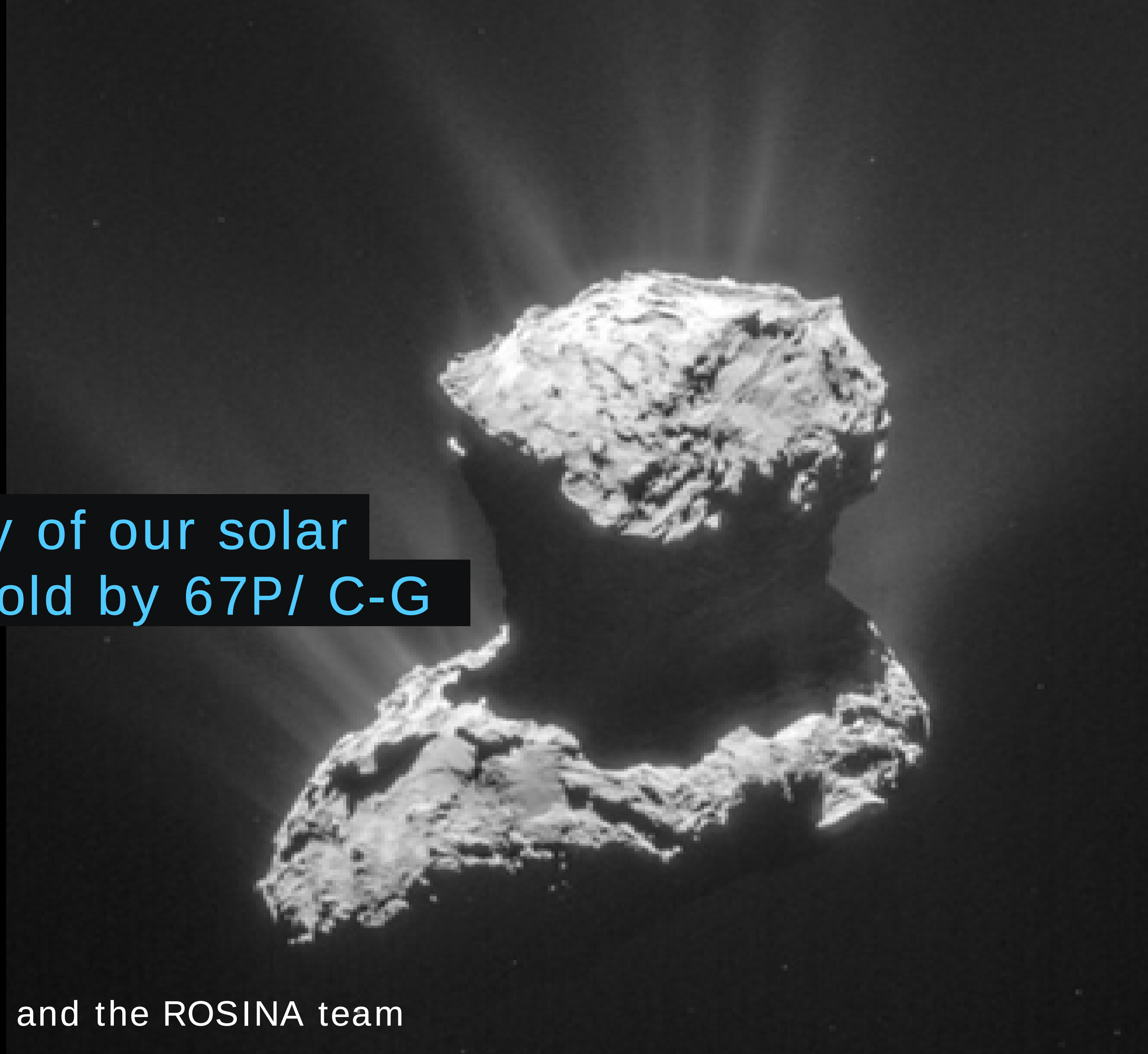
# The story of our solar system told by 67P/ C-G

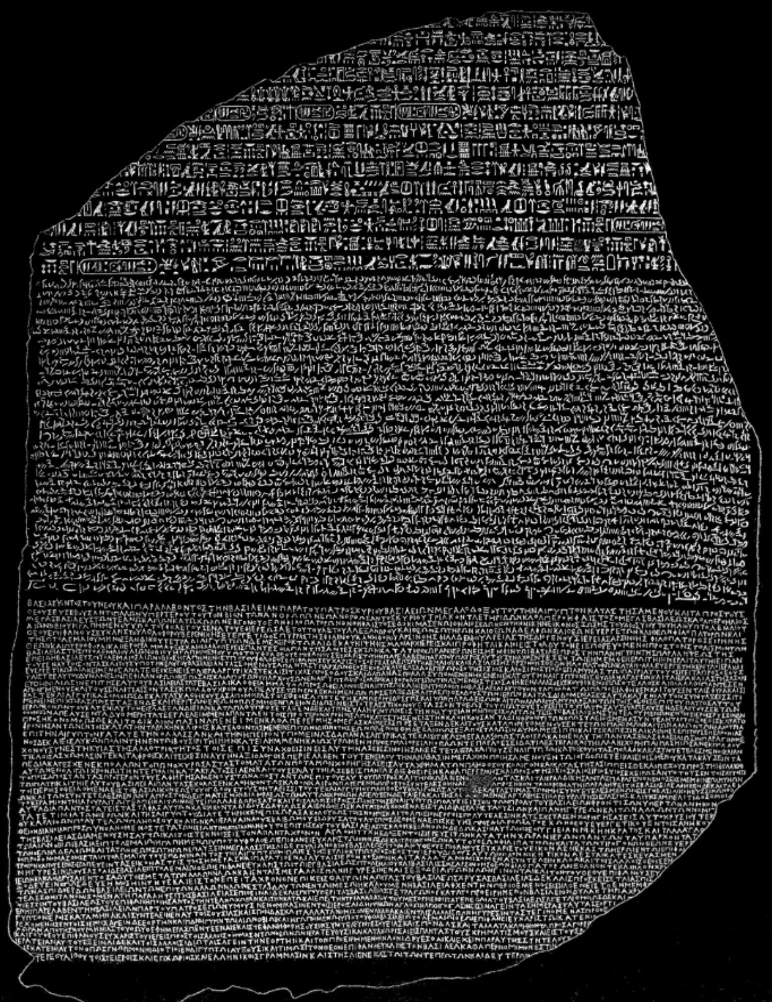


K. Altwegg and the ROSINA team

## From the coma and nucleus to deciphering the Rosetta stone

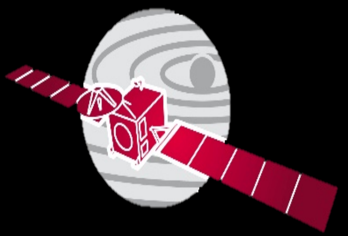
The ultimate goal of Rosetta:

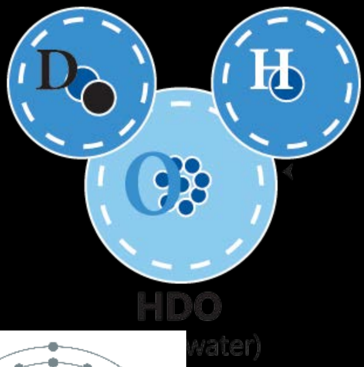
Decipher the origin of the solar system, the Earth and life by studying a comet



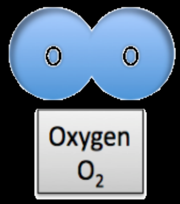
…..starting from the chemical composition

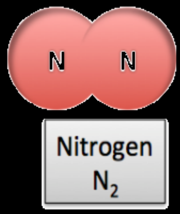
# …..starting from the chemical composition

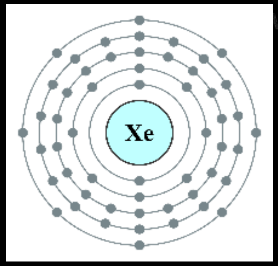


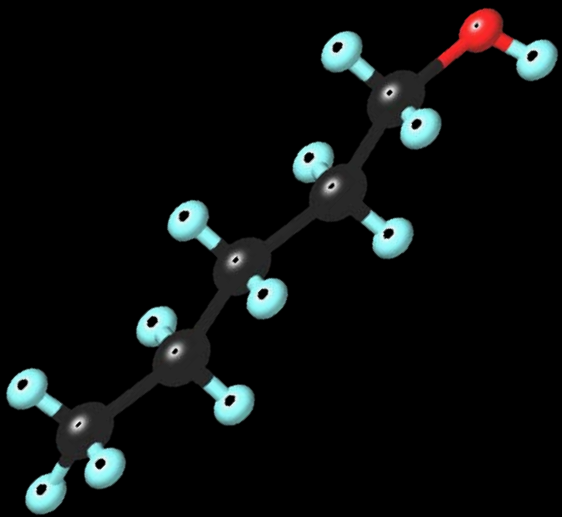


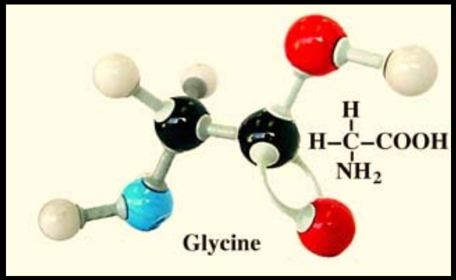

Let each species tell its own tale



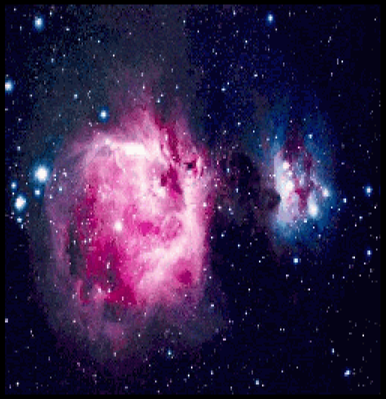





Giant Molecular Cloud

Star forming region

Interstellar medium

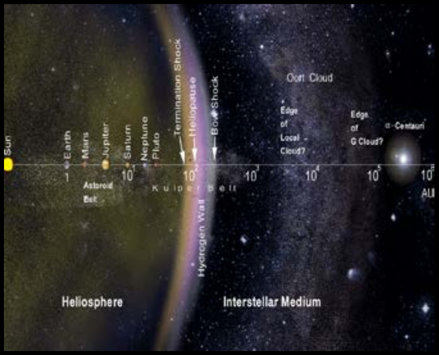


Evolution of the material

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

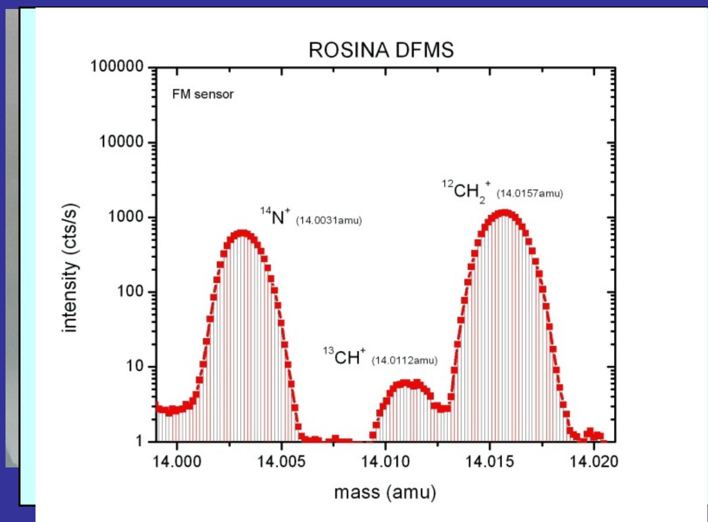
Protoplanetary nebula

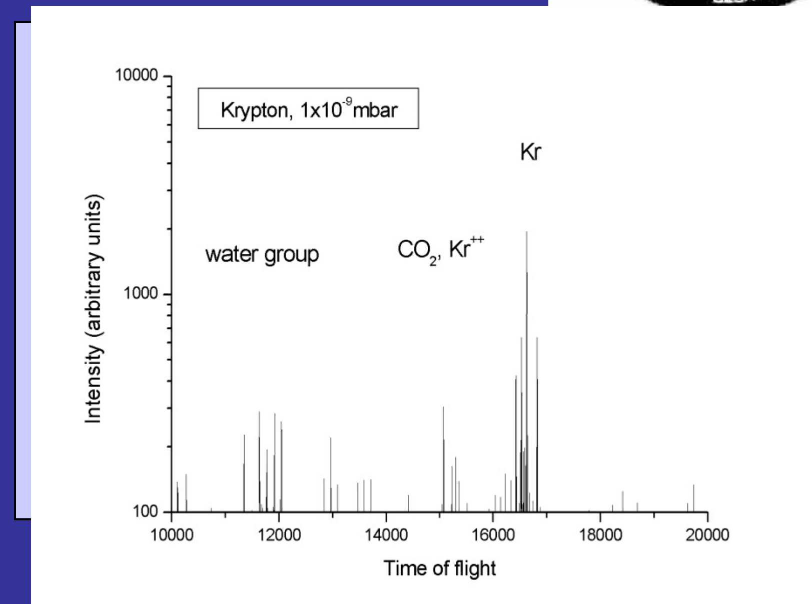
Evolution of life




Solar system

# ROSINA Features

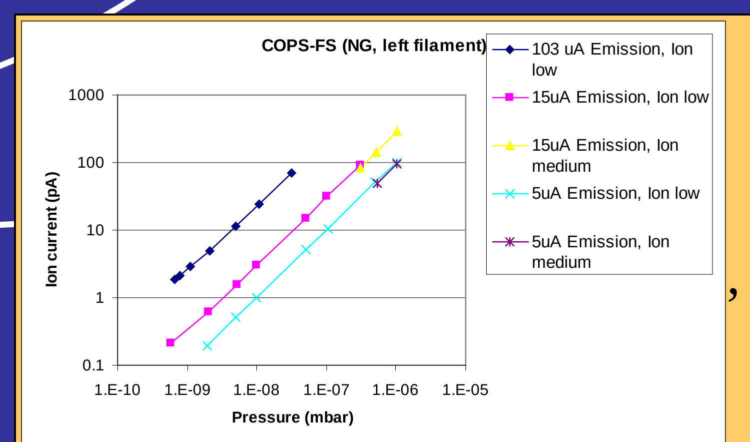



**DPU**

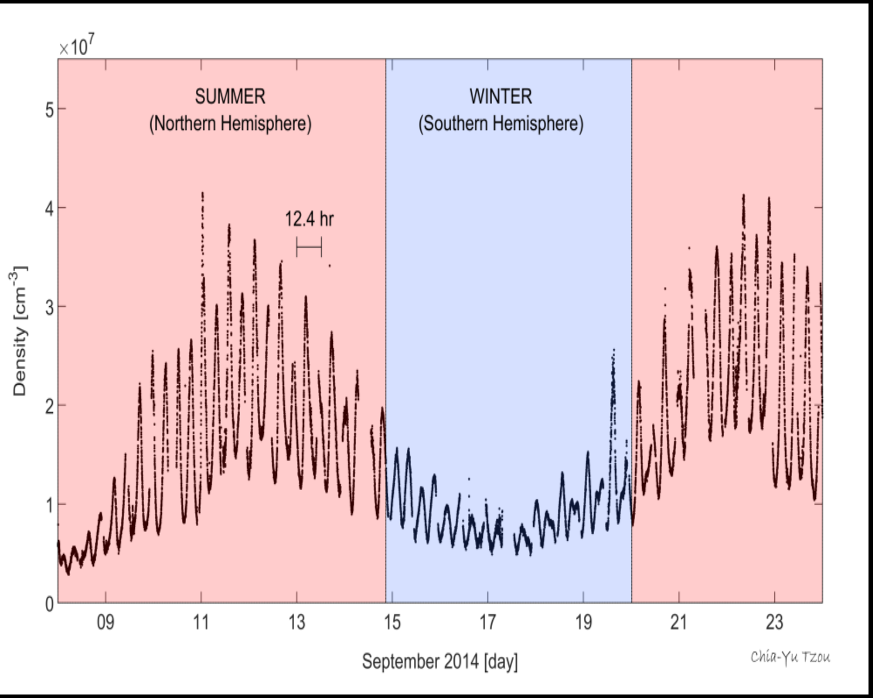
Digital data processing unit, fully redundant

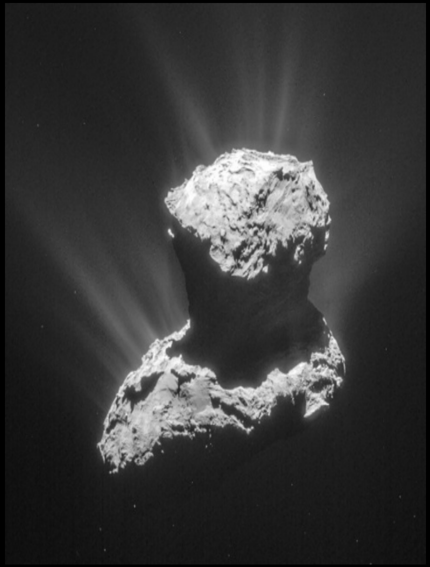
2.2 kg, 5 W

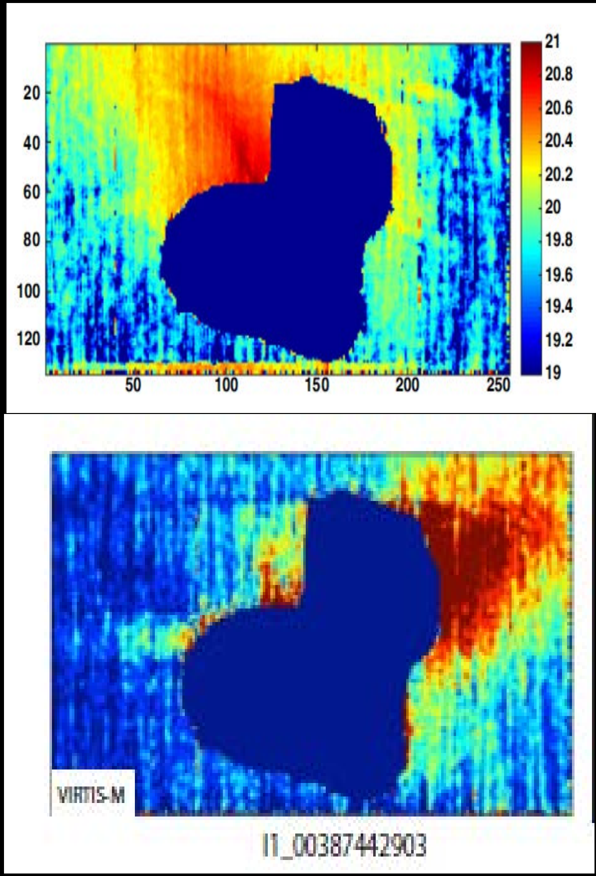


# A close look at 67P's neutral heterogeneous coma

Total density (ROSINA-COPS)






Neutral water (top) and $CO_2$ outgassing measured by VIRTIS (Fougère et al., 2016, data from Migliorini et al., 2016)

# A very dynamical coma seen in the plasma

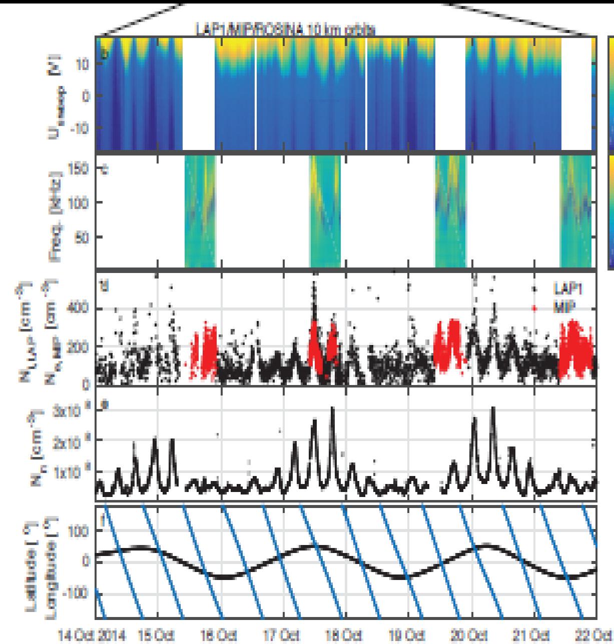
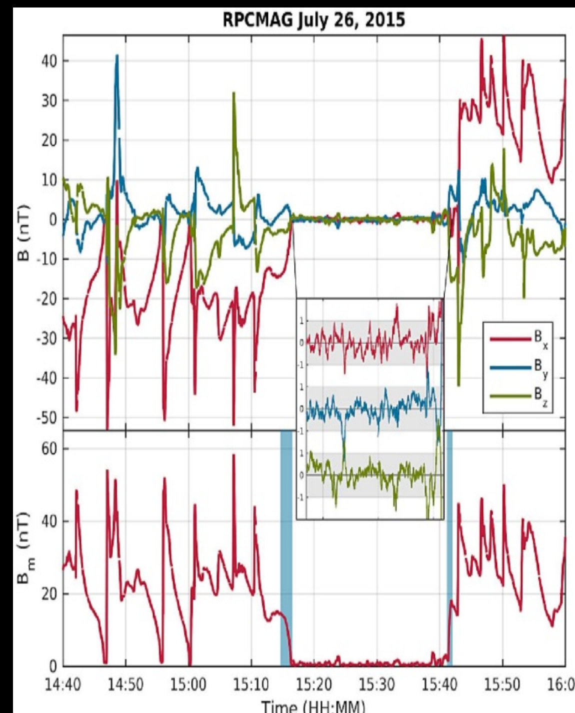



**Figure 1.** Time series of Rosetta RPC-LAP/MIP data from the bound orbits at 10 km distance. The individual panels show (a) the cometocentric distance of Rosetta, with the inset showing the trajectory of Rosetta around the comet in CSO coordinates with time color-coded along the track, (b) sweep data from LAP1 where the bias voltage is shown swept from -18V to +18 V and the collected current is color-coded, (c) active spectrogram from MIP (d) derived ion density from the LAP1 sweeps (black) and electron density measured by MIP (red), (e) ROSINA/COPS neutral density and (f) latitude (black) and longitude (blue).

Comparison of plasma and neutral gas (Edberg et al., 2015)




Diamagnetic cavity
C. Goetz et al., 2016

Plasma waves: the singing comet
Richter et al., 2016

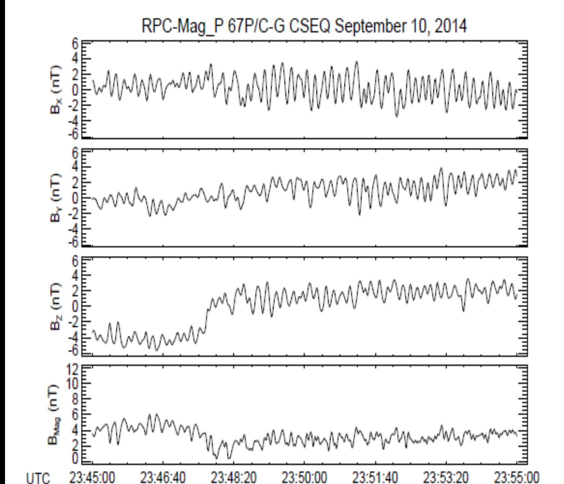
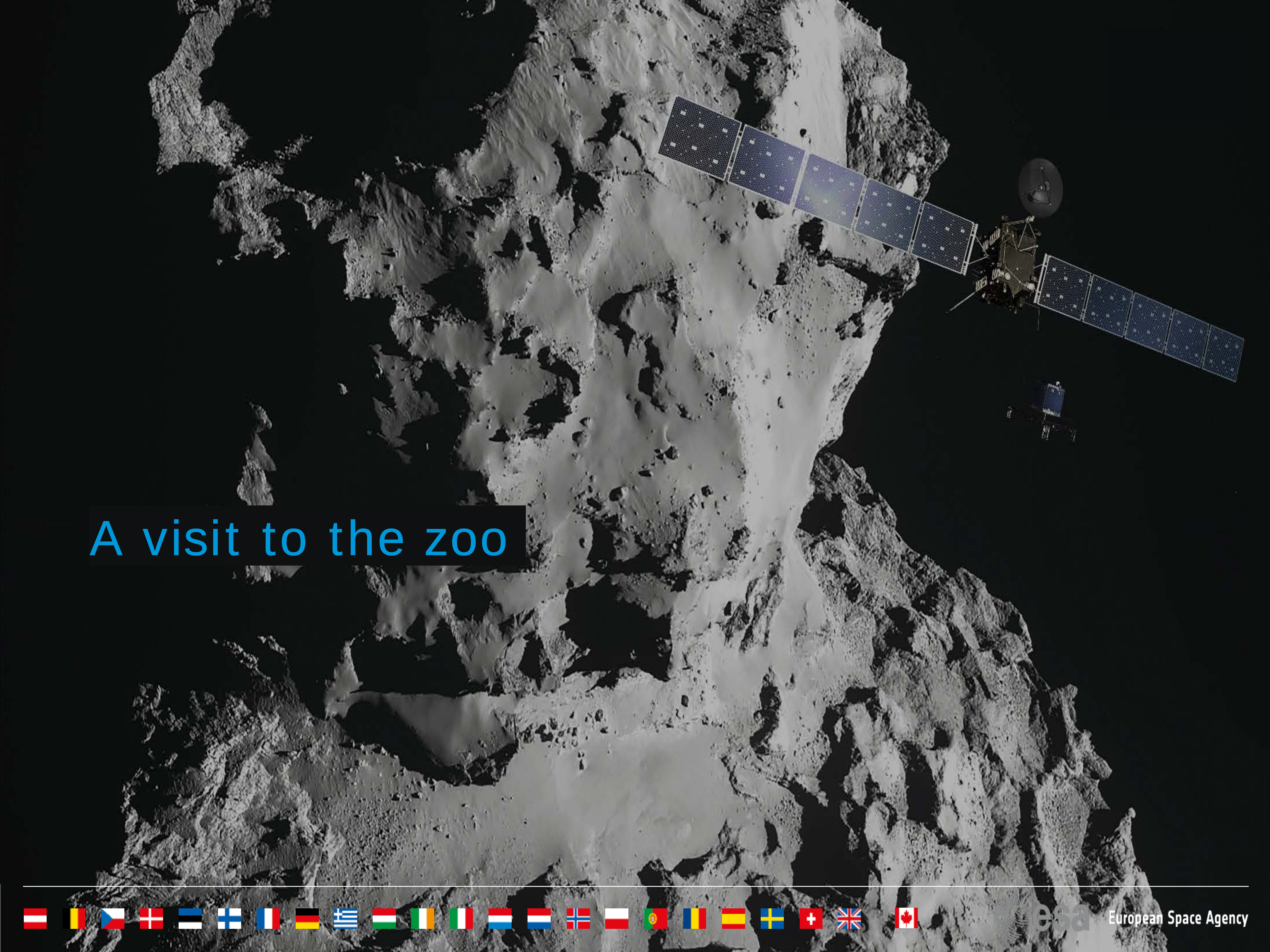
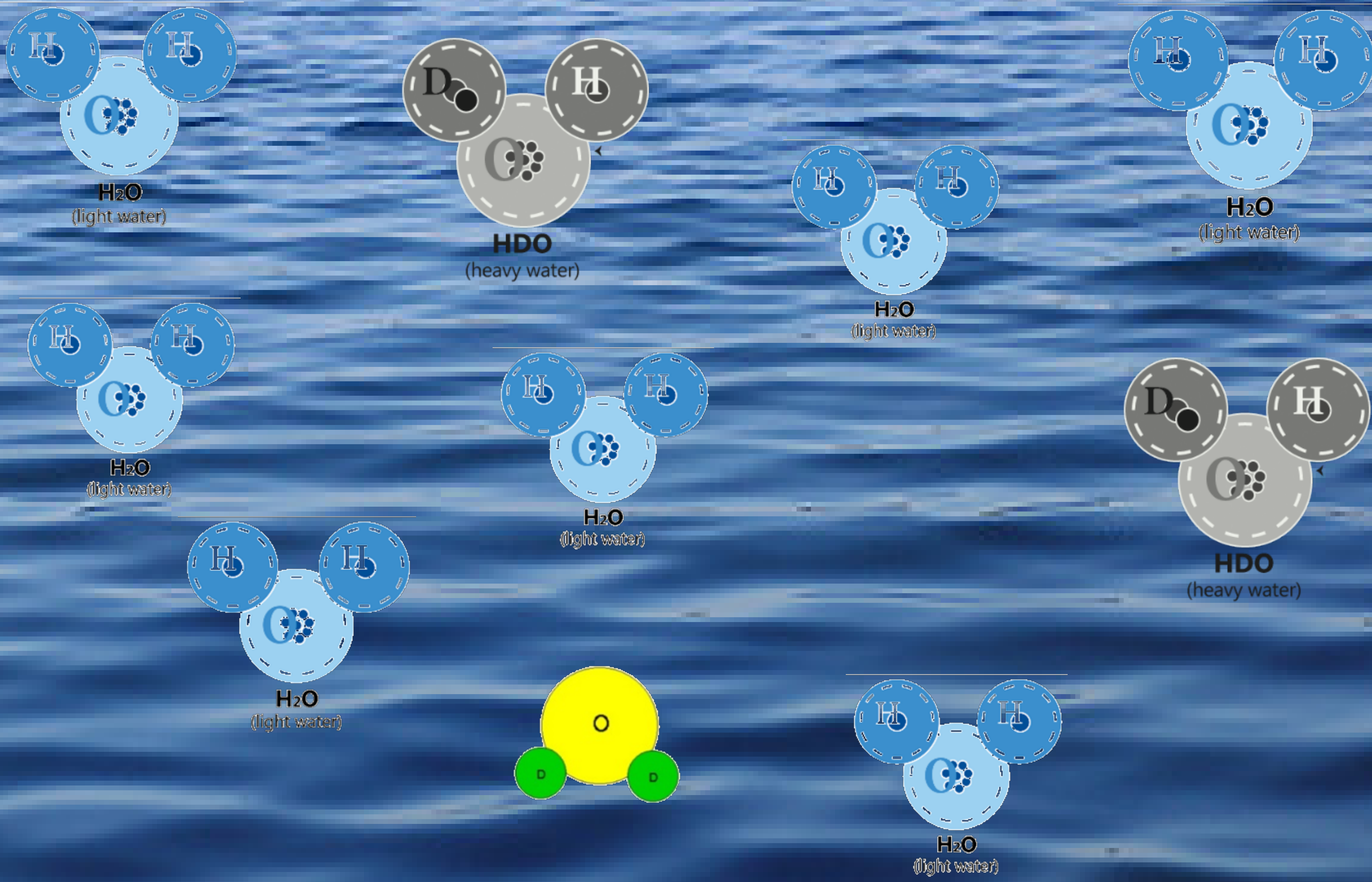



**Figure 1.** Example of magnetic field observations made onboard the Rosetta spacecraft on 10 September 2014, 23:45–23:55 UTC. The position vector of the spacecraft in the comet-centered solar equatorial (CSEQ; for details see text) coordinate system was (3.9, −20.6, 20.4) km.

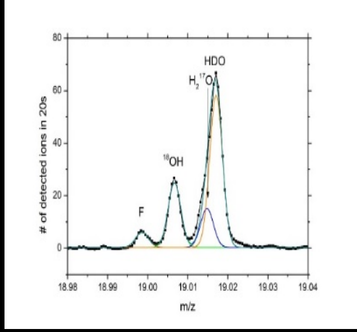
# A visit to the zoo

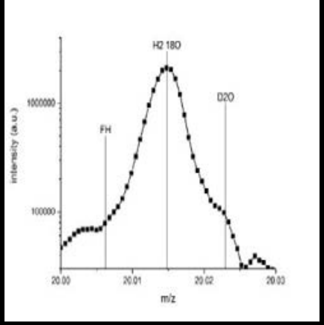


# ROSETTA Zoo

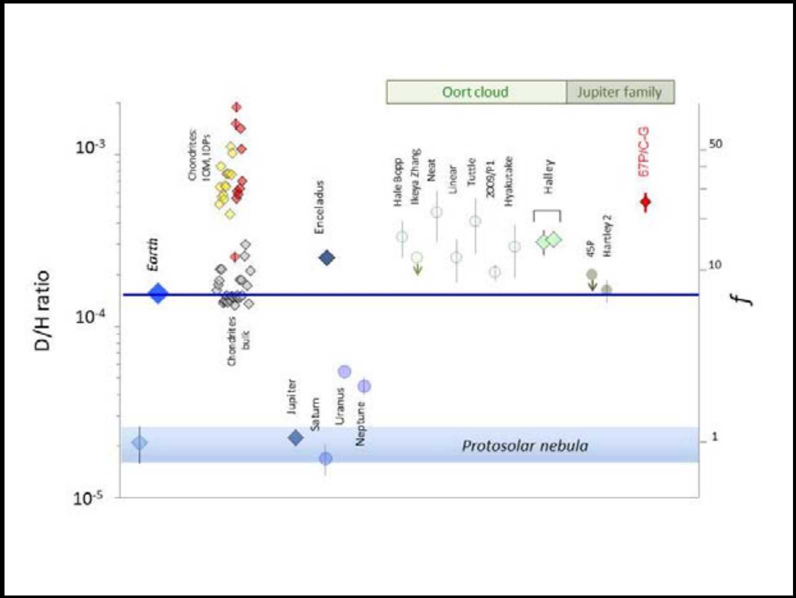

H₂O
(light water)
HDO
(heavy water)
H₂O
(light water)
H₂O
(light water)
H₂O
(light water)
H₂O
(light water)
HDO
(heavy water)
H₂O
(light water)
O
D
D
H₂O
(light water)

# Deuterated species




| **Comet 67 P/C-G** | **Molecular clouds** |
|---|---|
| D/H ~5.3 $10^{-4}$ in $H_2O$ | D/H ~ 8 $10^{-4}$ – $10^{-2}$ in $H_2O$ |
| $D_2O$ / HDO ~1 % | 1.2 % |




[D2O/HDO] / [HDO/H2O] ~17
In thermal equilibrium this ratio has to be 0.25

- Water is inherited from the presolar cloud
- The big variability of D/H in comets points to the fact that they were formed over a large region, that the comet families (Oort cloud, Kuiper belt, etc.) were not formed separately, but just have a dynamically different history
- The Earth did not get the bulk of its water from comets

# ROSETTA Zoo

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

# The presence of highly volatile species tells us

- 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 inherited as part of the water ice from the presolar cloud.

- Other explanations for O2 involve a lot of H2O2, 4 orders of magnitude higher than what is measured or plasma (ionized pickup water), which is also 4 orders of magnitude off (**not to be discussed Here and Now**)

# ROSETTA Zoo

Cyanogen
($C_2N_2$)

HF
HCl
HBr
P

Acetylene
HCN
Acetonitri
Formaldehyde

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

Na, Si, K

## What's the composition of a comet?

Before Rosetta, we thought that....

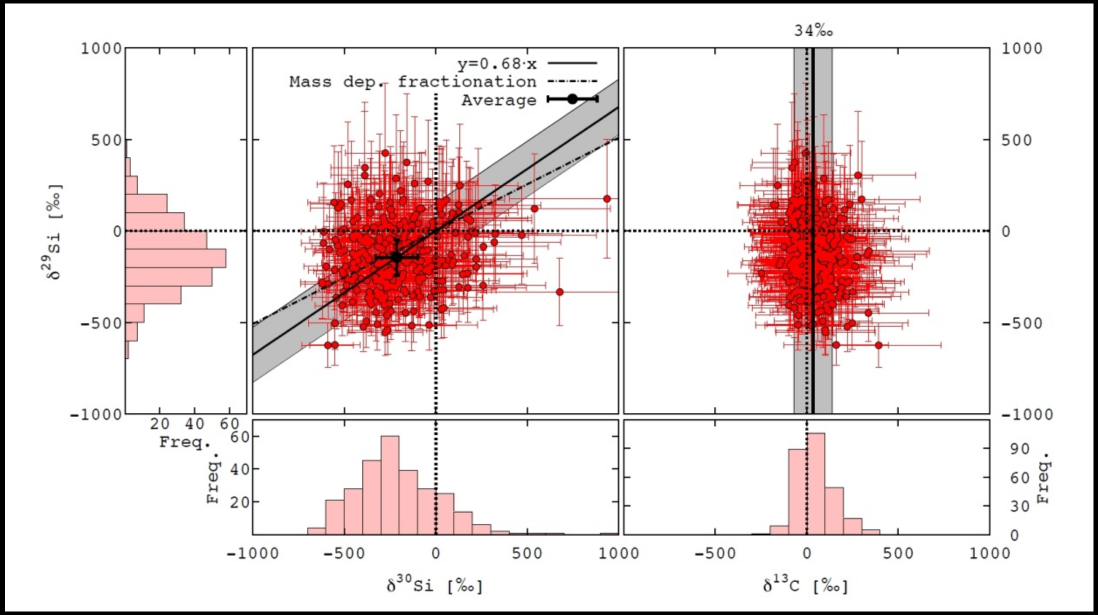
Cometary ice contains simple molecules, which have formed in the gas phase.

- True, but....

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

- True, but....

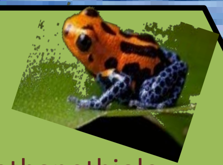
# Silicon isotopes of 67P – Indication of a heterogeneous protosolar nebula




**Highlight in Astron. & Astrophysics**

Evidence for depletion of heavy silicon isotopes at comet 67P/Churyumov-Gerasimenko, Rubin et al., April 2017

# ROSETTA Zoo



$S_2$
$S_3$
$S_4$
Methanethiole
(CH3SH)
Ethanethiol
(C2H5SH)
Thioformaldehyde
(CH2S)

Cyanogen
(C2N2)

HF
HCl
HBr
P

Acetylene
HCN
Acetonitri
Formaldehyde

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

Hydrogensulfide
Carbonylsulfide
Sulfur monoxide
Sulfur dioxide
Carbon disulfide

Na, Si, K

# Sulphur inventory of comets

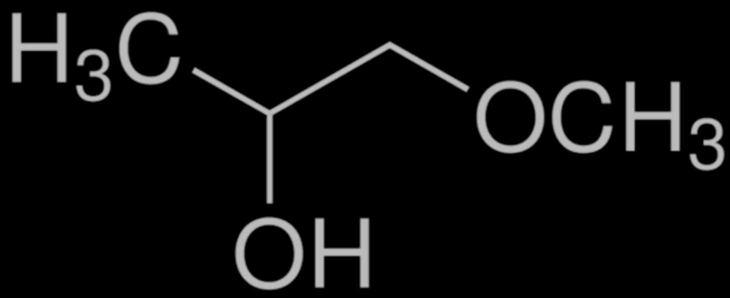
- Interstellar material contains sulphur in cosmic abundance while presolar clouds are mysteriously depleted in sulphur.
- Comets contain species which can only be formed on dust grains (e.g. $S_2$, $S_3$, $S_4$...).
- They must have been inherited from the presolar cloud. Therefore, most sulphur in 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 means it must have survived the formation of the solar system in the ice.
- Some ice is directly inherited from our native cloud.


ROSETTA Zoo
Macromolecules
Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane
$S_2$
$S_3$
$S_4$
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)

- ## Complex organics
- seen by ROSINA and by COSAC & Ptolemy on the lander
- More complex than anticipated
- Large amount and diversity
- Prebiotic molecules




ROSETTA Zoo
Macromolecules
Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane
Glycine
(Aminoacid
$S_2$
$S_3$
$S_4$
Methanethiole (CH3SH)
Ethanethiol (C2H5SH)
Thioformaldehyde
(CH2S)
Ammonia
Methylamine
Ethylamine
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
Hydrogensulfide
Carbonylsulfide
Sulfur monoxide
Sulfur dioxide
Carbon disulfide
Na, Si, K

# Comets do not contain life

but


ROSETTA Zoo
Macromolecules
Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane
$H_2N$ OH O
Glycine
(Aminoacid
$S_2$
$S_3$
$S_4$
Methanethiole (CH3SH)
Ethanethiol (C2H5SH)
Thioformaldehyde
(CH2S)
Ammonia
Methylamine
Ethylamine
Cyanogen
(C2N2)
Formic acid
Acetic acid
Acetaldehyde
Ethylenglycol
Propylenglycol
Butanamide
Argon
Krypton
Xenon
HF
HCl
CH3Cl
HBr
P
Acetylene
HCN
Acetonitril
Formaldehyde
Benzene
Toluene
Xylene
Benzoic acid
Naphthalene
Methanol
Ethanol
Propanol
Butanol
Pentanol
Nitrogen
N≡N
Oxygen
Hydrogenperoxyd
Carbon monoxide
Carbon dioxide
Hydrogensulfide
Carbonylsulfide
Sulfur monoxide
Sulfur dioxide
Carbon disulfide
Na, Si, K

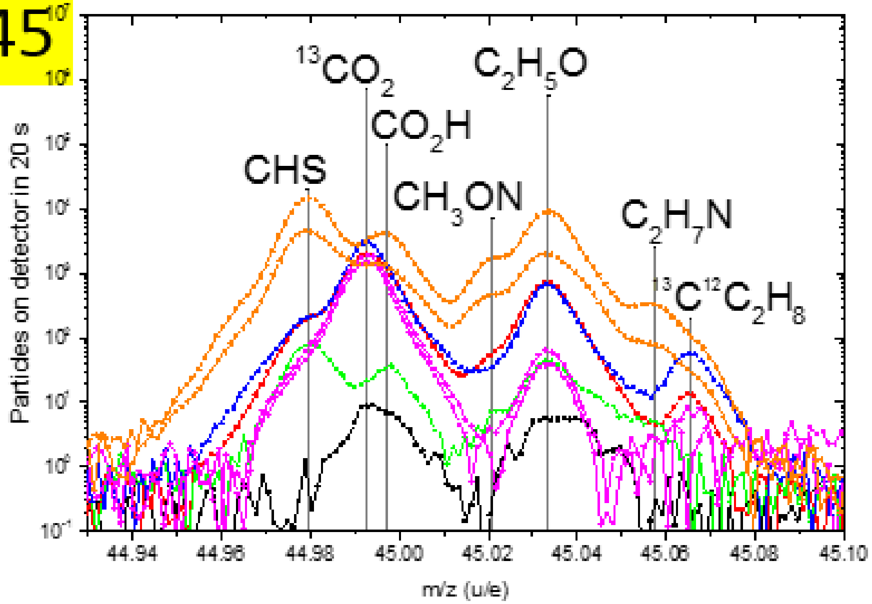
## Did comets bring the Earth atmosphere (and as a consequence organic material)?

The answer is given by the noble gases of 67P

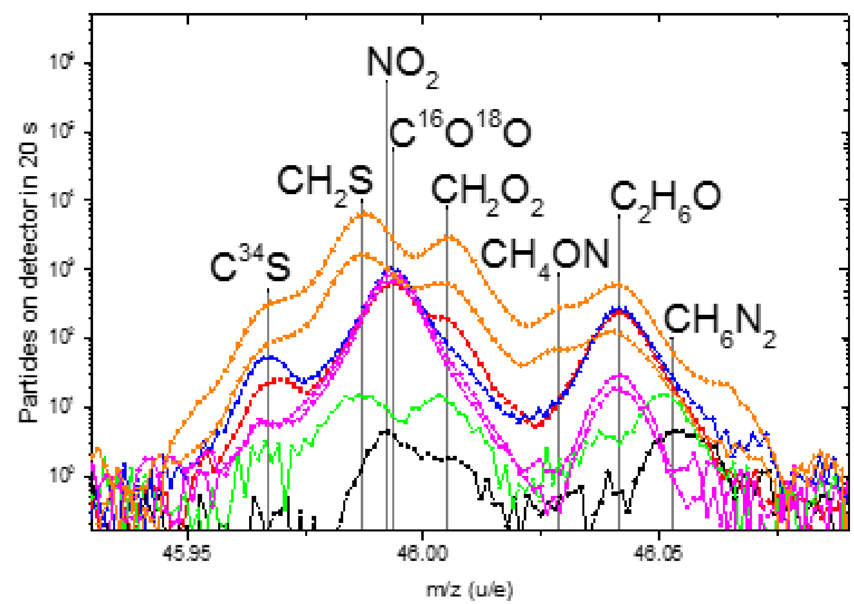
- The abundance of argon ( $^{36}Ar$ and $^{38}Ar$) of 67P is compatible with a delivery of the terrestrial atmosphere by comets (late heavy bombardment) without changing the D/H in water.
- Xenon isotopes are the clues to a quantitative assessment of how much material was delivered by comets to the Earth (see next issue of “Science” (June 9, 2017), under embargo ☹


ROSETTA Zoo
Macromolecules
$C_nH_m$
$C_nH_mO$
$C_nH_mS$
$C_nH_mN$
$C_nH_mON$
$C_nH_mOS$
n = 1…8
Unsaturated carbon chains and rings
Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane
$H_2N$ OH O
Glycine (Aminoacid
$S_2$
$S_3$
$S_4$
Methanethiole (CH3SH)
Ethanethiol (C2H5SH)
Thioformaldehyde (CH2S)
Ammonia
Methylamine
Ethylamine
Cyanogen (C2N2)
Formic acid
Acetic acid
Acetaldehyde
Ethylenglycol
Propylenglycol
Butanamide
Argon
Krypton
Xenon
HF
HCl
CH3Cl
HBr
P
Acetylene
HCN
Acetonitril
Formaldehyde
Benzene
Toluene
Xylene
Benzoic acid
Naphthalene
Methanol
Ethanol
Propanol
Butanol
Pentanol
Nitrogen
Oxygen
N≡N
Hydrogenperoxyd
Carbon monoxide
Carbon dioxide
Hydrogensulfide
Carbonylsulfide
Sulfur monoxide
Sulfur dioxide
Carbon disulfide
Na, Si, K

45

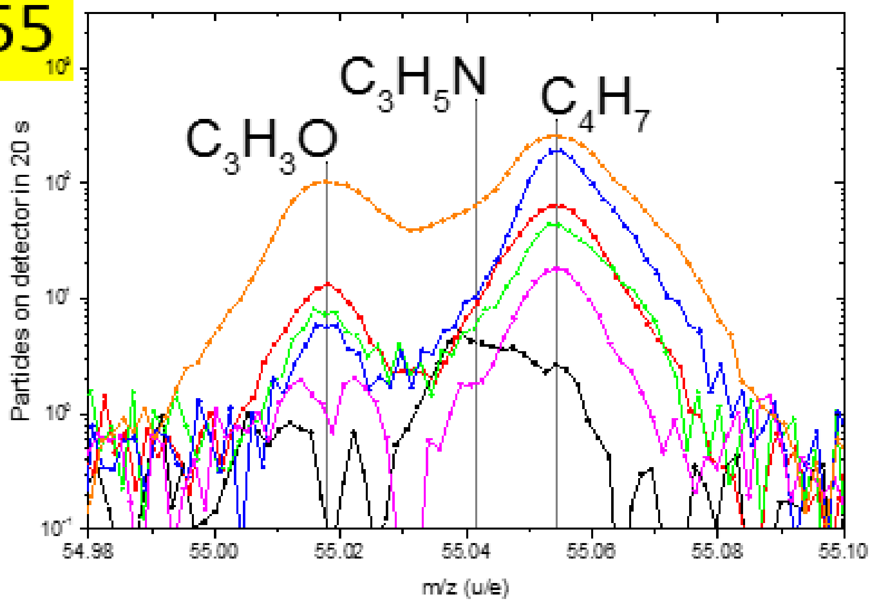


$^{13}CO_2$
$C_2H_5O$
$CO_2H$
CHS
$CH_3ON$
$C_2H_7N$
$^{13}C^{12}C_2H_8$
Particles on detector in 20 s
m/z (u/e)

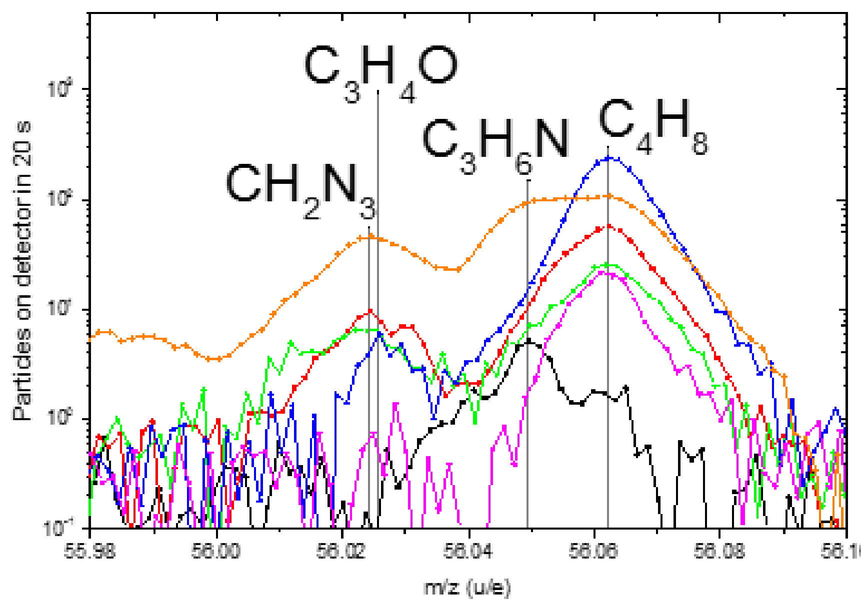



$NO_2$
$C^{16}O^{18}O$
$CH_2S$
$CH_2O_2$
$C_2H_6O$
$C^{34}S$
$CH_4ON$
$CH_6N_2$
Particles on detector in 20 s
m/z (u/e)

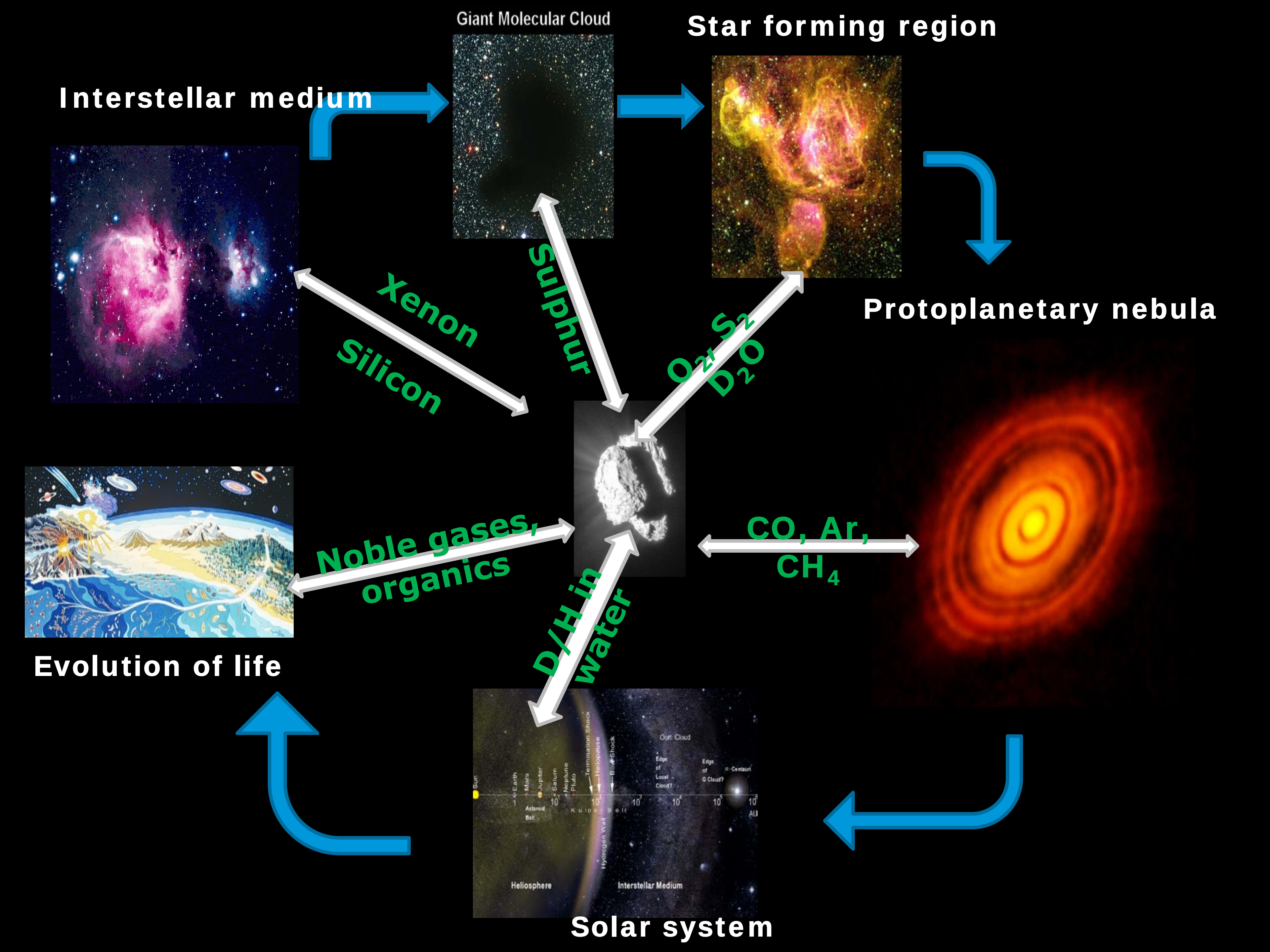

55



$C_3H_5N$
$C_4H_7$
$C_3H_3O$
Particles on detector in 20 s
m/z (u/e)

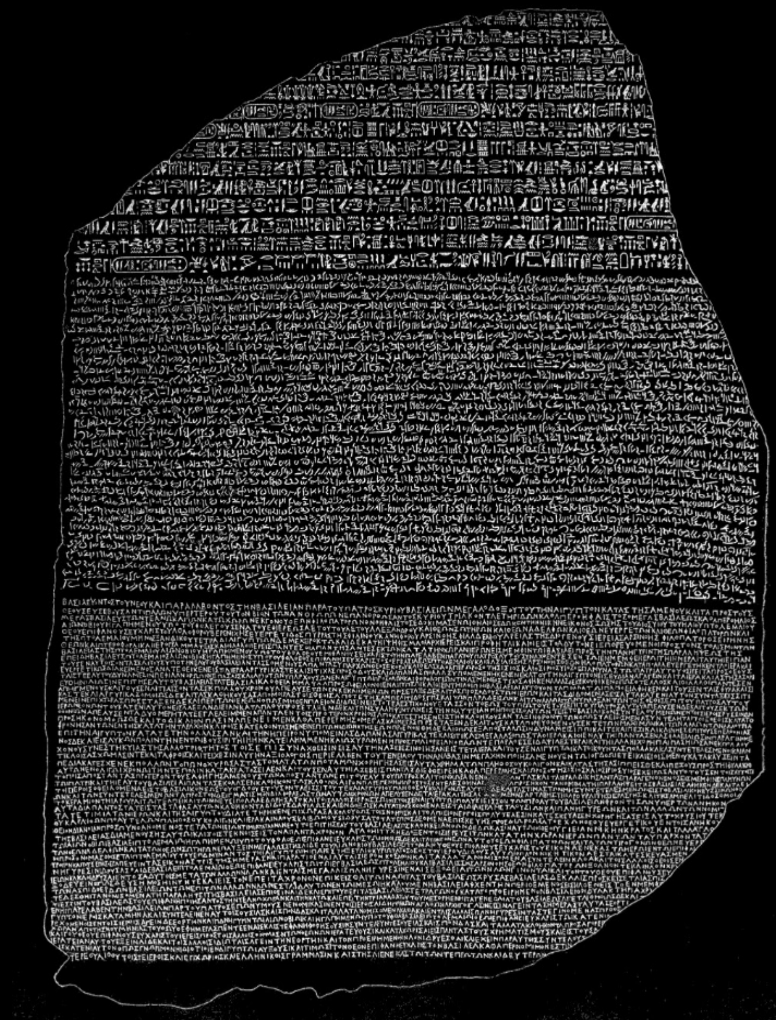
$C_3H_4O$
$C_3H_6N$
$C_4H_8$
$CH_2N_3$
Particles on detector in 20 s
m/z (u/e)



Giant Molecular Cloud
Star forming region
Interstellar medium
Protoplanetary nebula
Xenon
Silicon
Sulphur
$O_2$, $S_2$
$D_2O$
Noble gases, organics
CO, Ar, $CH_4$
D/H in water
Evolution of life
Solar system

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

Rosetta has more than achieved its goals



Number of publications

| 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24 | 19 | 39 | 61 | 29 | 22 | 42 | 27 | 55 | 31 | 54 | 153 | 176 | >50 | **>782** |

# Next steps

- **Analyze the remaining 90% of data!**
- **Start planning the next cometary mission(s):**
  - Visit another comet with a low D/H (e.g. Hartley 2) for comparison to study its volatile composition in situ (ESA M-mission)
  - Visit a main belt comet (ESA M-mission)
  - Visit a comet with a landing device (e.g. CHopper-mission: land and hop and dig) (ESA M-mission or NASA discovery mission class, needs RTG's)
  - Bring back a refractory sample (NASA New frontier mission class, under study)
  - Bring back a cryogenic (<80K?) sample (L-mission class, needs substantial technical development, purpose of this workshop)

# → THE COMETARY ZOO: GASES DETECTED BY ROSETTA

esa

### THE LONG CARBON CHAINS
Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane

### THE AROMATIC RING COMPOUNDS
Benzene
Toluene
Xylene
Benzoic acid
Naphtalene

### THE KING OF THE ZOO
Glycine (amino acid)

### THE "MANURE SMELL" MOLECULES
Ammonia
Methylamine
Ethylamine

### THE "POISONOUS" MOLECULES
Acetylene
Hydrogen cyanide
Acetonitrile
Formaldehyde

### THE VOLATILES
Nitrogen
Oxygen
Hydrogen peroxide
Carbon monoxide
Carbon dioxide

### THE ALCOHOLS
Methanol
Ethanol
Propanol
Butanol
Pentanol

### 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



*Credits: Based on data from ROSINA*

## Acknowledgements

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- the Belgian Institute for Space Aeronomy (BIRA-IASP),
- Research Institute in Astrophysics and Planetology (IRAP)
- Institut Pierre Simon Laplace (IPSL), Paris, France,
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