Swiss National Science Foundation

Химический состав протопланетного диска Солнечной системы по результатам исследования кометы 67P/Чурюмова — Герасименко

Мария Николаевна Дроздовская
SNSF Ambizione Fellow

BErn Astrochemistry Research

“Динамическая и химическая эволюция протопланетных дисков”
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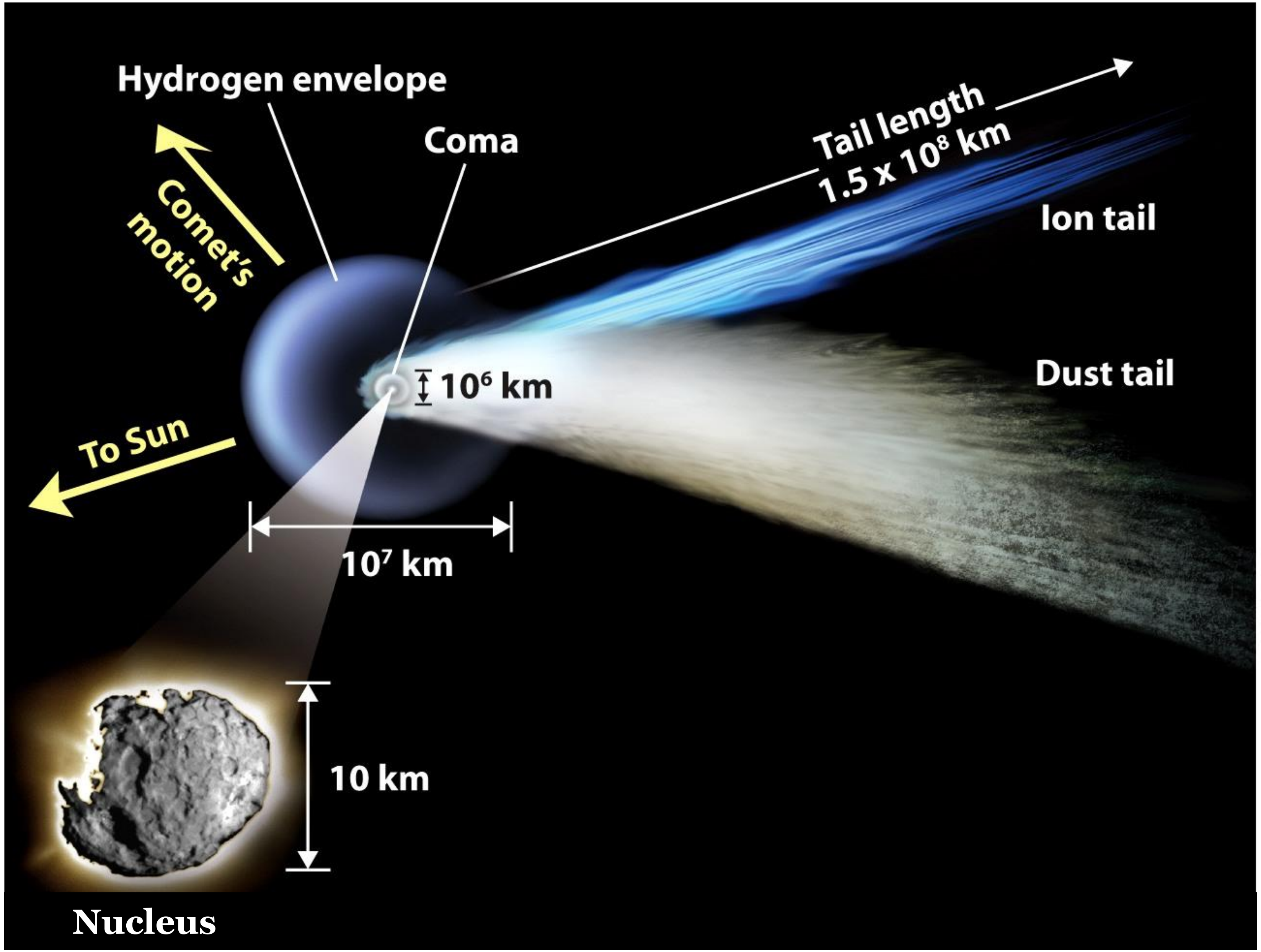
Universität Bern
CSH Center for Space and Habitability
PlanetS

A comet is…

- One of many (several thousand known, total population may be a trillion)
- Rarely a spectacular show for the ground-based observer
- Made of refractories (rocks and dust) and volatiles (gas and ice)
- Relic of our Solar System's formation
- An object we can probe in situ!

Could a comet tell us the exact chemical ingredients of our Solar System?

Comet C/1995 O1 (Hale-Bopp) on 4 April 1997
E. Kolmhofer, H. Raab; Johannes-Kepler-Observatory, Linz, Austria
(http://www.sternwarte.at)



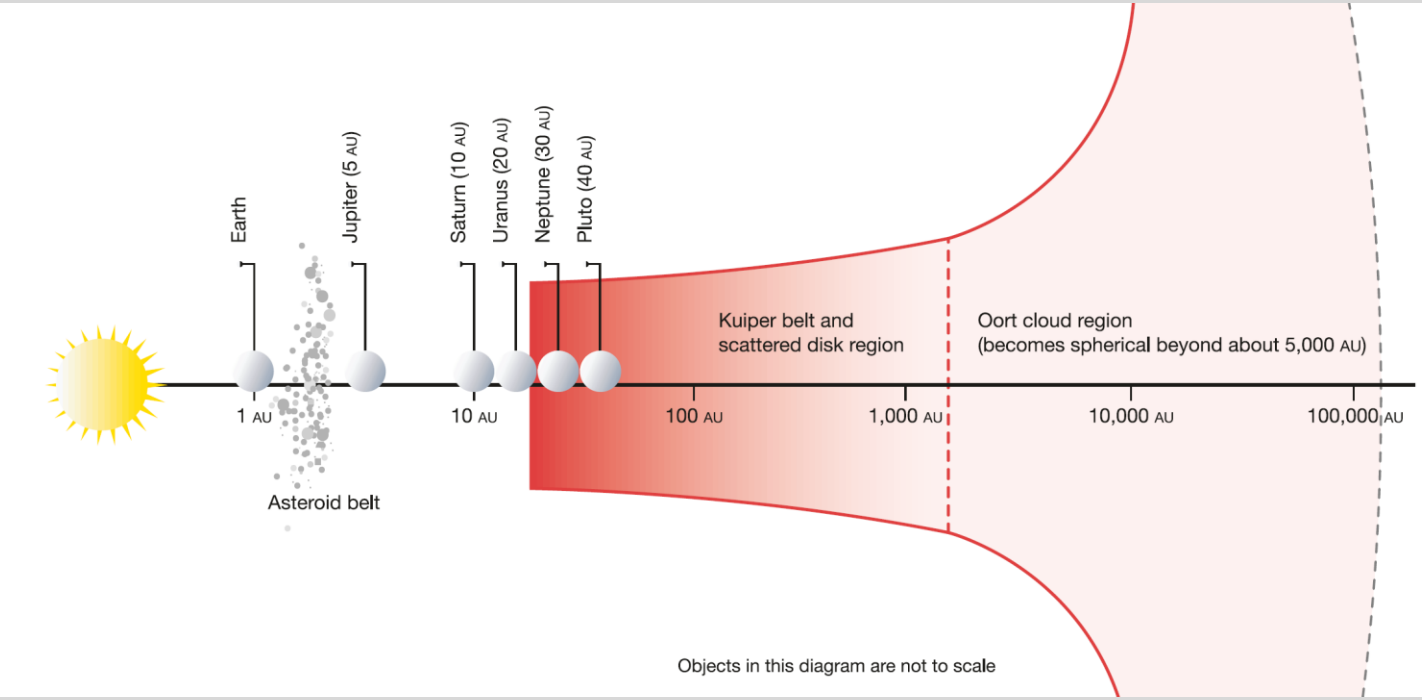
Comet structure

- Dust-to-Water mass ratio ≠ Dust-to-Volatiles mass ratio ≠ Refractory-to-Ice mass ratio
- 0.64-7.5 range for 67P/C-G
  (Choukroun et al. 2020 and the references therein)
- "Icy mudballs" or "Dirty snowballs"??

Figure 15-26
Universe Tenth Edition

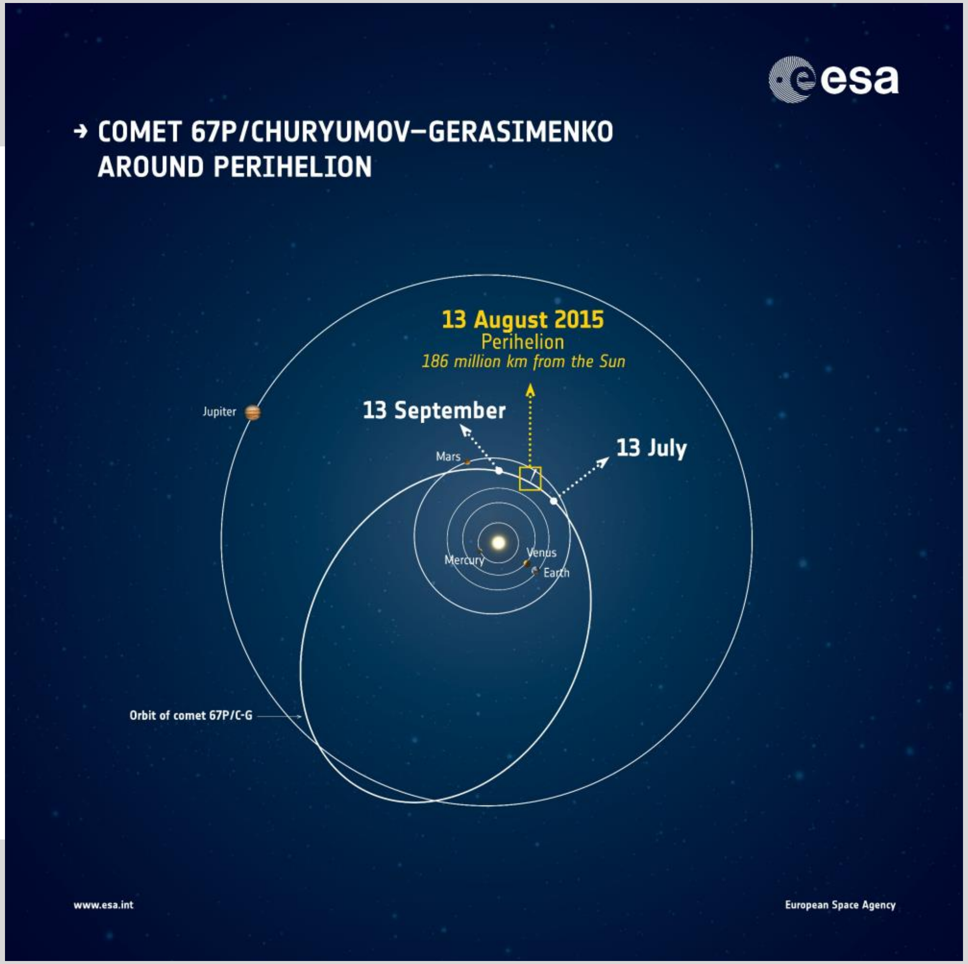
Where do comets come from today?

Comet reservoirs



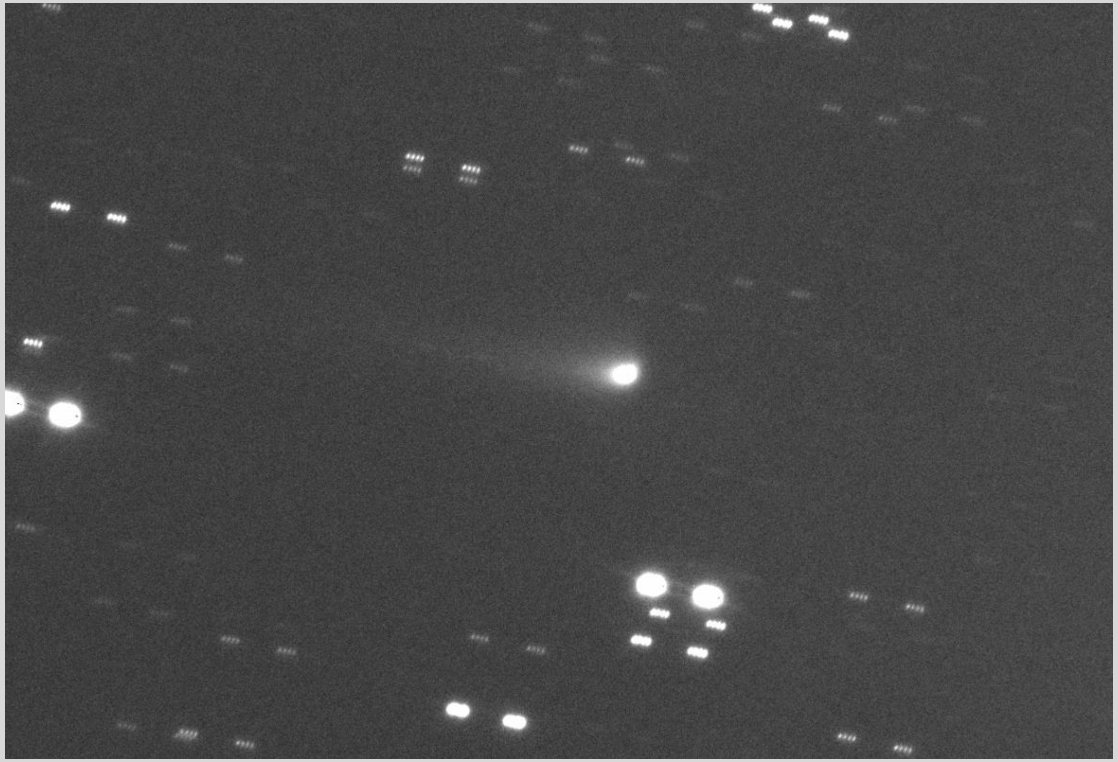
Stern 2003

Jupiter-Family comet (JFC)



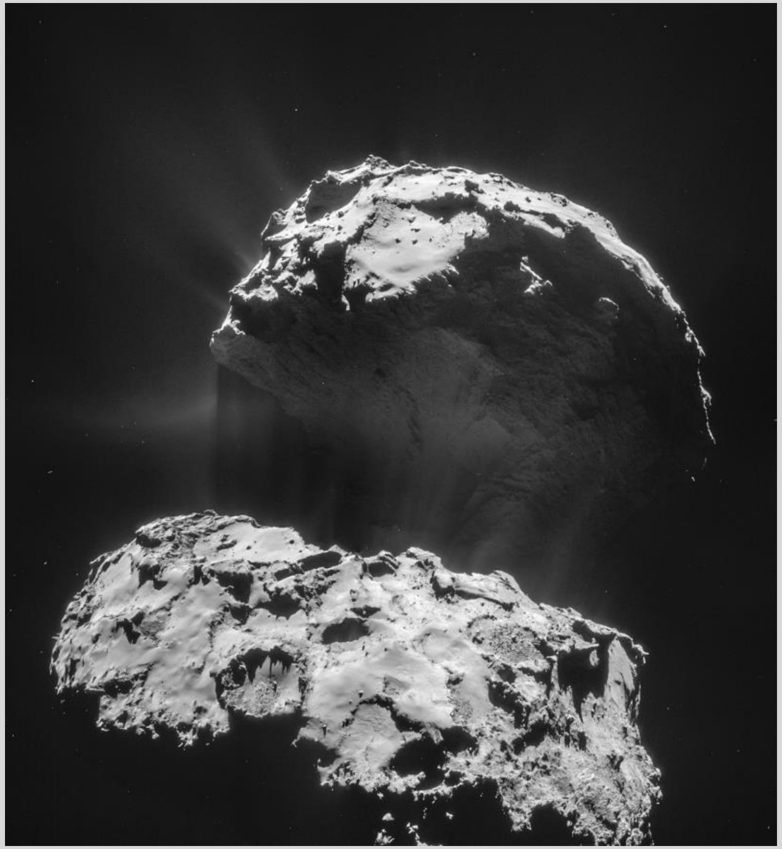
67P/ Churyumov-Gerasimenko

From afar... 😫



Comet 67P/Churyumov-Gerasimenko on 24 July 2015
Colin Snodgrass / Geraint Jones / Liverpool Telecope

And up close! 🤩

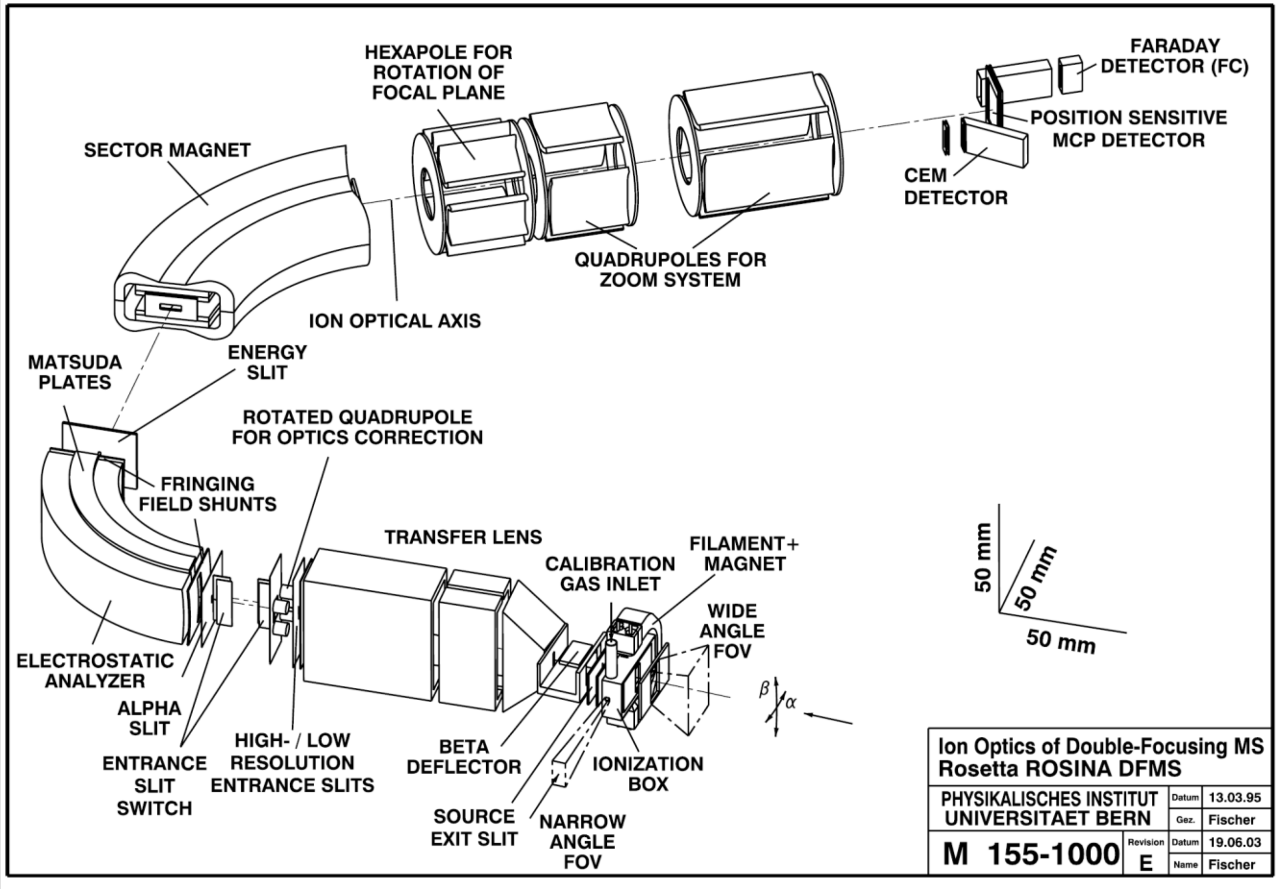


03/02/2015;
ESA/Rosetta/NAVCAM,

Что известно о химическом составе кометы 67P/Чурюмова — Герасименко и её происхождении?

ROSINA
(Rosetta Orbiter Spectrometer for Ion and Neutral Analysis)

1. Double Focusing magnetic Mass Spectrometer (**DFMS**)
   mass range 12 – 150 amu
   mass resolution of 3000 for $m/z = 28$ at 1% peak height
   45 eV electron bombardment
2. Reflectron-type Time-of-Flight mass spectrometer (**RTOF**)
   mass range 1 – 300 + amu
   mass resolution of 500 + at 1% peak height
3. COmet Pressure Sensor (**COPS**)
   two pressure gauges measuring density and velocity of the cometary gas



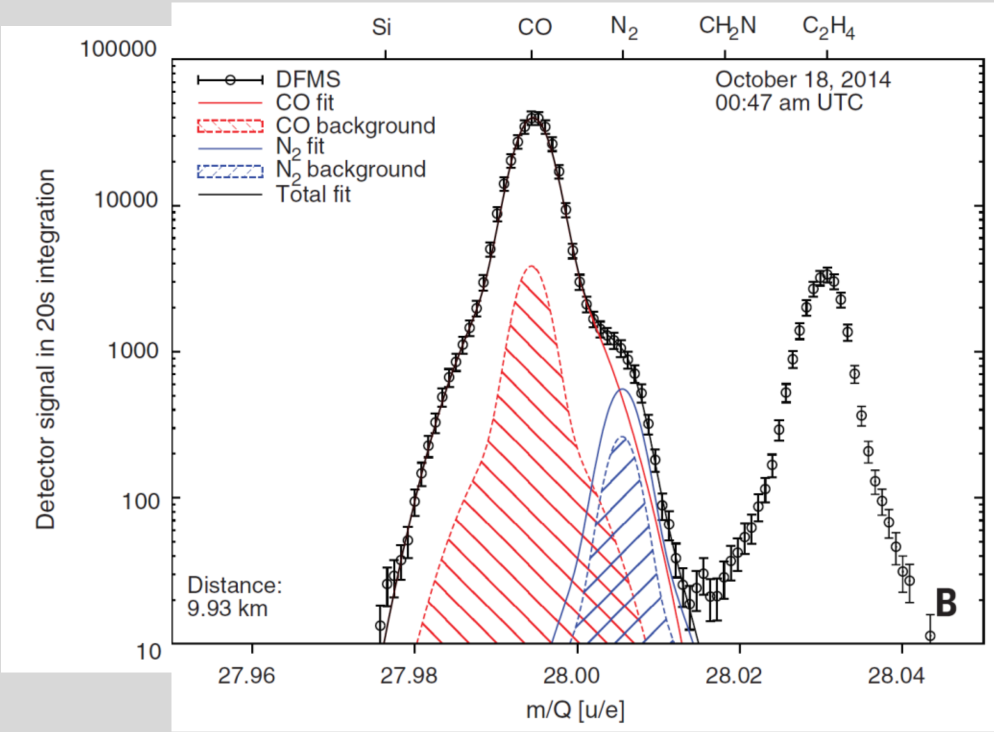
ROSINA measures coma gases

Balsiger 2007

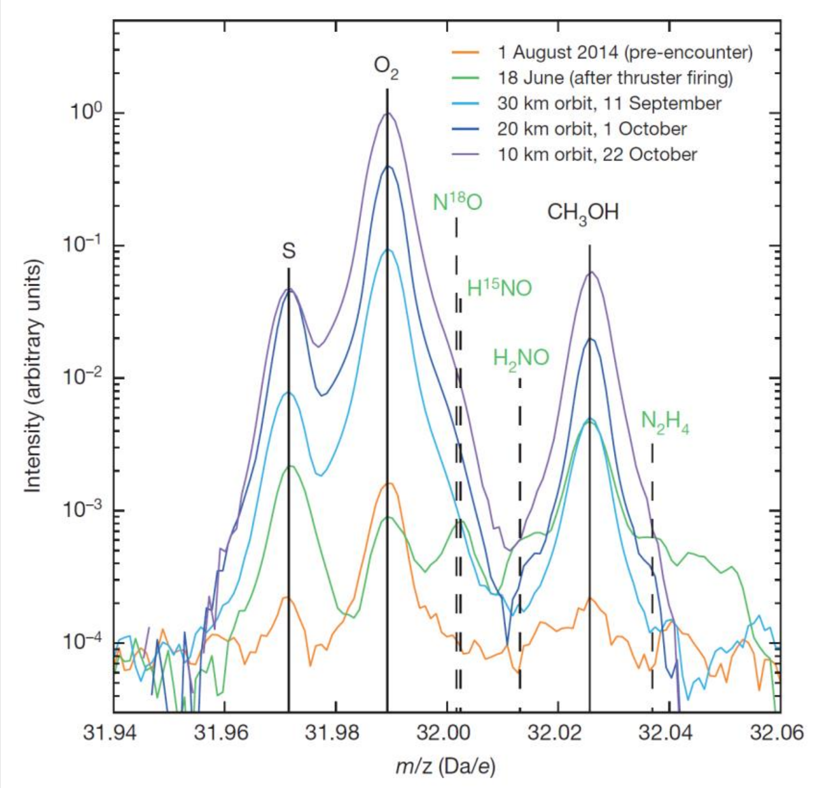
Highly-volatile molecules

ROSINA measurements of CO, N_2, O_2, noble gases indicate that the interior of comet 67P/C-G was not subject to significant heating since its formation

$CO/H_2O = 3.1 \pm 0.9$ % $N_2/H_2O = 0.089 \pm 0.024$ % $O_2/H_2O = 3.1 \pm 1.1$ %   (Rubin et al. 2019a)



Rubin et al. 2015a



Bieler et al. 2015b

→ 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 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

HIGH CHEMICAL DIVERSITY & COMPLEXITY OF VOLATILES

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

Are cometary molecules found beyond our Solar System?

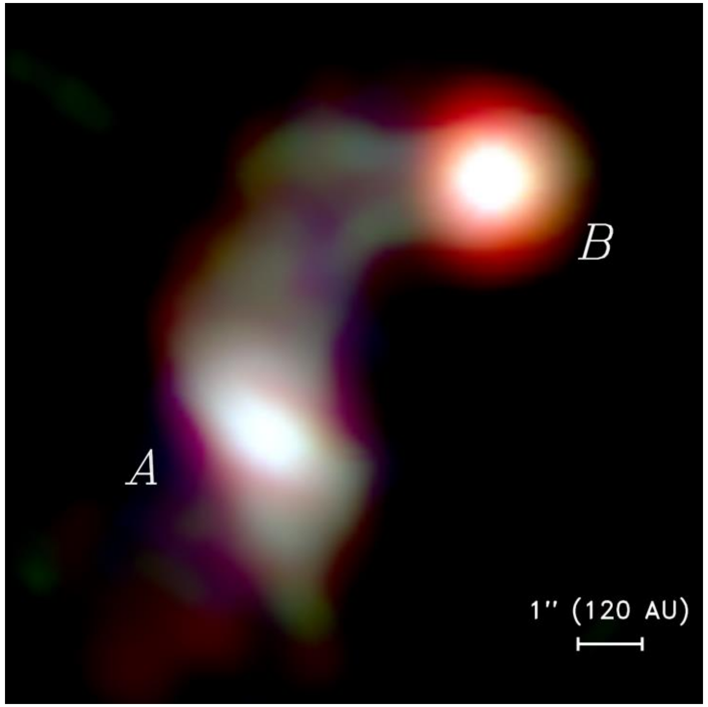
Yes!

- 40 of the 71 parent species in 67P/C-G are also detected in prestellar and/or protostellar sources
- Most isotopic ratios in volatiles of 67P/C-G are non-solar

Altwegg et al. 2019
(also, e.g., Le Roy et al. 2015; Calmonte et al. 2016; Gasc et al. 2017; Altwegg et al. 2017a, 2017b, 2019; Rubin et al. 2018, 2019a, 2019b; Schuhmann et al. 2019)

Let's perform a quantitative comparison with the *Rosetta*-ROSINA data!
=> We need an analogously complete chemical inventory of a star-forming region…

IRAS 16293-2422



Unbiased Protostellar Interferometric Line Survey (ALMA-PILS)

PI: Jes Jørgensen

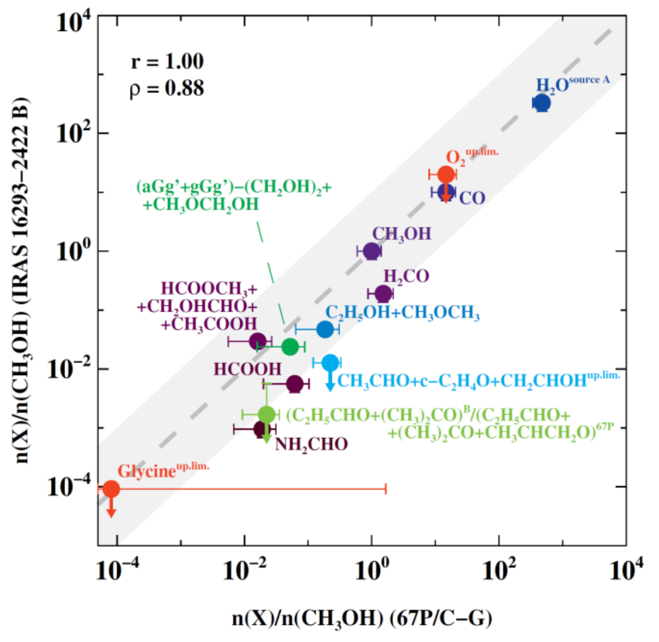
329 – 363 GHz (Band 7)

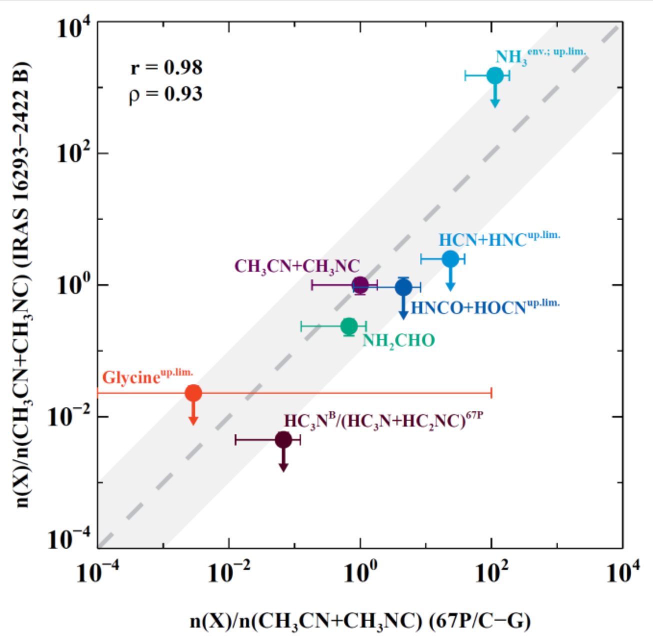
On small 70 au scales

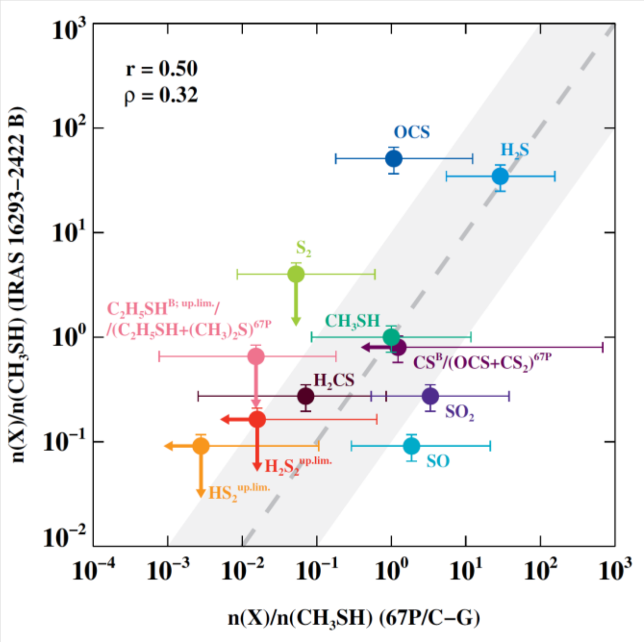
(e.g., Jørgensen et al. 2016, 2018; Coutens et al. 2016; Lykke et al. 2017; Ligterink et al. 2017; Calcutt et al. 2018b; Drozdovskaya et al. 2018; Manigand et al. 2019; van der Wiel et al. 2019)

Molecular inventory of IRAS 16293-2422 B versus 67P/C-G

CHO-bearing molecules **N-bearing molecules** **S-bearing molecules**

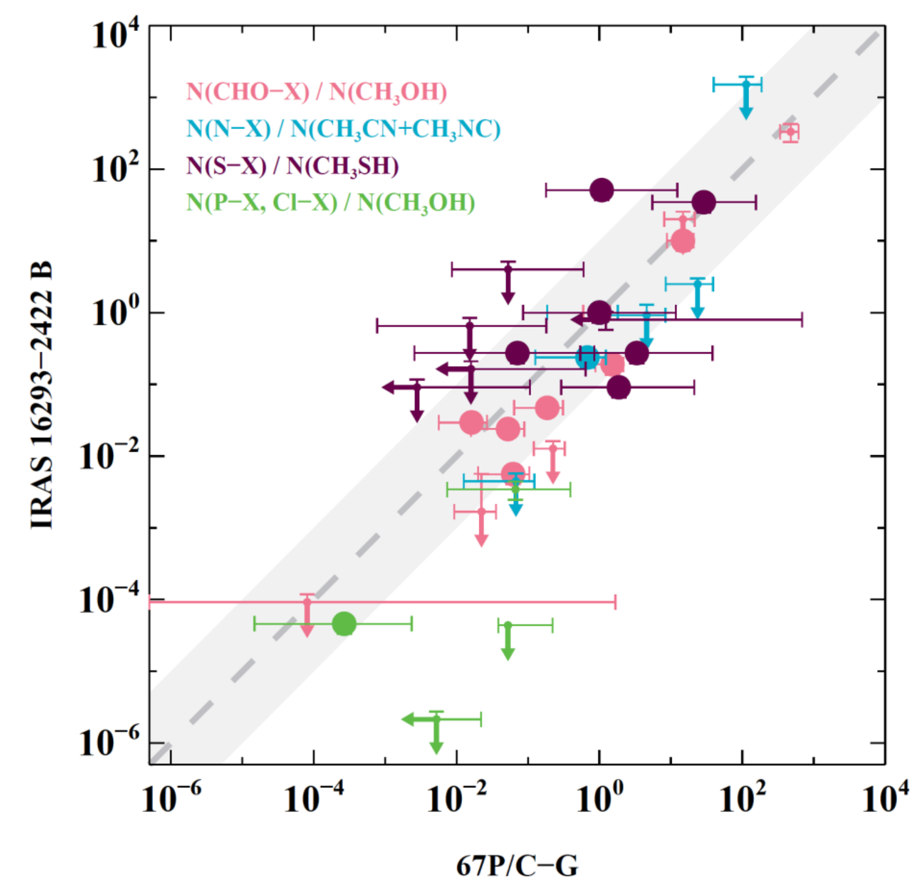






P- and Cl-bearing molecules were also probed for the first time.

Drozdovskaya et al. 2019

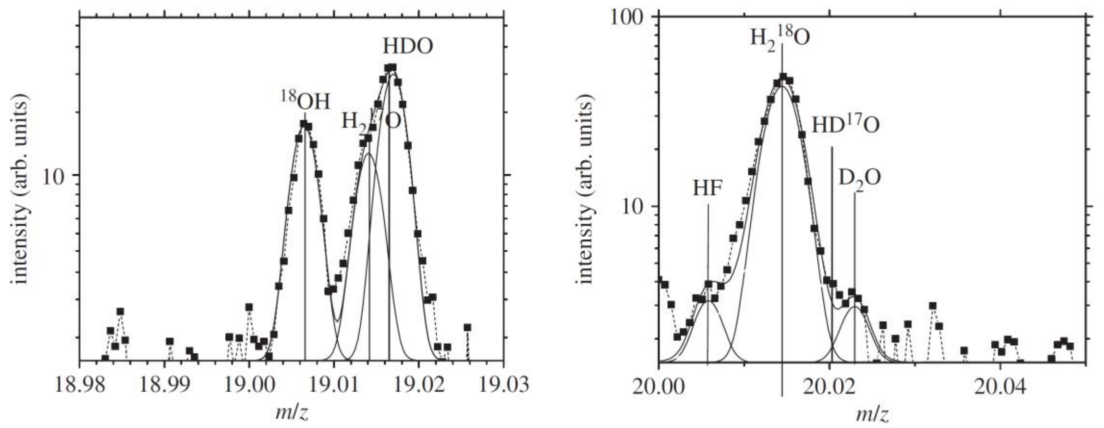


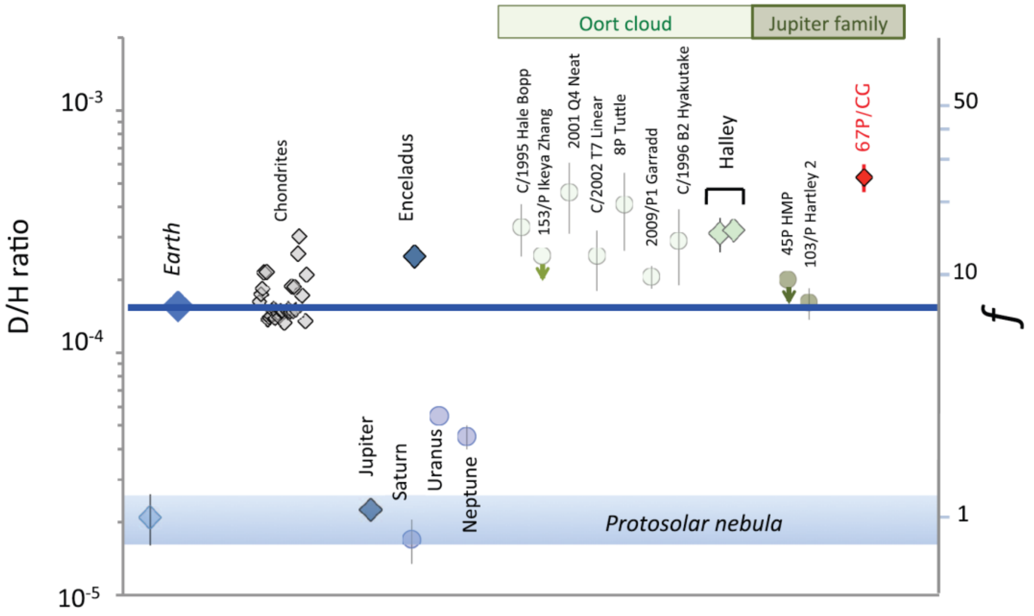
Drozdovskaya et al. 2019

Protostellar and cometary molecular inventories correlate

- CHO-, N-, S-, P-, and Cl-bearing volatiles correlate between protostar IRAS 16293-2422 B and comet 67P/C–G, with some scatter
- Cometary relative abundances tend to be higher than protostellar for CHO- and N-bearing species:
  - Are volatile molecules destroyed near the protostar before entry into the protoplanetary disk?
  - Have more been produced by the time of incorporation into the comet?
  - Could it stem solely from variations in the reference molecules (CH_3OH and CH_3CN)?

Inheritance, alongside some chemical alteration!





Altwegg et al. 2017a

Water deuteration

- D/H = $(5.3 \pm 0.7) \times 10^{-4}$, which is 3 times the terrestrial value (Altwegg et al. 2015)
- D_2O/HDO relative to HDO/H_2O = 17, while 0.25 is statistically expected (Altwegg et al. 2017a)
- D/H is consistent for both lobes of the comet (Schroeder et al. 2019a)
- Isotopic ratios do not change over the course of the mission

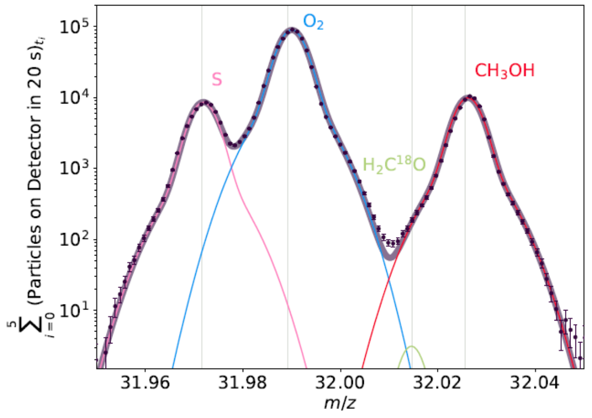
Water deuteration in comet 67P/C-G is high and compatible with early phases of low-mass star formation

Methanol deuteration

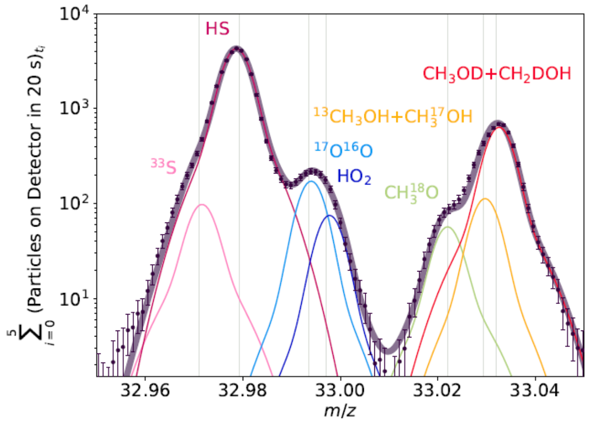
- D-methanol ($CH_3OD + CH_2DOH$) / CH_3OH = 5.5 ± 0.46 %
- D_2-methanol ($CH_2DOD + CHD_2OH$) / CH_3OH = 0.00069 ± 0.00014 %
- First-time detections of these species in a comet
- D/H ratio = 0.71 – 6.6 %
  (accounting for statistical corrections for the location of D in the molecule and including statistical error propagation in the ROSINA measurements)

Deuteration of complex organic species such as methanol is possible via grain-surface chemistry only in the earliest phases of star formation

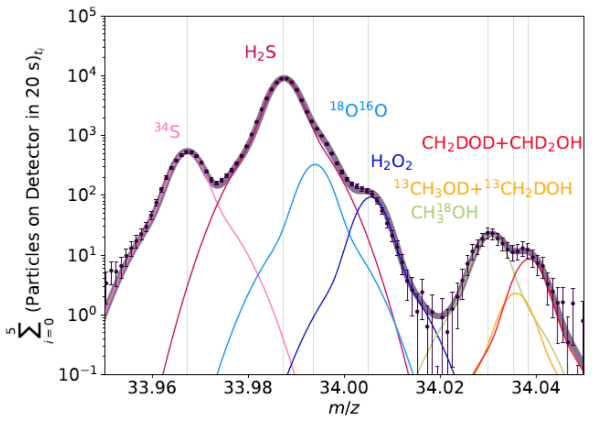
Drozdovskaya et al. 2021



(a) Normal methanol



(b) Mono-deuterated methanol

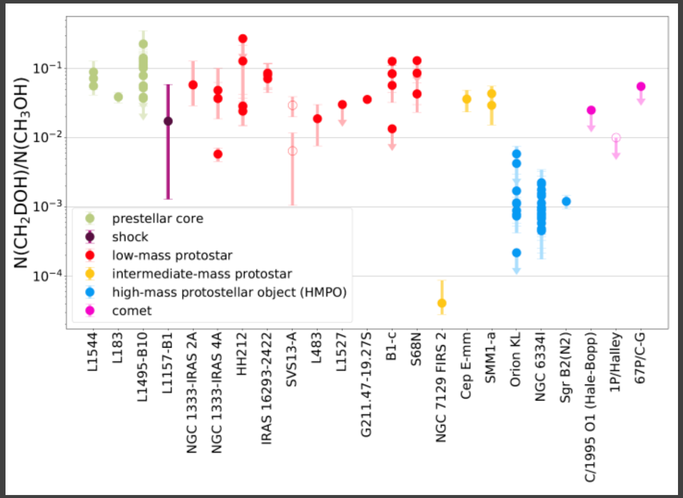


(c) Di-deuterated methanol

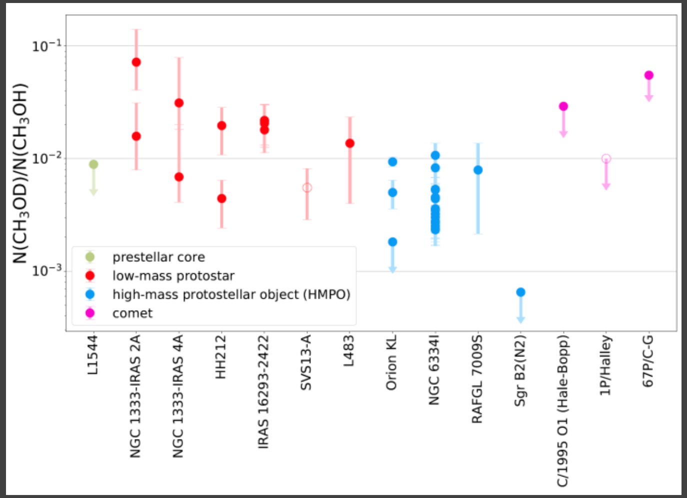
CH_2DOH

CH_3OD

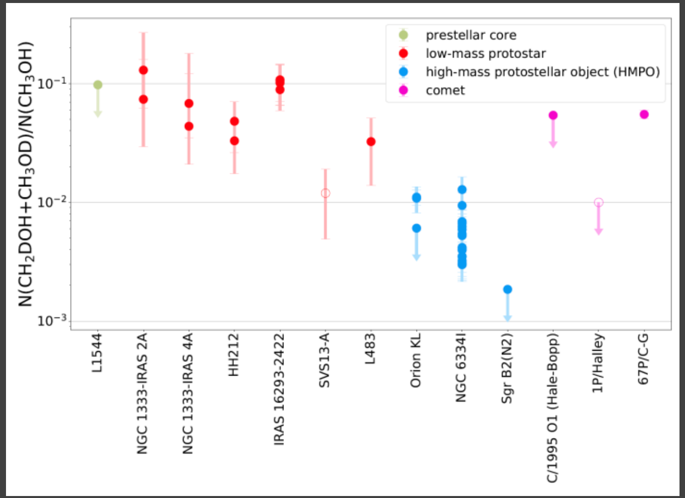
$CH_2DOH+CH_3OD$



forms from CO hydrogenation to CH_3OH and subsequent H-D substitution reactions in CH_3-R



could form via H-D exchange reactions in OH-R in the presence of deuterated water ice



Drozdovskaya et al. 2021

METHANOL DEUTERATION FROM STAR-FORMING REGIONS TO COMETS

The cometary D-methanol/methanol ratio agrees most closely with that in prestellar cores and low-mass protostellar regions.

CONCLUSIONS

1. Химический состав новорождённой Солнечной системы включает сложные органические вещества и содержит полный набор элементов, важных для развития жизни.

2. Обнаружение высоколетучих веществ и высокого уровня дейтерирования молекул (воды и метанола) указывает на холодное (10 – 20 К) прошлое кометы 67P/Чурюмова — Герасименко и её происхождение.

3. Схожесть химических составов кометы 67P/Чурюмова — Герасименко, околозвёздного диска IRAS 16293-2422 B и других регионов, в которых формируются новорождённые звёзды, позволяет предположить, что все протопланетные диски могут содержать схожие вещества в ранних стадиях своего развития.

All further details: Drozdovskaya et al. 2019, Drozdovskaya et al. 2021 and the references therein