The volatile composition of comet 67P/Churyumov-Gerasimenko

Martin Rubin and the ROSINA Team

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The Cosmic Cycle of Dust and Gas in the Galaxy
Rencontres du Vietnam, Quy Nhon, 9 July 2018

Interstellar
medium

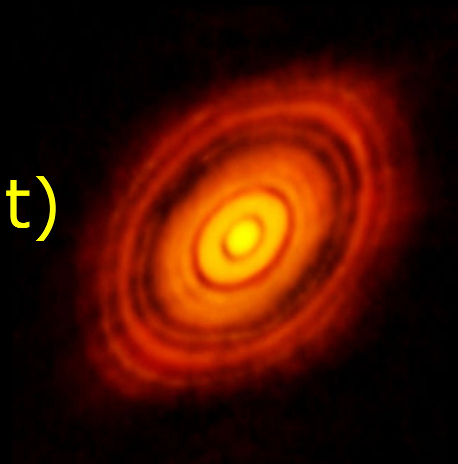
Giant Molecular Cloud

Star forming region

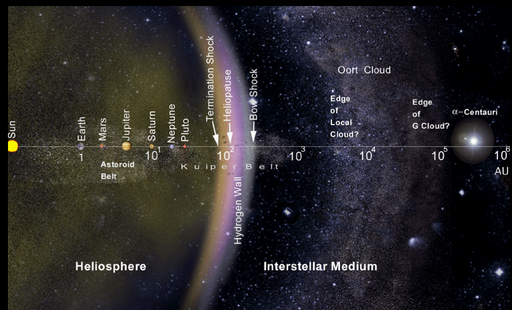
The cosmic cycle:
Evolution of the material

- Starting conditions
- Chemistry
- Physical conditions (d, T, t)

Protoplanetary
nebula



Evolution of life

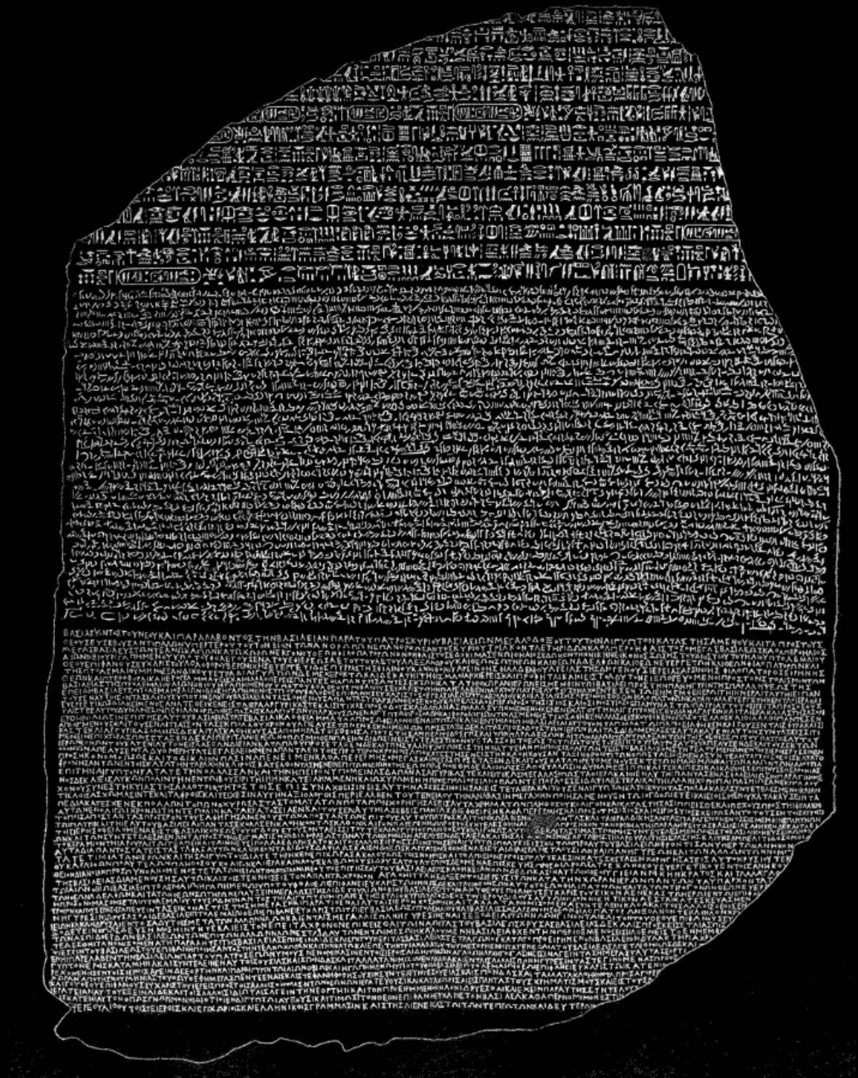


Solar system

From the coma and nucleus to deciphering the Rosetta stone

The ultimate goal of Rosetta:

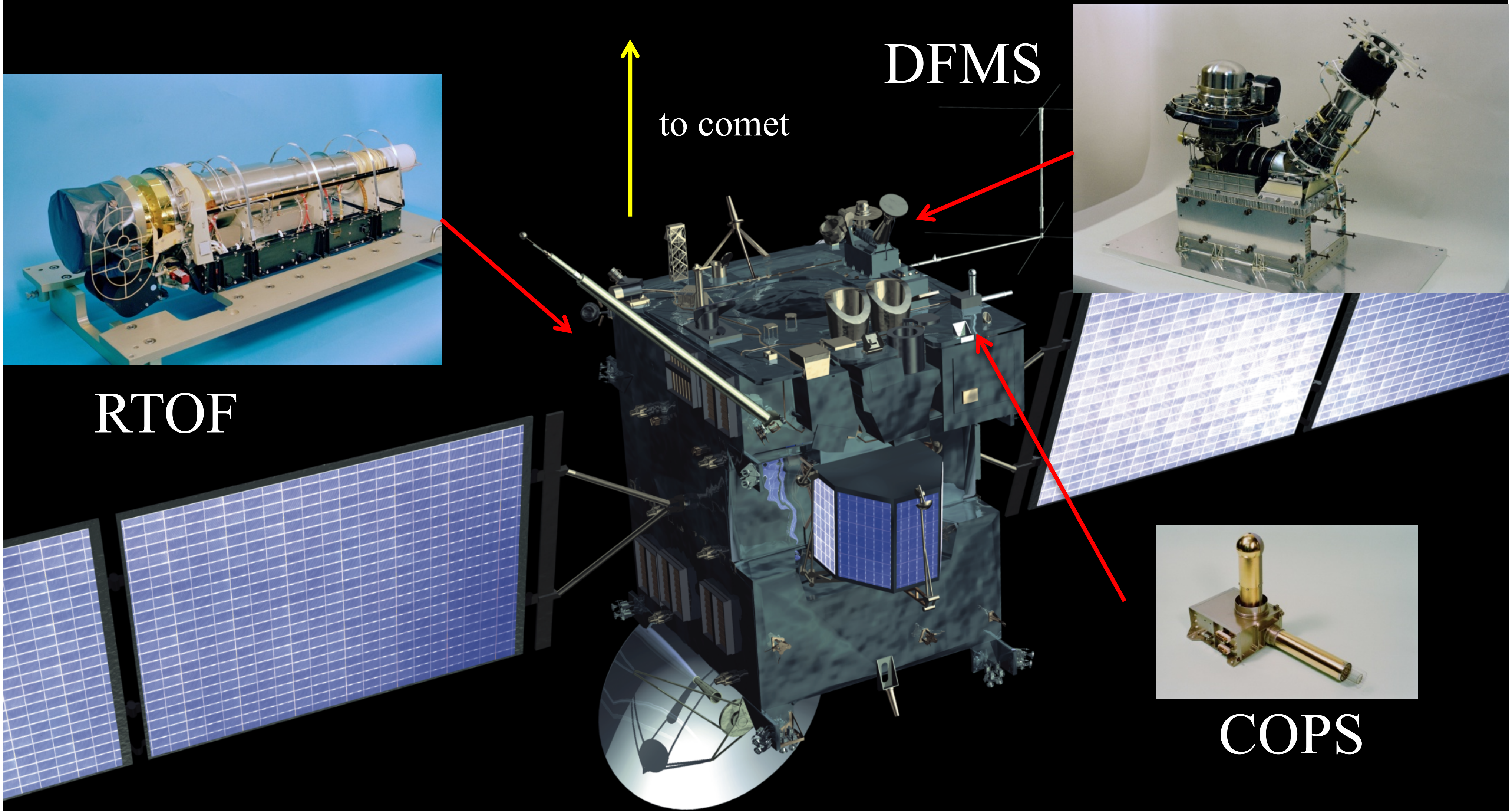
Decipher the origin of the solar system, the Earth and life by studying a comet



Payload

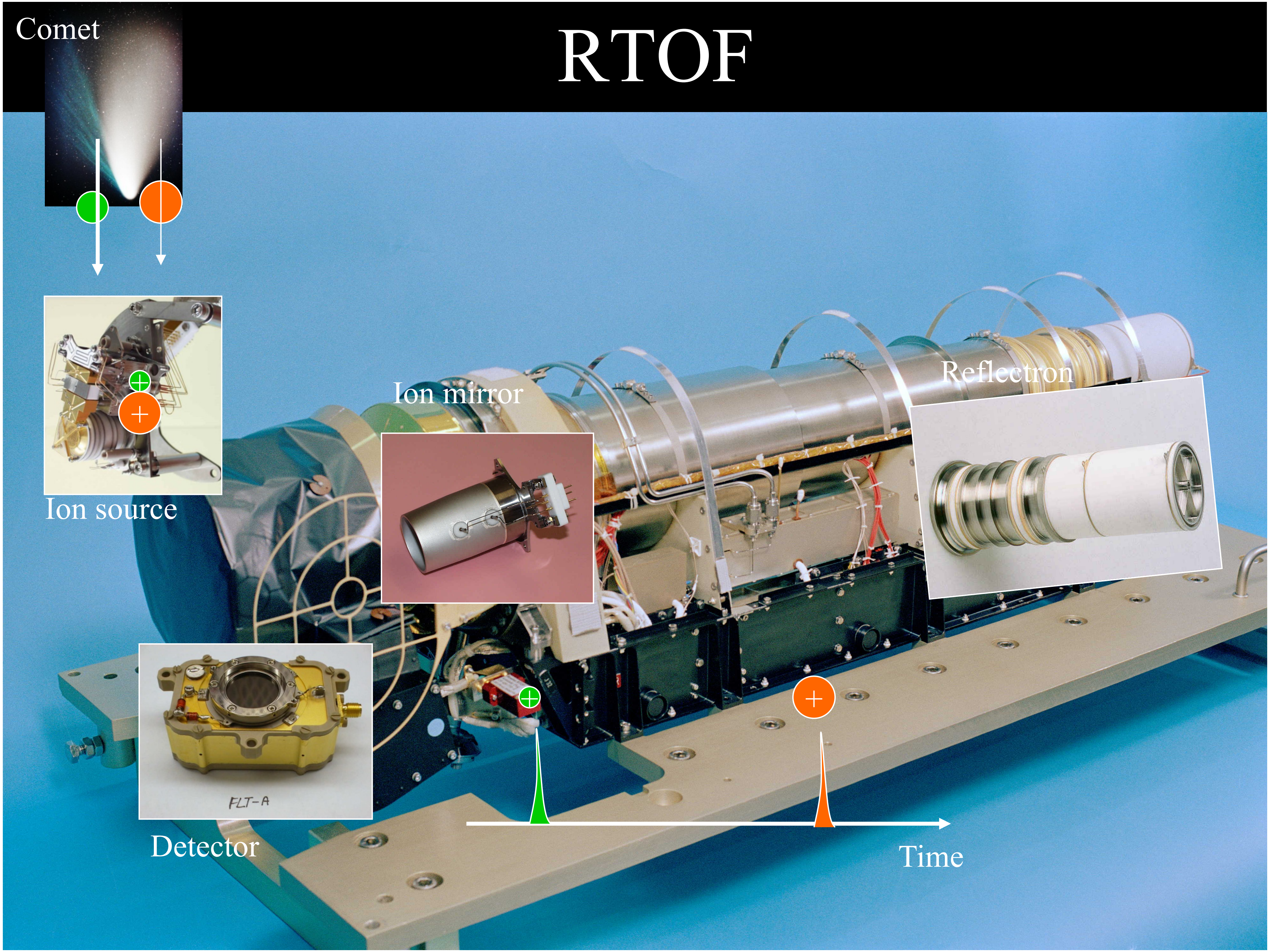
OSIRIS	Camera	28 kg
ROSINA	Gas-Mass spectrometer	35 kg
COSIMA	Dust-Mass spectrometer	20 kg
GIADA	Dust flux analyzer	4.5 kg
MIDAS	Dust microscope	5.5 kg
VIRTIS	Infrared-Spectrometer	23 kg
MIRO	Microwave-Experiment	16.2 kg
ALICE	Ultraviolet-Spectrometer	2.2 kg
RPC	Plasma instruments	5.7 kg
RSI	Radio Experiment	0.0 kg
CONSERT	Comet Nucleus Sounder	2.0 kg
LANDER Philae	with 10 experiments	100 kg

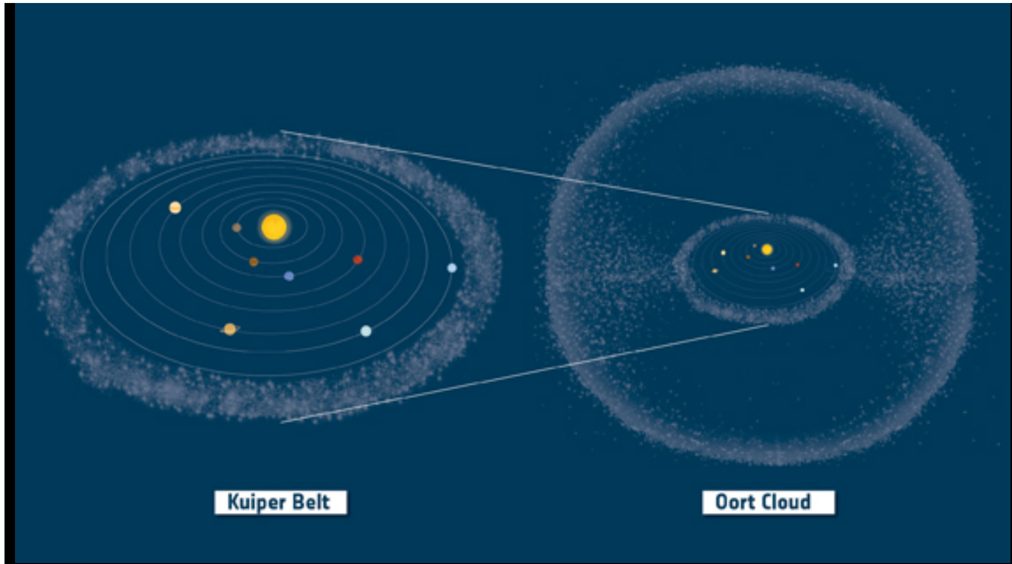
Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA)

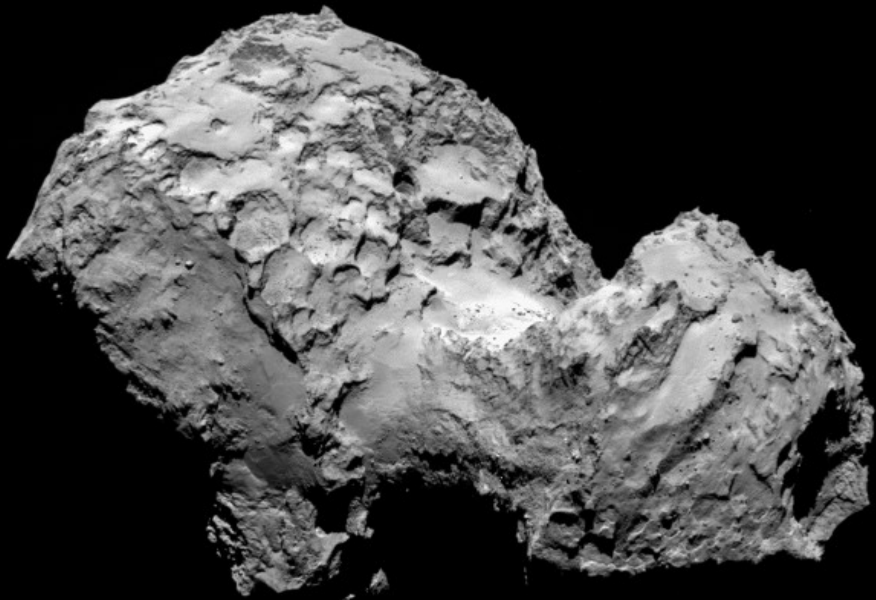


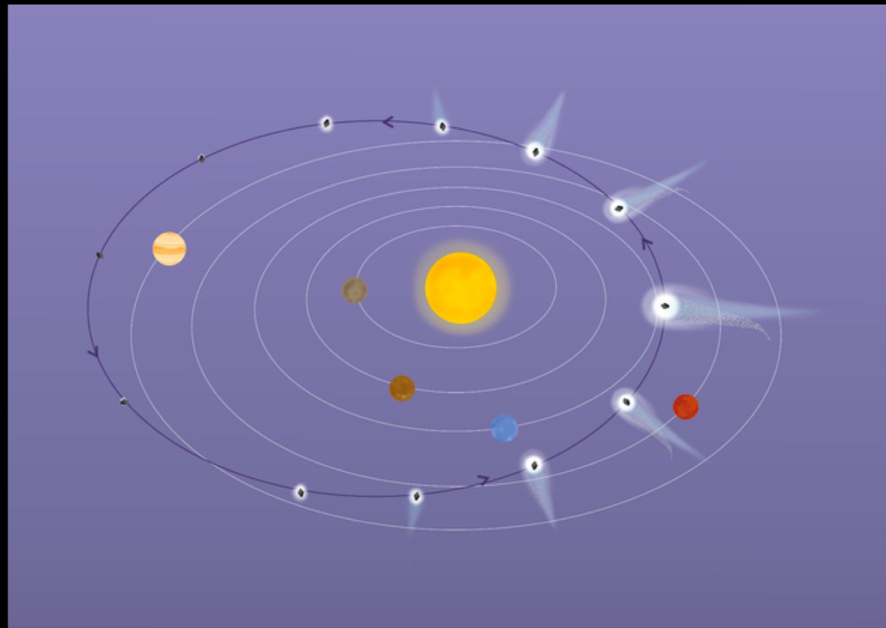
… measures gas density and composition in the atmosphere of the comet

RTOF



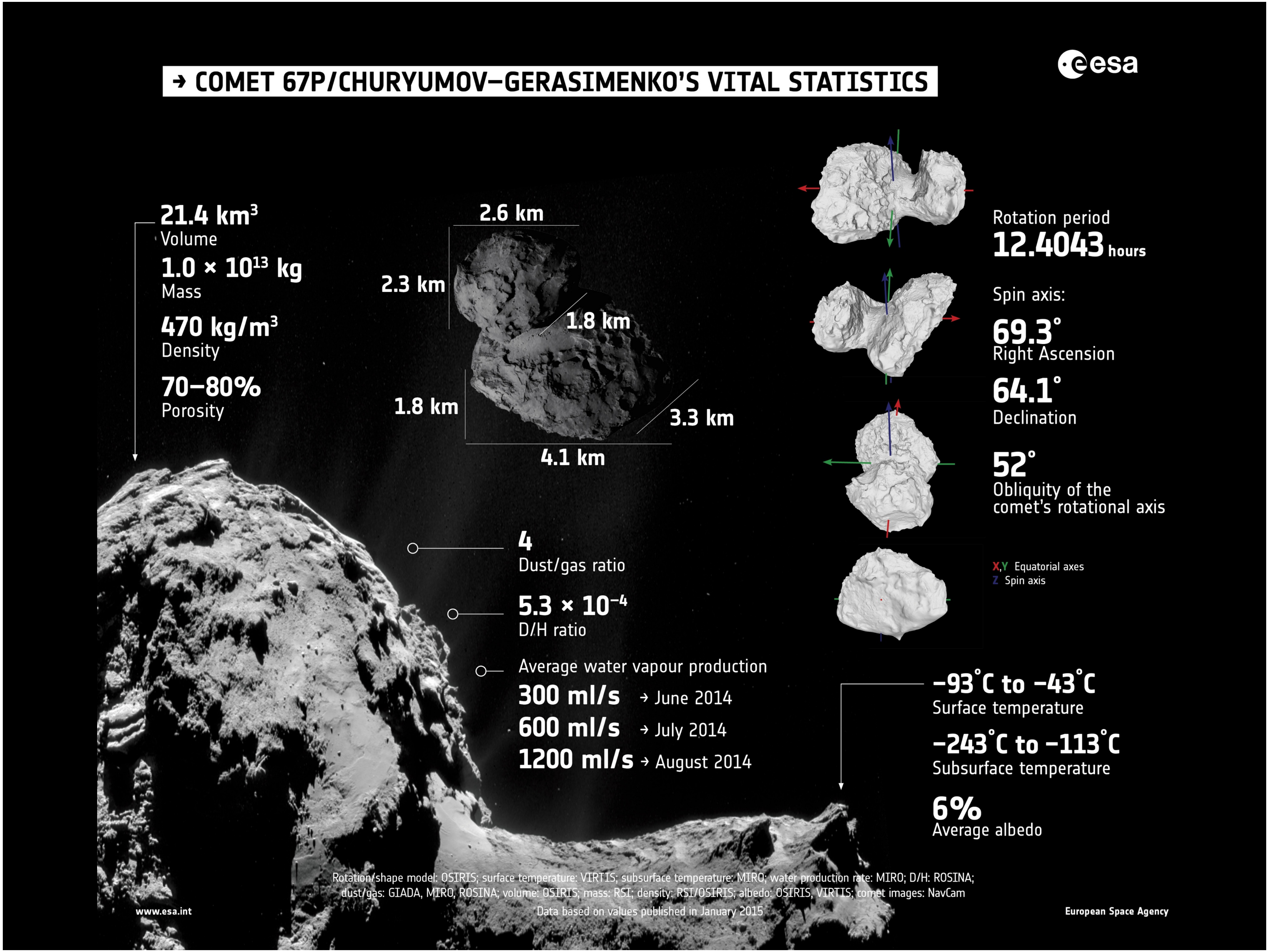






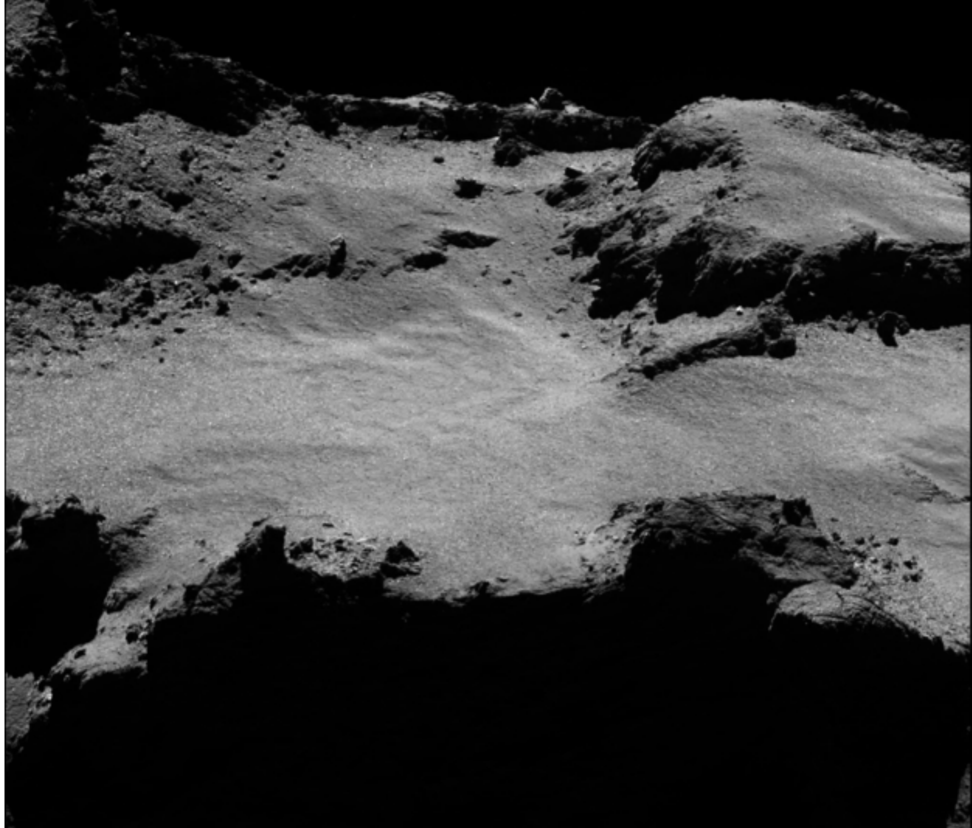
67P/Churyumov-Gerasimenko

Credit: ESA/Rosetta/MPS for OSIRIS Team
MPS/UPD/LAM/IAA/SSO /INTA/UPM/DASP/IDA



→ COMET 67P/CHURYUMOV–GERASIMENKO'S VITAL STATISTICS
esa
21.4 km³
Volume
1.0 × 10¹³ kg
Mass
470 kg/m³
Density
70–80%
Porosity
2.6 km
2.3 km
1.8 km
1.8 km
3.3 km
4.1 km
Rotation period
12.4043 hours
Spin axis:
69.3°
Right Ascension
64.1°
Declination
52°
Obliquity of the comet's rotational axis
X,Y Equatorial axes
Z Spin axis
4
Dust/gas ratio
5.3 × 10⁻⁴
D/H ratio
Average water vapour production
300 ml/s → June 2014
600 ml/s → July 2014
1200 ml/s → August 2014
−93°C to −43°C
Surface temperature
−243°C to −113°C
Subsurface temperature
6%
Average albedo
Rotation/shape model: OSIRIS; surface temperature: VIRTIS; subsurface temperature: MIRO; water production rate: MIRO; D/H: ROSINA;
dust/gas: GIADA, MIRO, ROSINA; volume: OSIRIS; mass: RSI; density: RSI/OSIRIS; albedo: OSIRIS, VIRTIS; comet images: NavCam
Data based on values published in January 2015
www.esa.int
European Space Agency

North



South

Credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

ROSETTA Zoo

Nitrogen $N \equiv N$
Oxygen
Hydrogenperoxyd
Carbon monoxide
Carbon dioxide

The presence of highly volatile species tells us

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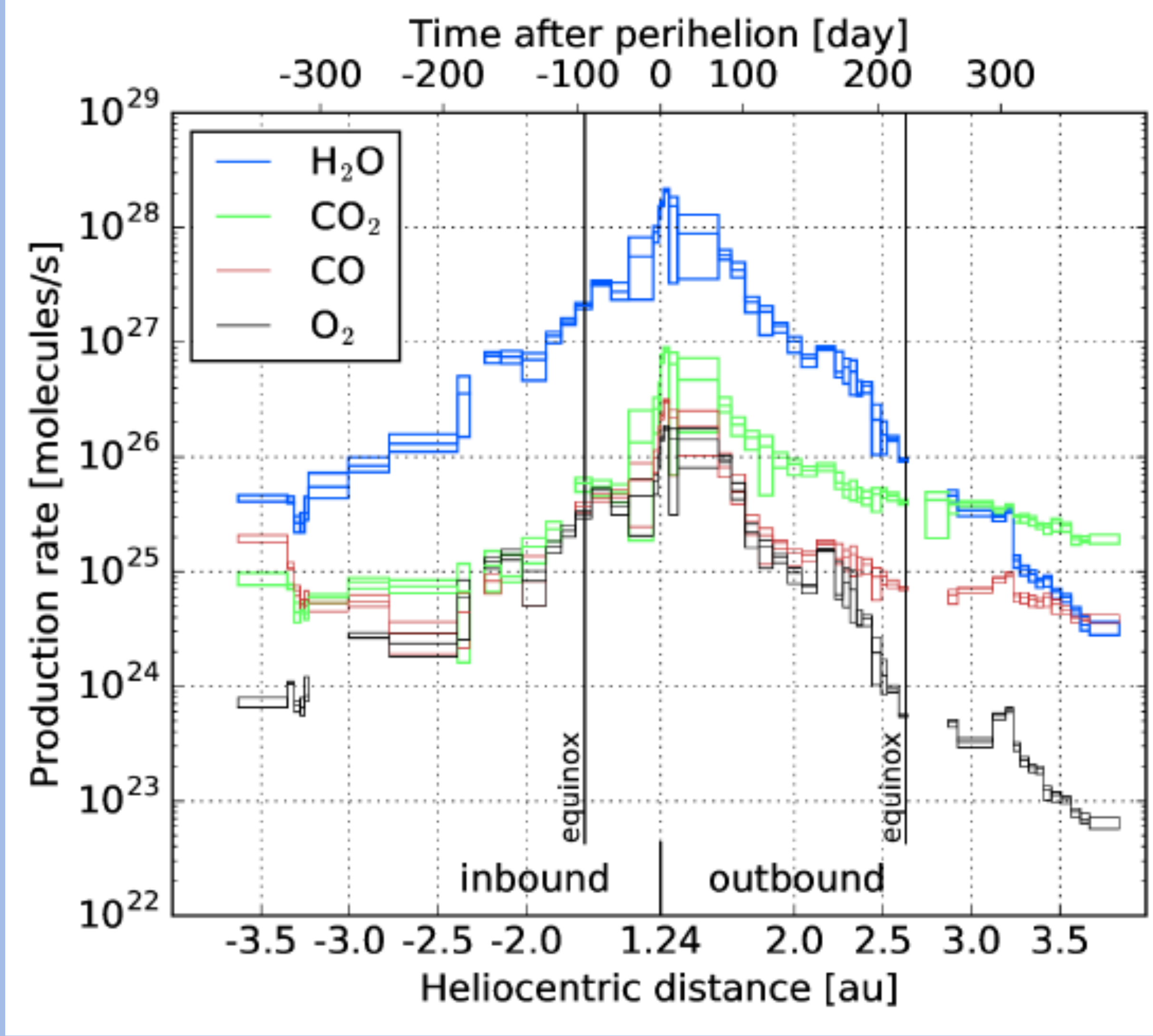
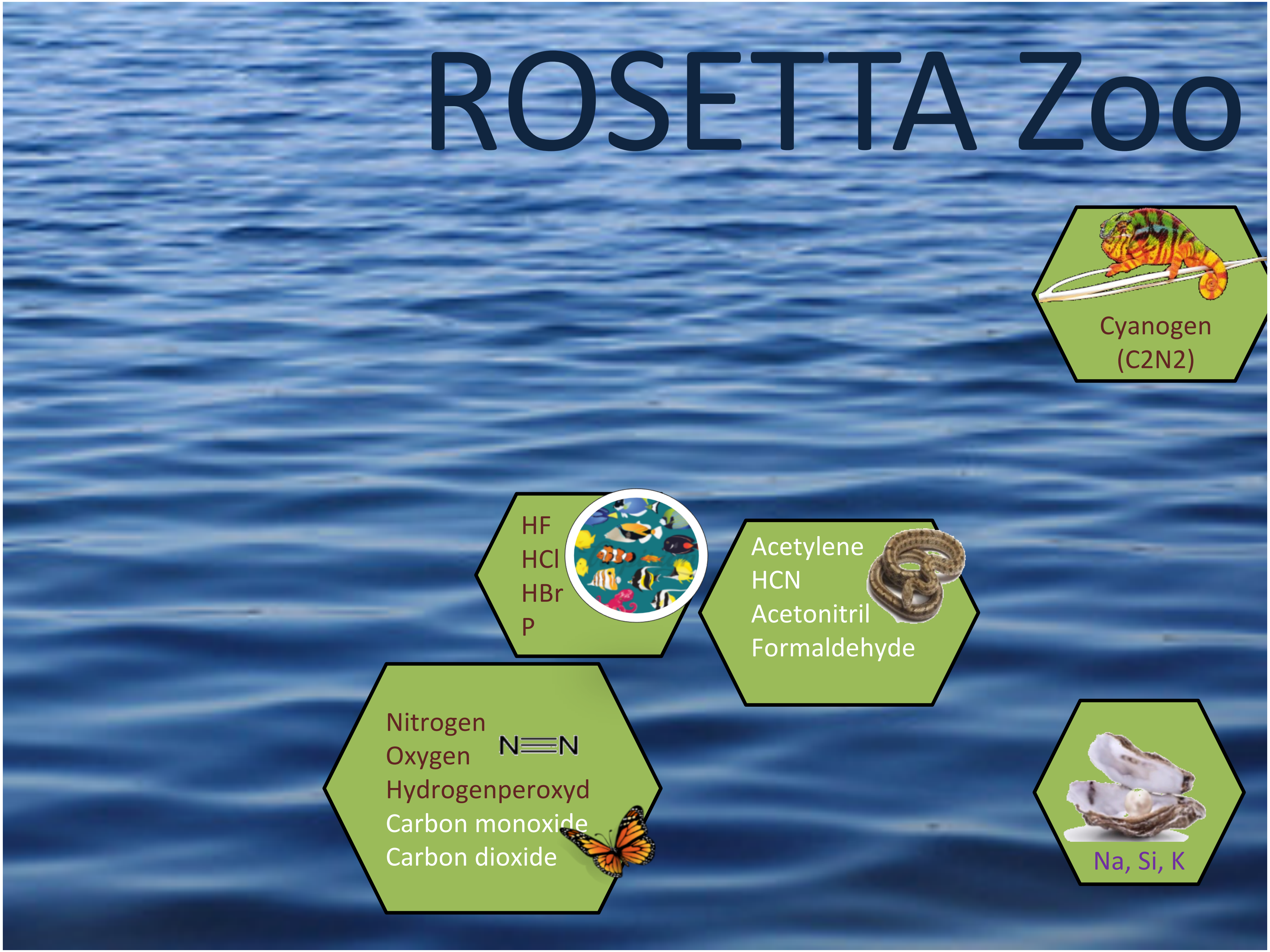
- That comets were never warm
- That comets cannot have been part of a big object (heating by radioactivity)
- That comets formed around 25 K (-250°C)
- O_2 is very puzzling, as it is very reactive. It is very well correlated to water and cannot be formed in the protosolar cloud. Therefore, it's most likely inherited as part of the water ice from the presolar cloud.

Indication of molecular cloud chemistry: O_2

- O_2/H_2O ~ 4% observed at 67P. O_2 and H_2O are well correlated. Lack of H_2O_2 and HO_2 (Bieler et al. 2015)
- O_2 cannot be formed in the protosolar nebula by radiolysis, therefore O_2 was formed in the star forming regions / molecular clouds either by radiolysis (Mousis et al., 2016) or gas phase chemistry (Taquet et al., 2016)
- O_2 is very well embedded in the water ice matrix



Läuter et al., submitted to MNRAS, 2018


ROSETTA Zoo
Cyanogen
(C2N2)
HF
HCl
HBr
P
Acetylene
HCN
Acetonitril
Formaldehyde
Nitrogen
Oxygen
N≡N
Hydrogenperoxyd
Carbon monoxide
Carbon dioxide
Na, Si, K

What's the composition of a comet?

Before Rosetta, we thought that....

Cometary ice contains simple molecules, which have formed in the gas phase.

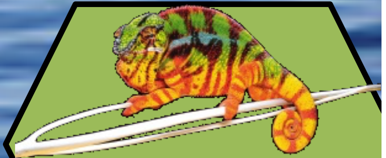
- True, but....

The refractory part (dust) is made out of Magnesium, Silicon, Iron, etc.

- True, but....

ROSETTA Zoo

S_2
S_3
S_4
Methanethiole (CH_3SH)
Ethanethiol (C_2H_5SH)
Thioformaldehyde (CH2S)



Cyanogen (C_2N_2)

HF
HCl
HBr
P

Acetylene
HCN
Acetonitril
Formaldehyde

Nitrogen
Oxygen
Hydrogenperoxyd
Carbon monoxide
Carbon dioxide

N≡N

Hydrogensulfide
Carbonylsulfide
Sulfur monoxide
Sulfur dioxide
Carbon disulfide

Na, Si, K

Sulfur inventory of comets

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- Interstellar material contains sulfur in cosmic abundance while presolar clouds are mysteriously depleted in sulfur
- Comets contain species which can only be formed on dust grains (e.g. S_2, S_3, S_4… by radiolysis of H_2S?).
- They must have been inherited from the presolar cloud. Therefore, most sulfur in presolar clouds is on grains which explains the apparent depletion (bias in observation).
- S_2 is very volatile and easily destroyed in the gas phase by UV. This indicates that it must have survived the formation of the solar system in the ice.
- Some ice is directly inherited from our native cloud.

Sulfur species (2 – 1.25 AU)

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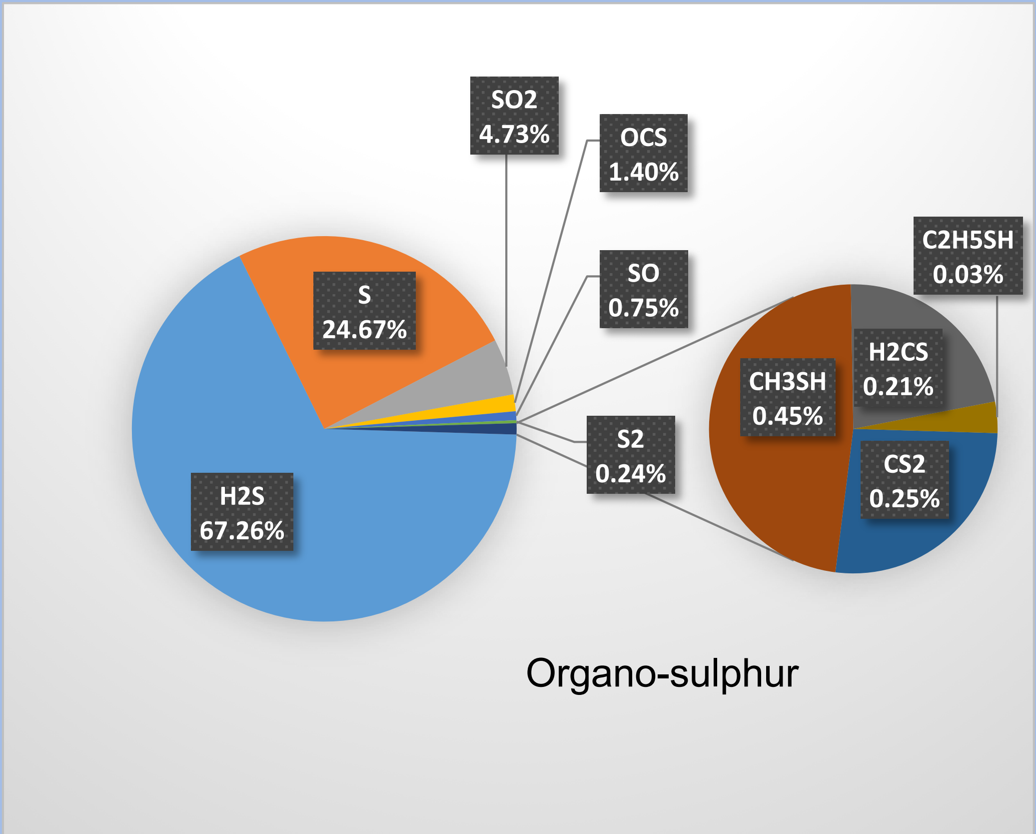
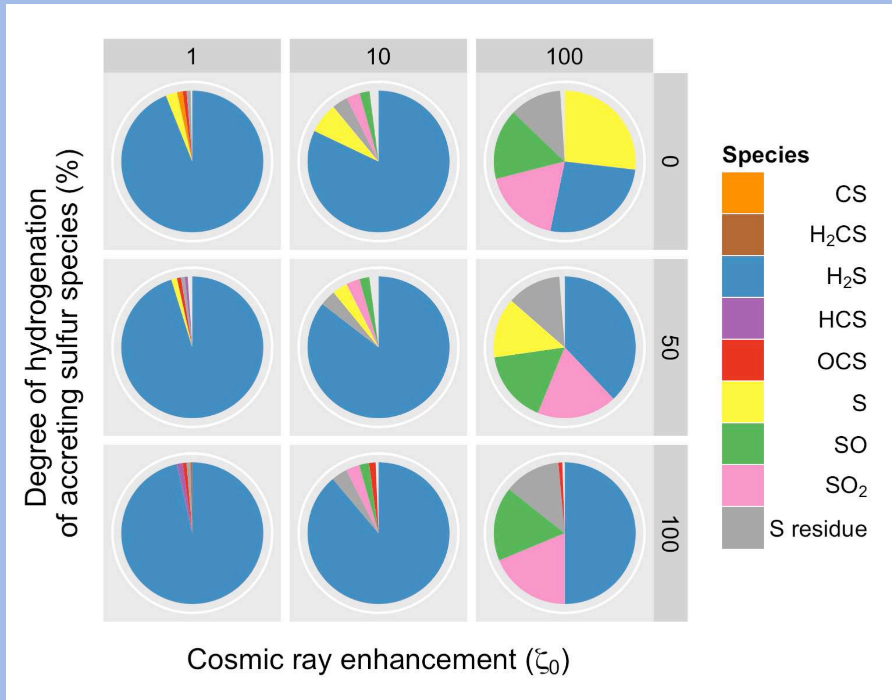


Calmonte et al., MNRAS, 2016
Sulphur species in 67P

Woods et al., MNRAS, 2014

A new study of an old sink of sulfur in hot molecular cores: the sulfur residue

The most abundant S-bearing species in the icy mantle at the end of the collapse phase (Phase I). 0, 50 and 100 on the vertical axis refer to the percentage of hydrogenation chosen (see text); 1, 10, 100 indicate a standard, an enhanced and a super-enhanced cosmic ionisation rate, respectively.

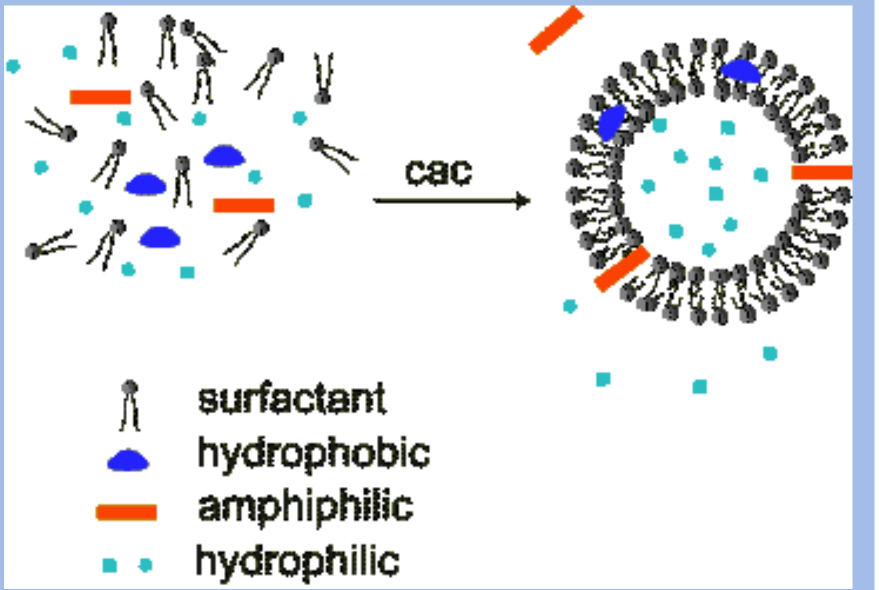


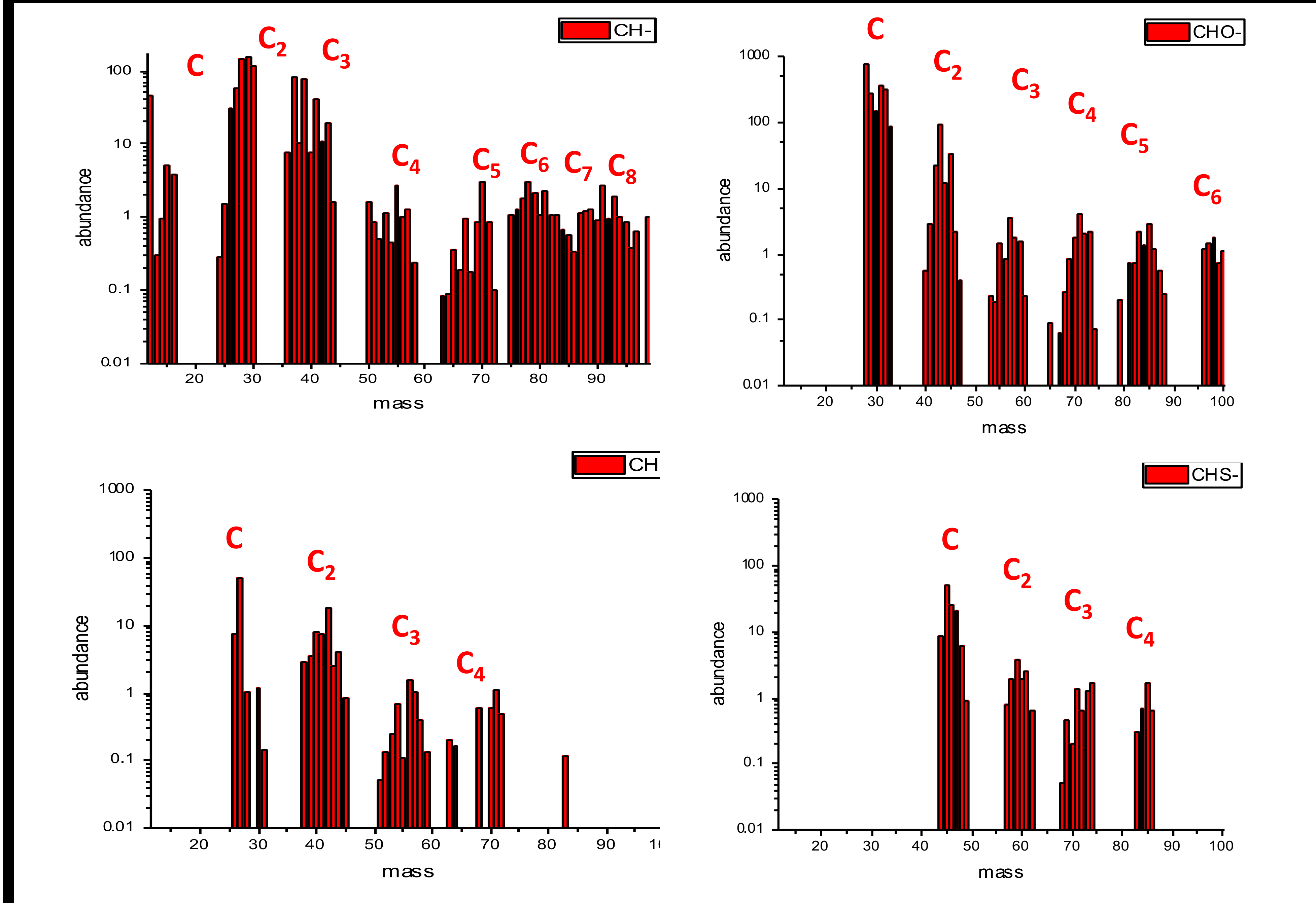

ROSETTA Zoo
Macromolecules
Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane
S2
S3
S4
Methanethiole
(CH3SH)
Ethanethiol (C2H5SH)
Thioformaldehyde
(CH2S)
Cyanogen
(C2N2)
Formic acid
Acetic acid
Acetaldehyde
Ethylenglycol
Propylenglycol
Butanamide
HF
HCl
HBr
P
Acetylene
HCN
Acetonitril
Formaldehyde
Benzene
Toluene
Xylene
Benzoic acid
Naphthalene
Methanol
Ethanol
Propanol
Butanol
Pentanol
Nitrogen
Oxygen
Hydrogenperoxyd
Carbon monoxide
Carbon dioxide
N≡N
Hydrogensulfide
Carbonylsulfide
Sulfur monoxide
Sulfur dioxide
Carbon disulfide
Na, Si, K

Hydrocarbons in comets

> Long carbon chains seen in the volatile part (ROSINA)
> Macromolecules (C-H) seen in the dust (COSIMA)
> Carbon signature seen on the surface (VIRTIS)
> Polyaromatic hydrocarbons detected in the volatile coma (benzene, naphthalene,..) (ROSINA)

> Prebiotic importance: such chains and rings are needed to form the first membrane-like structures




CH-
C
C_2
C_3
C_4
C_5
C_6
C_7
C_8
abundance
mass
CHO-
C
C_2
C_3
C_4
C_5
C_6
abundance
mass
CH
C
C_2
C_3
C_4
abundance
mass
CHS-
C
C_2
C_3
C_4
abundance
mass


ROSETTA Zoo
Macromolecules
Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane
H_2N
OH
O
Glycine
(Aminoacid)
S_2
S_3
S_4
Methanethiole
(CH_3SH)
Ethanethiol (C_2H_5SH)
Thioformaldehyde
(CH_2S)
Ammonia
Methylamine
Ethylamine
Cyanogen
(C_2N_2)
Formic acid
Acetic acid
Acetaldehyde
Ethylenglycol
Propylenglycol
Butanamide
HF
HCl
HBr
P
Acetylene
HCN
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Formaldehyde
Benzene
Toluene
Xylene
Benzoic acid
Naphthalene
Methanol
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Butanol
Pentanol
Nitrogen
Oxygen
Hydrogenperoxyd
Carbon monoxide
Carbon dioxide
N≡N
Hydrogensulfide
Carbonylsulfide
Sulfur monoxide
Sulfur dioxide
Carbon disulfide
Na, Si, K

Complex oxygen and nitrogen bearing compounds

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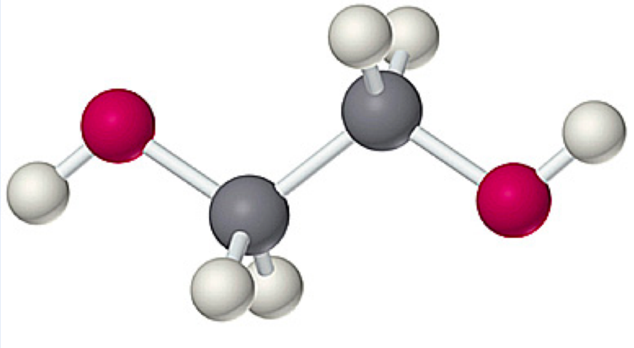
Seen by ROSINA in the coma

Signatures seen on the surface by COSAC and Ptolemy on the lander Philae

- More complex than anticipated
- Large amount and diversity
- Prebiotic molecules


Ethylene glycol

ROSETTA Zoo
Macromolecules
Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane
H_2N
OH
O
Glycine
(Aminoacid
S_2
S_3
S_4
Methanethiole
(CH_3SH)
Ethanethiol (C_2H_5SH)
Thioformaldehyde
(CH_2S)
Ammonia
Methylamine
Ethylamine
Cyanogen
(C_2N_2)
Formic acid
Acetic acid
Acetaldehyde
Ethylenglycol
Propylenglycol
Butanamide
Argon
Krypton
Xenon
HF
HCl
HBr
P
Acetylene
HCN
Acetonitril
Formaldehyde
Benzene
Toluene
Xylene
Benzoic acid
Naphthalene
Methanol
Ethanol
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Carbon monoxide
Carbon dioxide
N≡N
Hydrogensulfide
Carbonylsulfide
Sulfur monoxide
Sulfur dioxide
Carbon disulfide
Na, Si, K

Did comets bring the Earth's atmosphere (and as a consequence organic material)?

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The answer could be hidden in the noble gases of 67P

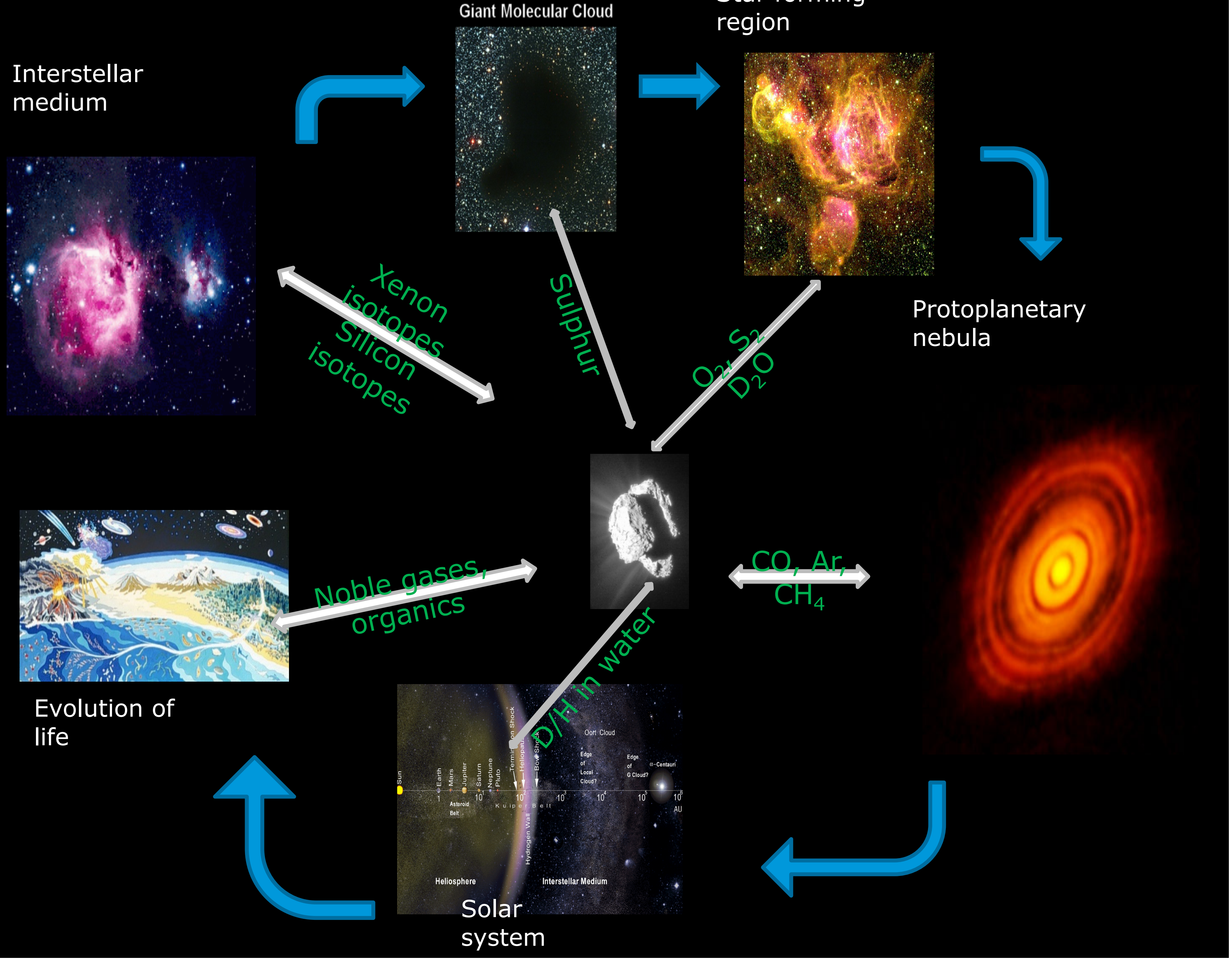
- Argon and krypton of 67P are compatible with a delivery of the terrestrial atmosphere by comets (late heavy bombardment) without changing the D/H in water (D/H in H_2O of the comet ~ 3.5x Earth!).
- The xenon in the Earth's atmosphere is not understood. It differs from mantle (chondritic) Xe and seems to contain a primordial source (U-Xenon), which has never been found. U-Xe is depleted in the heavy Xe-isotopes ^{134}Xe and ^{136}Xe.
- The xenon in 67P has some resemblance to U-Xe. 22% of 67P-Xe would be sufficient to explain the terrestrial atmospheric Xe.

Comets do not contain life …

Mass 67P: $1.0 \cdot 10^{13}$ kg (D/I 1:1, $Xe/H_2O = 2.4 \cdot 10^{-7}$ (Marty et al. 2017), 1% organics in ice (w/o refractories!))

- Mass terr. oceans: $1.4 \cdot 10^{21}$ kg → $3 \cdot 10^{8}$ comets (1‰–1%)
- Mass terr. atmosphere: $5.0 \cdot 10^{18}$ kg (Xe 400 ppb, 22% cometary) → $5 \cdot 10^{5}$ comets (100%)
- Biomass: $4.0 \cdot 10^{15}$ kg → $5 \cdot 10^{4}$ comets (10x)

ROSINA results contribute to the understanding of solar system formation



10 years of planning
10 years of design / construction
10 years of cruise
10 years of data analysis

Still a lot of questions to be answered!

Acknowledgements

The ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis) instrument package was designed and built by an international consortium led by the Space Research and Planetary Sciences Division, Physics Institute, University of Bern, Switzerland. Hardware subsystems were delivered by:

- the Belgian Institute for Space Aeronomy (BIRA-IASP),
- Research Institute in Astrophysics and Planetology (IRAP)
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- Lockheed Martin Advanced Technology Center (LMATC), Palo Alto
- MPS, Göttingen, Germany,
- Institute of Computer and Network Engineering at the TUB
- University of Michigan - Atmospheric, Oceanic and Space Sciences.

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