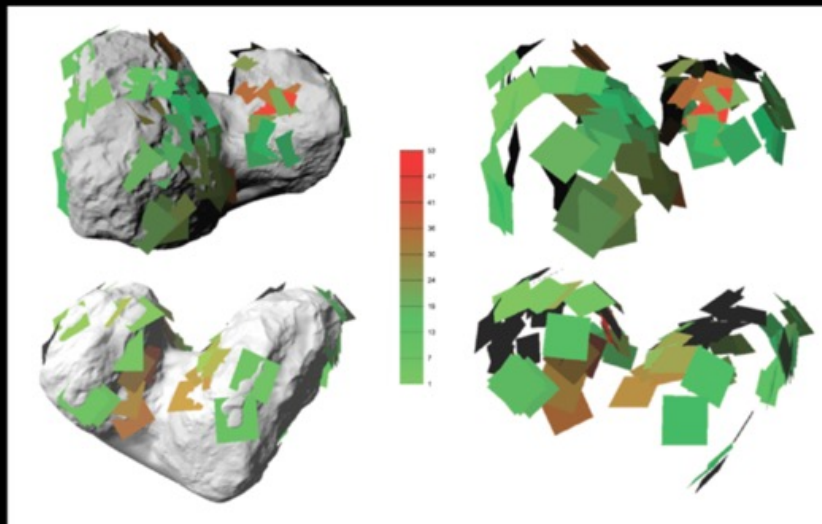
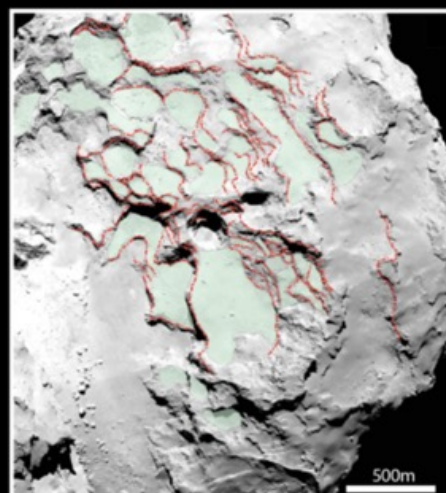
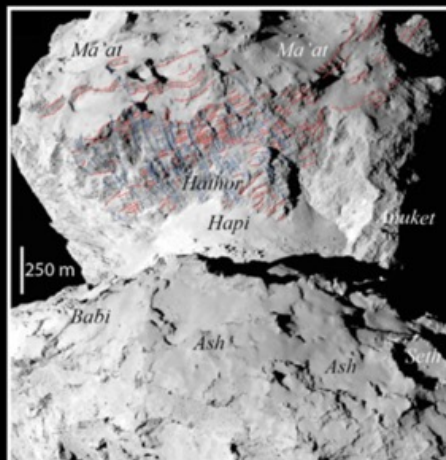
Fractures and debris in the Hathor region

Credit: ESA/Rosetta/OSIRIS Team

Thomas et al., Science 2015



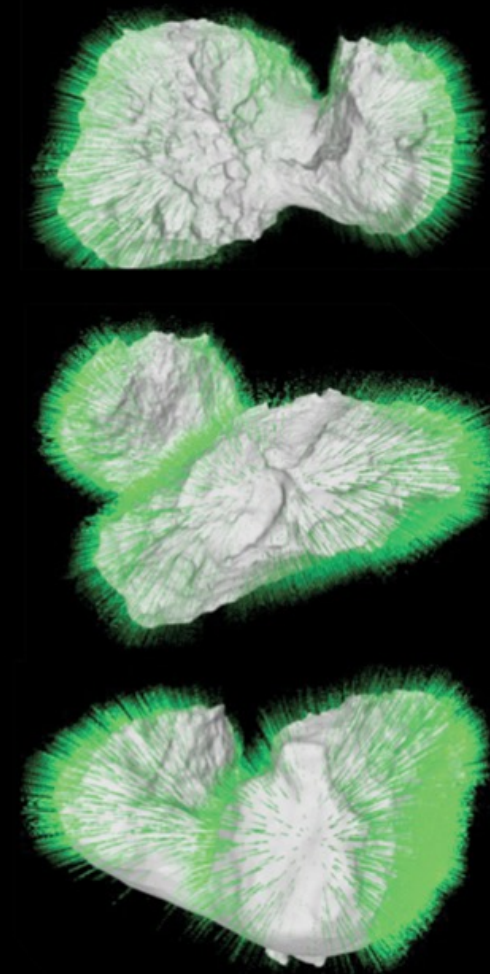
## → THE TWO LOBES OF COMET 67P/CHURYUMOV–GERASIMENKO



Left: high-resolution OSIRIS images were used to visually identify over 100 terraces (green) or strata – parallel layers of material (red dashed lines) – in exposed cliff walls and pits all over the comet surface (left top: Hathor and surrounding regions on comet's small lobe; bottom: Seth region on comet's large lobe).

Above: a 3D shape model was used to determine the directions in which the terraces/strata are sloping and to visualise how they extend into the subsurface. The strata 'planes' are shown superimposed on the shape model (above left) and alone (above right) and show the planes coherently oriented all around the comet, in two separate bounding envelopes (scale bar indicates angular deviation between plane and local gravity vector).

Right: local gravity vectors visualised on the comet shape model perpendicular to the terrace/strata planes further demonstrate the independent nature of the two lobes.



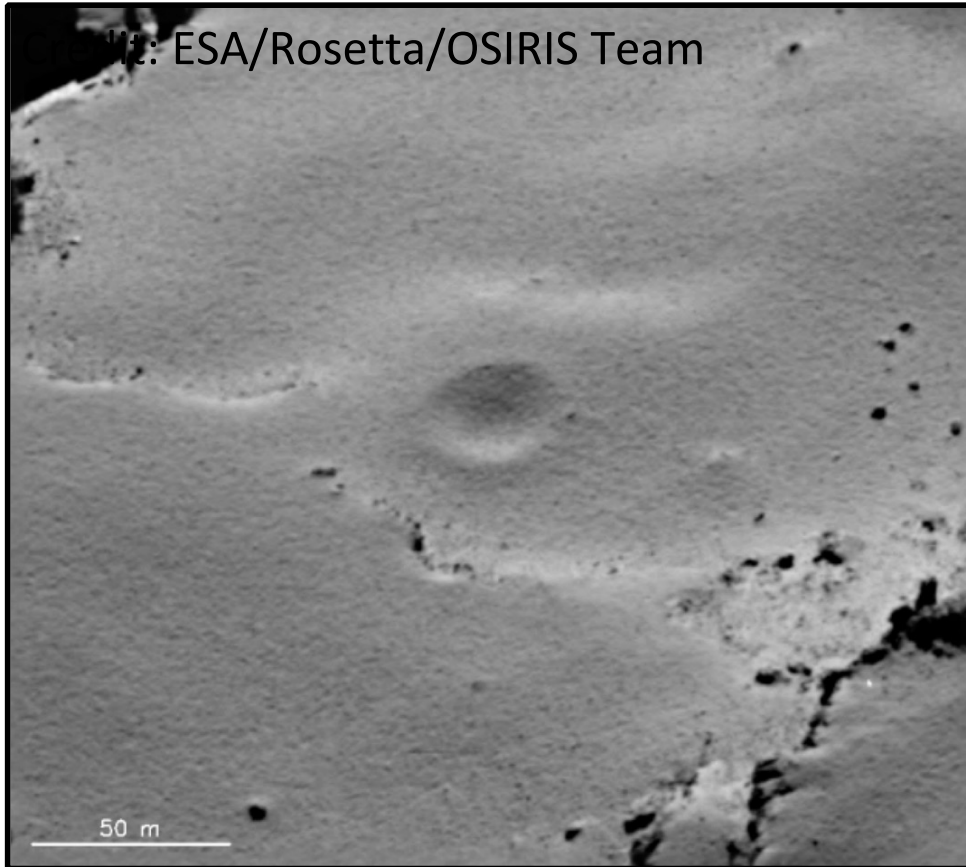
Wall meter scale structures in the Seth region.

Credit: ESA/Rosetta/OSIRIS Team

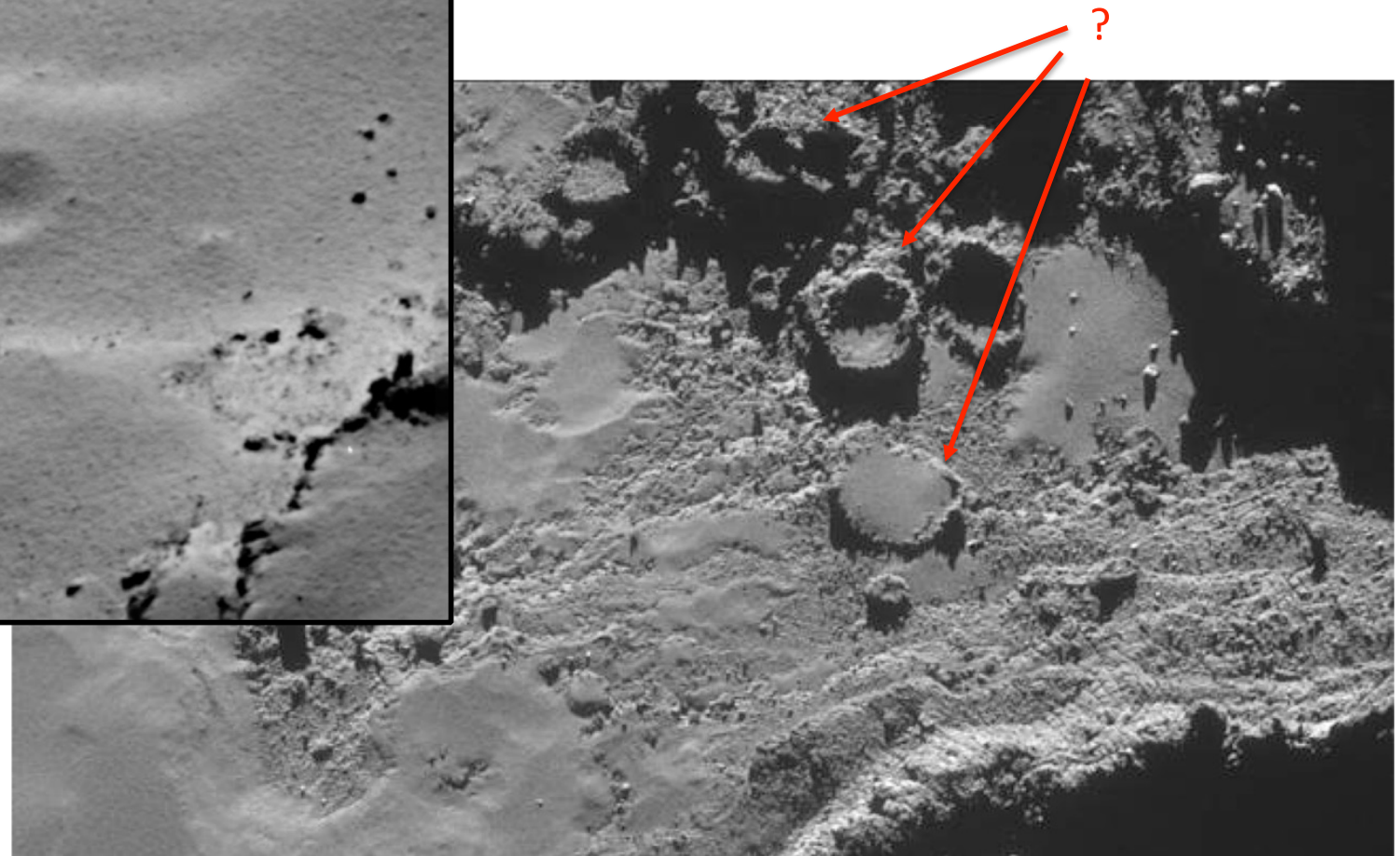
Sierks et al., Science 2015



## Craters ?



Sierks et al., Science 2015

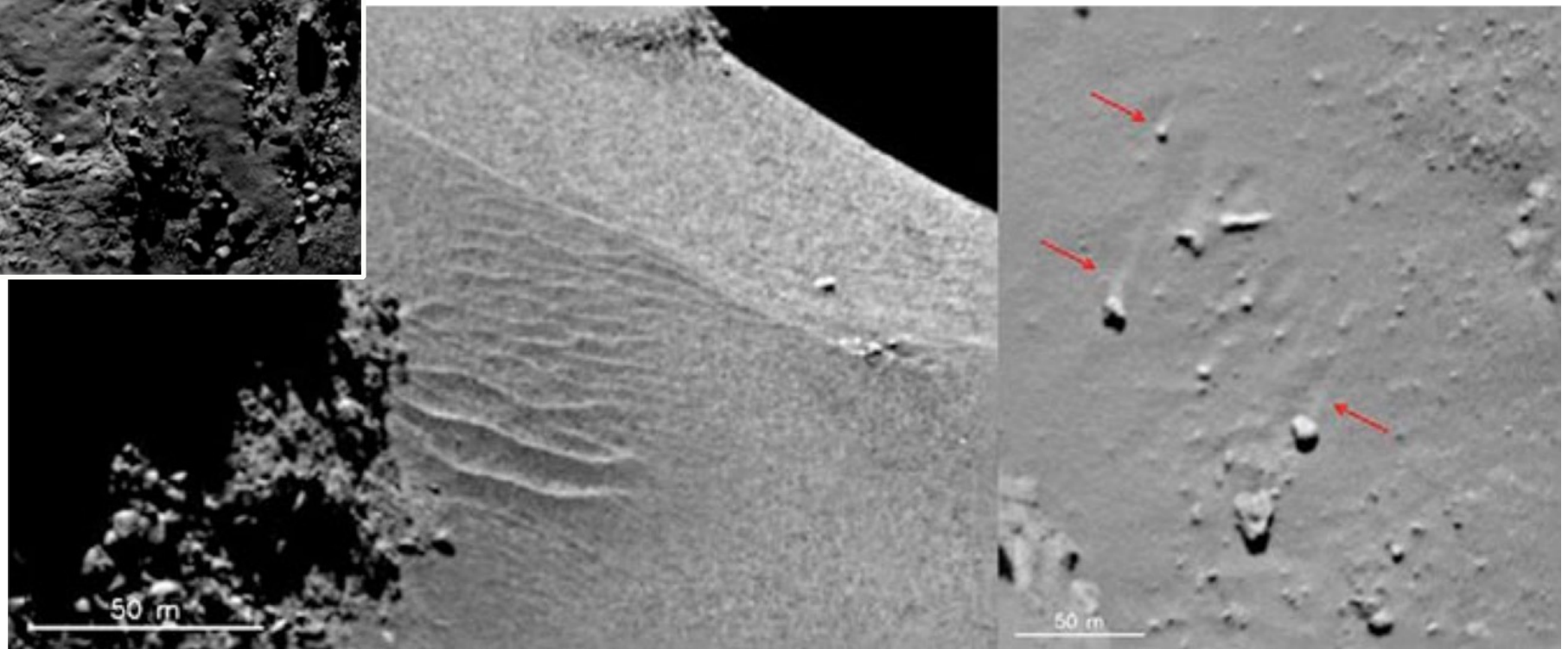


Cryovolcanism ?



dunes ?

Credit: ESA/Rosetta/OSIRIS Team



## Subsurface temperature from MIRO

=> A very low thermal inertia ( $\sim 10$  to  $50 \text{ J K}^{-1} \text{ m}^{-2} \text{ s}^{-0.5}$ )  
(Gulkis et al. 2015)

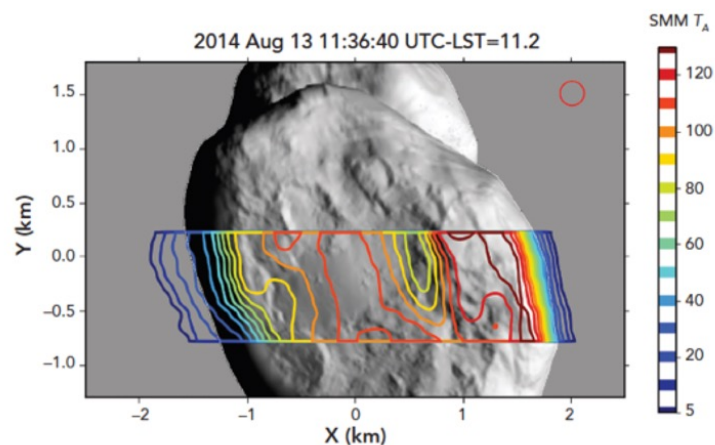
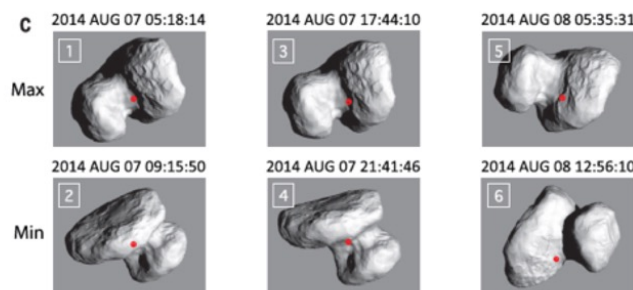
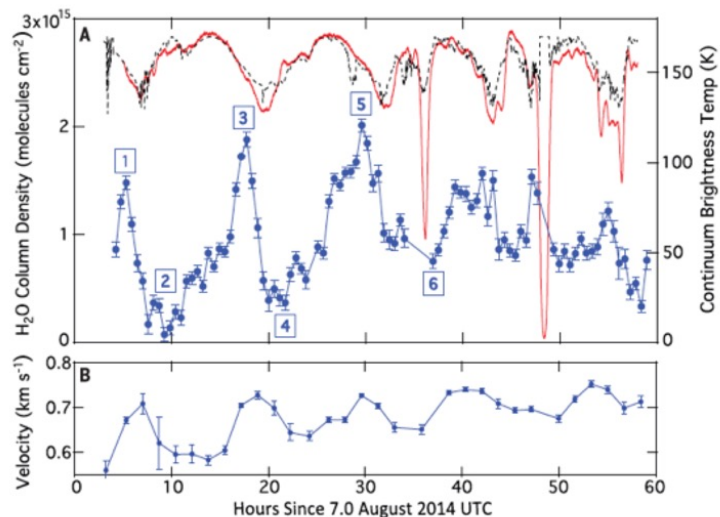
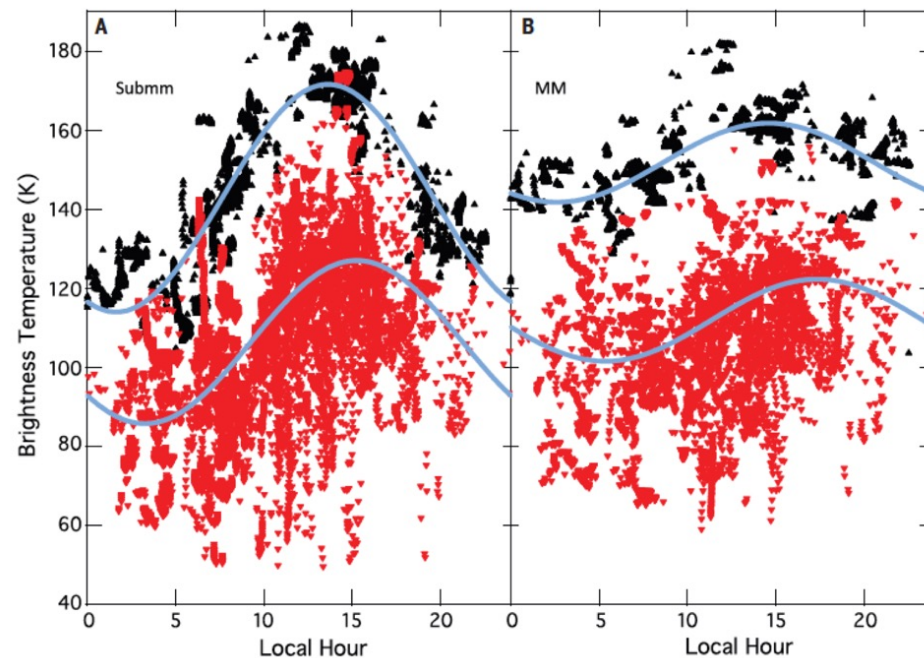


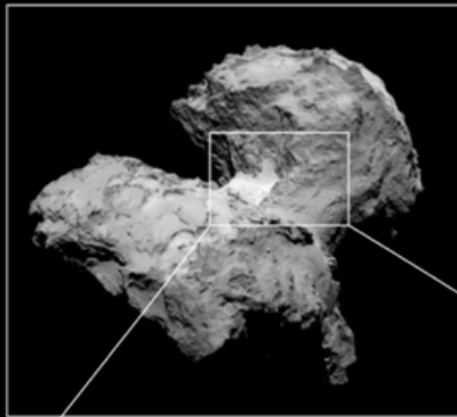
Fig. 5. Brightness temperatures as a function of local solar time, from MIRO continuum measurements of September 2014, are shown for effective latitude bins of 20° to 30° N (black data points) and 20° to 30° S (red data points). The solid curves are diurnal sinusoidal fits to the data. Both effective latitudes and the local solar time are computed from the shape model-derived surface orientation at the MIRO beam center. Only points for which the MIRO beams lie entirely within the nucleus are included. The data are restricted to the 100° to 200° longitude band in order to eliminate data in the neck region, where extreme shadowing conditions obscure the interpretation of the diurnal heating curve. (A) Submillimeter data. (B) Millimeter data.



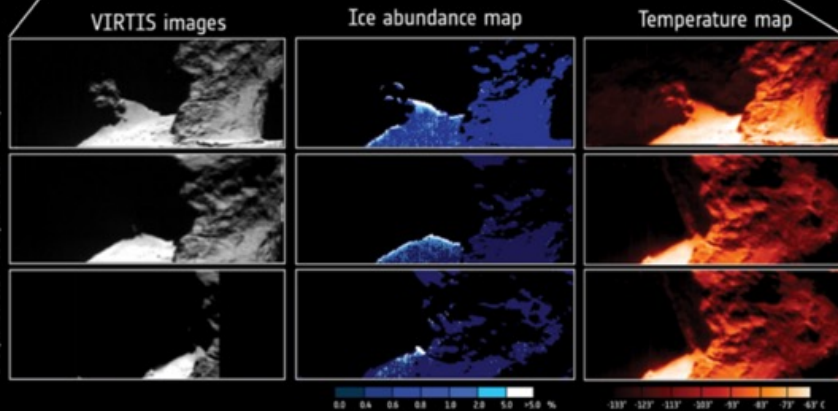


## → THE CYCLE OF WATER ICE AT COMET 67P/CHURYUMOV–GERASIMENKO

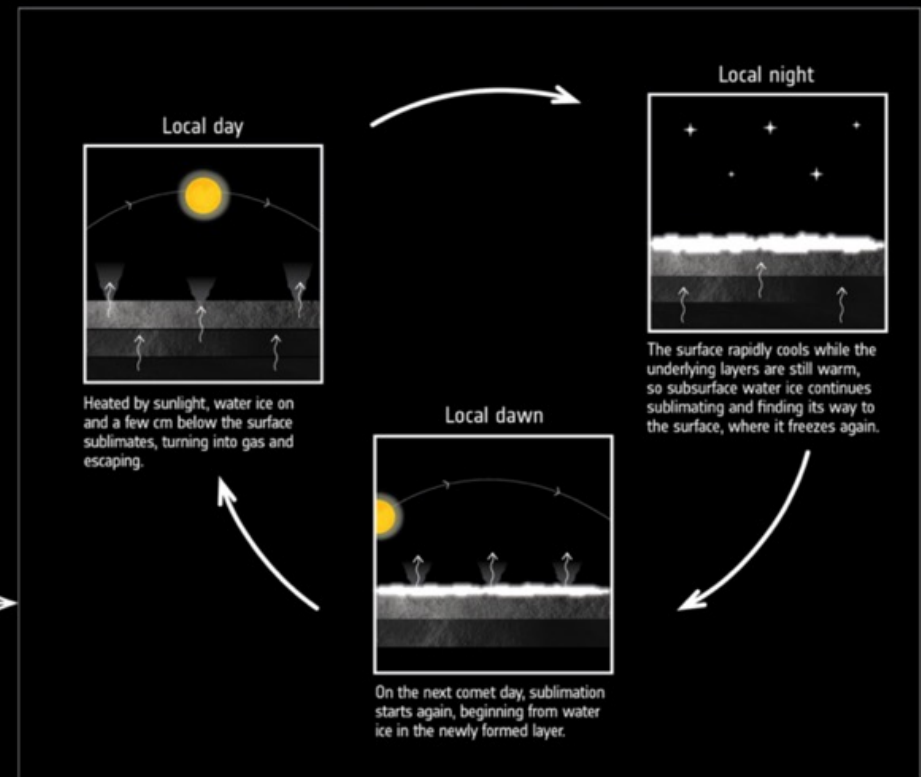
Comet on 2 September 2014



12 September 2014  
13 September 2014  
14 September 2014



Water ice cycle at the comet





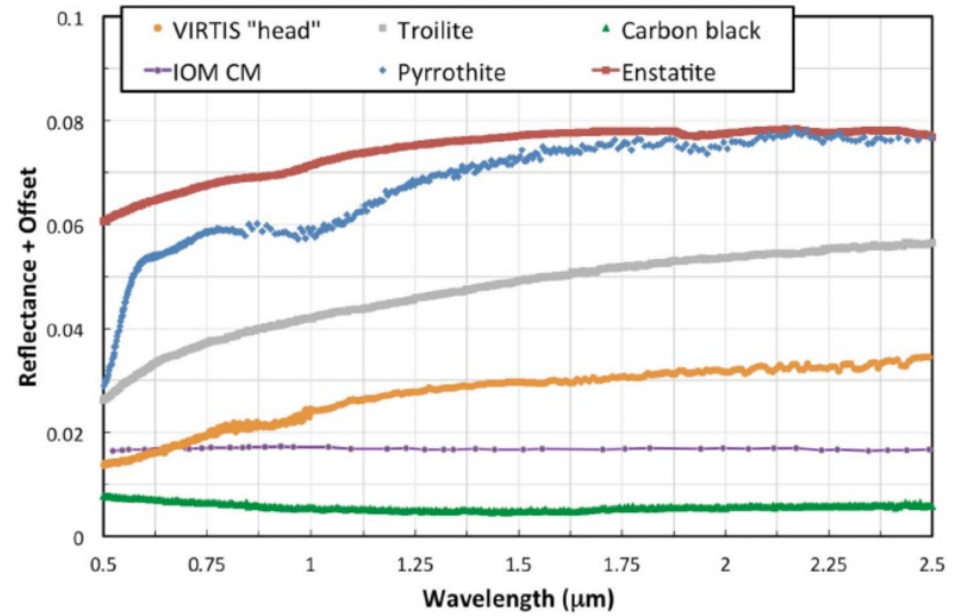
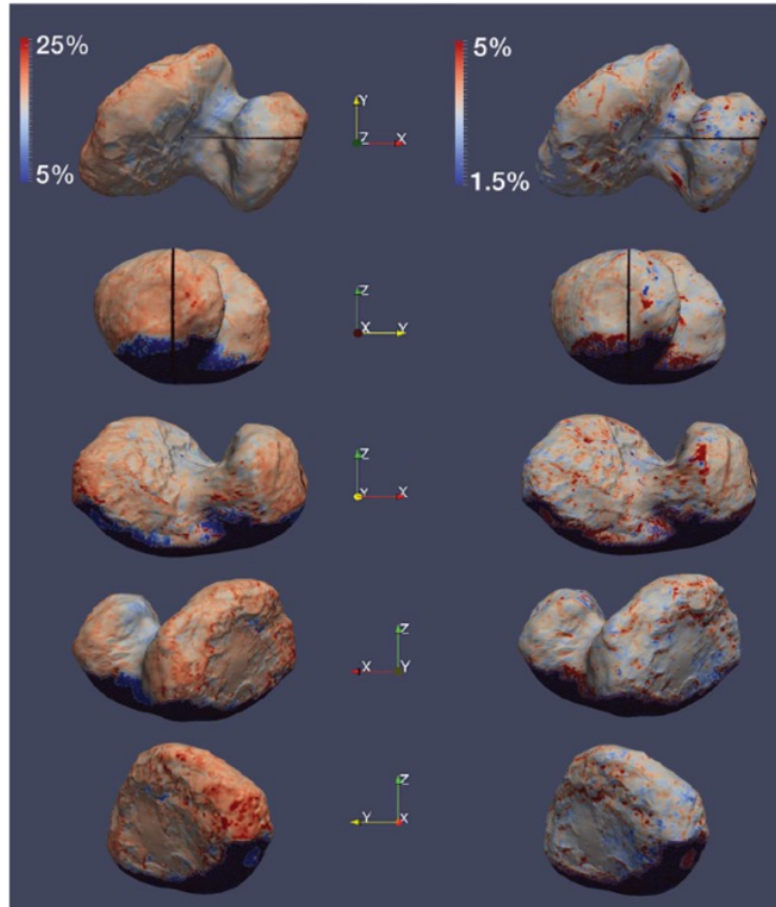
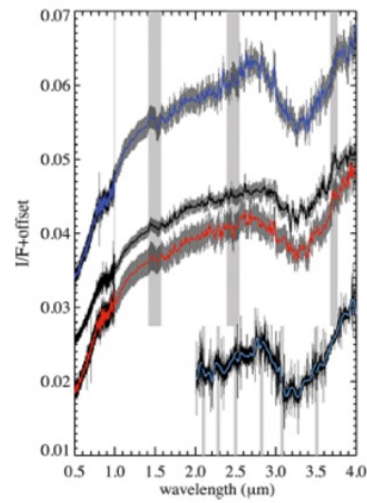
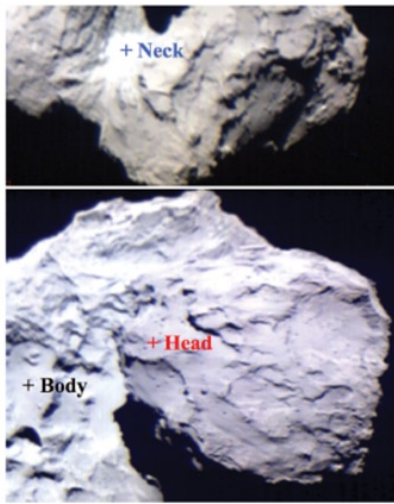


Fig. 3. The spectrum of the head shown in Fig. 1 is compared (in the spectral range 0.5 to 2.5  $\mu\text{m}$ ) to the spectra of several other compounds described in the text. Enstatite, pyrrhothite, and troilite spectra are scaled down by 100, 75, and 50%, respectively. The Murchison IOM is from (16), enstatite spectrum from (29), troilite and carbon black spectra from (30), and pyrrhothite spectrum from (31).

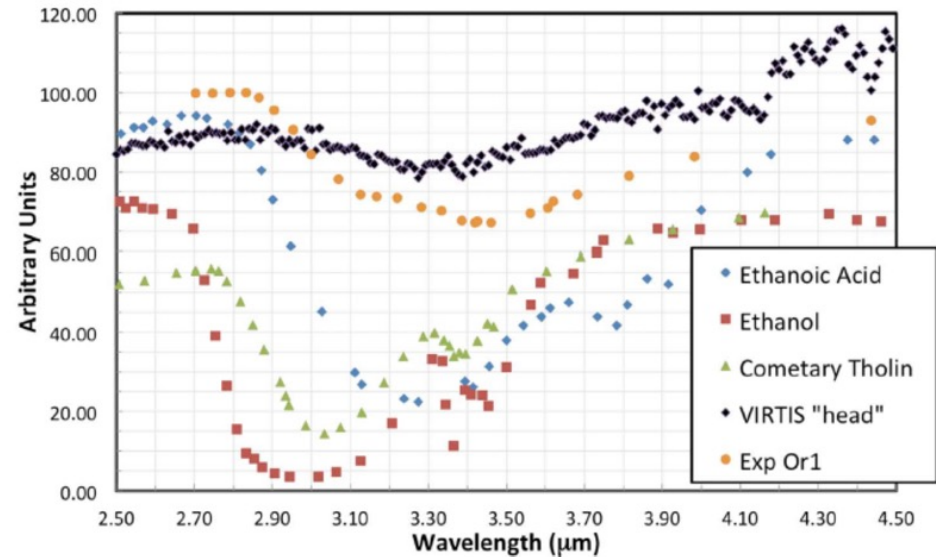
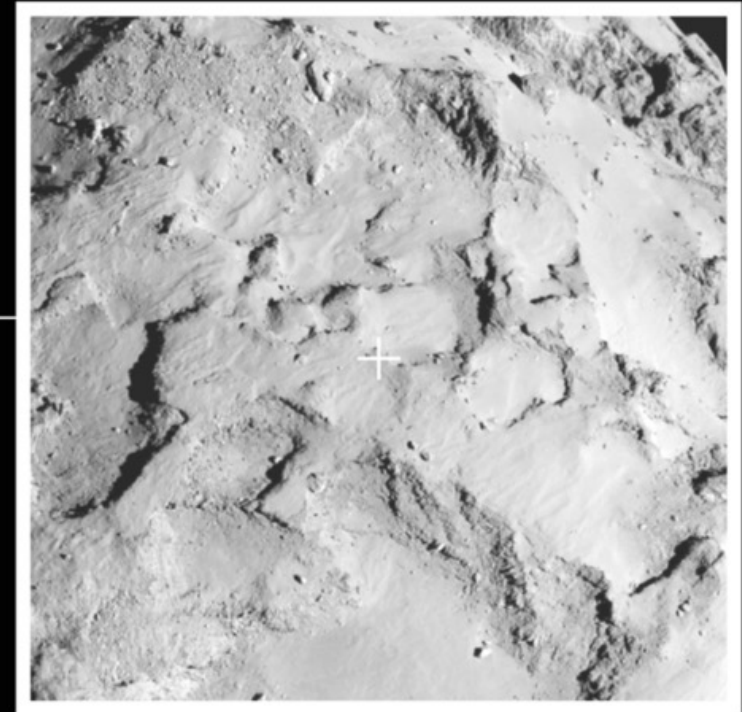
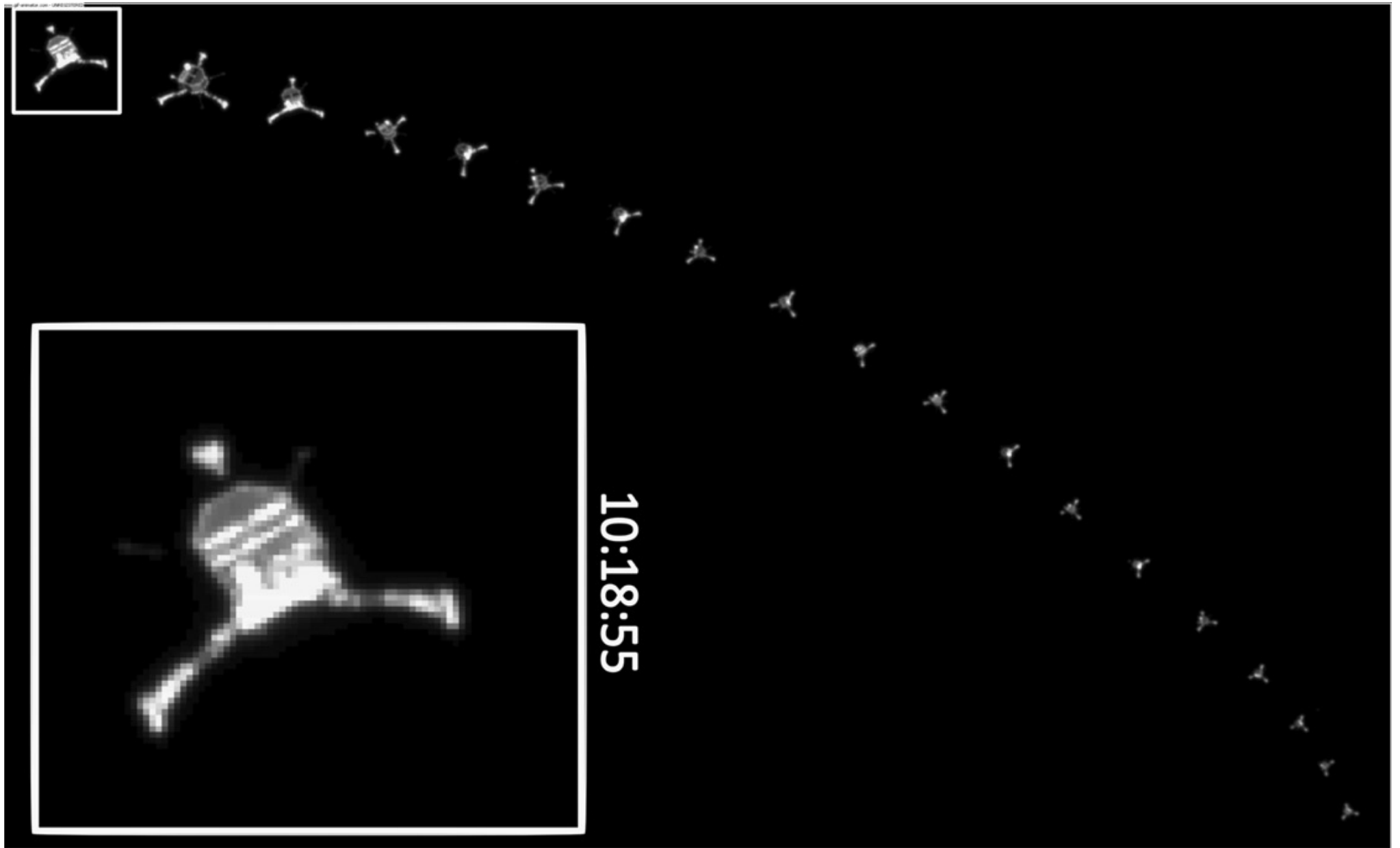


Fig. 4. The spectrum of the head in the spectral range 2.5 to 4.5  $\mu\text{m}$  is compared to several other organic compounds described in the text. The VIRTIS spectrum is rescaled in arbitrary units to compare the X-H stretch region with ethanol and ethanoic (acetic) acid spectra (32), a cometary tholins (obtained after ion irradiation of a mixture of 80%  $\text{H}_2\text{O}$ , 16%  $\text{CH}_3\text{OH}$ , 3.2%  $\text{CO}_2$ , and 0.8%  $\text{C}_2\text{H}_6$ ) (33), and a refractory residue (labeled "Exp Or1") obtained after UV irradiation of a mixture of  $\text{H}_2\text{O}:\text{CH}_3\text{OH}:\text{NH}_3:\text{CO}:\text{CO}_2$  in the ratio 2:1:1:1 (34).

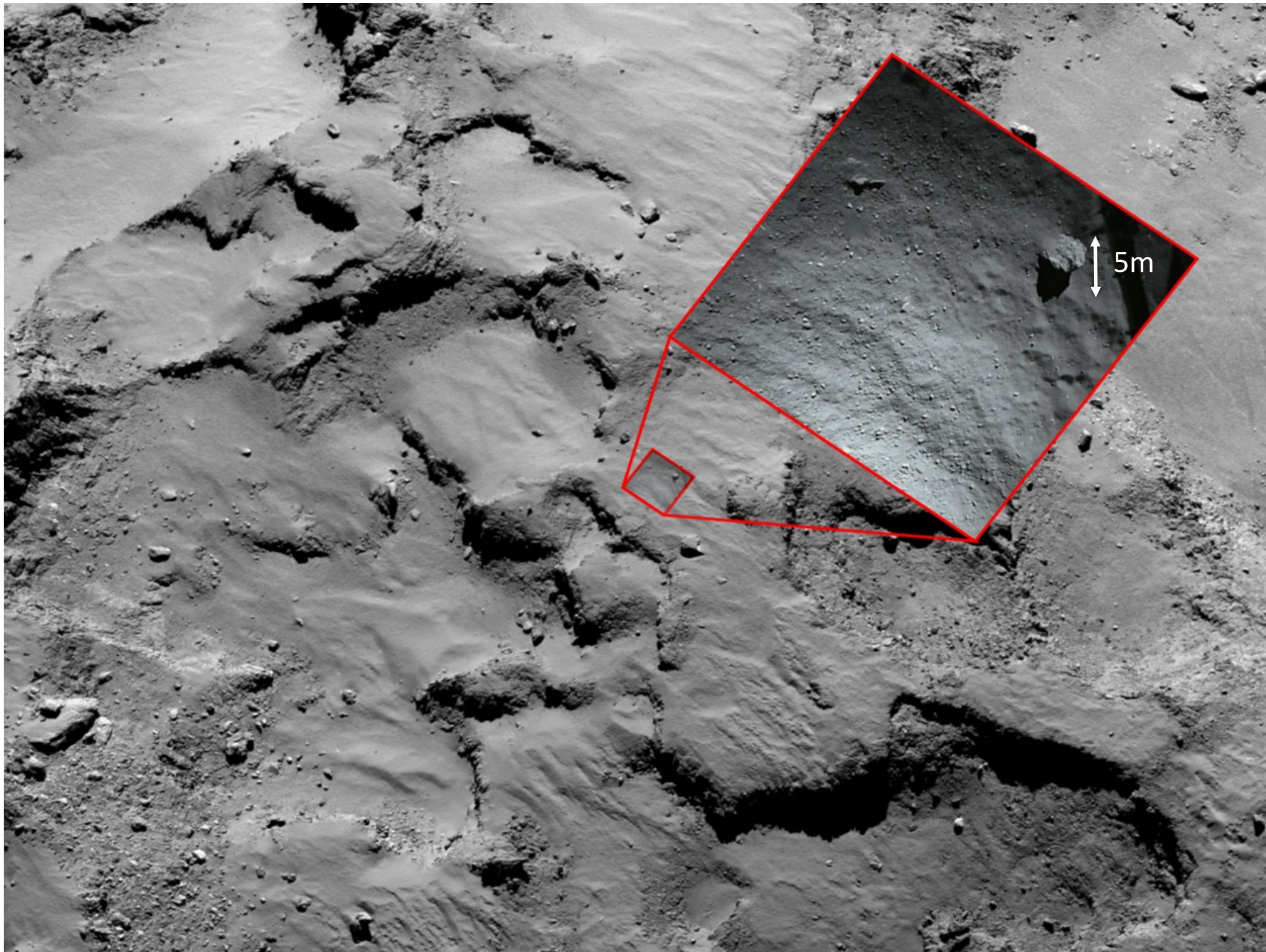
# → PHILAE'S LANDING SITE

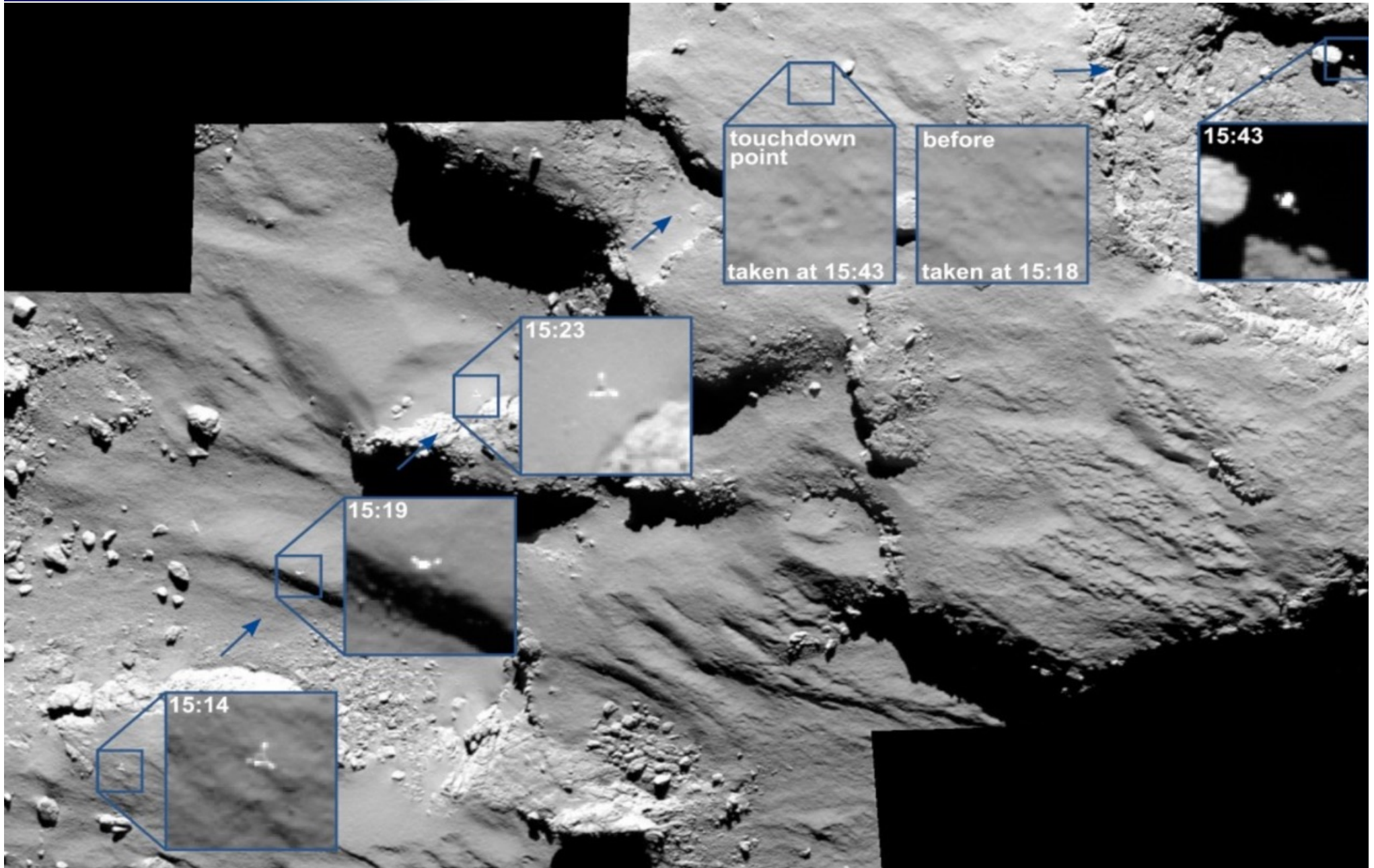




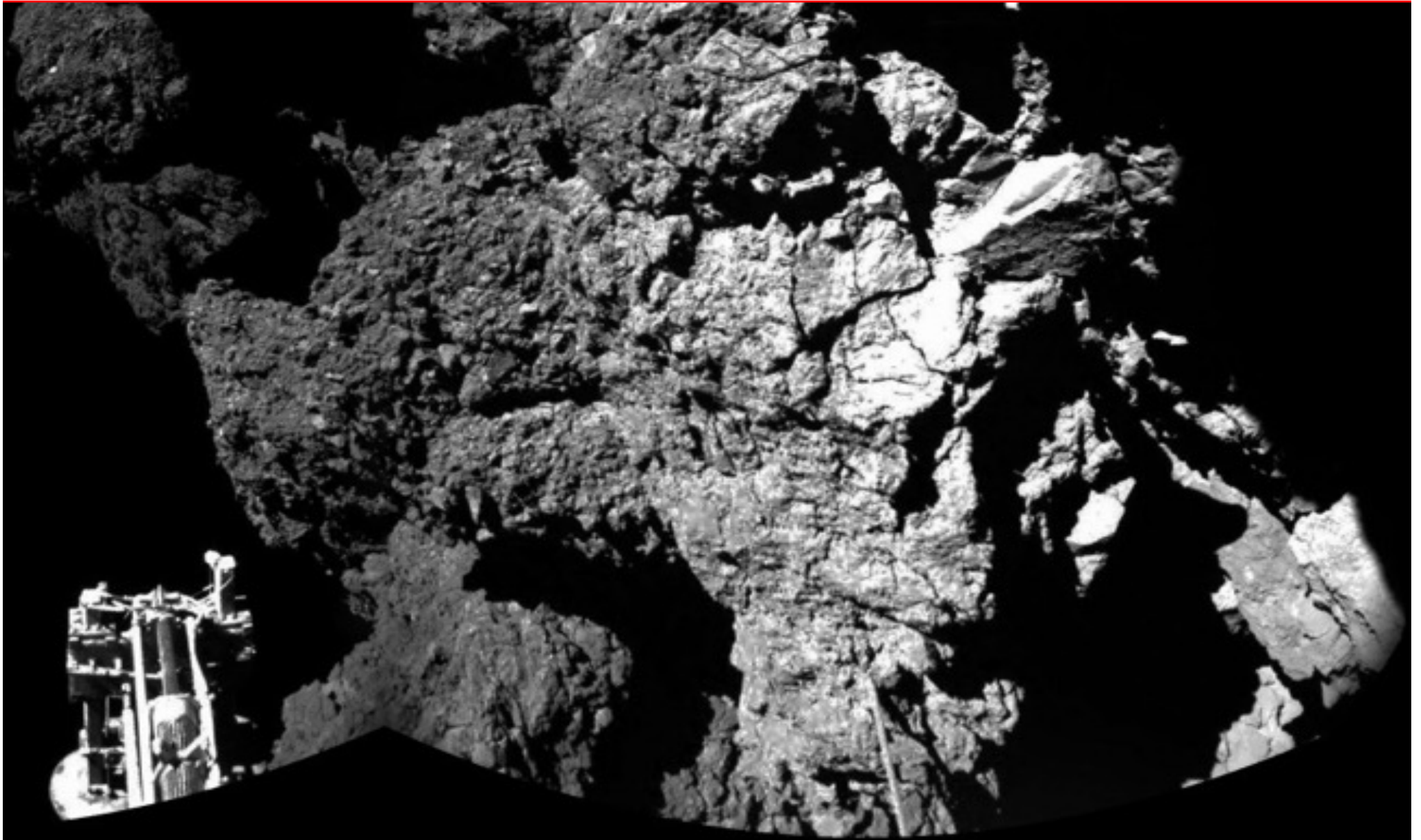
Time: 2014-11-12T09:23:18  
Frame = EMEJ2000

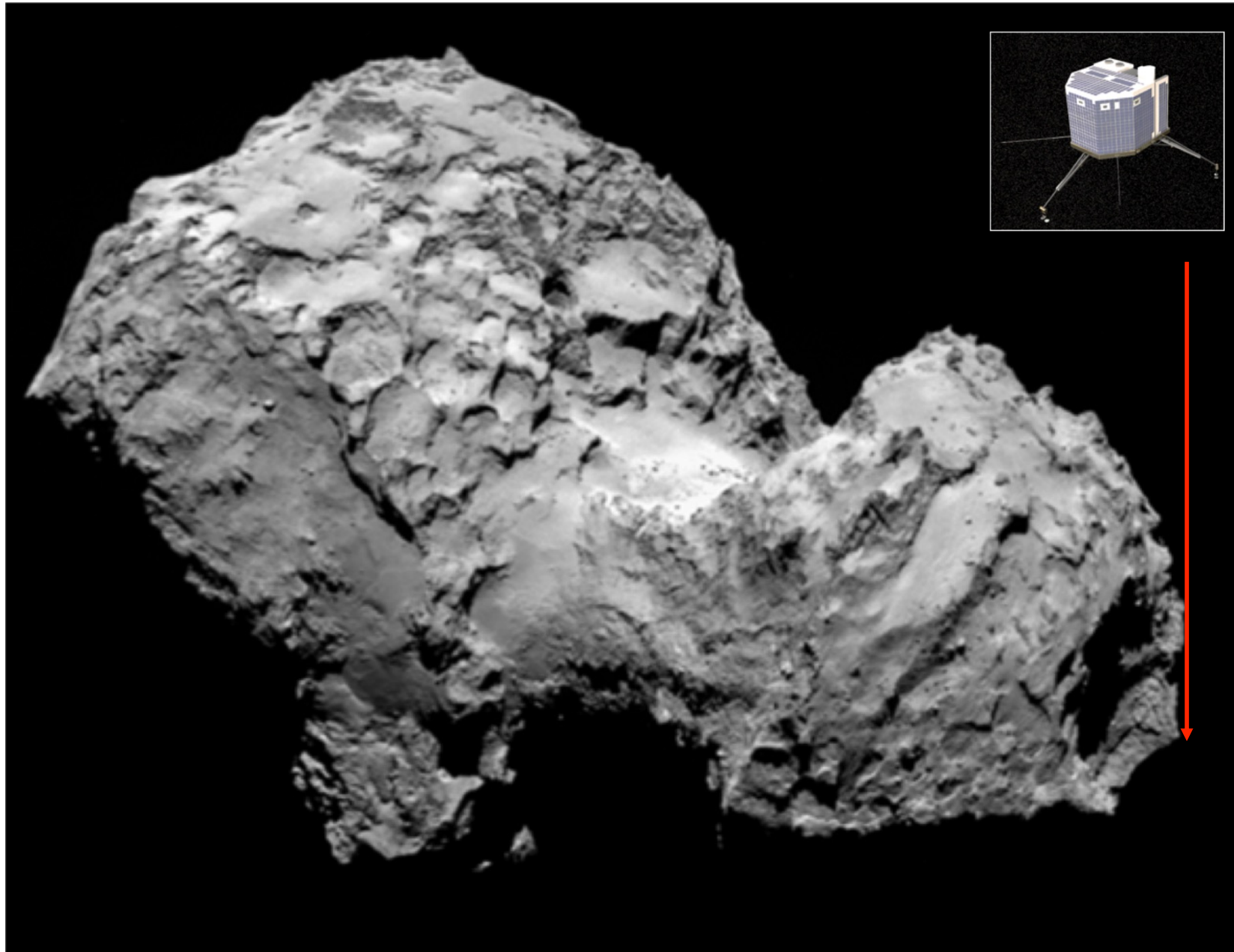




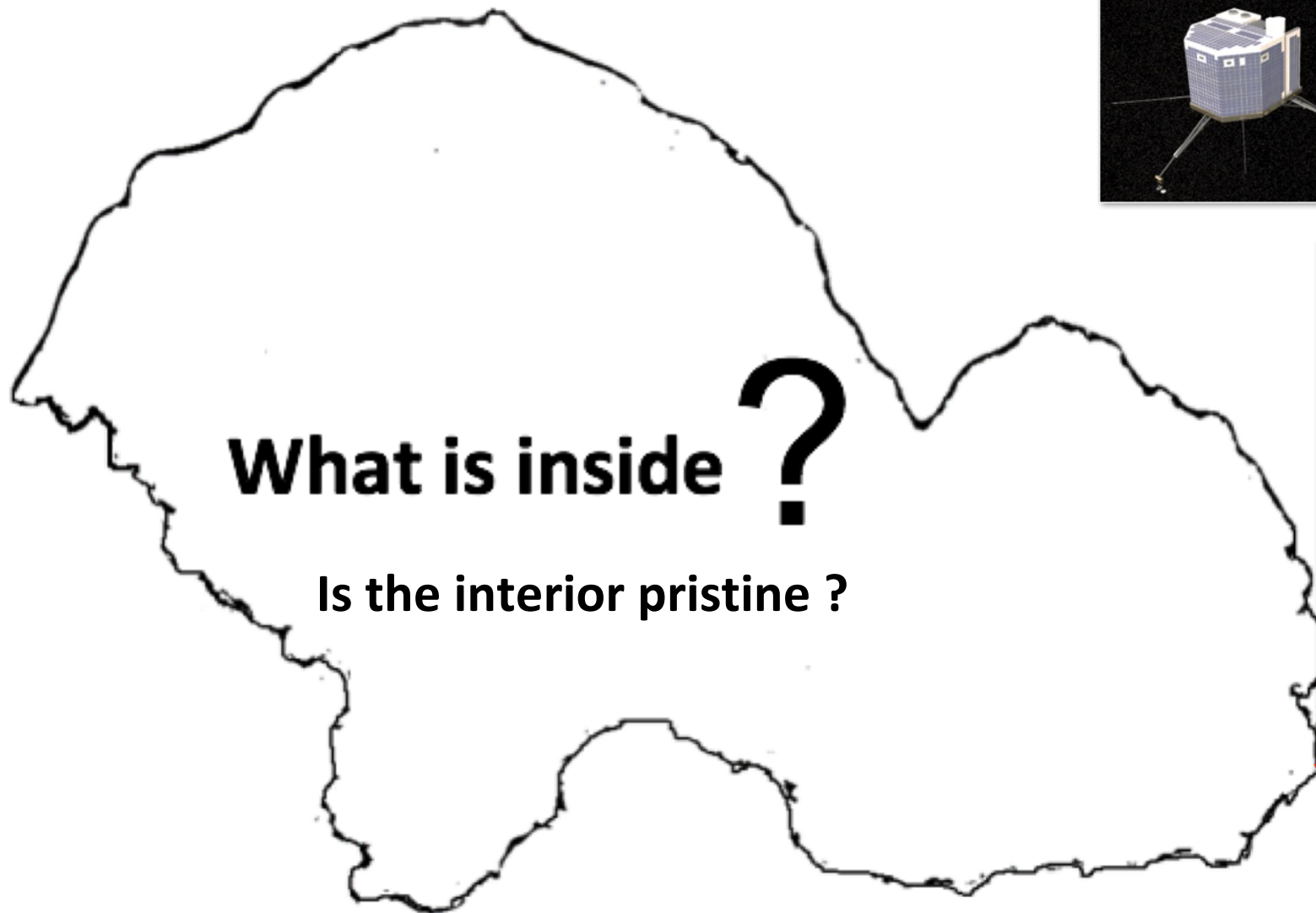
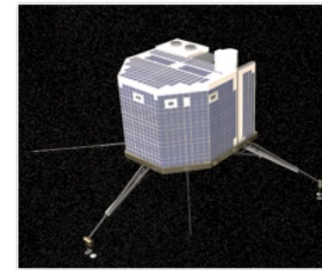


ESA / Rosetta / Philae / ÇIVA

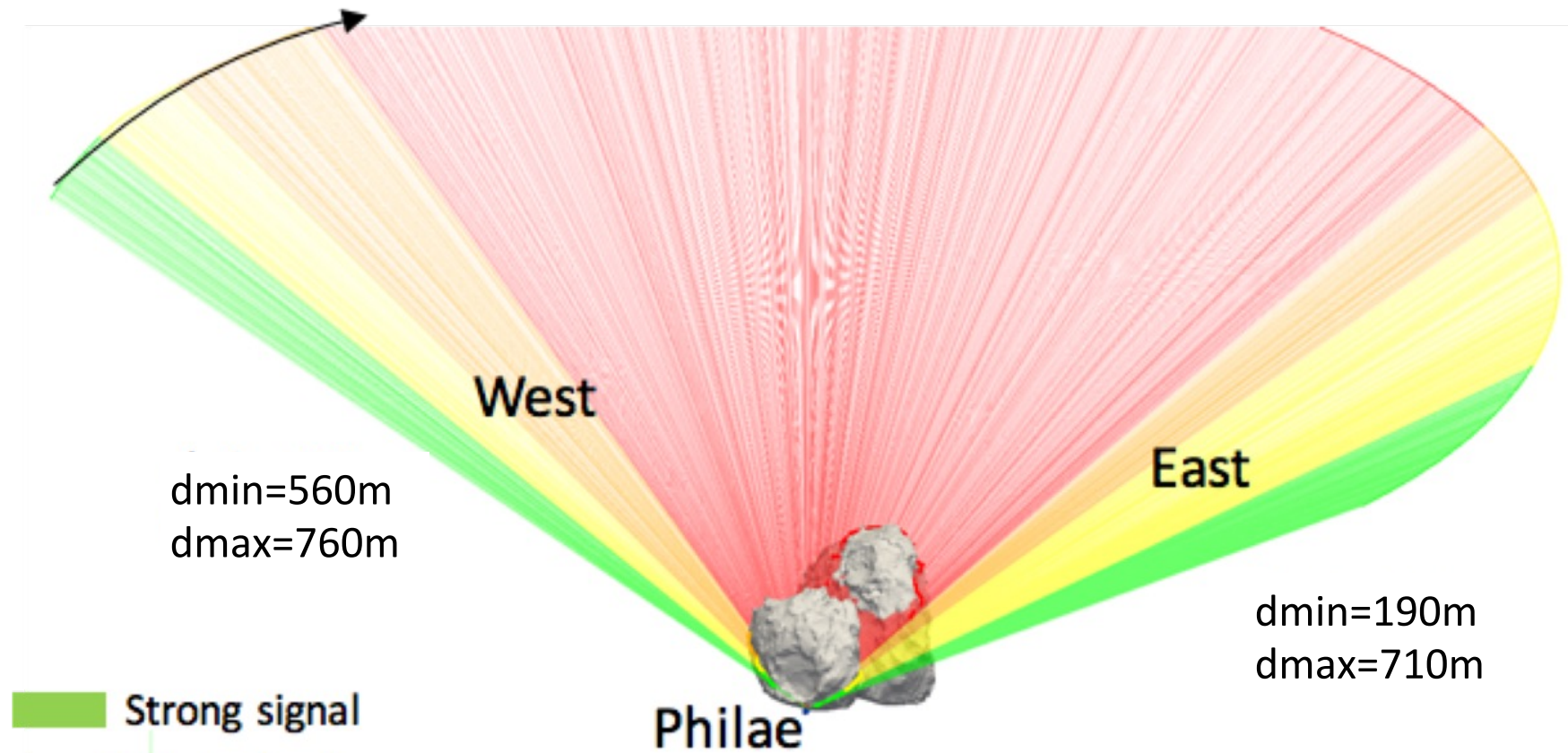








CONSERT data



- Strong signal
- Weak signal
- Very weak signal
- No signal detected

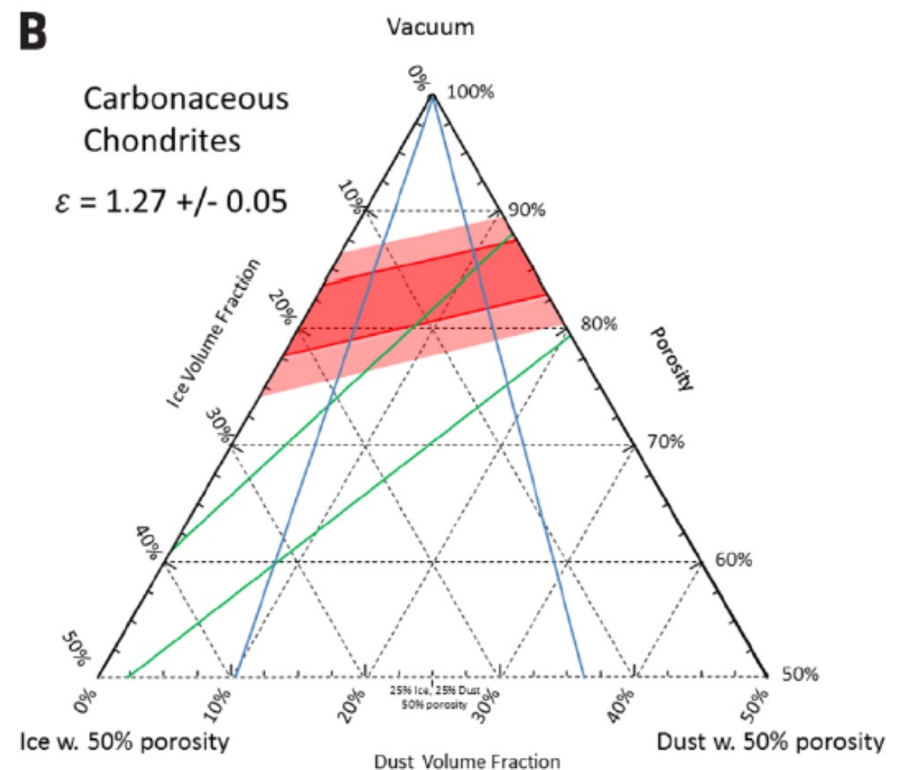
Propagation length across comet 190-760 m for the green signal

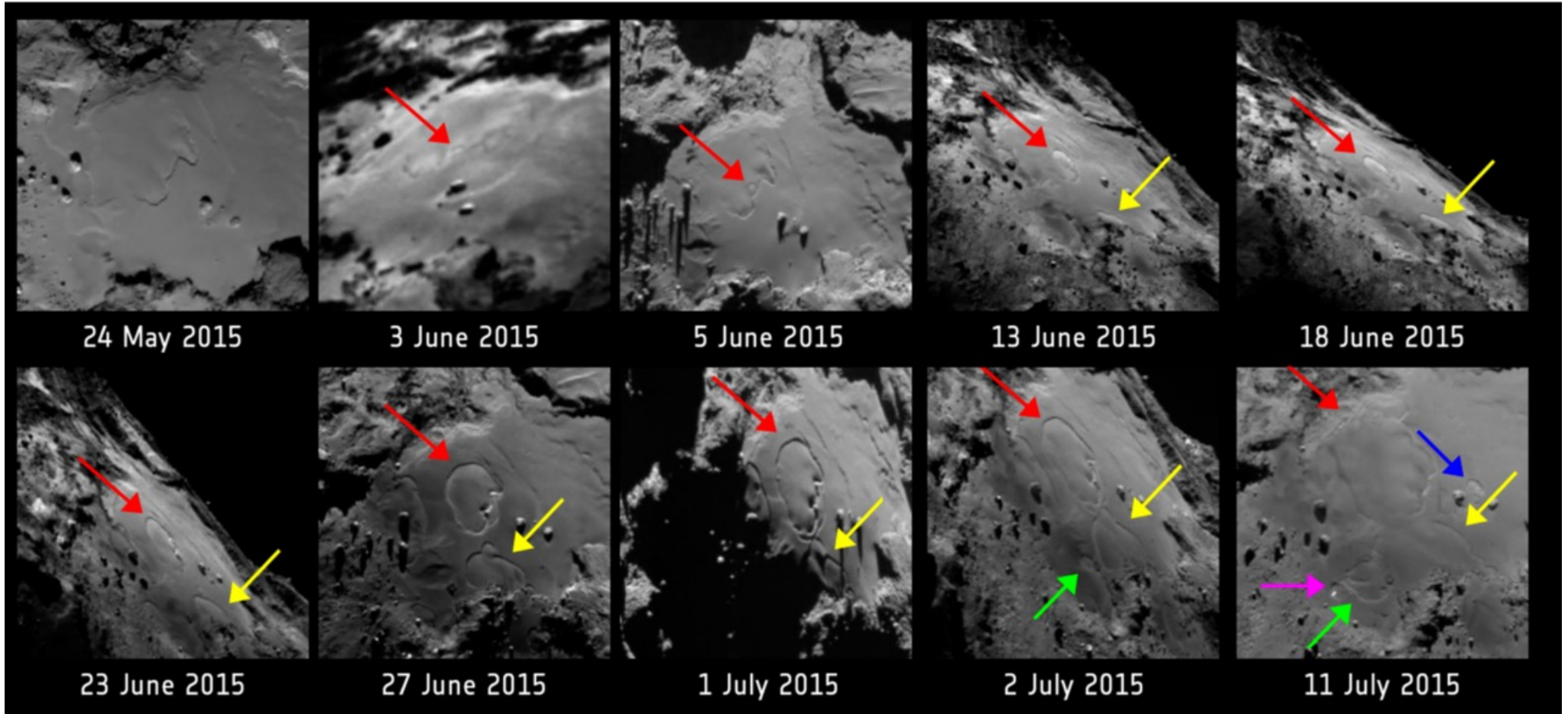
*Kofman et al., Science, 2015*

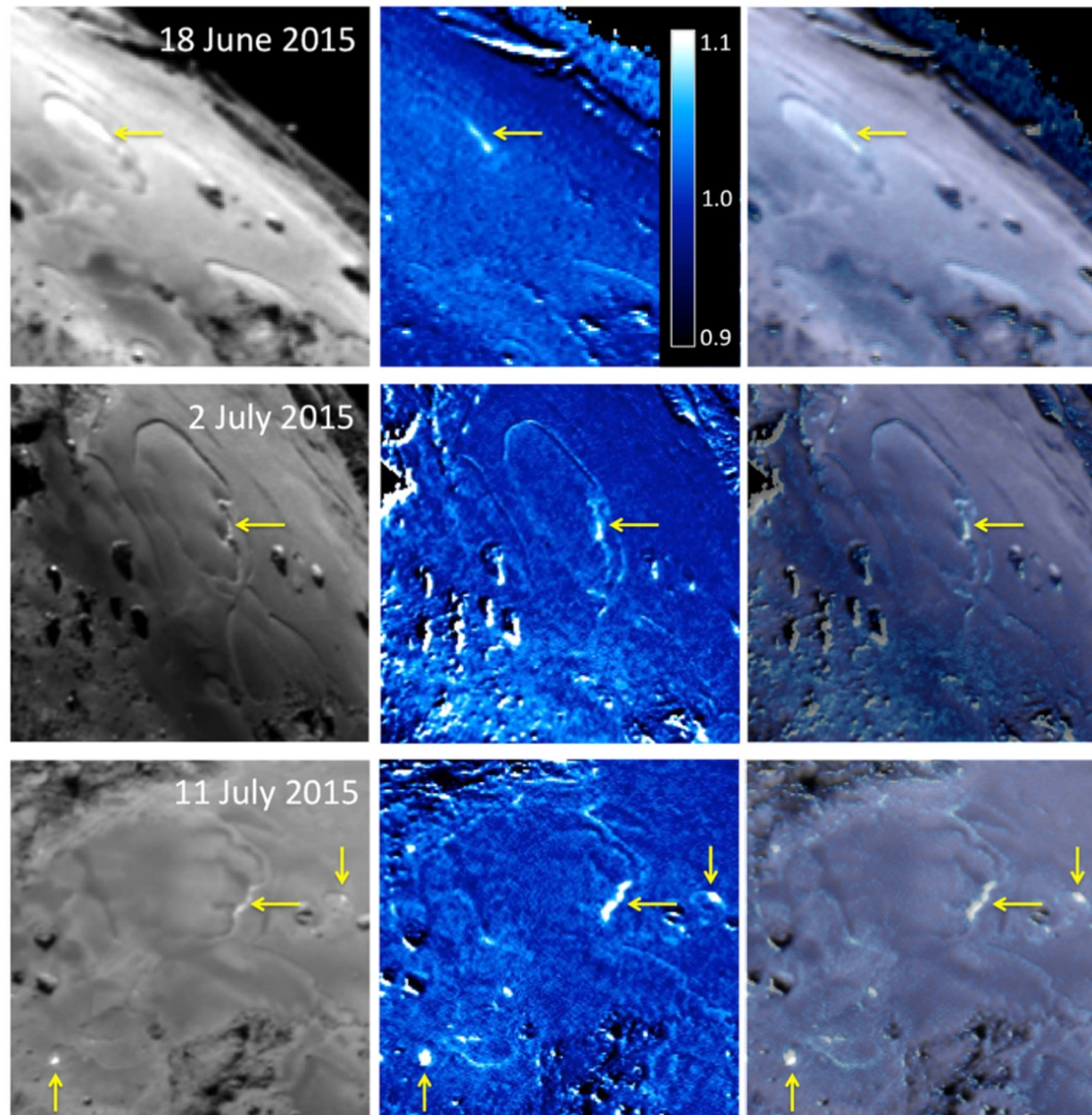
- From propagation delays measured by CONSERT  
 Mean permittivity  $1.27 \pm 0.05$  (H<sub>2</sub>O ice:3.2, CO<sub>2</sub> ice:2.5)  
 Porosity : 75-85%  
 Dust/ice ratio  $\sim 0.4 - 2.6$   
 Density comet  $\sim 470 \text{ kg/m}^3$   
 Dust : analogous to Carbonaceous chondrites CC

*Kofman et al., Science 2015*  
*Sierks et al., Science 2015*  
*Pätzold et al., Nature, 2016*  
*Sierks et al., Science, 2015*

- From the density (volume and mass) :  
 Average density  $533 \pm 6 \text{ kg/m}^3$   
 Porosity  $> 70\%$
- A decrease of permittivity value with depth (2.4 -> 1.3) linked to higher porosity or more ice content. (*Ciarletti et al. A&A 2015*)
- No indications of internal structures at the scale of CONSERT's wavelength  $\sim 1\text{m}$  (*Ciarletti et al. MNRAS 2017*)



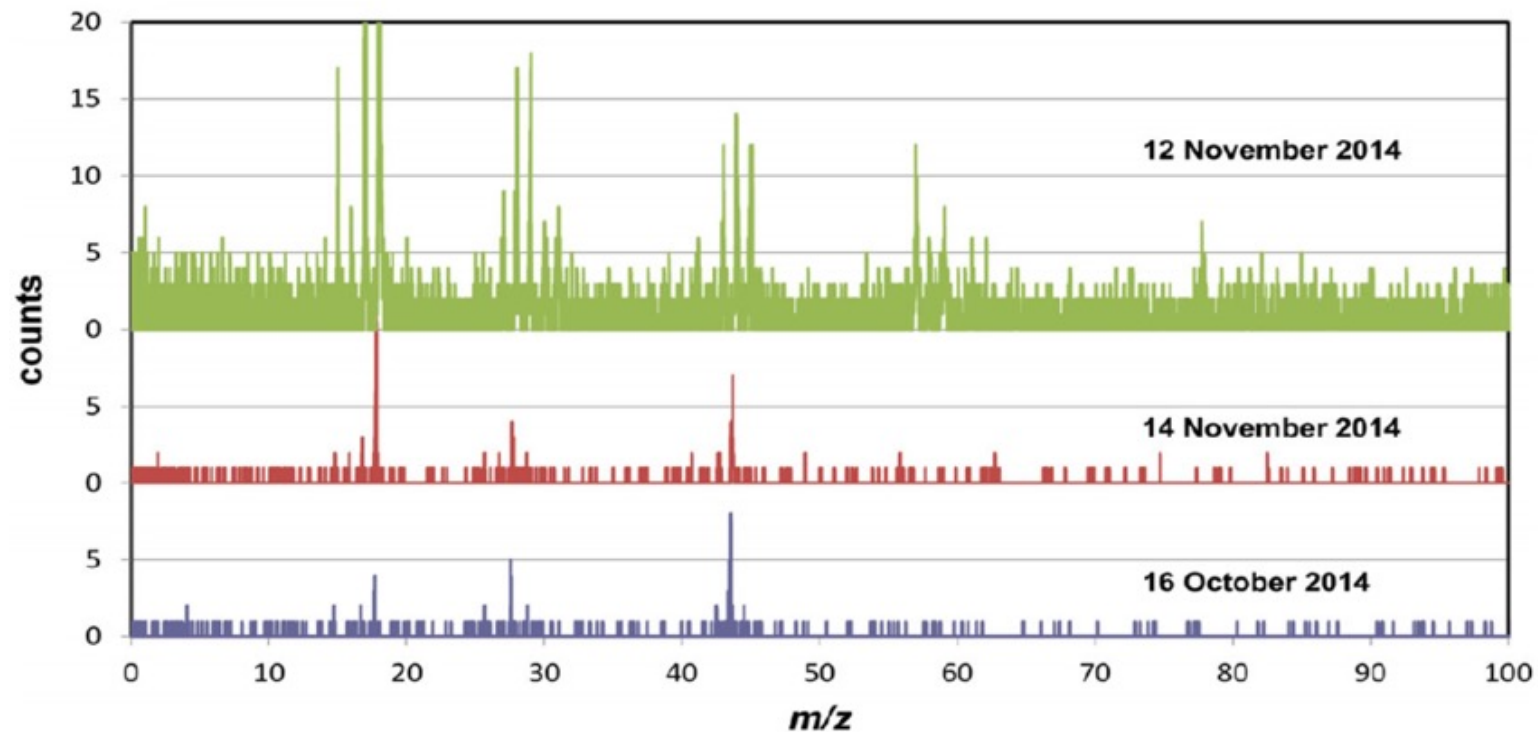




Comets have provided compounds required for the birth of life on Earth :

PTOLEMY : complex molecule chains as : polyoxymethylene (O-CH<sub>2</sub>), composition ratios of water (75%), CO<sub>2</sub> (15%), CO (7%), Autres (3%) ?

COSAC : 16 organic molecules identified, with 4 never detected in space (methyl-isocyanate, acétone, propionaldéhyde, and acétamide)



## → THE COMETARY ZOO: GASES DETECTED BY ROSETTA



### THE LONG CARBON

#### CHAINS

Methane  
Ethane  
Propane  
Butane  
Pentane  
Hexane  
Heptane



### THE AROMATIC RING COMPOUNDS

Benzene  
Toluene  
Xylene  
Benzoic acid  
Naphthalene



### THE KING OF THE ZOO

Glycine (amino acid)



### THE "MANURE SMELL" MOLECULES

Ammonia  
Methylamine  
Ethylamine



### THE "POISONOUS" MOLECULES

Acetylene  
Hydrogen cyanide  
Acetonitrile  
Formaldehyde



### THE ALCOHOLS

Methanol  
Ethanol  
Propanol  
Butanol  
Pentanol



### THE VOLATILES

Nitrogen  
Oxygen  
Hydrogen peroxide  
Carbon monoxide  
Carbon dioxide



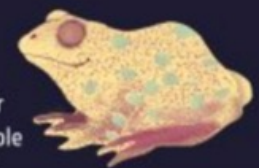
### THE "SMELLY" MOLECULES

Hydrogensulphide  
Carbonylsulphide  
Sulphur monoxide  
Sulphur dioxide  
Carbon disulphide



### THE "SMELLY AND COLOURFUL"

Sulphur  
Disulphur  
Trisulphur  
Tetrasulphur  
Methanethiole  
Ethanethiol  
Thioformaldehyde



### THE TREASURES WITH A HARD CRUST

Sodium  
Potassium  
Silicon  
Magnesium



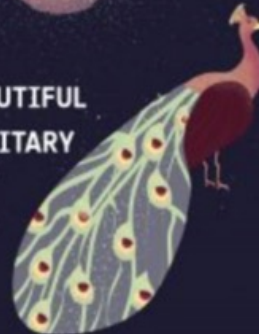
### THE "SALTY" BEASTS

Hydrogen fluoride  
Hydrogen chloride  
Hydrogen bromide  
Phosphorus  
Chloromethane



### THE BEAUTIFUL AND SOLITARY

Argon  
Krypton  
Xenon



### THE "EXOTIC" MOLECULES

Formic acid  
Acetic acid  
Acetaldehyde  
Ethylenglycol  
Propylenglycol  
Butanamide

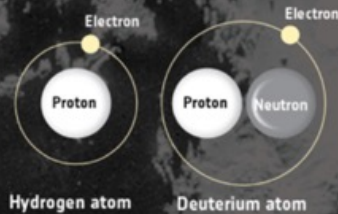
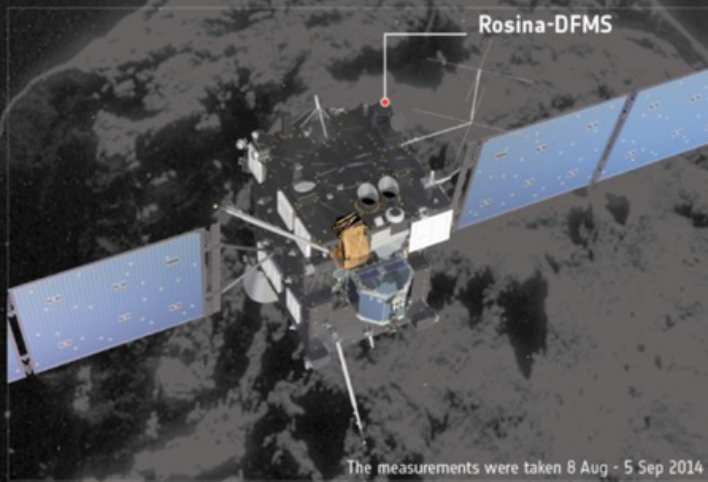


### THE MOLECULE IN DISGUISE

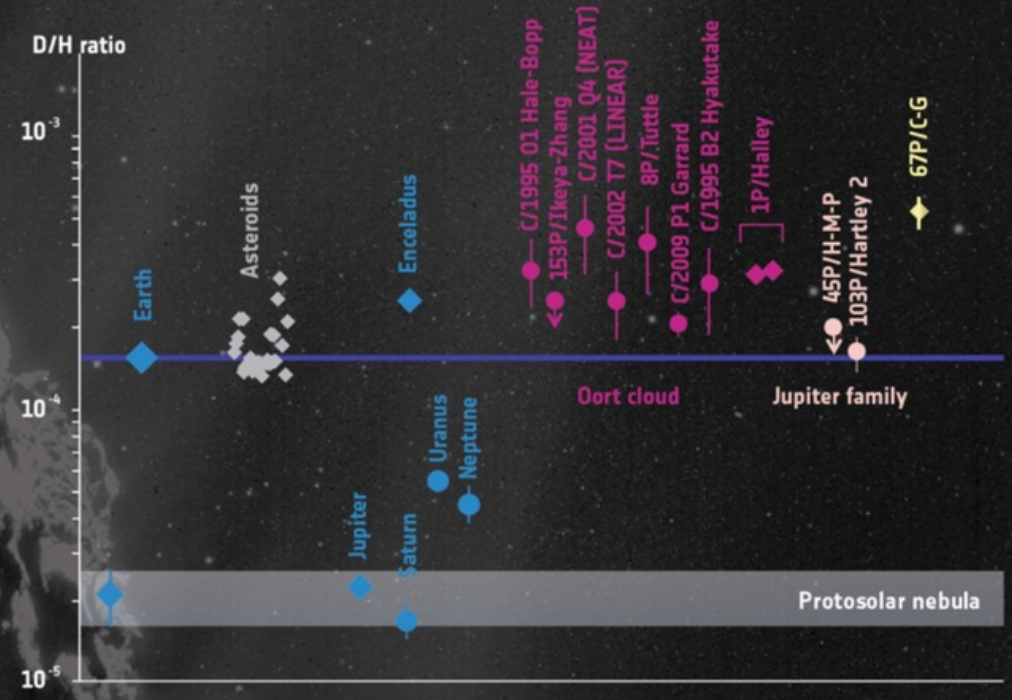
Cyanogen



Rosetta's ROSINA instrument finds Comet 67P/Churyumov-Gerasimenko's water vapour to have a significantly different composition to Earth's oceans.

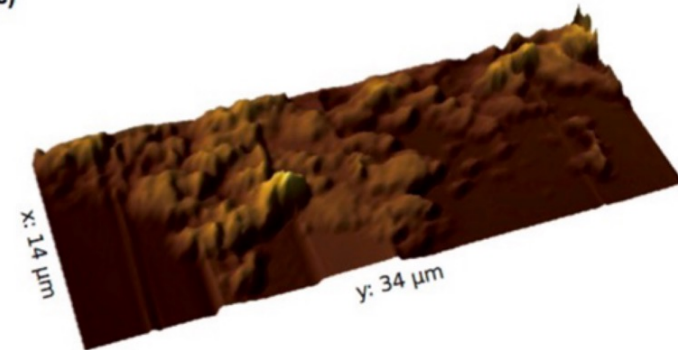
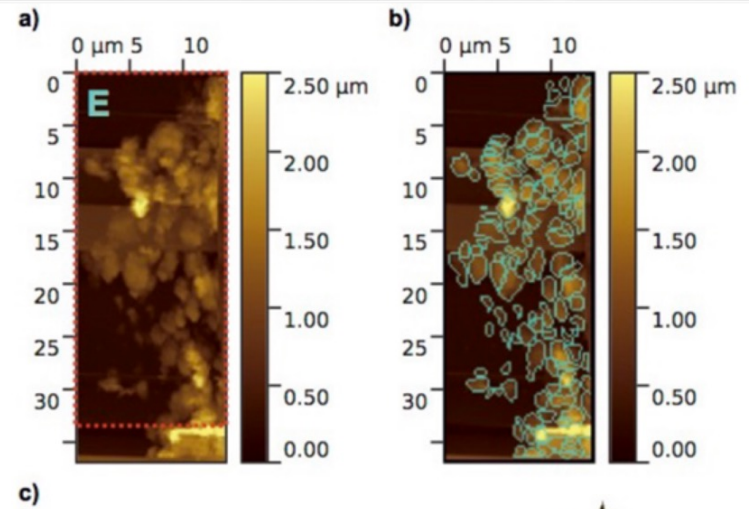
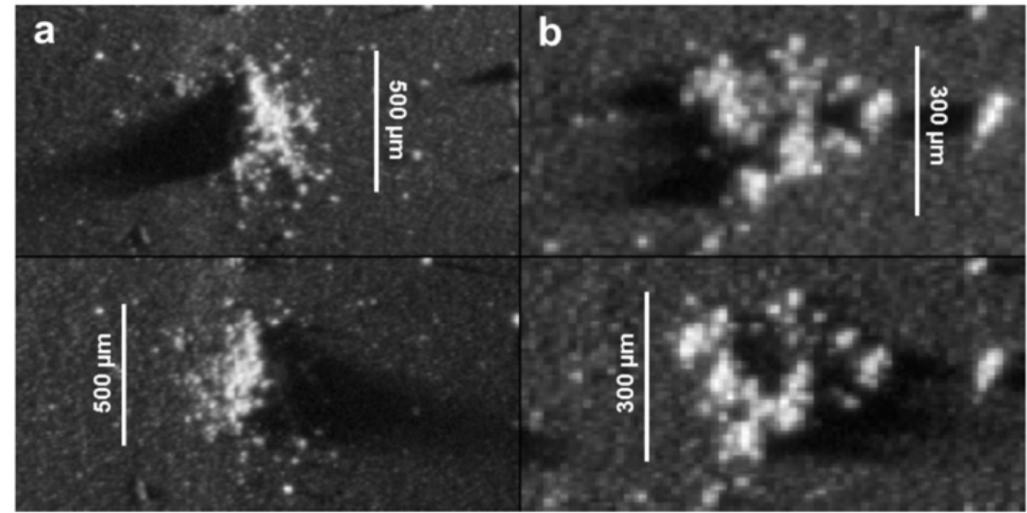
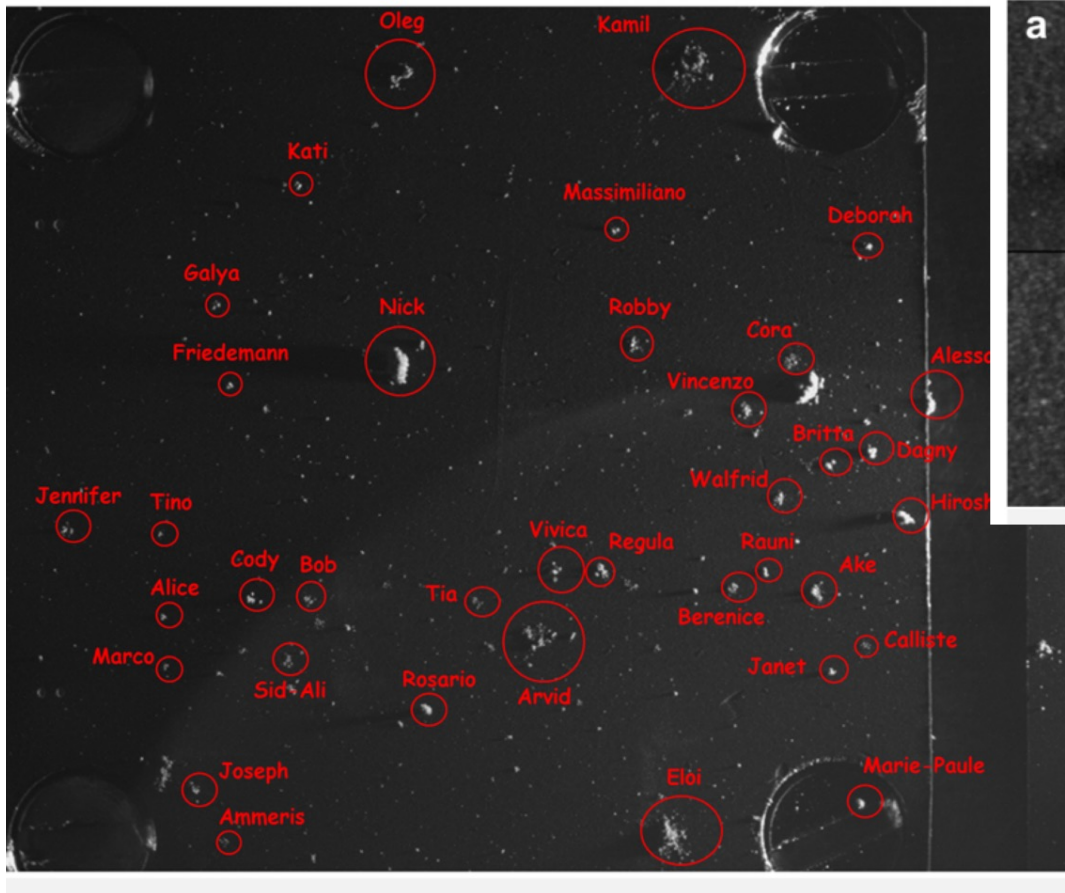


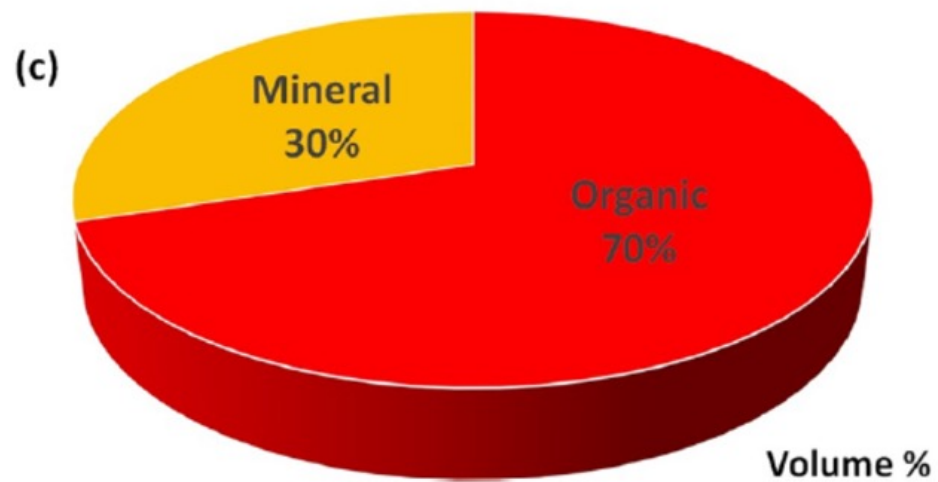
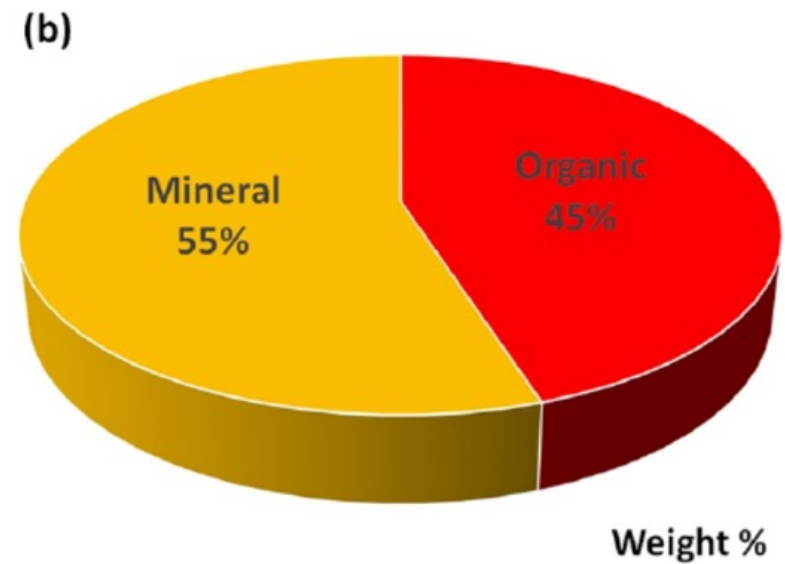
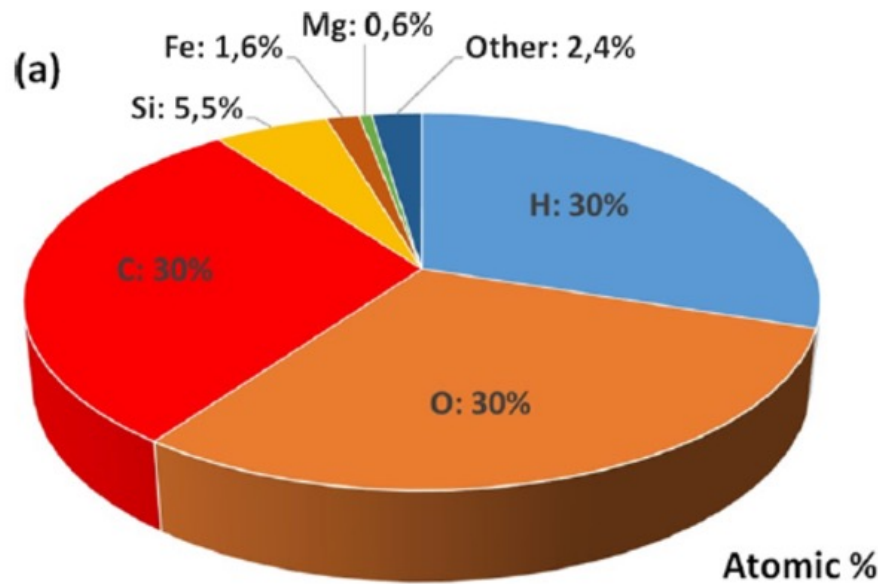
The ratio of deuterium to hydrogen in water is a key diagnostic to determining where in the Solar System an object originated and in what proportion asteroids and comets may have contributed to Earth's oceans



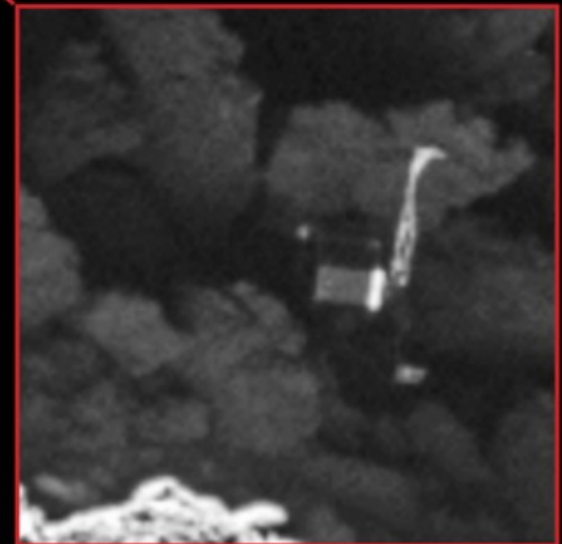
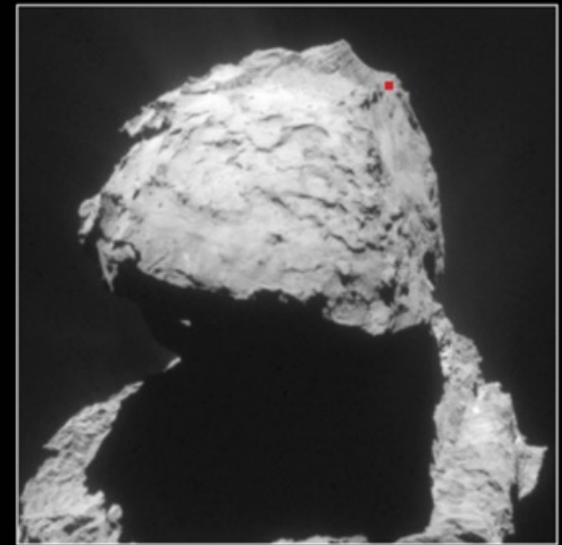
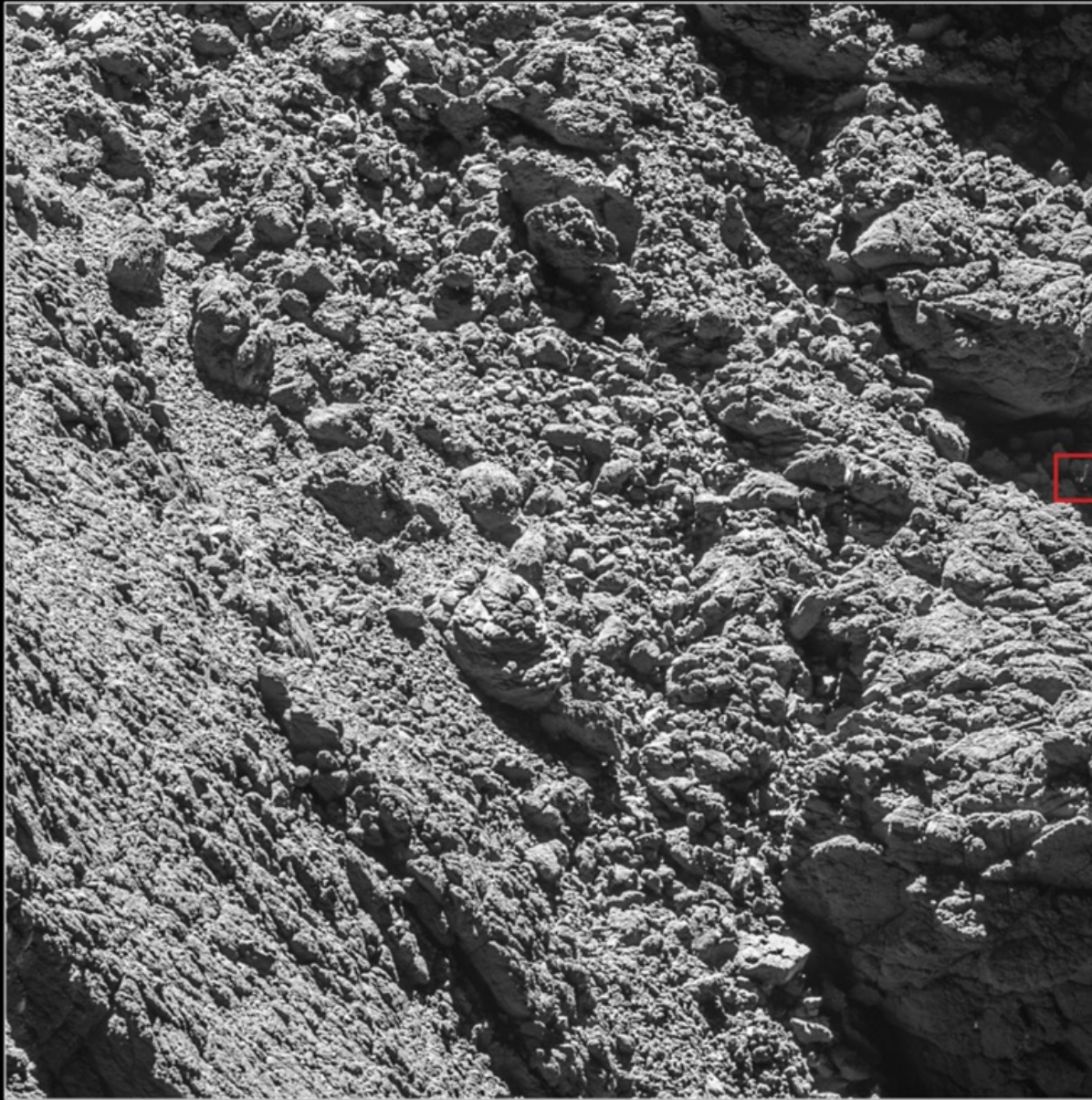
D/H ratio for different Solar System objects, grouped by colour as planets and moons (blue), chondritic meteorites from the Asteroid Belt (grey), comets originating from the Oort cloud (purple) and Jupiter family comets (pink). Comet 67P/C-G, a Jupiter family comet, is highlighted in yellow. ◆ = data obtained in situ ● = data obtained by astronomical methods

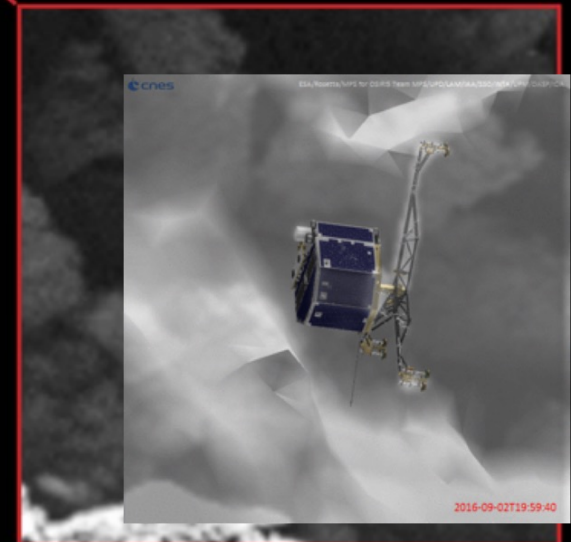
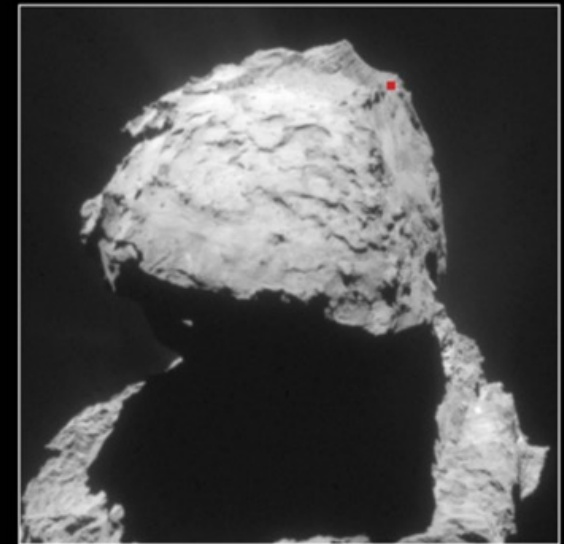
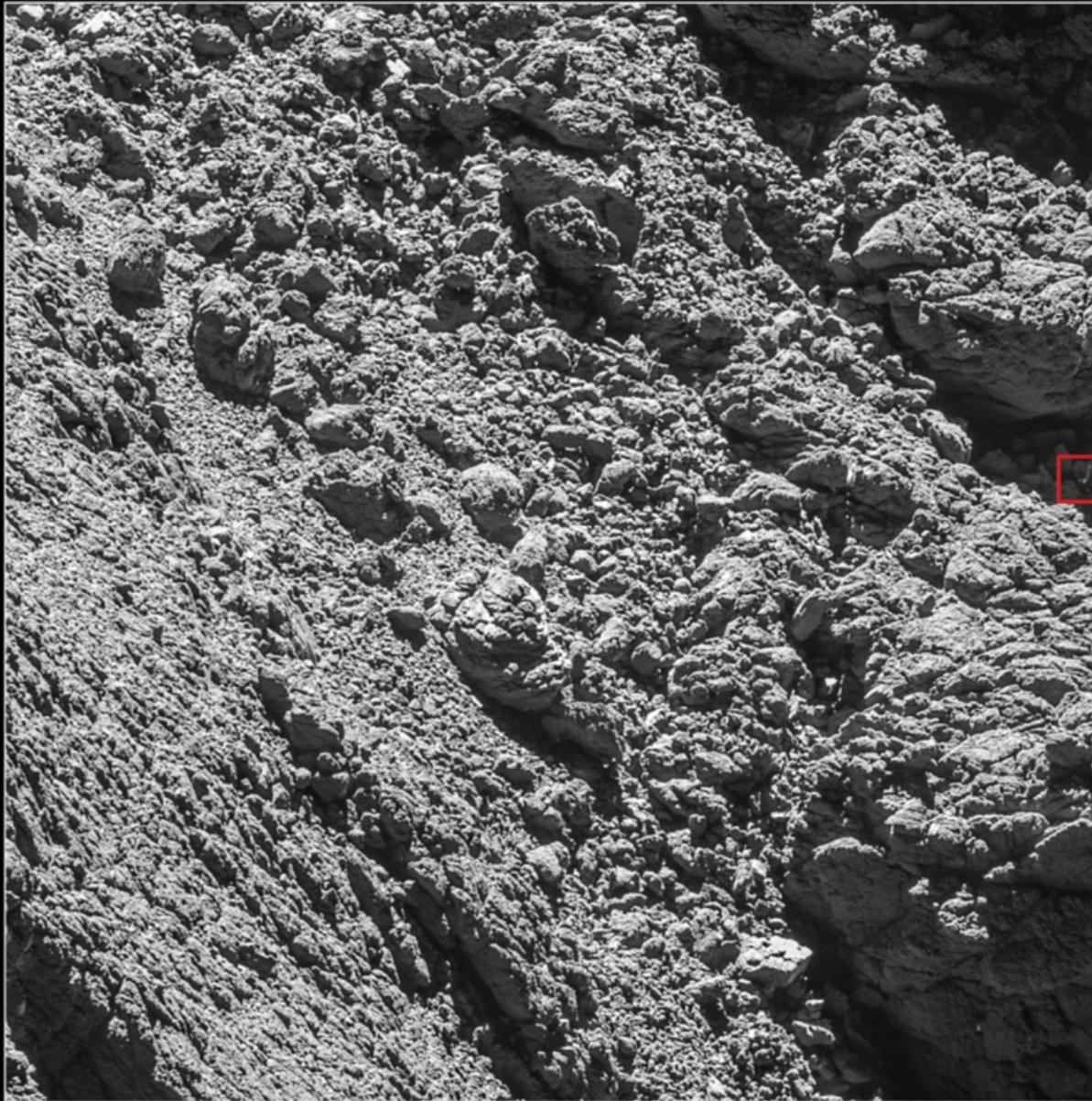






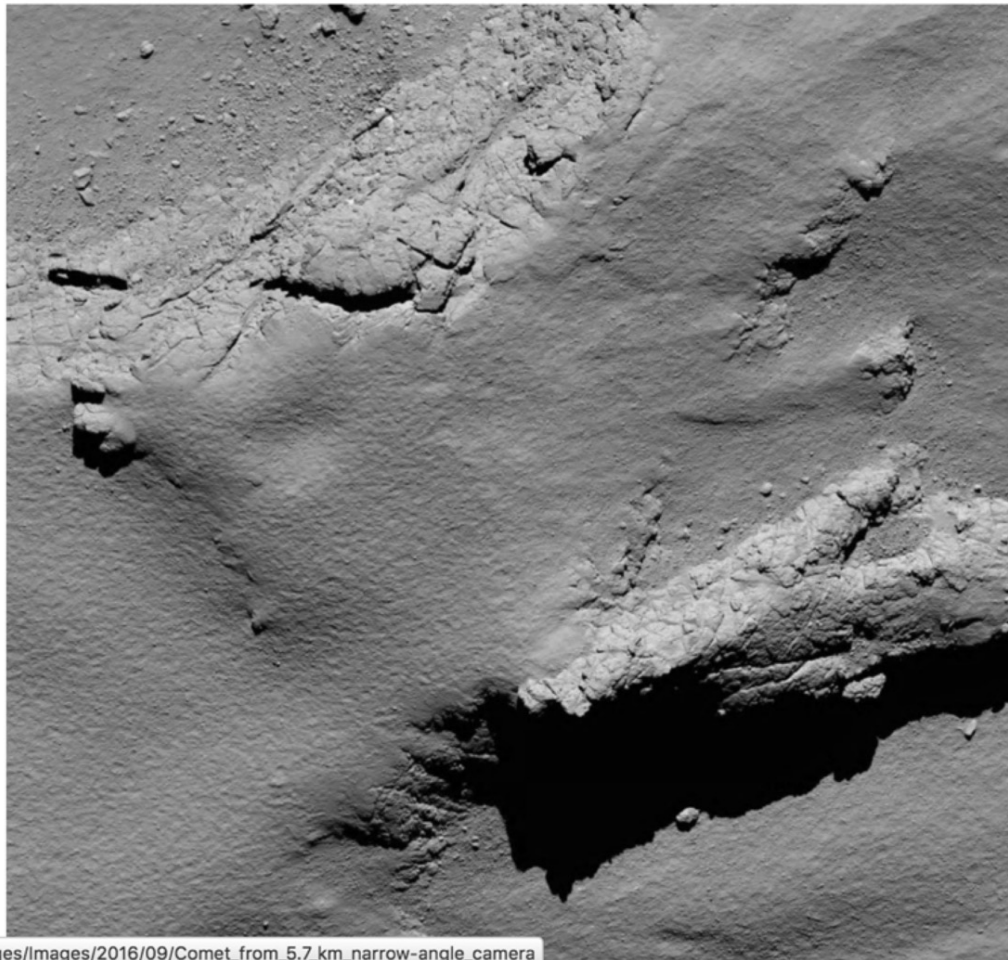
Levasseur-Regourd et al. SSR 2018





## → COMET LANDING DESCENT IMAGE – 5.7 KM

Another striking image of the Ma'at region of Comet 67P/Churyumov-Gerasimenko from Rosetta's descent onto the surface of the comet, taken with the OSIRIS narrow-angle camera at 08:21 GMT from an altitude of about 5.7 km.



images/Images/2016/09/Comet\_from\_5.7\_km\_narrow-angle\_camera



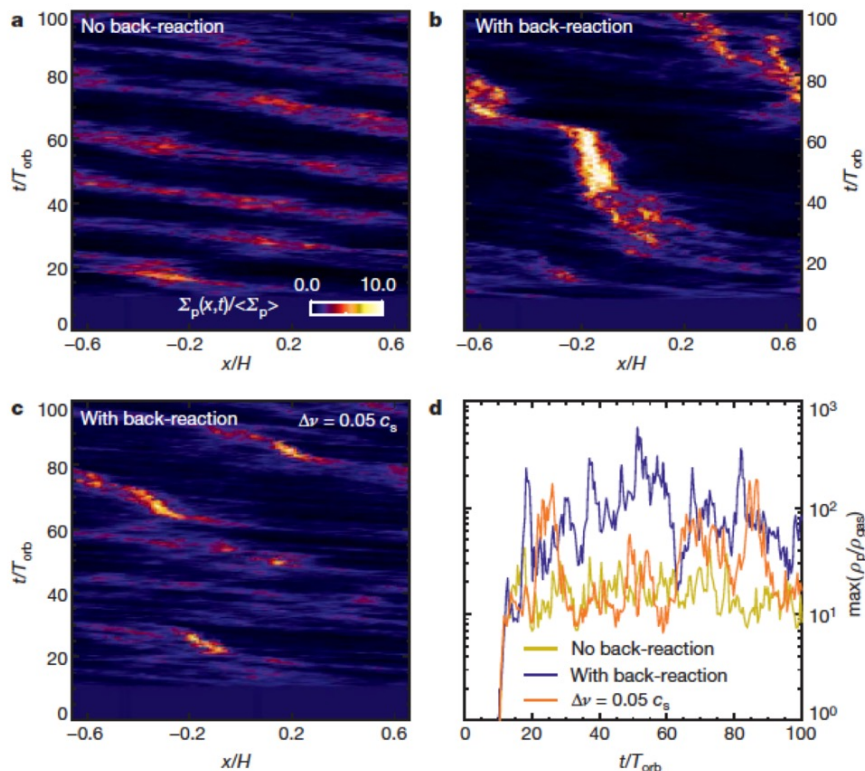
nature

Vol 448 | 30 August 2007 | doi:10.1038/nature06086

LETTERS

**Rapid planetesimal formation in turbulent circumstellar disks**

Anders Johansen<sup>1</sup>, Jeffrey S. Oishi<sup>2,3</sup>, Mordecai-Mark Mac Low<sup>1,2</sup>, Hubert Klahr<sup>1</sup>, Thomas Henning<sup>1</sup> & Andrew Youdin<sup>4</sup>



nature astronomy
Letters  
<https://doi.org/10.1038/nature06086>

**Catastrophic disruptions as the origin of bilobate comets**

Stephen R. Schwartz<sup>1,2\*</sup>, Patrick Michel<sup>1</sup>, Martin Jutzi<sup>3</sup>, Simone Marchi<sup>4</sup>, Yun Zhang<sup>5,6</sup> and Derek C. Richardson<sup>6</sup>

No pristine comets





Thank you for your attention !