The *Rosetta* Mission to Comet 67P/Churyumov-Gerasimenko

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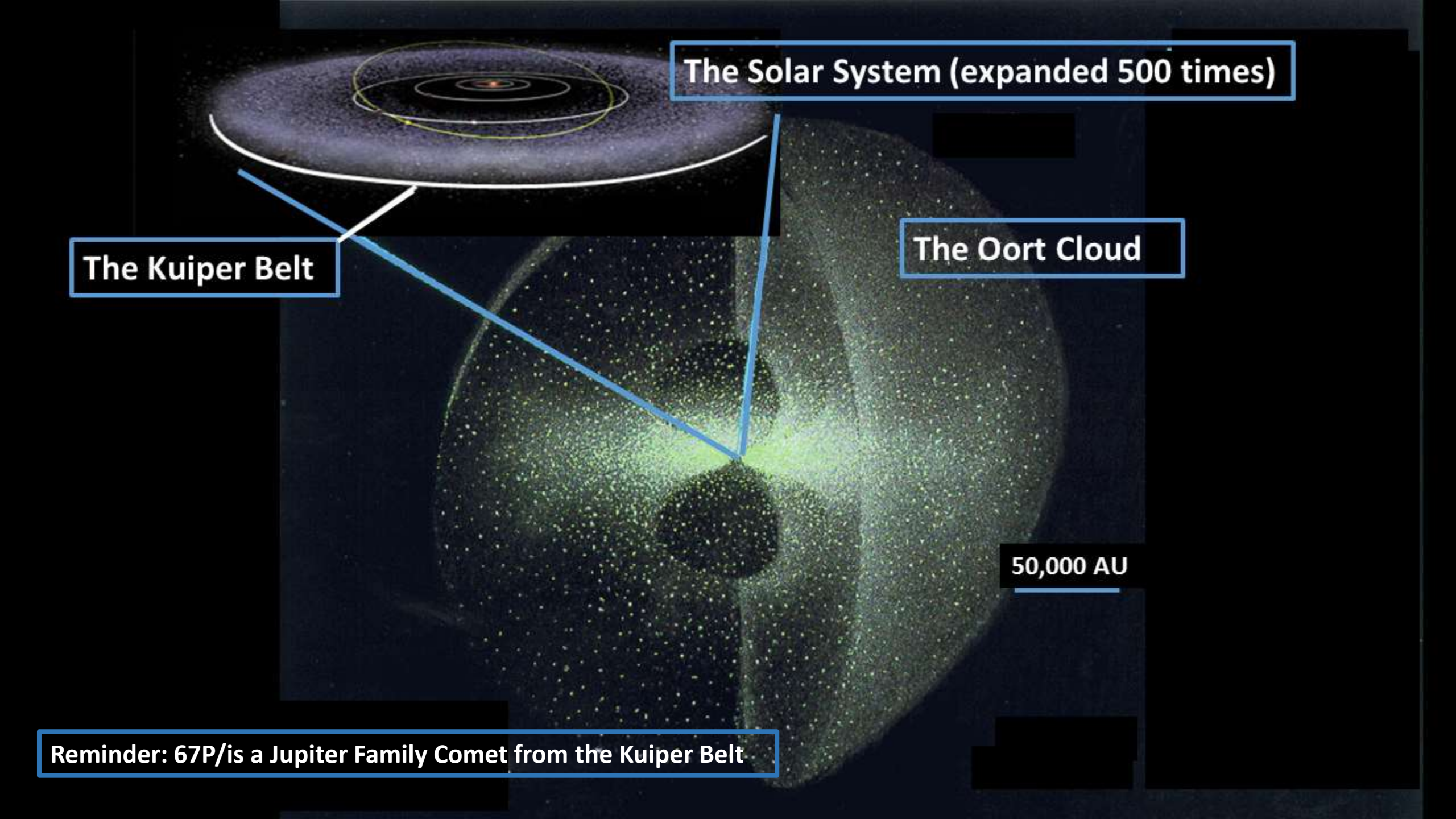
Image: NASA/W. Liller

Main topics and questions

- Comets as clues to the origin of solar systems: What we learned from *Rosetta*
- Clues to the conditions of the early solar nebula and the Earth (N_2, O_2, and H_2, plus Ne, Ar, and Xe)
- Connections between comets, the protosolar nebula, and the ISM
- Comets' role in the origins of life
- Did water on the Earth come from comets?
- How active are comets and can we see geologic processes occurring or even disintegration? What role does water play in evolution?
- Comets as astrophysical laboratories
- The key importance of laboratory studies to understanding the data



Reminder: 67P/is a Jupiter Family Comet from the Kuiper Belt

US and European Missions to Comets, before *Rosetta*

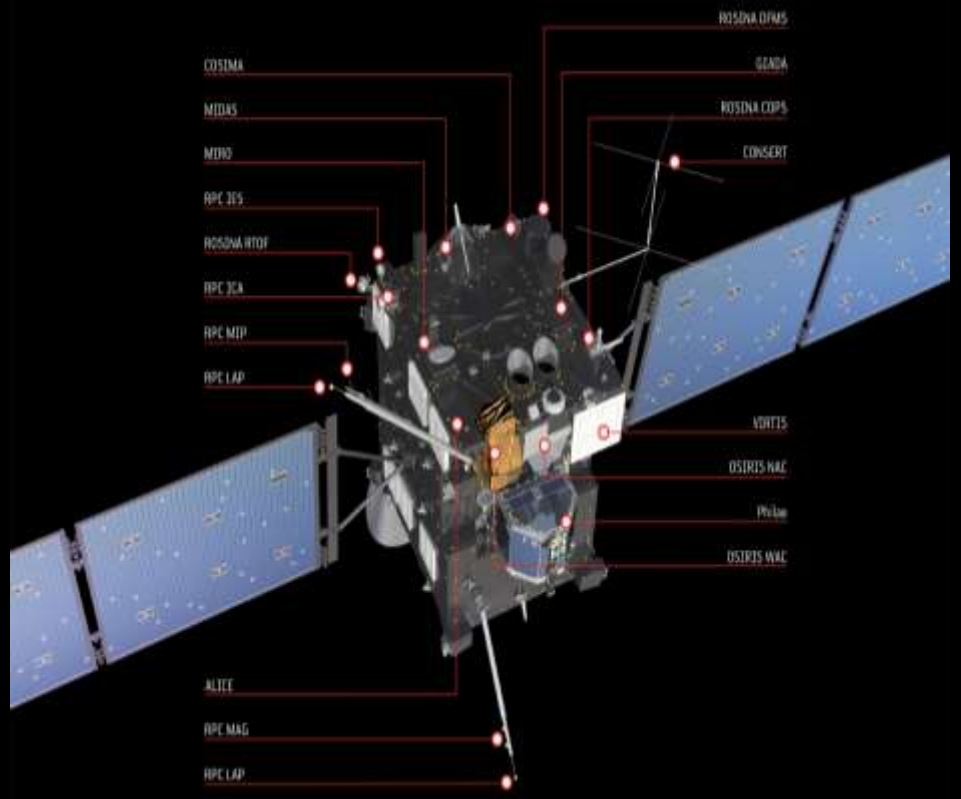
Halley: *Giotto* (1985)

8 km

Borrelly: *Deep Space 1* (1998)

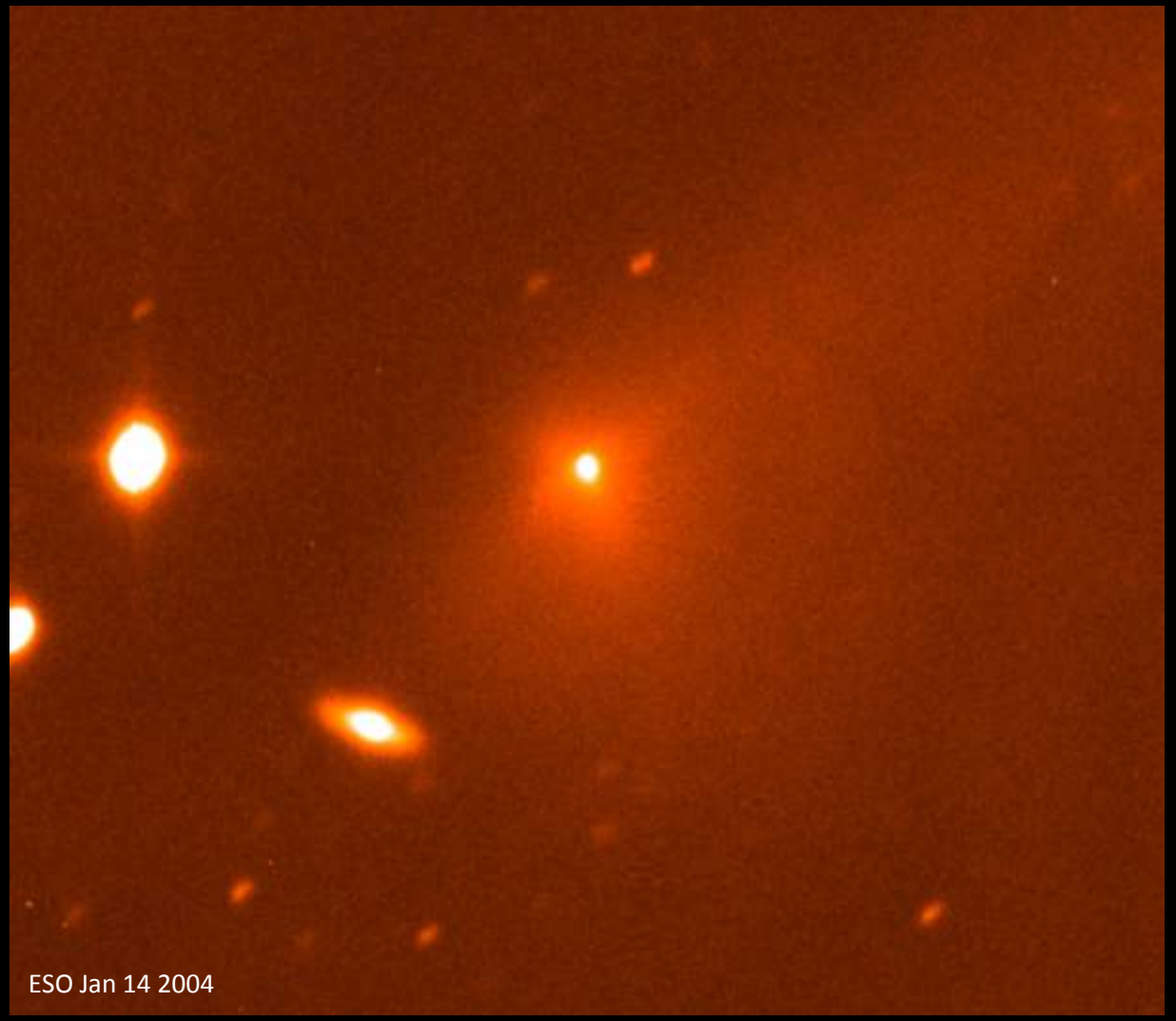
Wild 2: *Stardust* (2003)

Tempel 1 (2005)
Hartley (2010):
Deep Impact



Instrument	Purpose	Country of Origin
Alice	Ultraviolet spectrometer	United States
CONSERT	Radar tomography	France
COSIMA	Dust composition	Germany
GIADA	Dust detector	Italy
MIDAS	Atomic Force Microscope	Austria
MIRO	Microwave spectrometer/radiometer	United States
OSIRIS	Narrow-angle and wide-angle cameras	Germany
ROSINA	Gas composition	Switzerland
RPC	Magnetometer, plasma detectors	Various, inc. US
RSI	Radio science investigation	Germany
VIRTIS	Infrared spectrometer	Italy

Best image of 67P before *Rosetta* launch

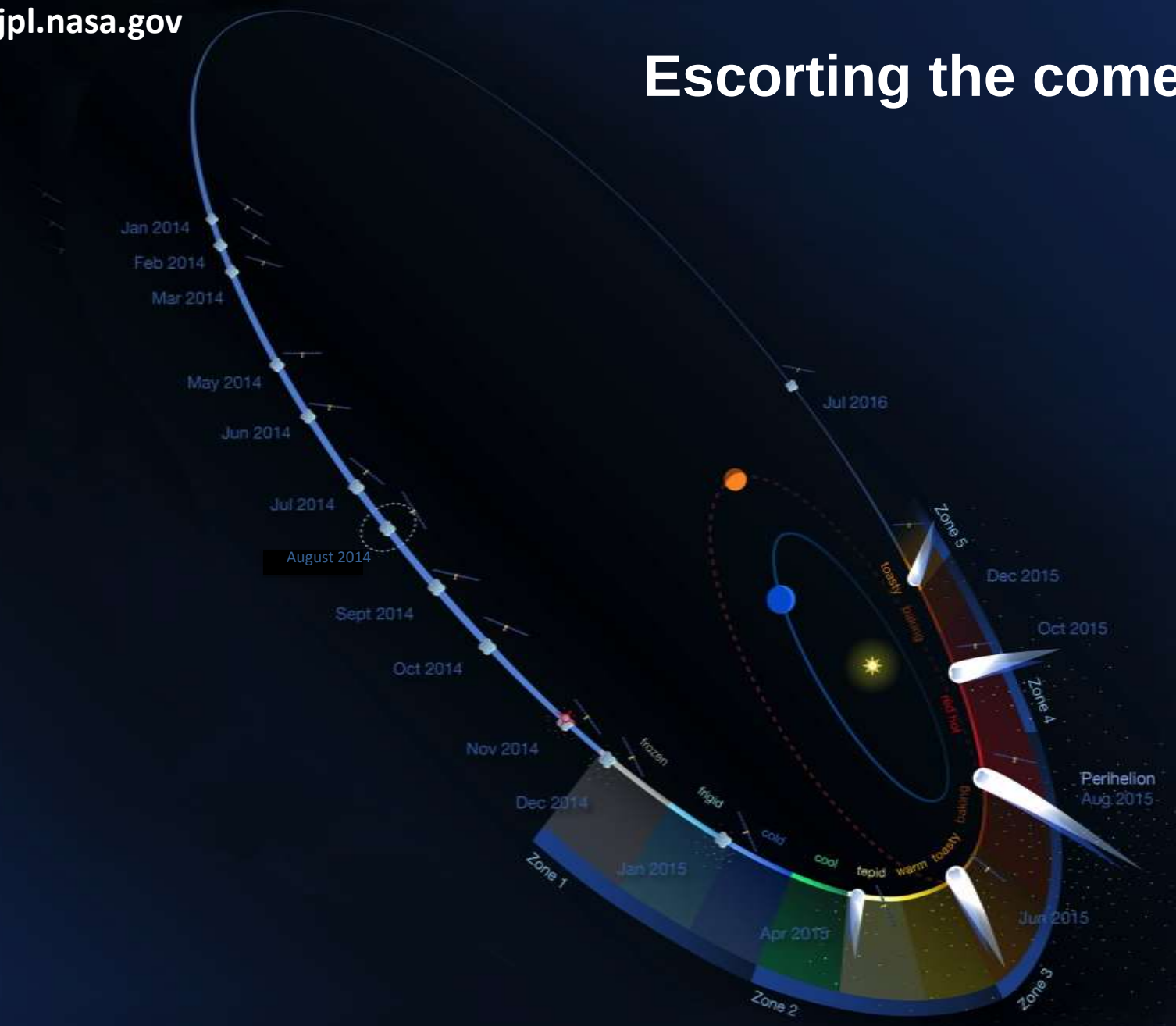


ESO Jan 14 2004

1.2 - 5.7 AU from sun

Rosetta.jpl.nasa.gov

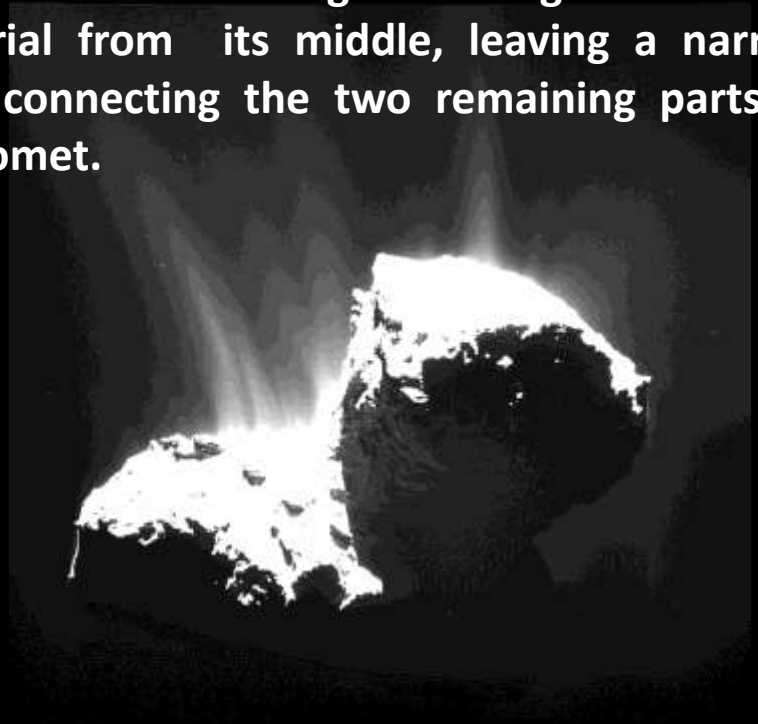
Escorting the comet



Credit: NASA/JPL Caltech

One comet or two?

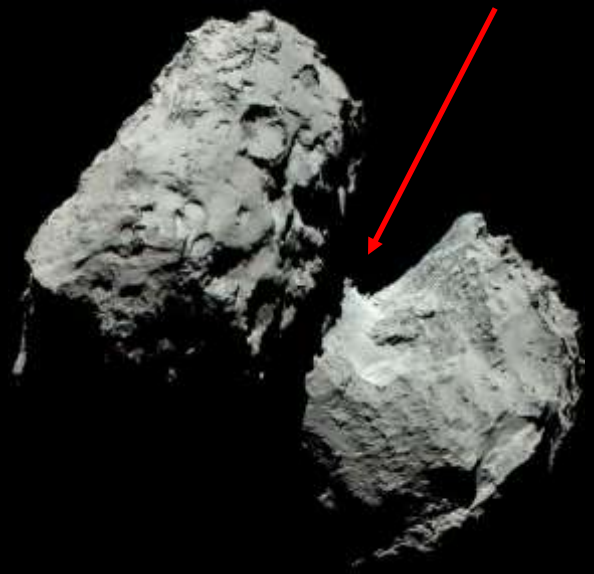
The comet may consist of two large planetestimals (“little planets”) stuck together during its formation. Another possibility is that Comet 67P outgassed a great deal of material from its middle, leaving a narrow neck connecting the two remaining parts of the comet.



Rosetta orbiter instruments will continue to study the data (morphology, composition, density etc.) on how different the two parts of the comet are to determine whether they originally came from the same body.

Credits: Rosetta
Primary Instrument: OSIRIS

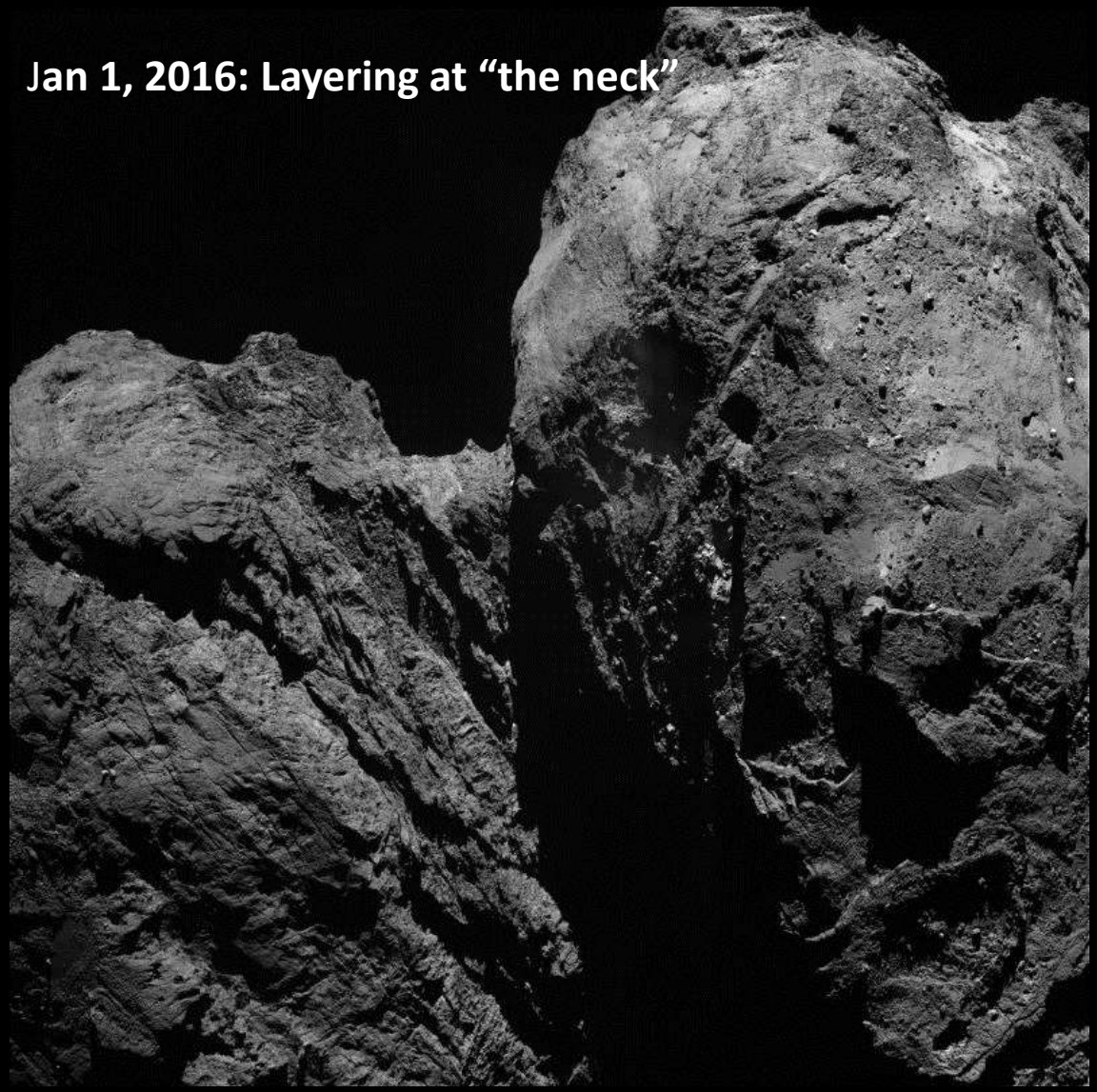
The two components of Rosetta’s comet, showing they are connected by a narrow neck.



Conclusion: Slow speed collisions could have formed many comets

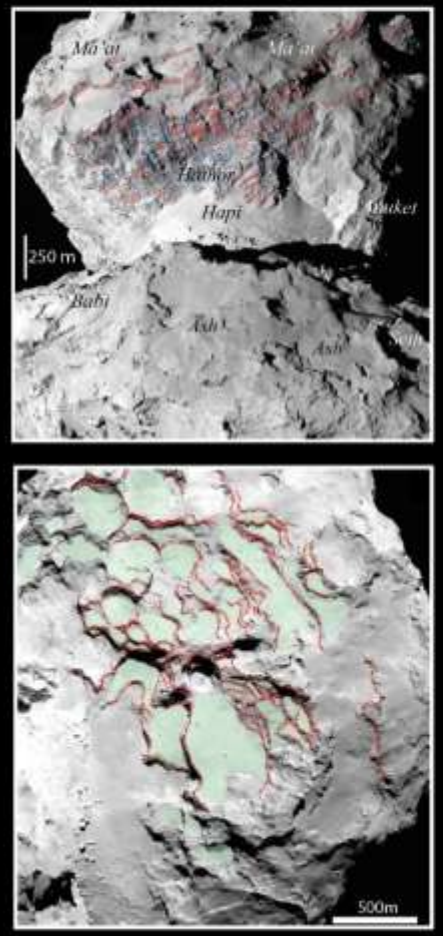
Layering and boulders

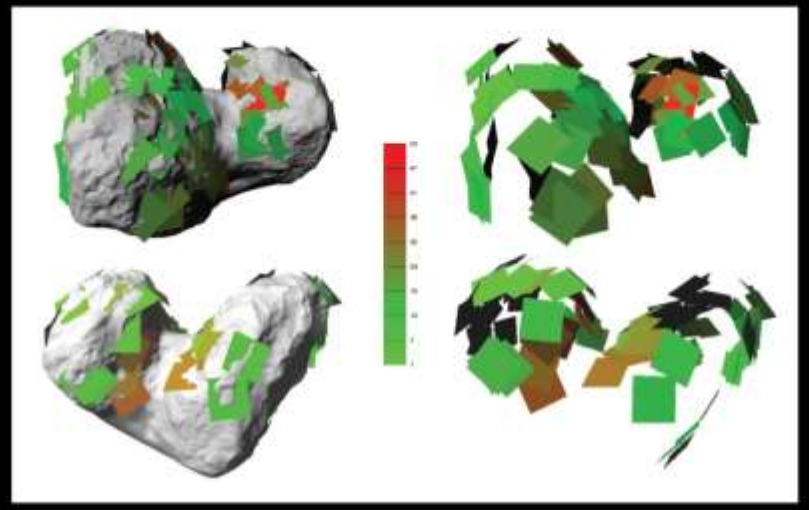
Jan 1, 2016: Layering at “the neck”



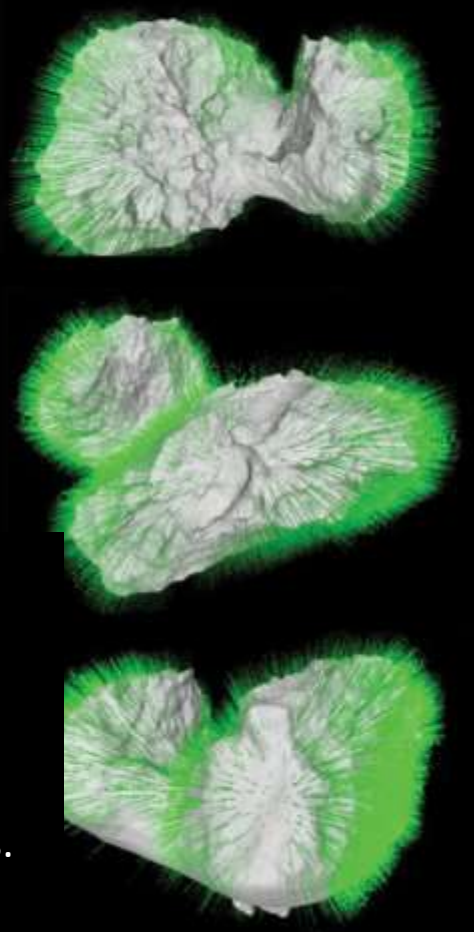
March 19 , 2016 Layers

Two lobes of comet 67P





OSIRIS images were used to visually identify over 100 terraces, which were superimposed on a 3-D shape model (above). The terraces on each component bound two distinct envelopes. Local gravity vectors (right) also show the independent nature of the two lobes.



www.esa.int

ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; M. Massirani et al. (2015).

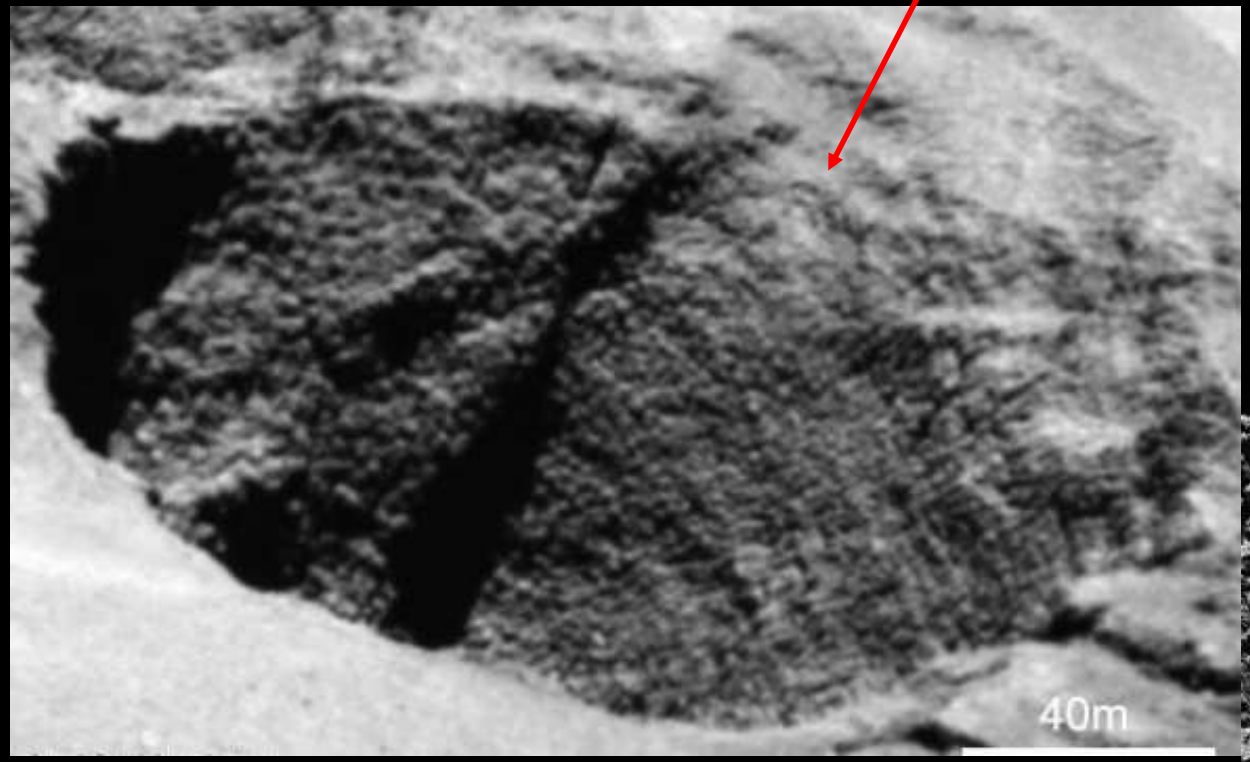
European Space Agency

Credits: ESA/ Rosetta
Primary Instrument: OSIRIS

Conclusion: The comet is made up of two smaller comets

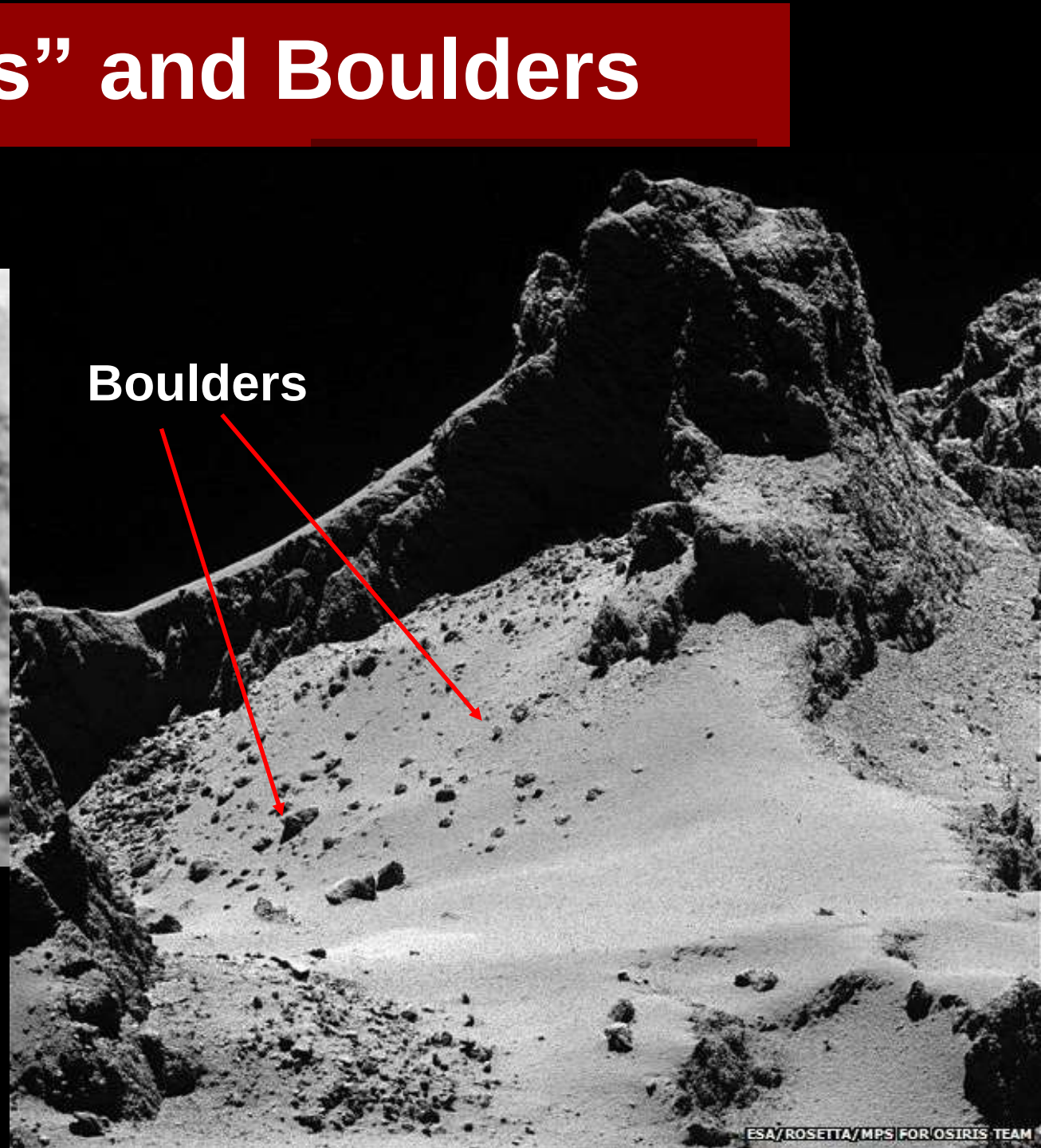
“Dinosaur Eggs” and Boulders

“Dinosaur eggs” in a pit in the comet.



Even smaller planetesimals may have been glimpsed on the comet 67P/Churyumov-Gerasimenko by the *Rosetta* spacecraft. Peering into a deep pit, the camera spied conglomerations of spherical boulders about 3 meters in size. Scientists nicknamed these objects “dinosaur eggs”.

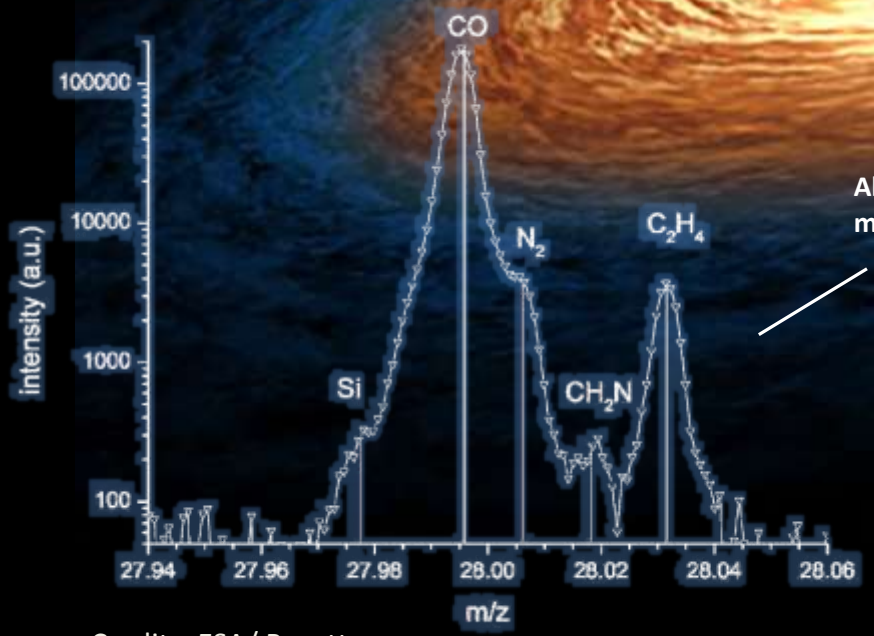
Boulders



Discovery of N_2

ROSINA was designed to differentiate between CO & N_2, all at mass 28.

We can finally get accurate assessment of amount of N_2 in primitive materials!



Credits: ESA/ Rosetta
Primary Instrument: ROSINA

All the species ROSINA can identify at mass 28!

NH_3 (ammonia)

$^{15}NH_2$-

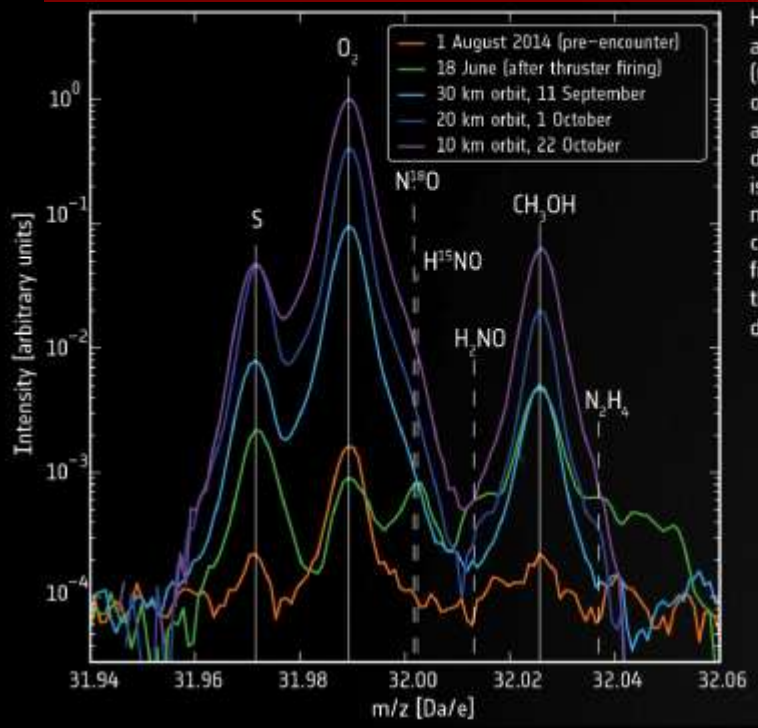
$^{14}NH_2$

N_2

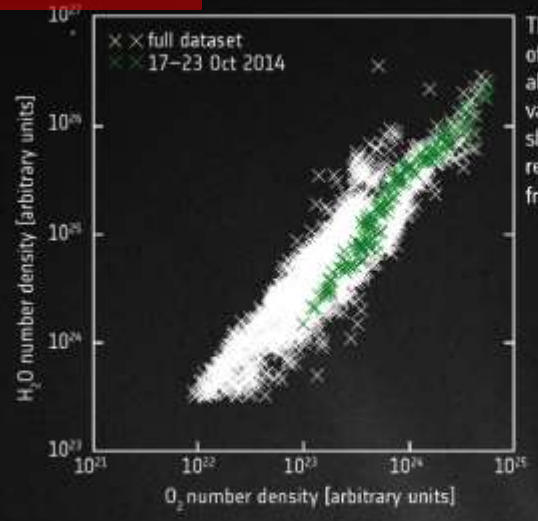
N_2 forms in very cold places. The new measurement tells us that our comet formed at about 30 K

Conclusion: Nitrogen confirms that the comet formed near the inner edge of the Kuiper Belt

Discovery of molecular oxygen



High-resolution measurements allowed molecular oxygen (O_2) to be distinguished from other species like sulphur (S) and methanol (CH_3OH). The detection of the coma gases is stronger closer to the comet nucleus, as expected. The contribution to the detection from contamination from the spacecraft thruster firings during manoeuvres is very low.



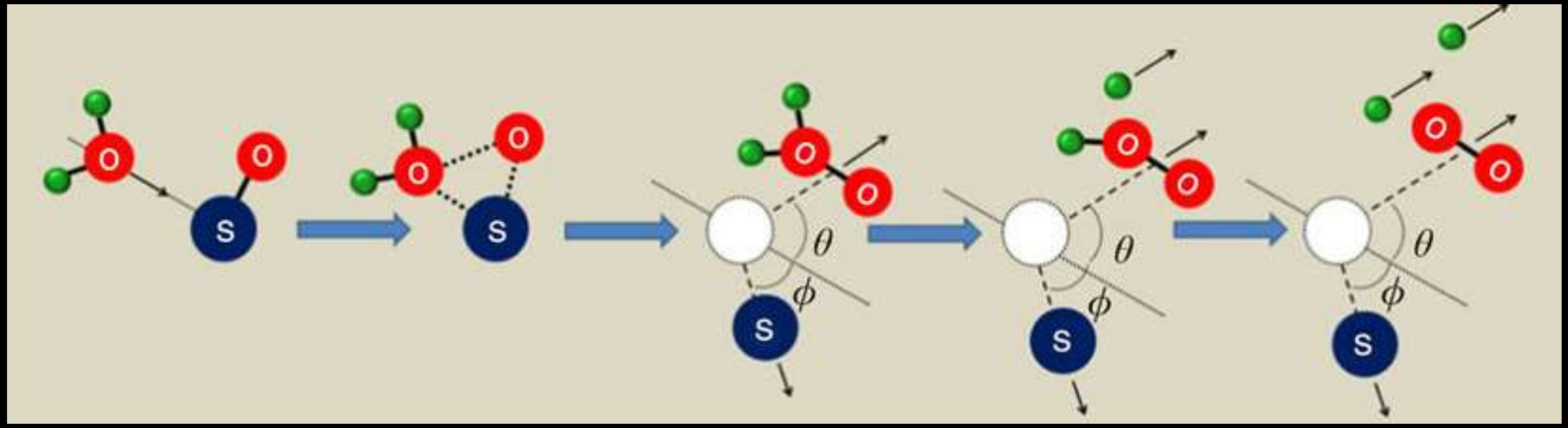
The strong correlation of molecular oxygen abundance with water vapour indicates a shared origin and release mechanism from the nucleus.

Conclusion: Molecular oxygen must have been abundant when the comet was forming

Credits: ESA/ Rosetta
Primary Instrument: ROSINA

Problematical: Little O_2 in ISM
Lab work comes to rescue

"Dynamical molecular oxygen production in cometary coma" Yao&Giapis, *Nature Comm.* 2017. Solar wind-surface-gas phase interaction (Eley-Rideal reaction) produces O_2 on surface. A Caltech ultra-high vacuum ion scattering system validated the mechanism and the rates.



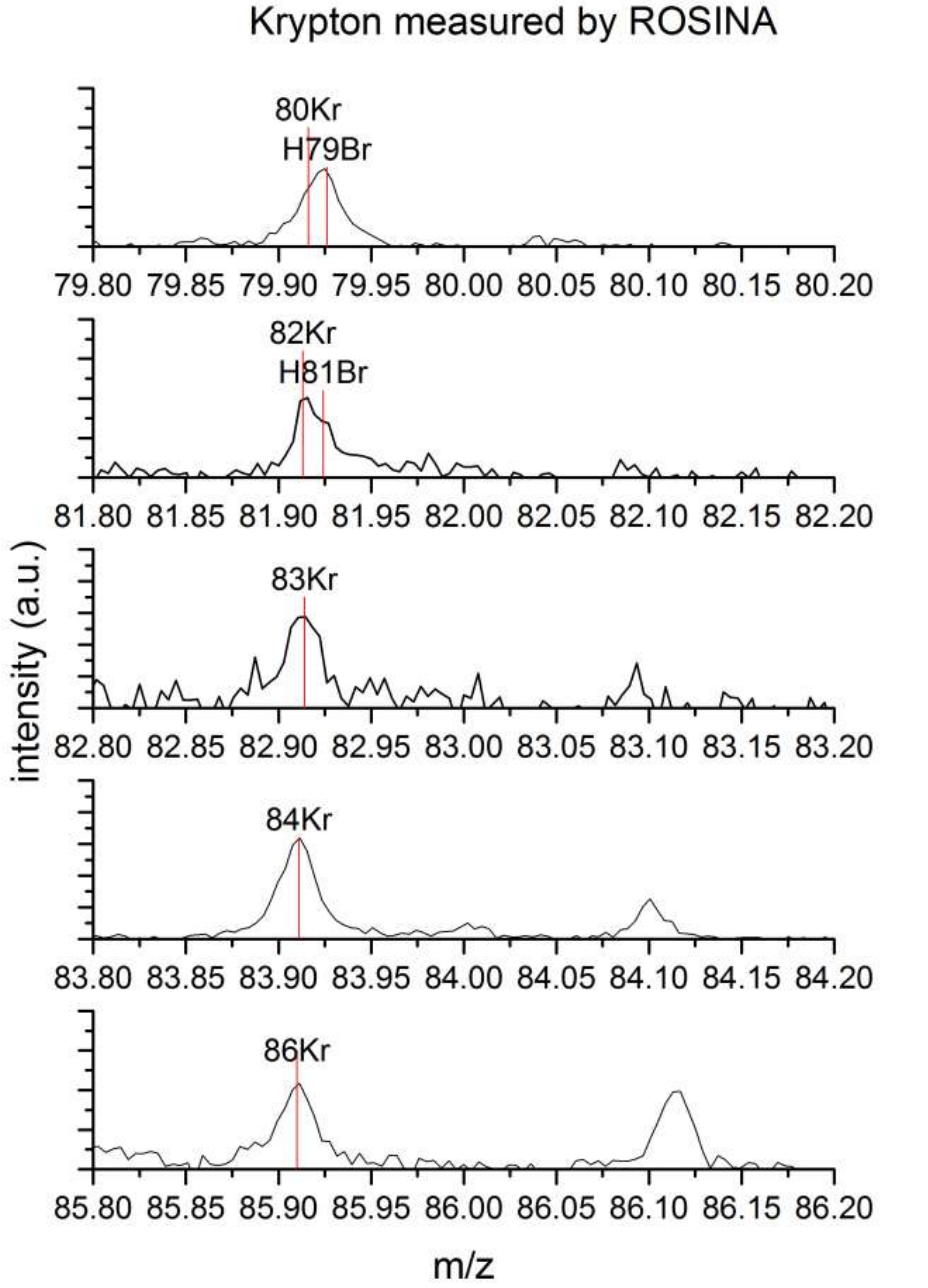
Noble gasses detected

Noble gasses are tracers of long-term processes, both astrophysical and terrestrial.

Noble gasses can be used to understand how much comets contributed to planetary atmospheres (at least the noble gasses). Xenon is 22 ± 5% cometary xenon

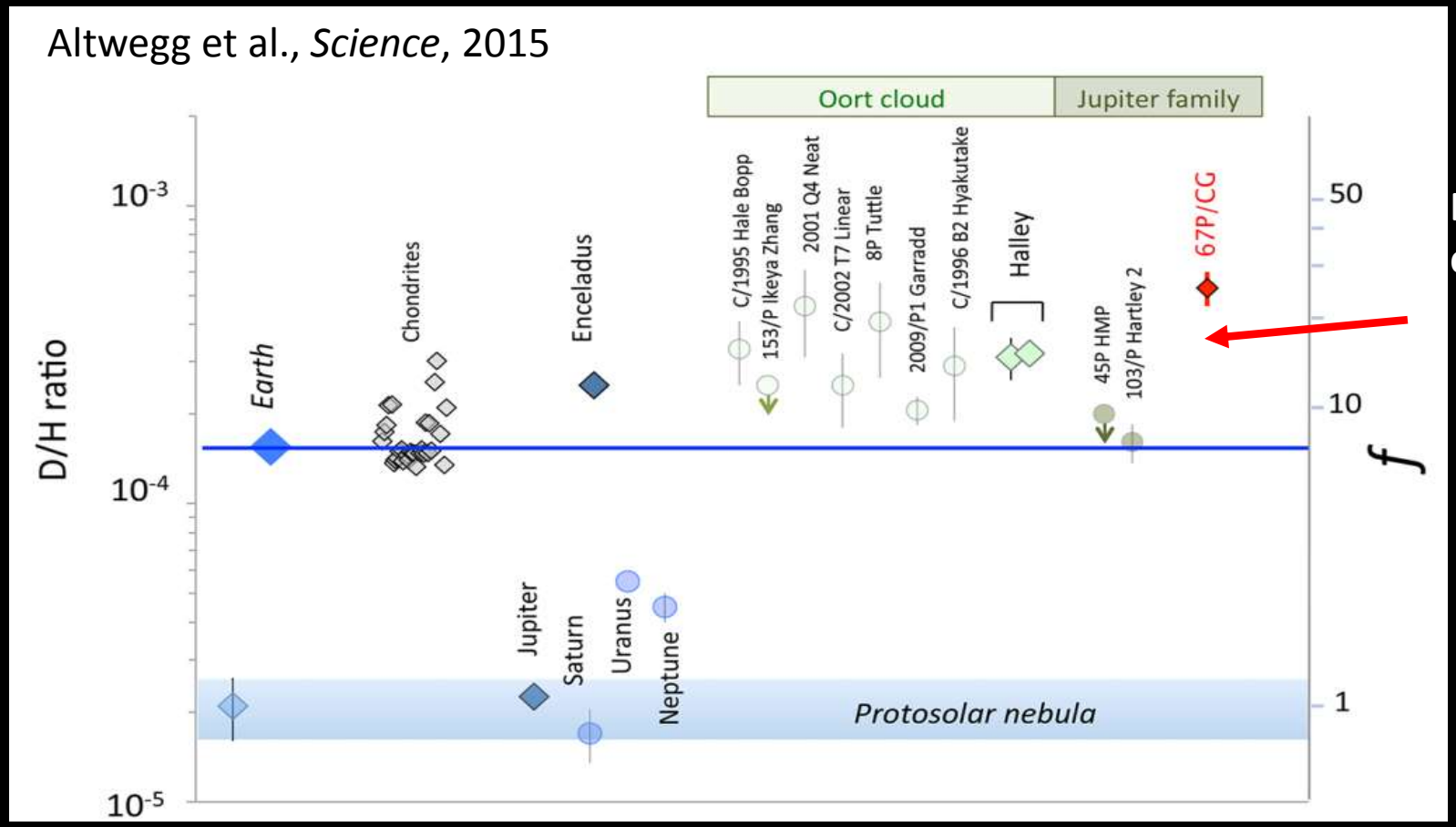
(Marty et al., Science 2017)

Abundance of noble gasses also shows comet formed in a cold place



m/z=mass/charge

ROSINA measures D/H in H_2O from 67P/CG



Eley-Rideal reactions can also produce heavy water, but not enough.

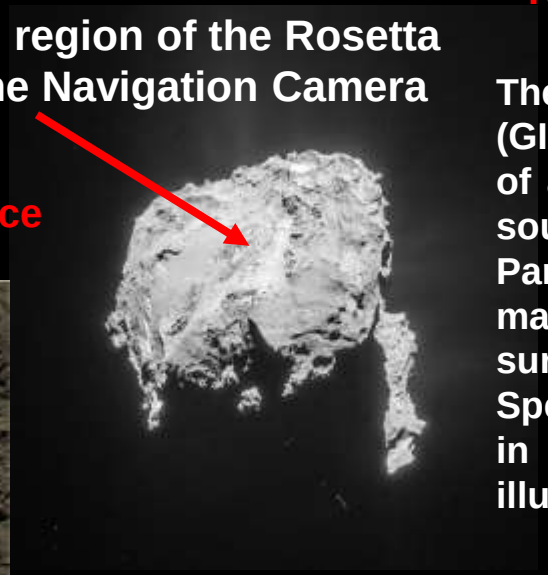
The ratio of deuterium to normal hydrogen can be used to trace the origin of water in the Solar System, and to understand how icy bodies are related. The high D/H ratio at 67P compared with other Jupiter Family Comets – which are believed to originate in the Kuiper Belt- questions the validity of current dynamical models. Variable heliocentric distances for JFCs might be required to explain the range of values. In addition, the high D/H ratio measured at 67P questions whether JFCs may have significantly contributed to bringing water to Earth.

Water and Ice on Comet 67P/Churyumov-Gerasimenko

Like comets in general, 67P/ Churyumov-Gerasimenko is a abundant source of water. This water is released from the comet as it approaches the sun. The Microwave Instrument for the Rosetta Orbiter (MIRO) found that during its active period the comet produces sufficient water to fill an Olympic swimming pool every 100 days. The ultraviolet spectrometer ALICE found indirect evidence for water: electrons from water molecules that were ionized by sunlight. The water that is released forms the jets and coma that give comets their glorious appearance.

Regions where water ice was detected by VIRTIS

Illuminated Imhotep region of the Rosetta comet as seen by the Navigation Camera

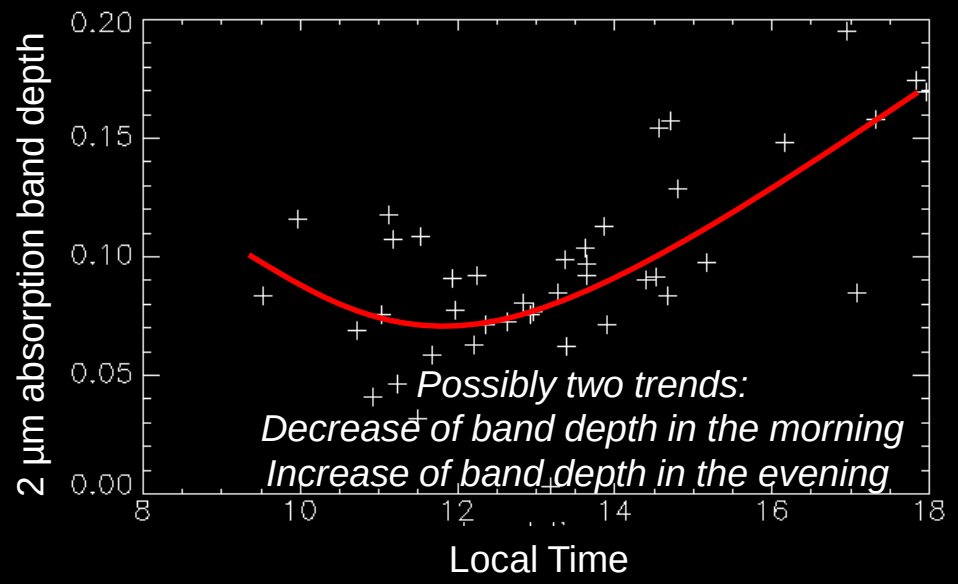


A bright spot of fresh ice

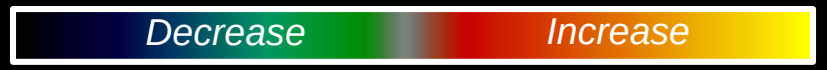
The Grain Impact Analyzer and Dust Accumulator (GIADA) revealed a surface of ice and dust in the ratio of about 1 to 4. But the presence of water ice, the source of the outgassed material, has been elusive. Part of the reason is that the dust is very dark and masks the presence of water ice on the comet's surface. Finally, the Visual Infrared Thermal Mapping Spectrometer (VIRTIS) obtained spectra of water ice in the Imhotep region of the comet as it was illuminated by solar radiation.

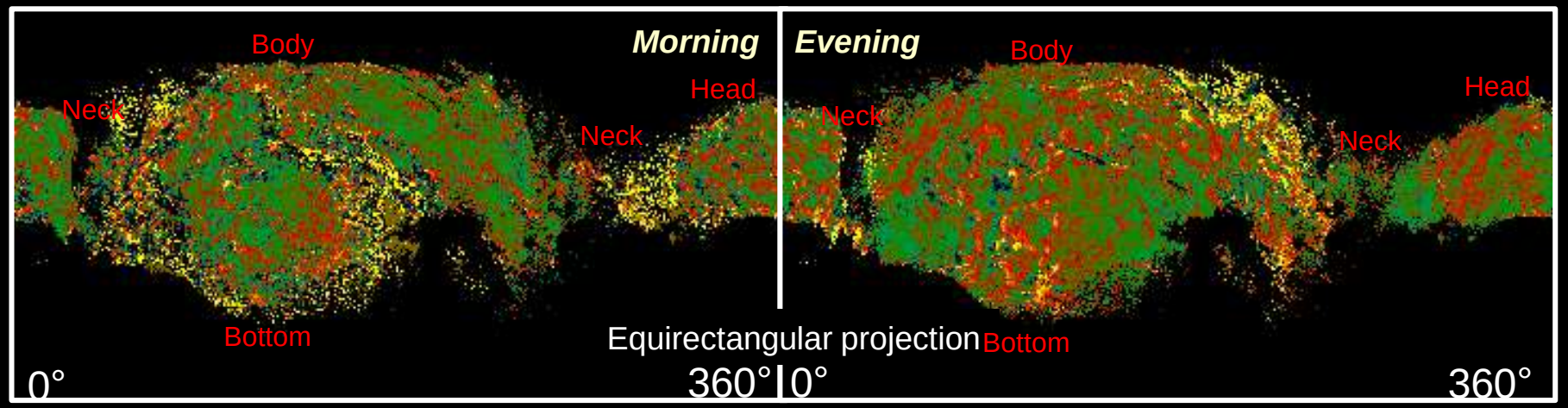
Filacchione et al., 2016; Image credits: ESA

Variations of H_2O ice at the surface



The absorption band depth of H_2O decreases in the morning and increases in the evening mostly near the neck, suggesting diurnal variations of the H_2O exposed at the surface of the comet nucleus

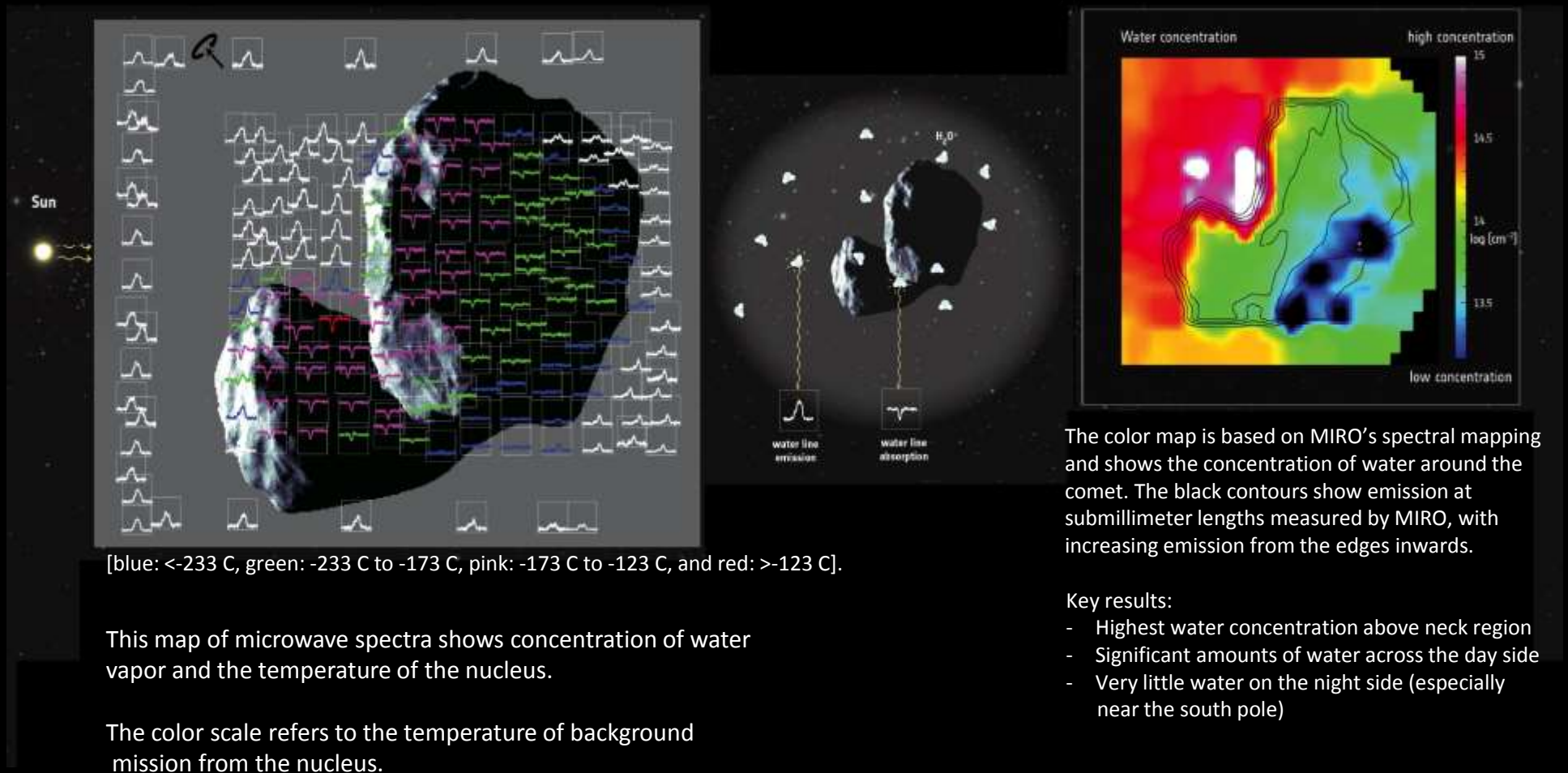




Credits: ESA/ Rosetta
Primary Instrument: VIRTIS

Conclusion: Ice forms as frost at night and sublimates during the day

First map of water vapor around 67P



[blue: <-233 C, green: -233 C to -173 C, pink: -173 C to -123 C, and red: >-123 C].

This map of microwave spectra shows concentration of water vapor and the temperature of the nucleus.

The color scale refers to the temperature of background mission from the nucleus.

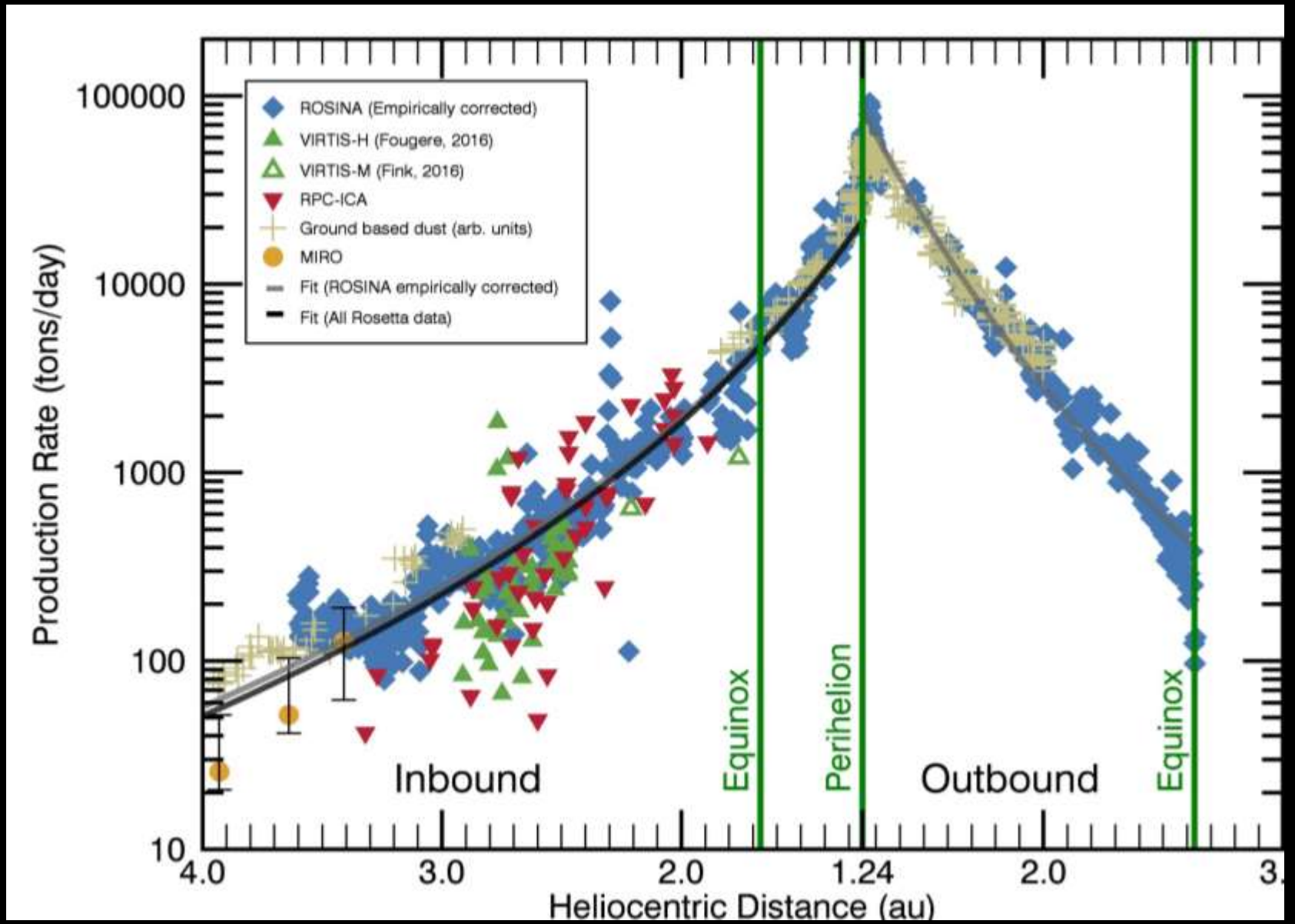
The color map is based on MIRO's spectral mapping and shows the concentration of water around the comet. The black contours show emission at submillimeter lengths measured by MIRO, with increasing emission from the edges inwards.

Key results:
- Highest water concentration above neck region
- Significant amounts of water across the day side
- Very little water on the night side (especially near the south pole)

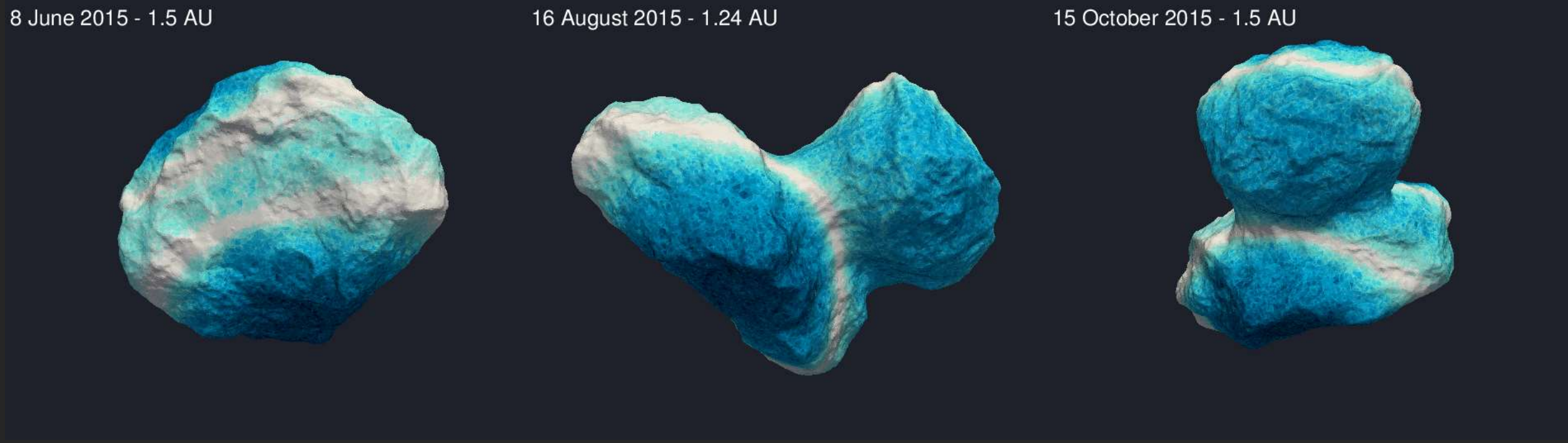
Credits: ESA/ Rosetta
Primary Instrument: MIRO

Conclusion: Water sublimation is driven by seasonal and diurnal illumination from the Sun

Water production (Hansen et al., 2016

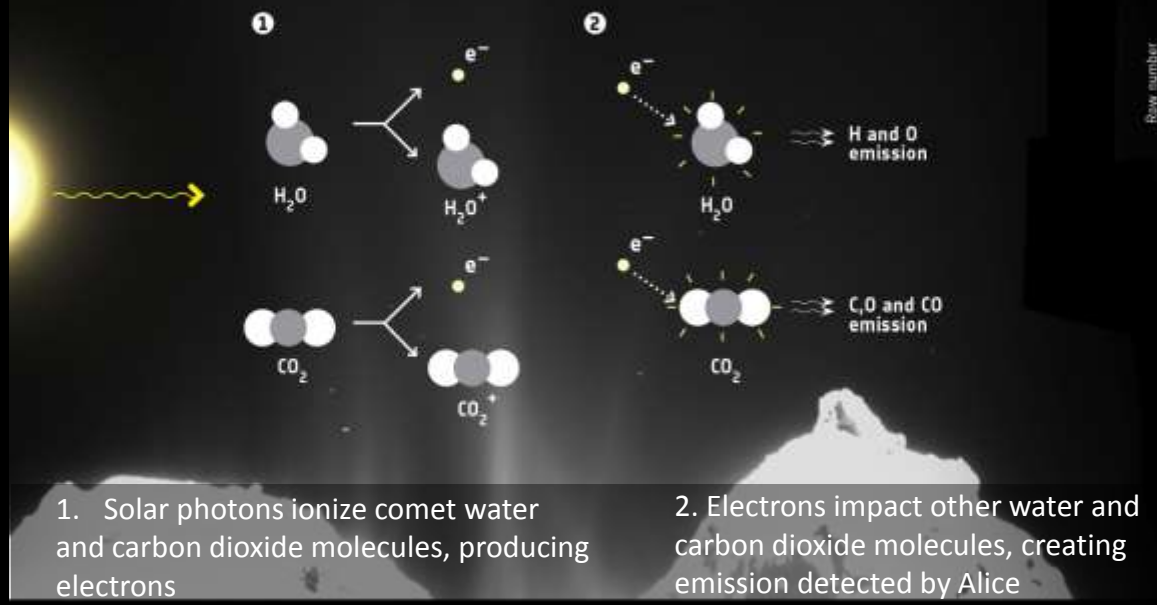


Water production, cont'd



Electrons break-up H_20 and CO_2

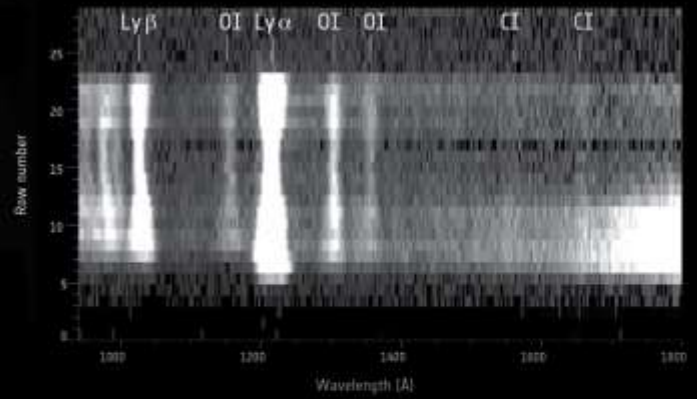
Rosetta's close study of Comet 67P at ultraviolet wavelengths has revealed that electrons and not photons are responsible for rapid breakup of water and carbon dioxide molecules erupting from the surface. This process takes place close to the surface (1km).



1. Solar photons ionize comet water and carbon dioxide molecules, producing electrons

2. Electrons impact other water and carbon dioxide molecules, creating emission detected by Alice

Example of a spectral image (below) obtained by Alice for positions in the comet's coma indicated in the NavCam image (above). The emission by oxygen (OI) and carbon (CI) in the coma are indicated. The bright bands labelled Lyα and Lyβ are due to electron impact on H_2O.

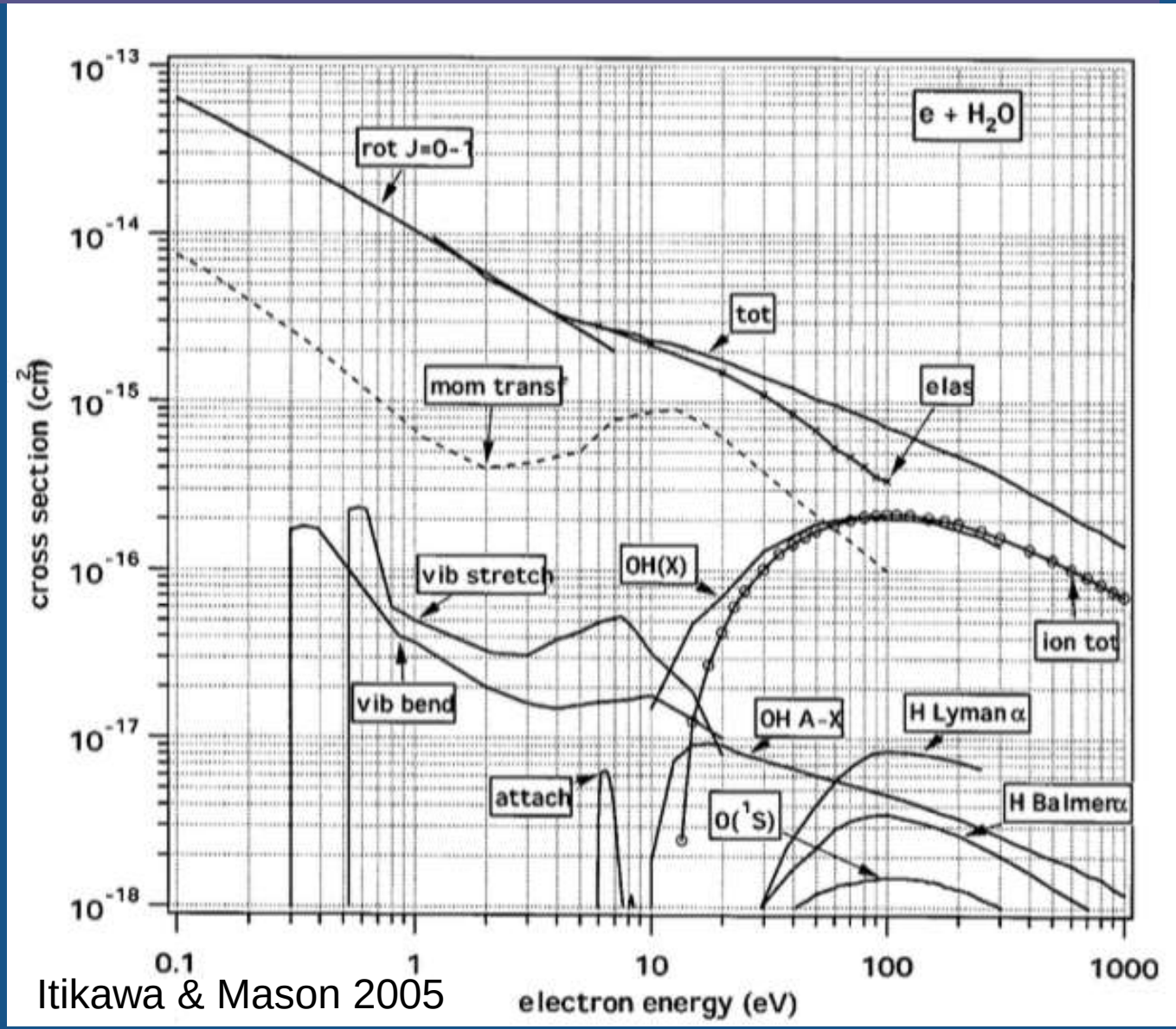


Conclusion: Coma is a very active environment where volatiles interact with solar wind and sunlight as soon as they are emitted from the interior.

Credits: ESA/ Rosetta
Primary Instrument: Alice (Feldman et al.,

Electron – water collisions: lab work validated!

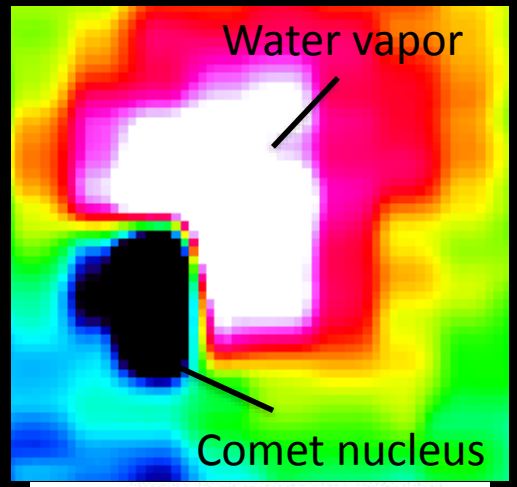
Near perihelion (May 2015), the fragments of OH, O, etc. stopped being produced by the electrons. Why? The abundant water cooled the electrons to below 10 ev;
The electrons were no longer energetic enough to create the fragments.
Data illustrating this process was produced in the lab 10 years earlier.



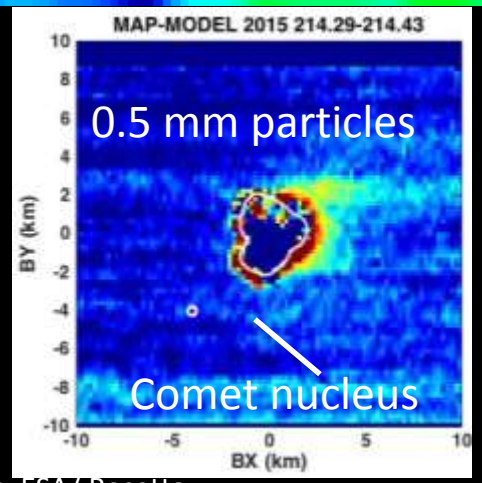
Itikawa & Mason 2005

Comet jet recipe: 4 parts dust, 1 part ice

Rosetta is telling us how much dust and ice are coming off comet 67P as it orbits the Sun.



High velocity gas (1 km/s) lifts and drives the dust away from the nucleus.



The comet emits all sizes of dust, from particles smaller than a human hair to clumps the size of a basketball. The large particles are important because they account for most of the mass lost by the comet. Observations show the source of the material coming off the nucleus.

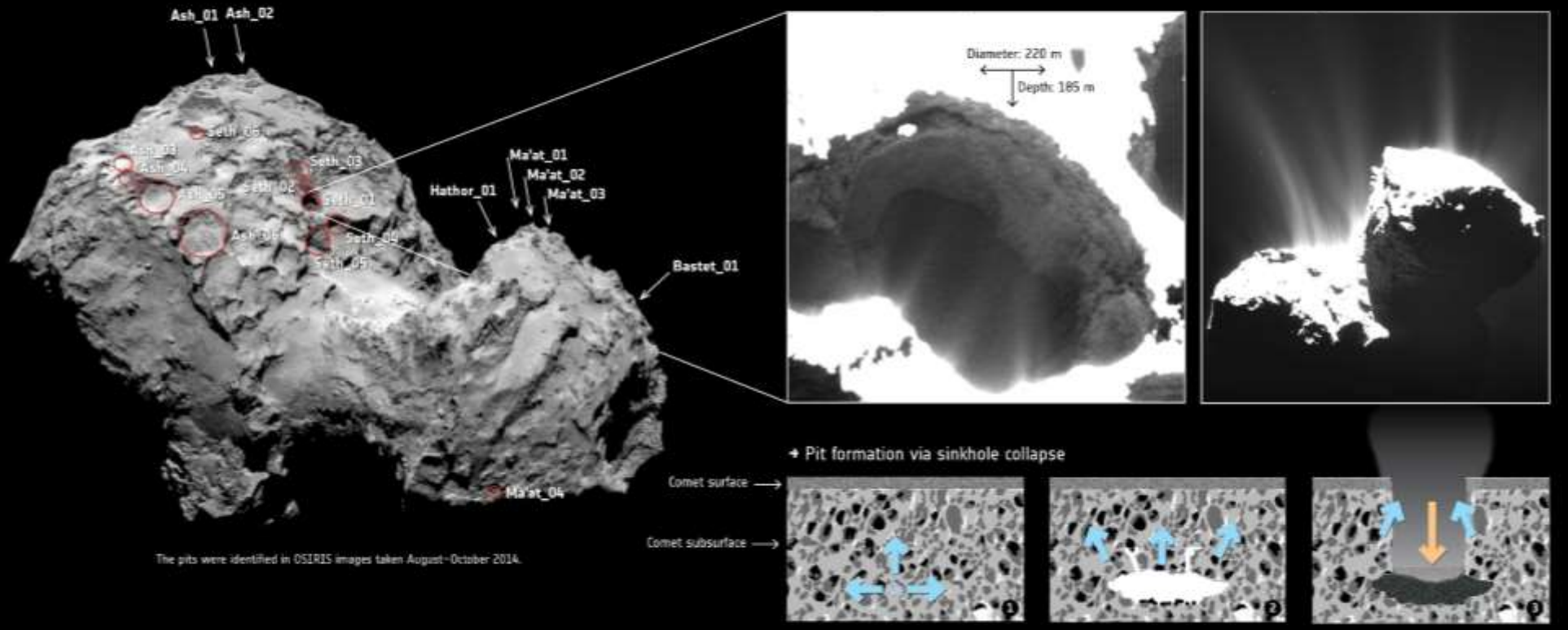
What comes off the comet is about 80% dust by mass, and 20% gas.

Conclusion: Activity on comet lifts the surface particles forming the coma and the tail

Credits: ESA/ Rosetta
Primary Instrument: MIRO/GIADA

Active Pits

Close-up of Seth_01 shows jets emanating from the pit walls

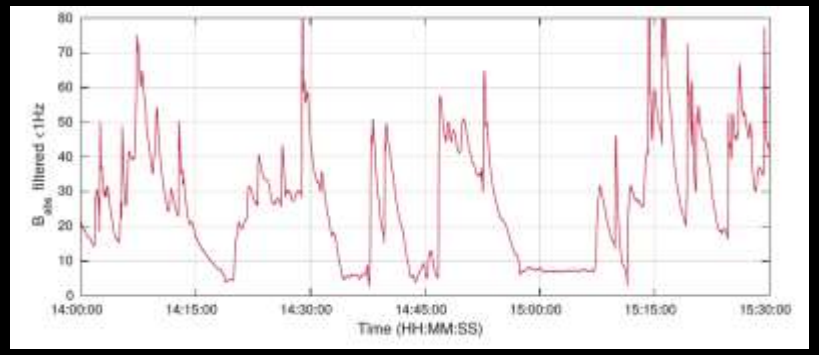


Heat causes the subsurface ices to sublimate, forming a cavity. When the the surface weakens and collapses, a pit forms, and the gasses sublimate

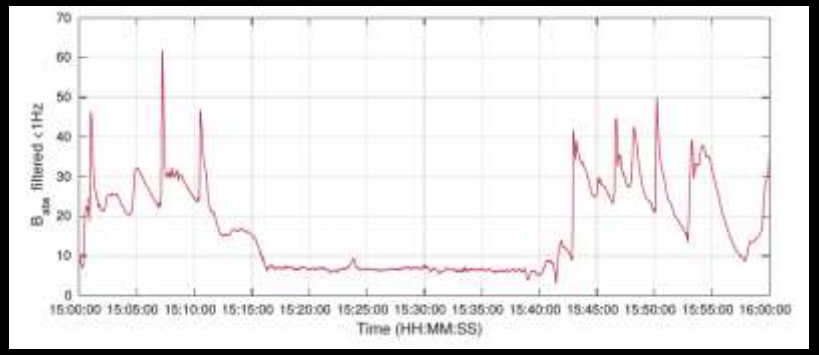
Credits: ESA/ Rosetta
Primary Instrument: OSIRIS

Conclusion: The activity is from side walls of pits and collapsed undersurface voids

The mystery of “mini” diamagnetic cavities discovered by *Rosetta*

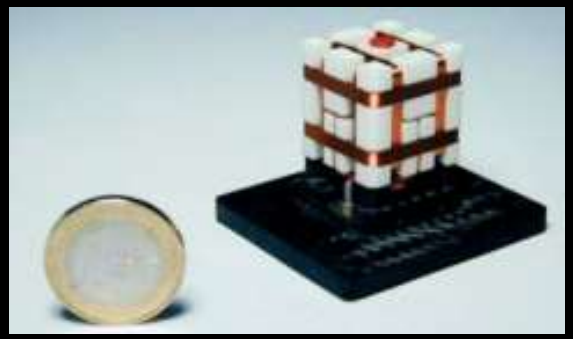


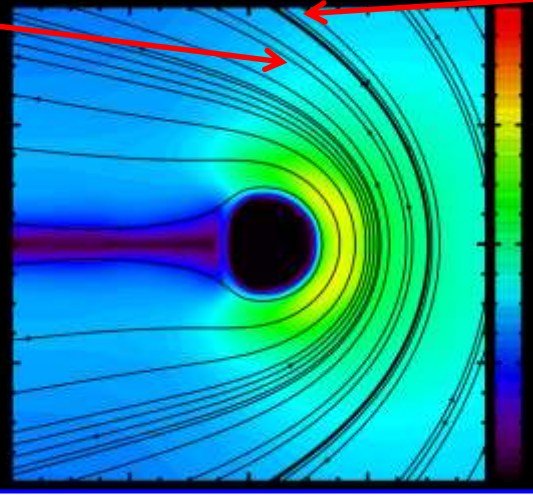
Many short (1-10 min long) periods of zero magnetic field were observed by the Magnetometer on July 29, 2015 (90^{o} phase angle, 335 km cometocentric distance)



One long (25 min long) period of zero magnetic field was observed on July 26, 2015 (85^{o} phase angle, 420 km cometocentric distance)

Rosetta’s fluxgate magnetometer





Simulated magnetic field magnitude for nominal solar wind conditions near perihelion (sun is on the right, color code is magnetic field magnitude, black lines are magnetic field lines). The diamagnetic cavity is ~50km around the nucleus.

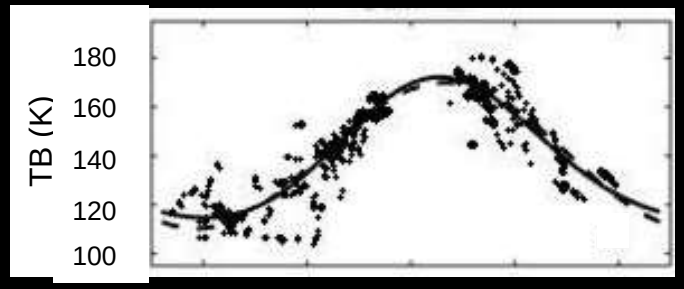
- s/c velocity (with respect of the nucleus) is~1m/s, therefore the size of the observed magnetic field free regions is 0.1km – 15 km.
- The magnetic field free regions are ~4-6 further than the estimated diamagnetic cavity boundary.
- The origin of these small diamagnetic cavity regions is not understood.
- Potential explanations are:
  - Localized gas jets
  - Dust jets
  - Highly unstable diamagnetic cavity boundaries (fingers)
  - … or something we did not think of yet...

Zero phase (April 9): The comet was fully illuminated

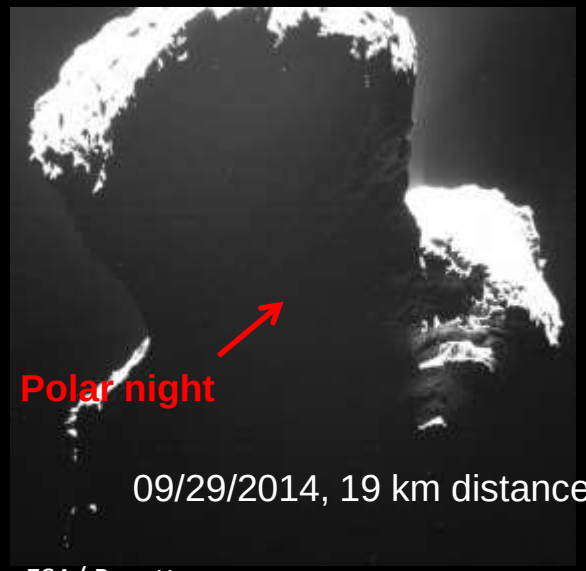
Zero phase observations can be modeled to derive surface porosity

The dark side of a comet: measurement of the heat capacity

By measuring day-to-night temperature variations all over the nucleus (example on the right), MIRO has determined that much of the comet is covered by a porous, mostly dusty layer at least centimeters thick



Southern Regions in polar night

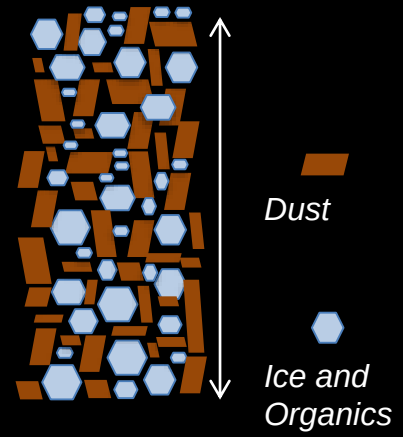


Credits: ESA/ Rosetta
Primary Instrument: MIRO

Extremely cold south polar regions near the end of their 5-year long winter, however, collect a lot of ice in the upper tens of centimeters (several inches).

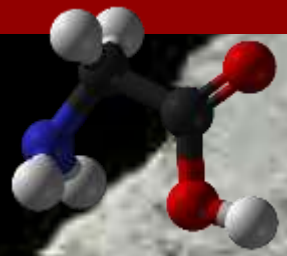
This ice sublimates and releases water vapor when summer arrives, making southern regions, in summer, the most active on the comet!

Top 20-50cm of comet surface



Conclusion: measuring the darkest parts helped understanding the surface of the comet

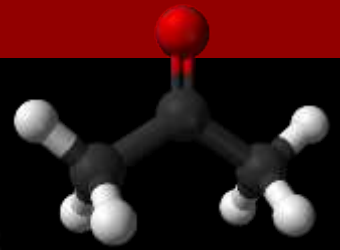
Organic molecules on the comet: A clue to the origins of life on Earth



Glycine: an amino acid
ISM - contested

*Propanol
CH_3CH_2CHO
ISM – yes!

*Acetone
$(CH_3)_2CO$
ISM – yes!



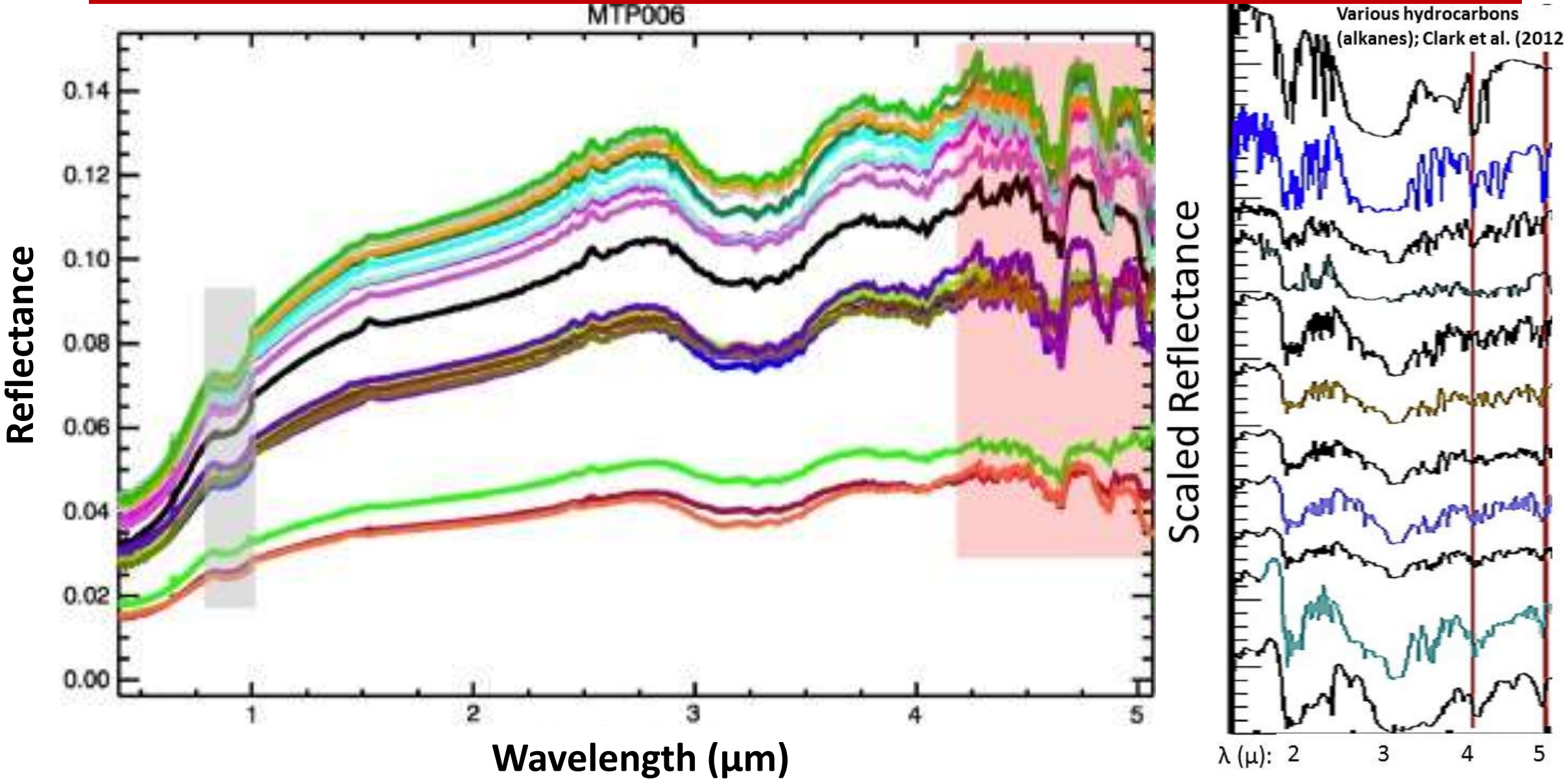
*Methyl isocyanate
CH_3NCO
ISM – yes!

*Acetamide
CH_3CONH_2
ISM – Yes!

Formaldehyde
CH_2O
ISM – yes!

*First seen on 67P/
16 organic molecules total

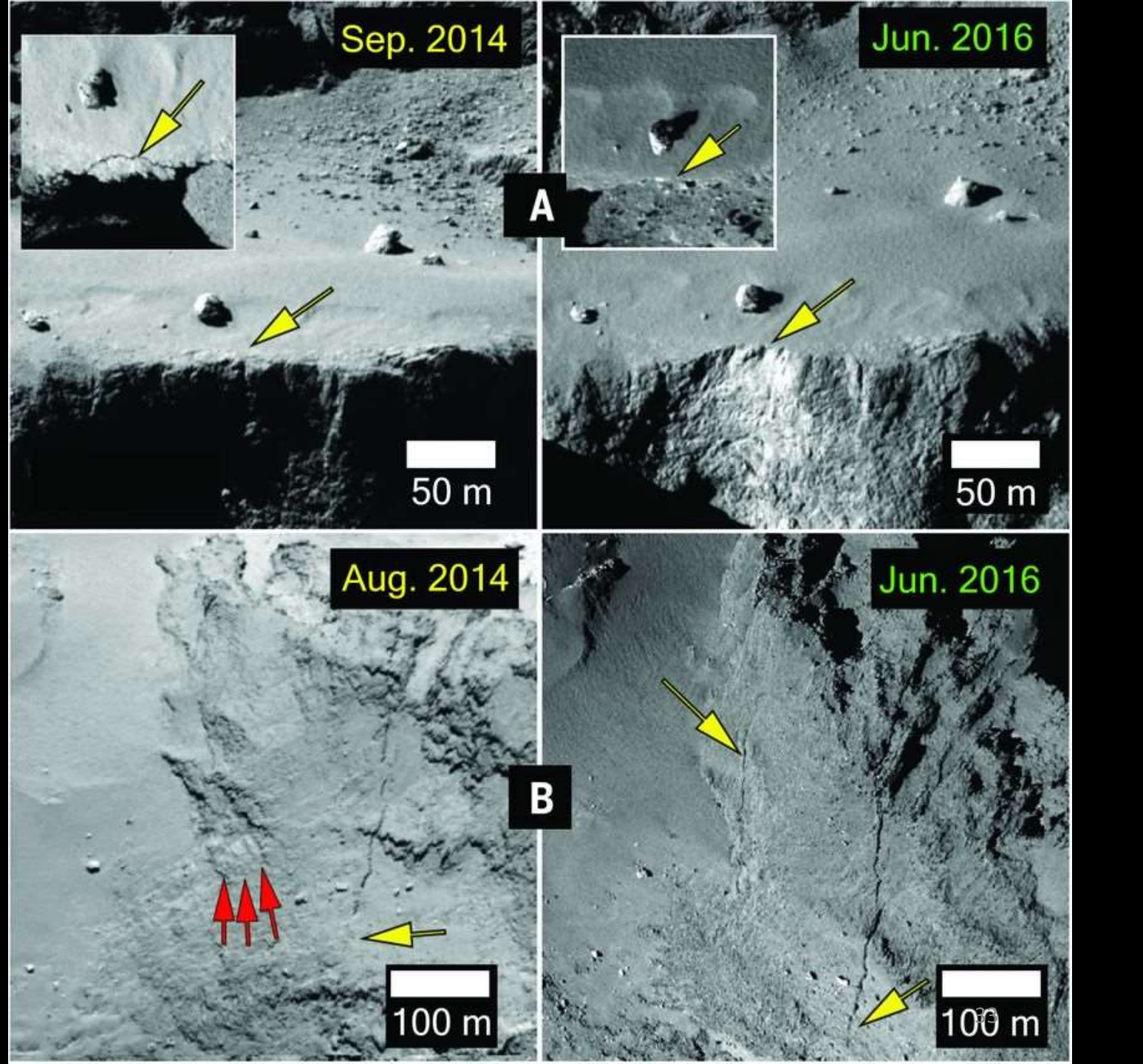
Composition of a comet (Filacchione et al. , 2016)



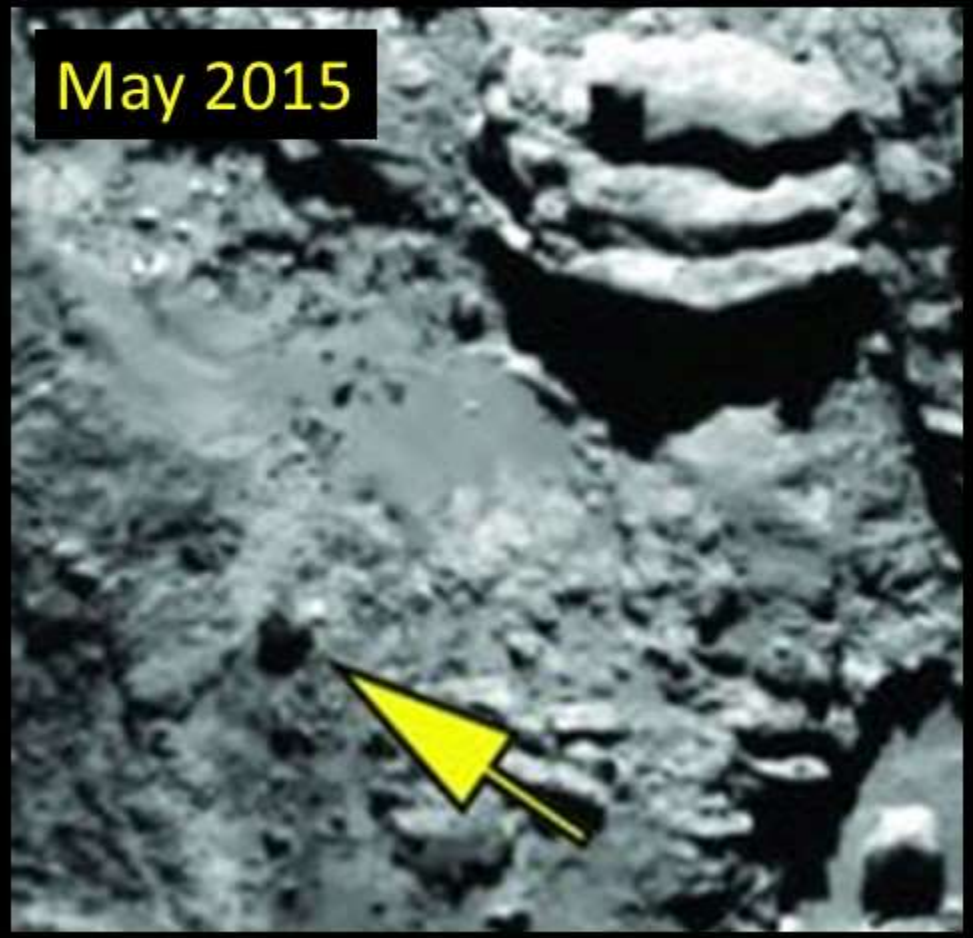
Changes on the comet

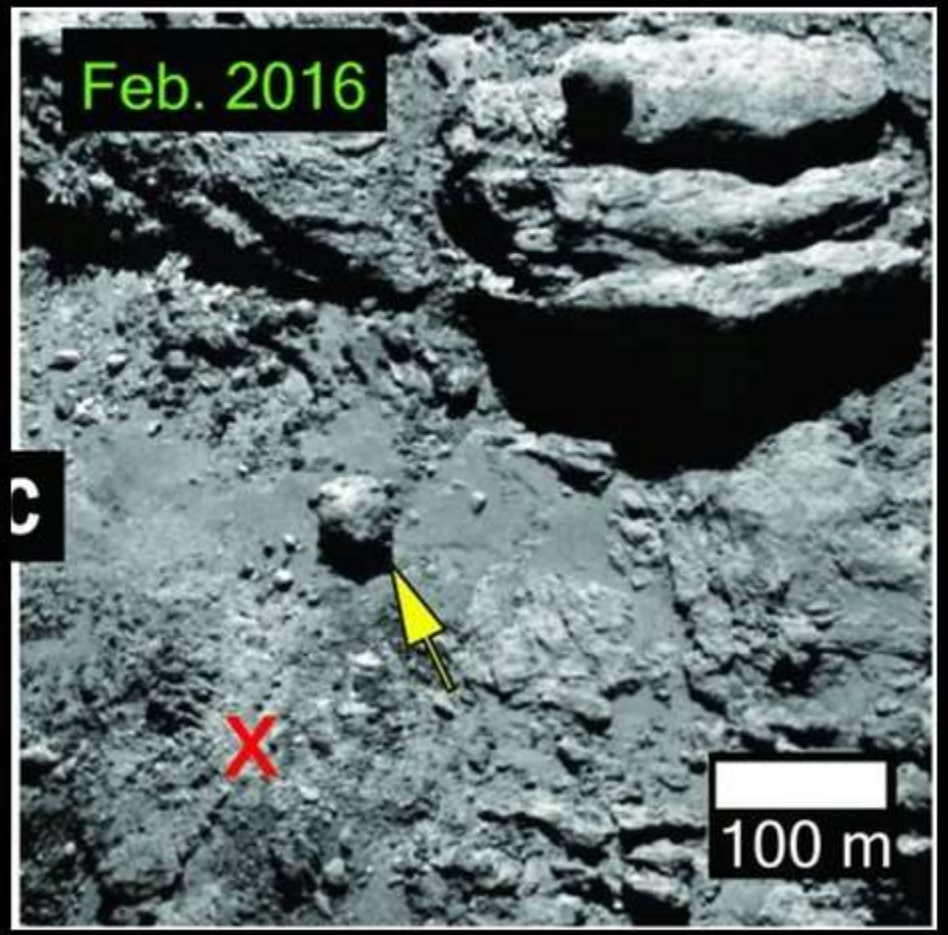
- Cliff collapses
- Cracks form

El-Maarry et al.,
Science 2017



Massive Boulder Moves!

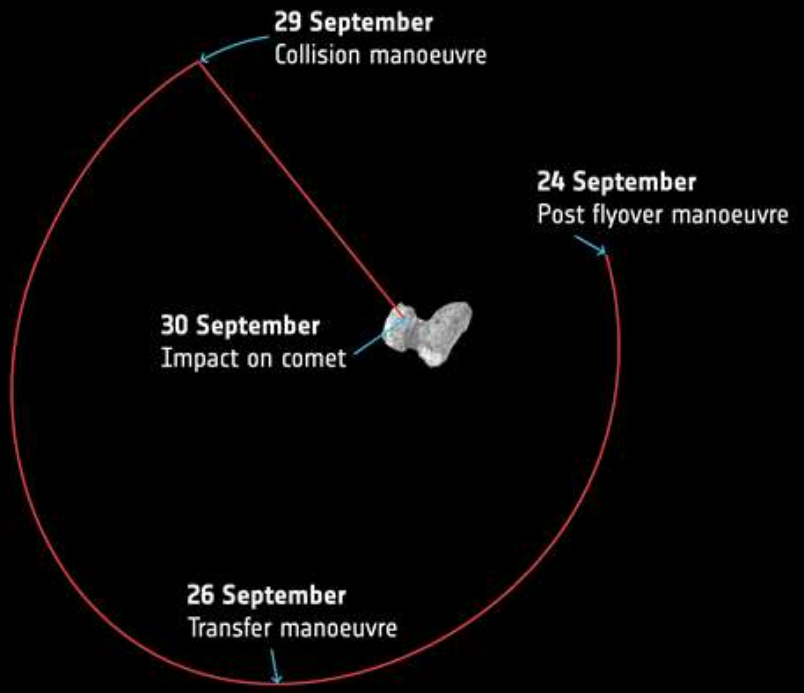


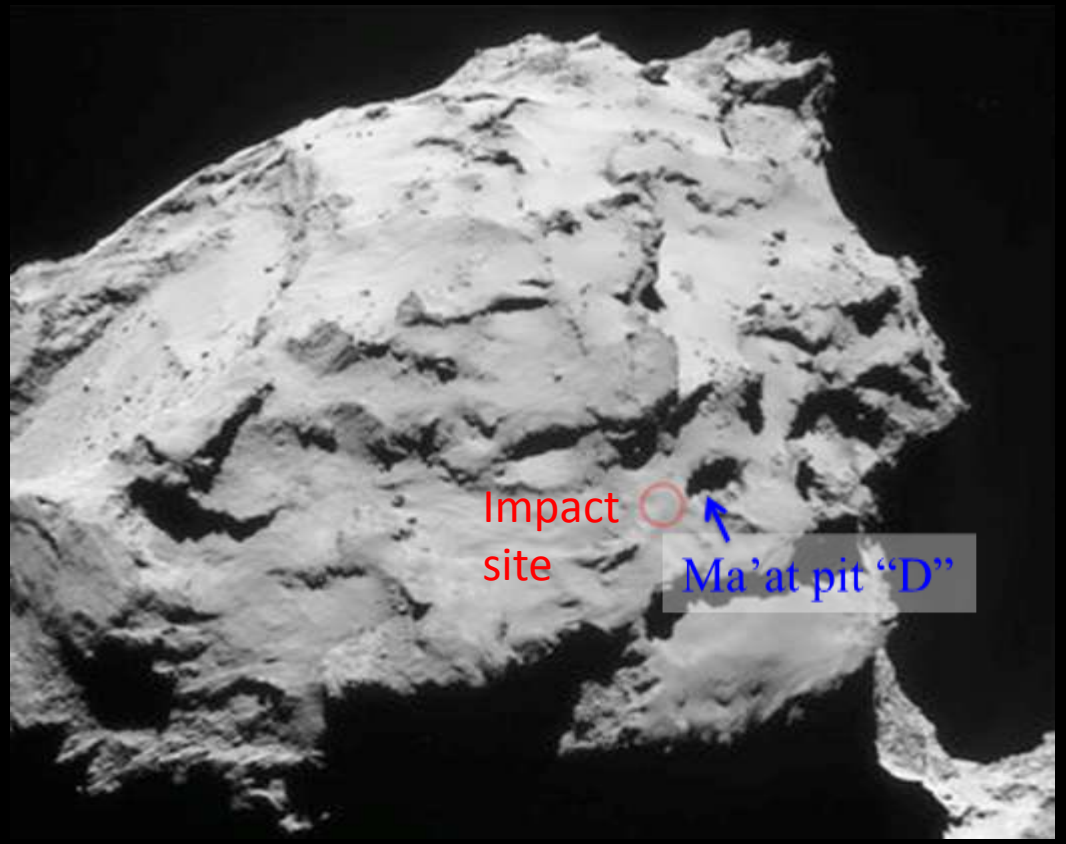


Mass is ~13X106 kg (250 kg on 67/P)

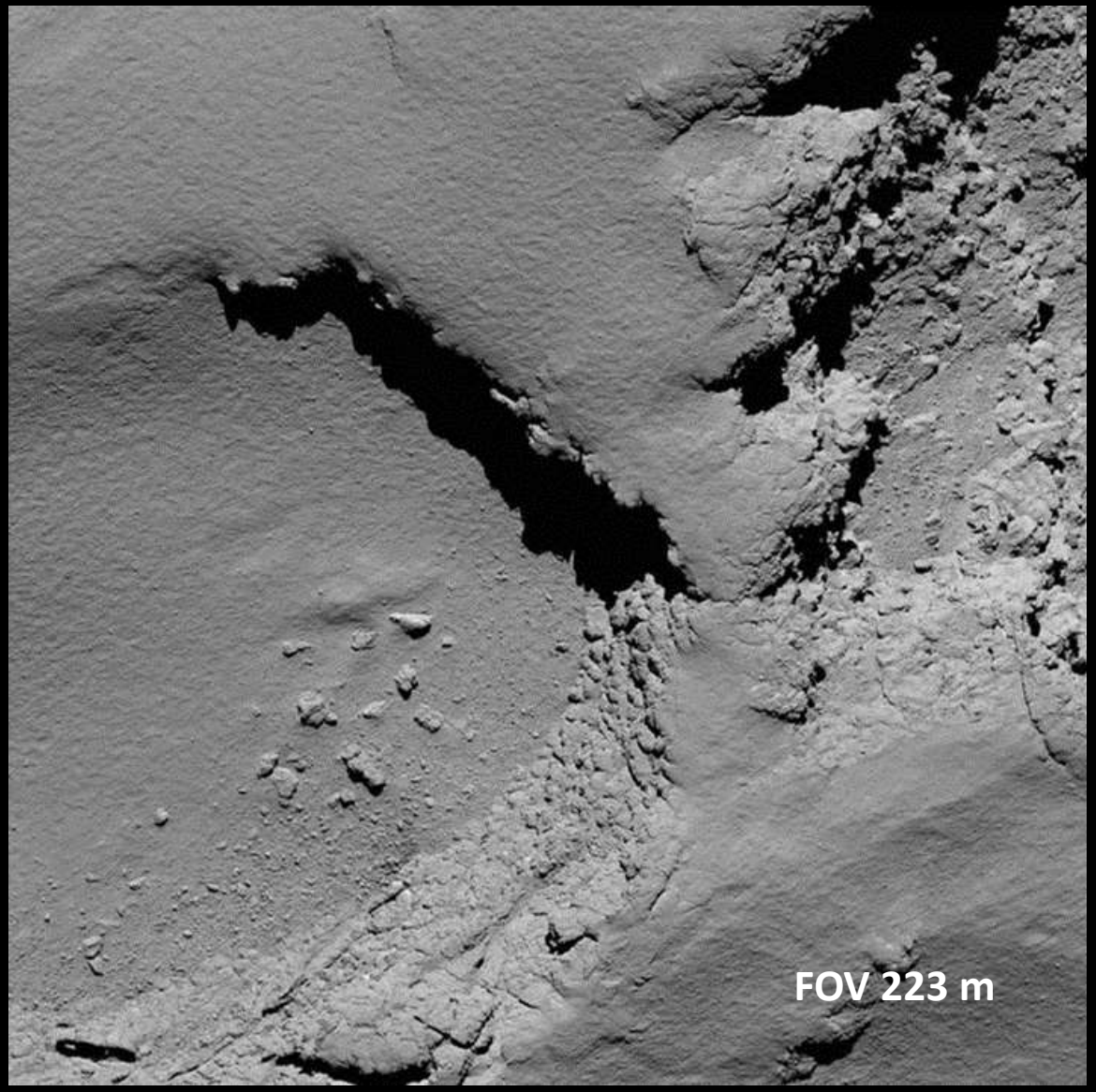
Rosetta End-of-Mission: Landing on 67P

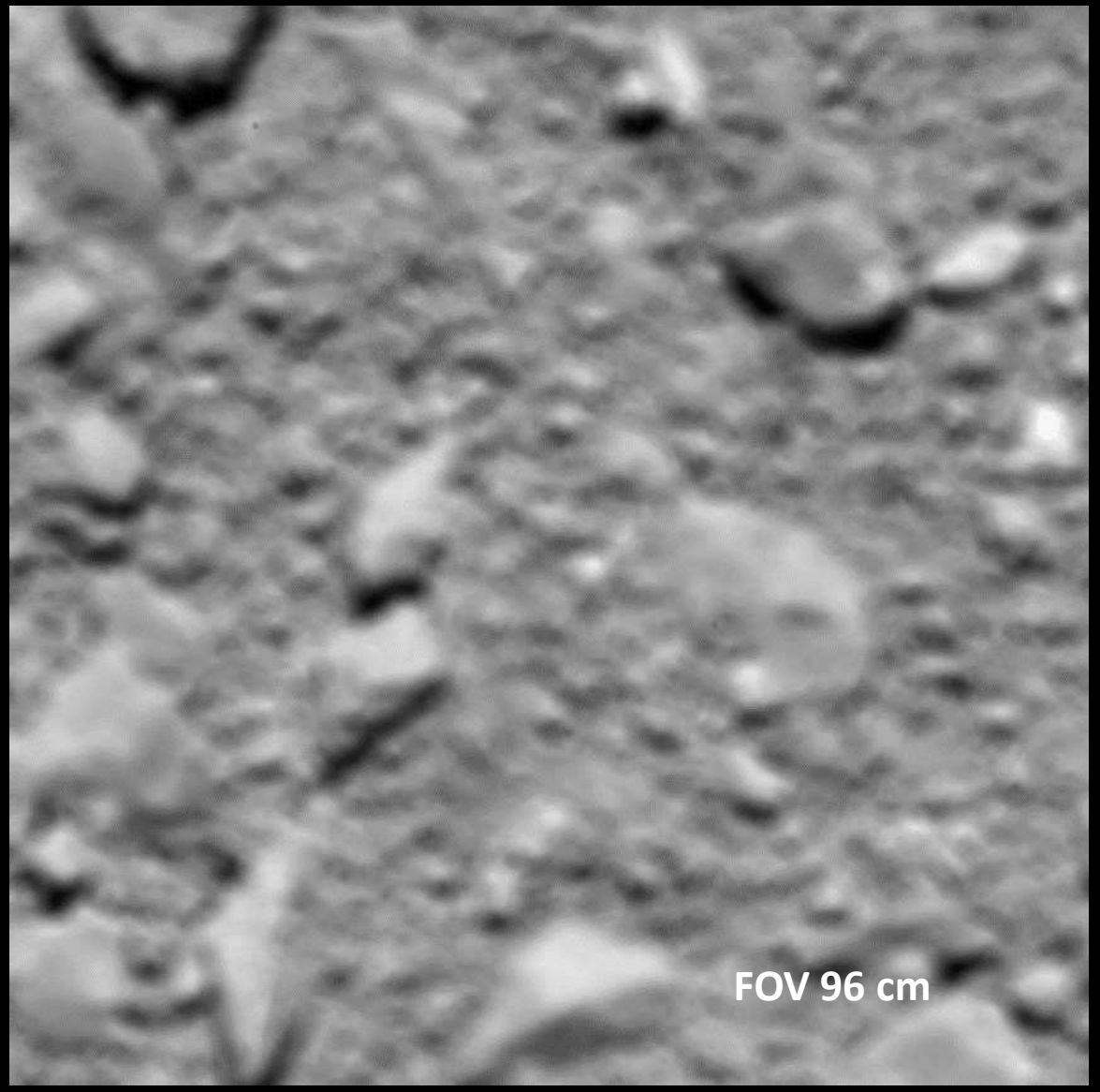
- **Targeted impact region just beside one large pit of the Ma'at region.**
- **Most instruments "ON" until the end.**



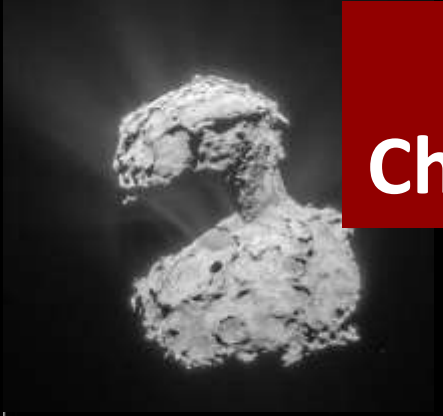


Final images before landing: 5.8 km and ~ 25 meters





Comet 67P/ Churyumov-Gerasimenko in context: Characterizing both comets and Kuiper Belt Objects (KBOs)



Wild-2
(*Stardust*)

Tempel-1
(*Deep Impact*)

2104 MU 69
New Horizons
KBO target 2019
~45 km radius
Occulation last week in S. Africa and Argentina

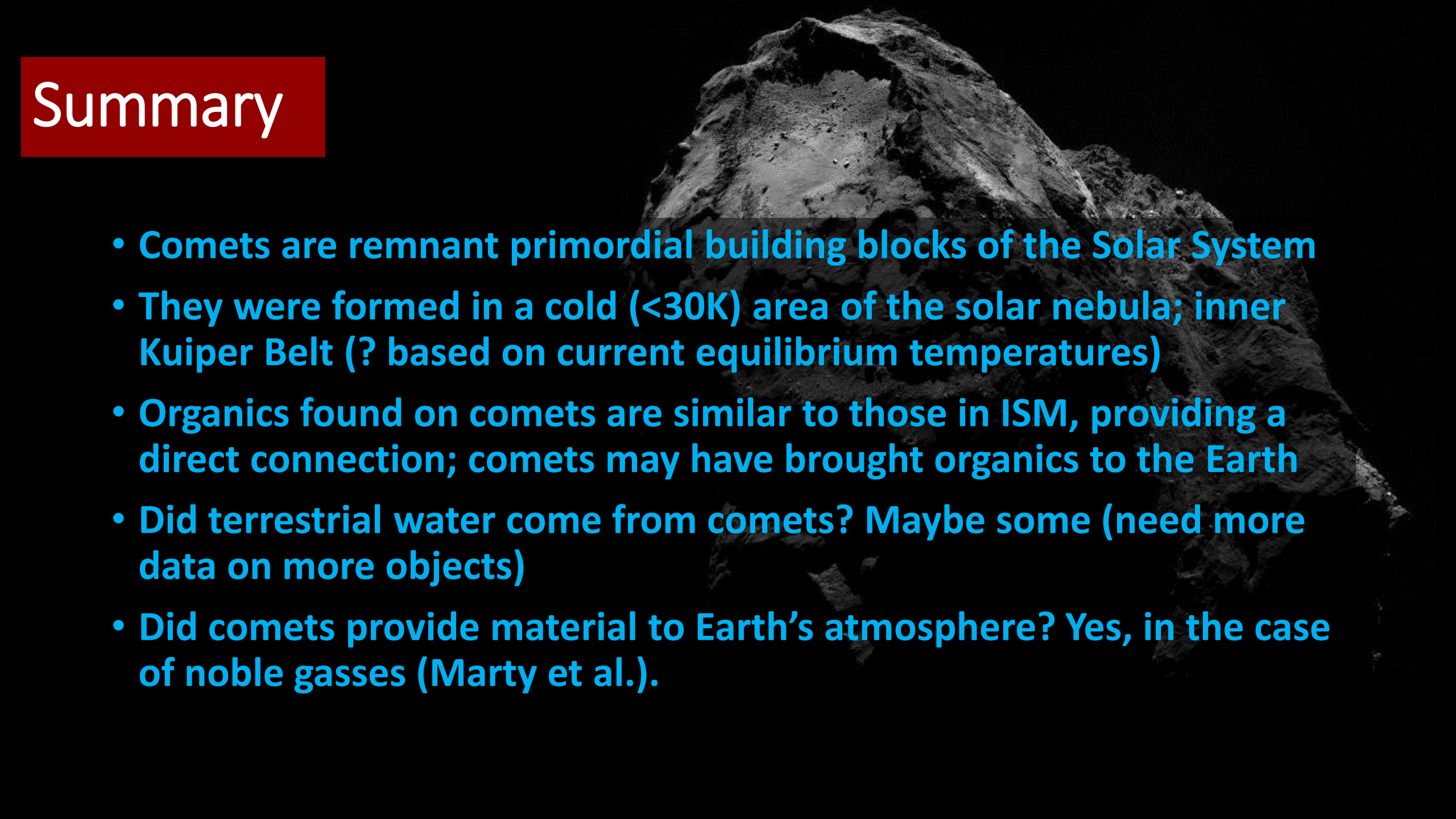
Phoebe
Cassini flyby
Captured KBO
Battered, dense (1.6 gm/cc)
Undifferentiated
107 km radius

Charon
New Horizons
Global melting
Differentiated (?)
606 km radius

Pluto
New Horizons
Largest known KBO
Differentiated
Active geology
1187 km radius

Comets
KBOs (increasing size)

Summary



- Comets are remnant primordial building blocks of the Solar System
- They were formed in a cold (<30K) area of the solar nebula; inner Kuiper Belt (? based on current equilibrium temperatures)
- Organics found on comets are similar to those in ISM, providing a direct connection; comets may have brought organics to the Earth
- Did terrestrial water come from comets? Maybe some (need more data on more objects)
- Did comets provide material to Earth's atmosphere? Yes, in the case of noble gasses (Marty et al.).