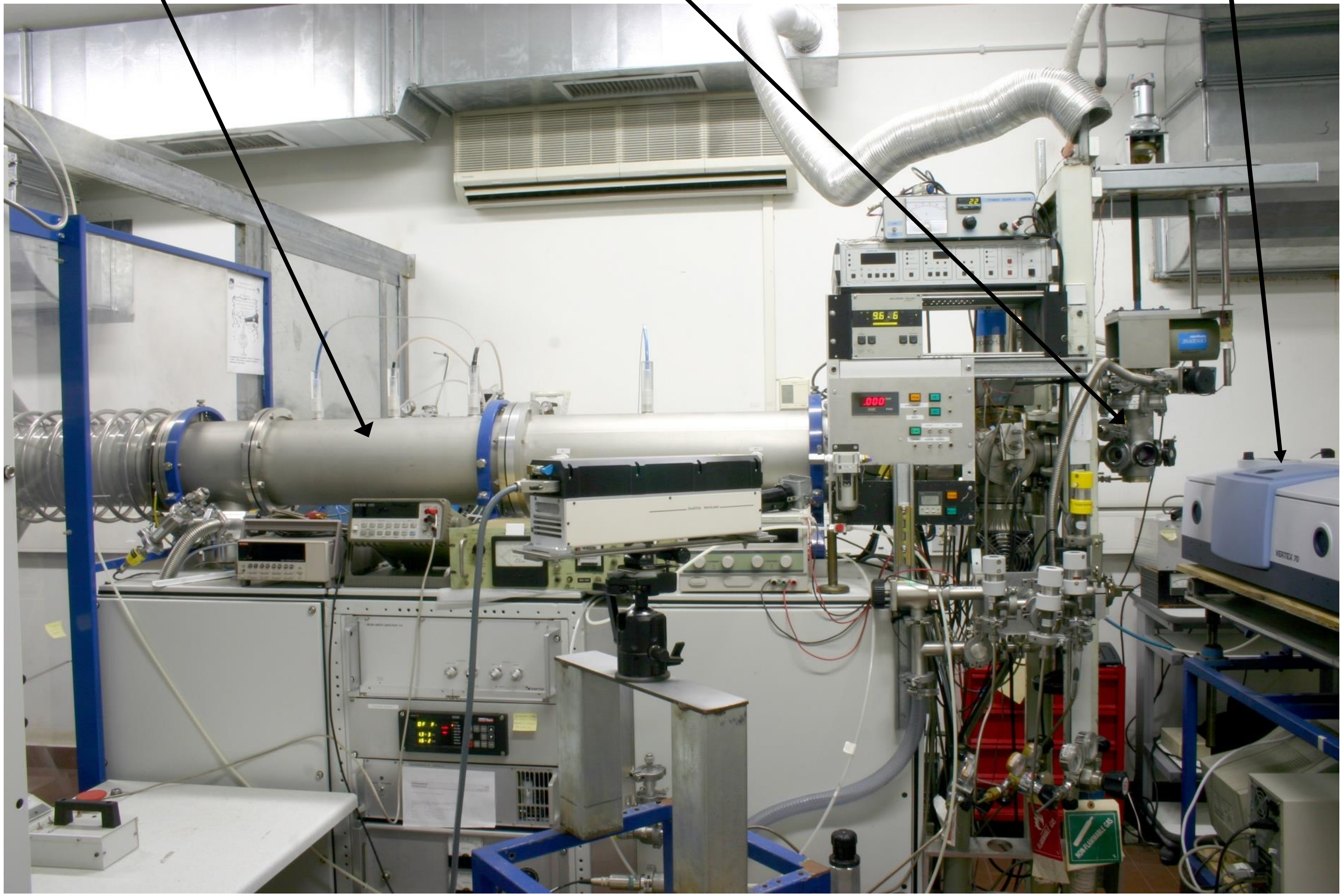
Experimental studies of the effects of cosmic rays in the chemistry of astrophysical ices

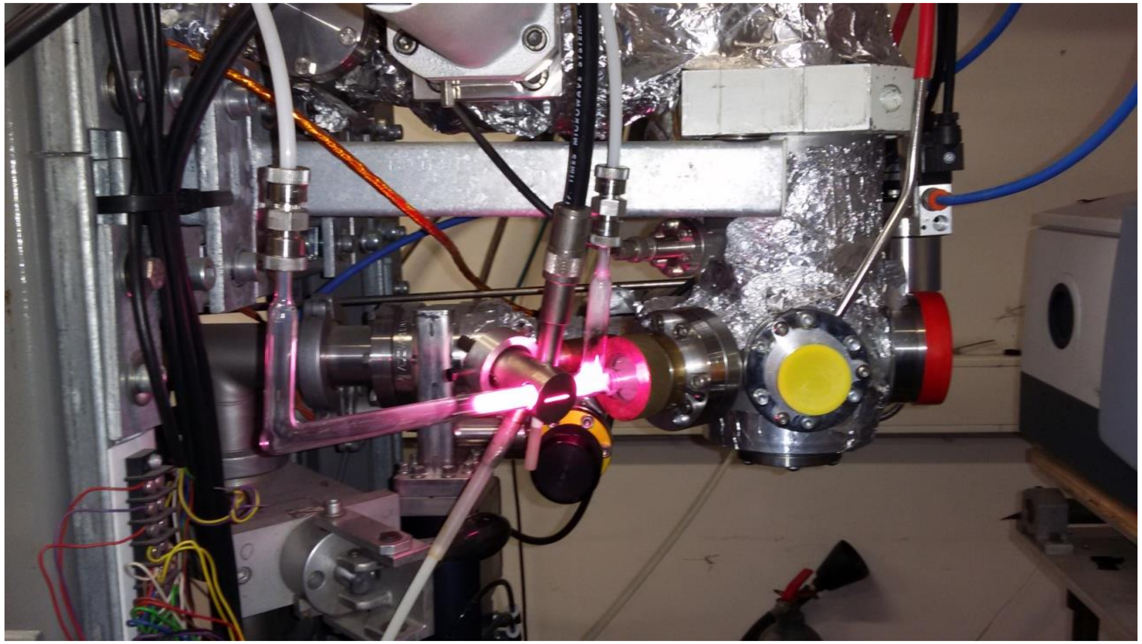
Maria Elisabetta Palumbo
INAF ï Osservatorio Astrofisico di Catania
mepalumbo@oact.inaf.it
http://www.oact.inaf.it/weboac/labsp/index.html

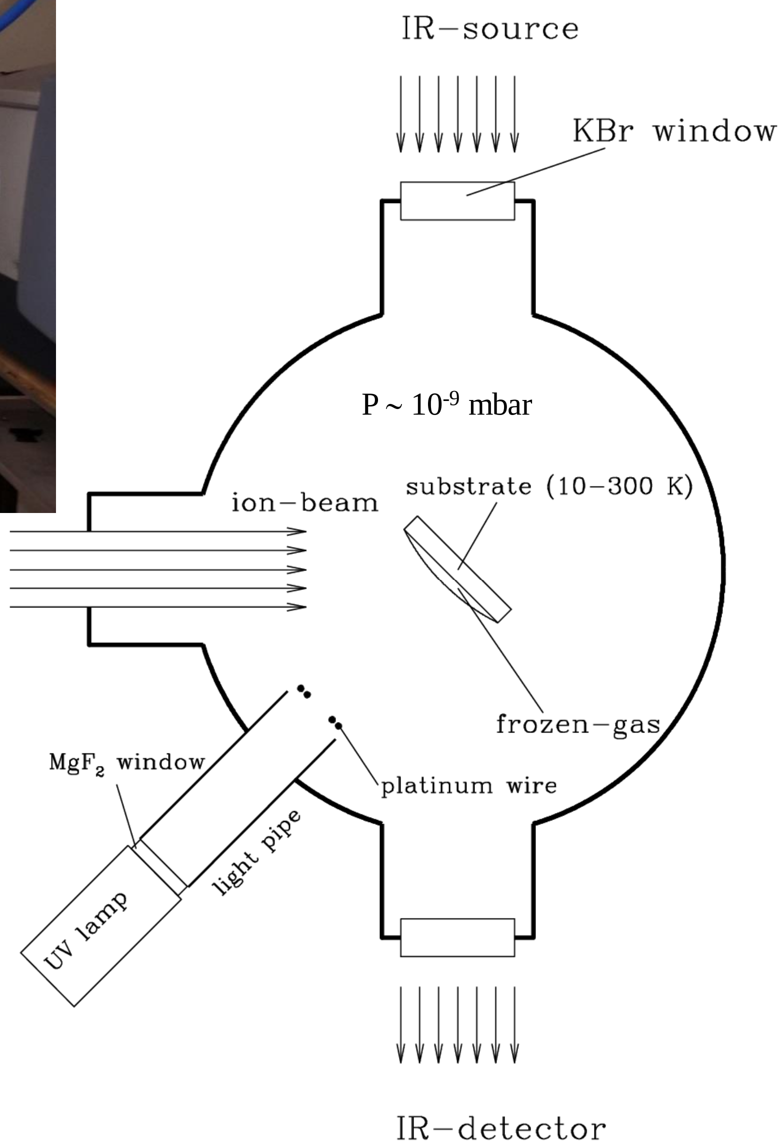
Laboratory for Experimental Astrophysics
Catania

Ion beam (100-400 keV) **Vacuum chamber** **FTIR spectrometer**



Vacuum chamber





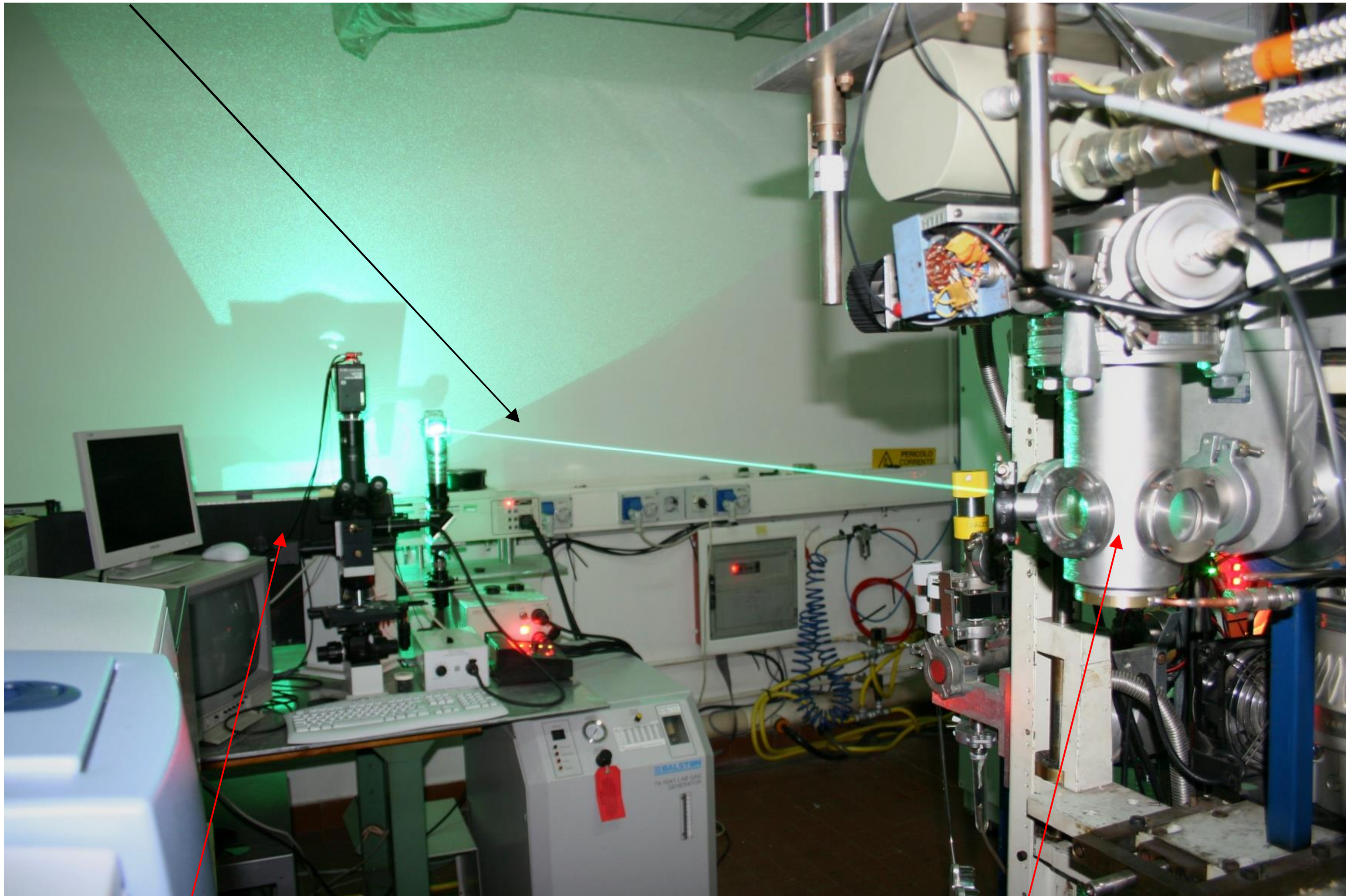
Analysis:

IR spectroscopy

Raman spectroscopy

In situ Raman spectroscopy

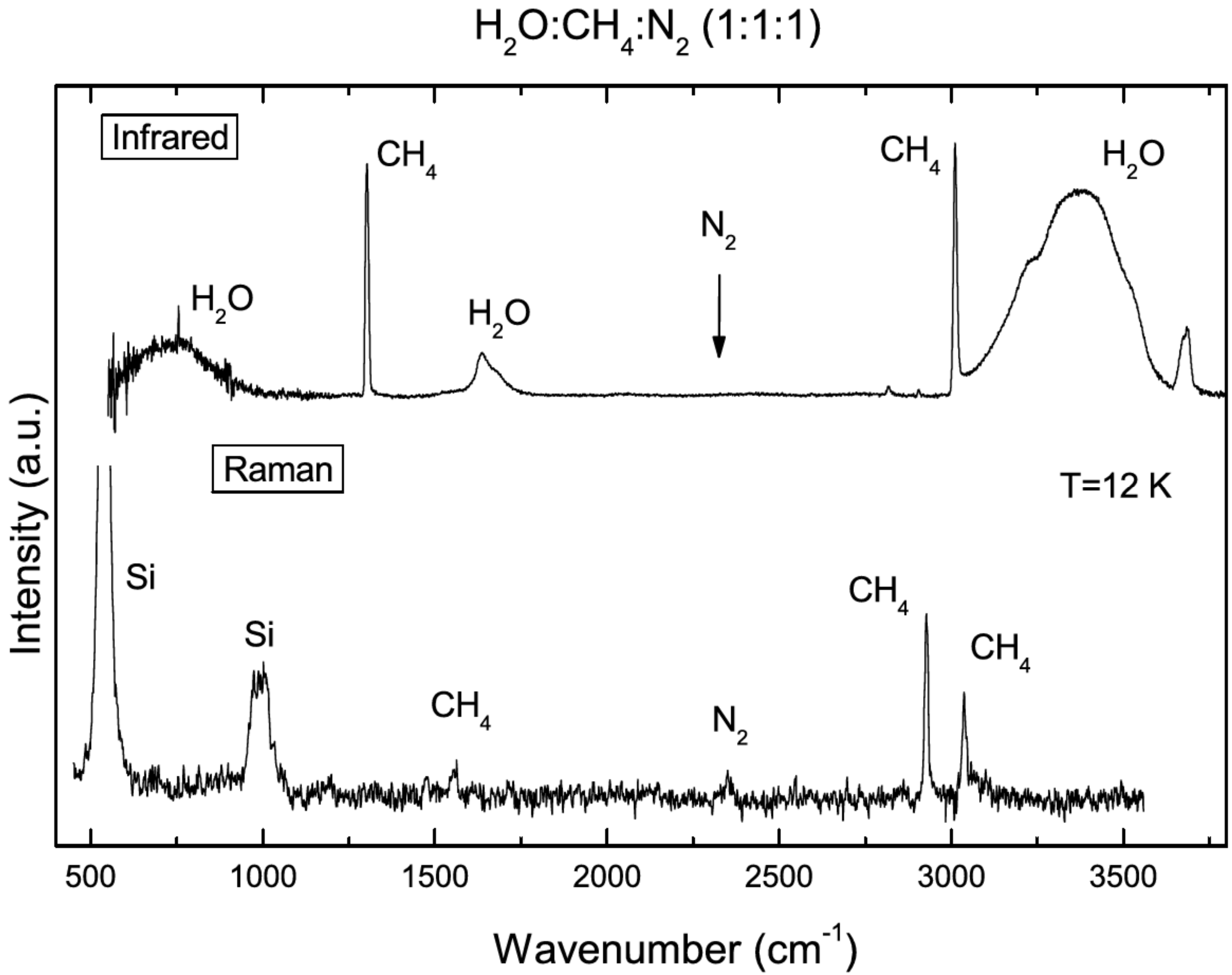
Laser Ar^+ (514.5 nm)



Raman spectrometer

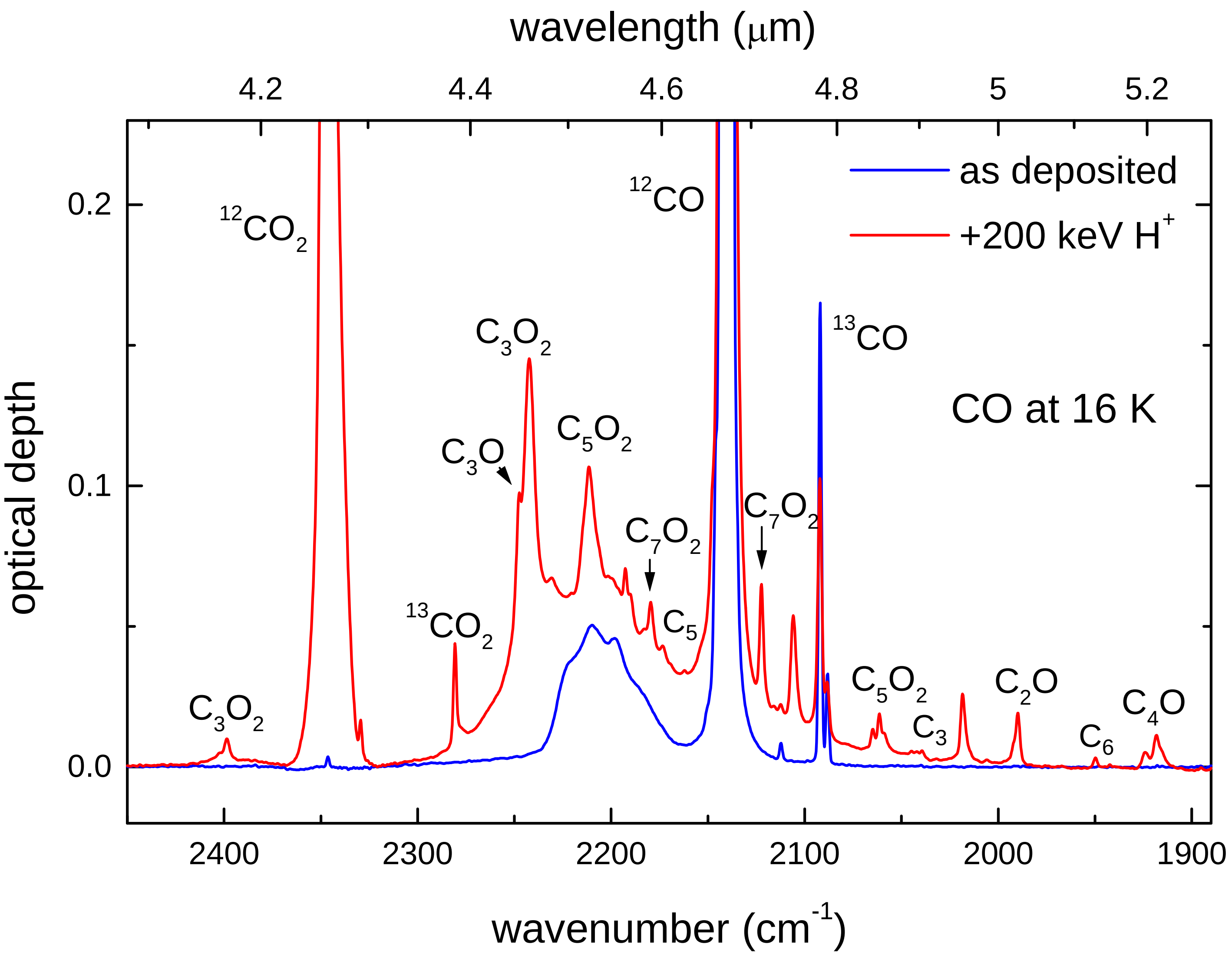
Vacuum chamber

IR and Raman spectroscopy



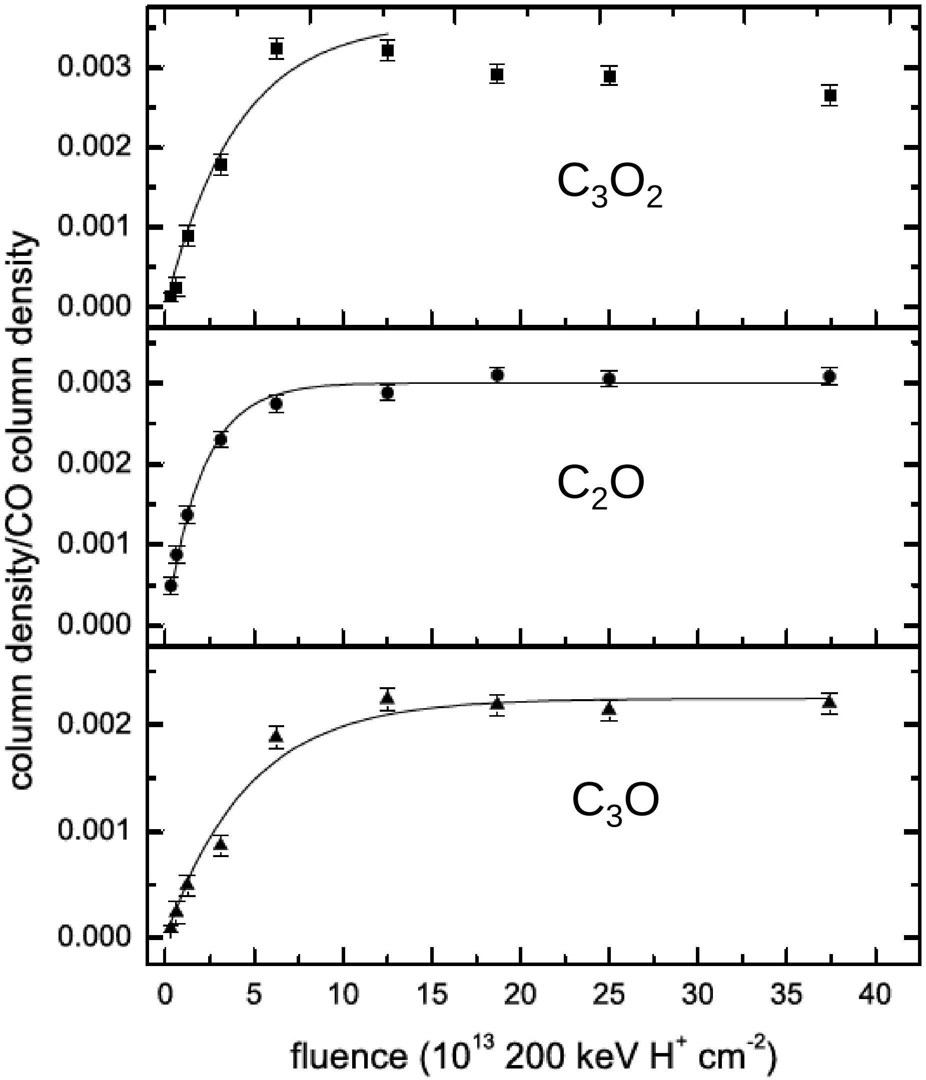
Palumbo M.E., Ferini G., Baratta G.A., 2004, Adv. Sp. Res. 33, 49

Formation of carbon chains



Trottier & Brooks 2004, ApJ 612, 1214; Loeffler et al. 2005, A&A 435, 587
Palumbo et al. 2008, ApJ 685, 1033; Seperuelo Duarte et al. 2010, A&A 512, A71

Formation of carbon chains



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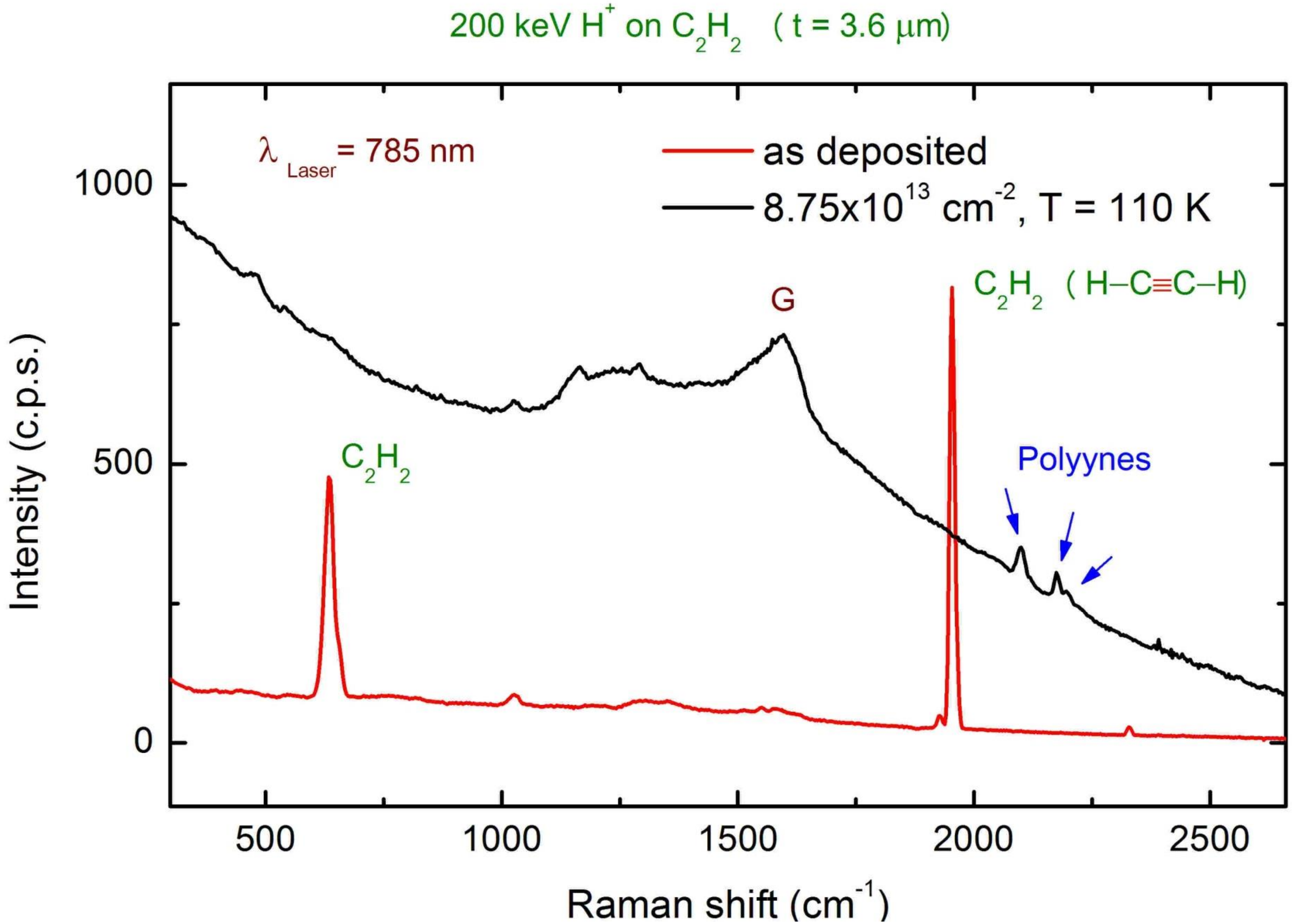
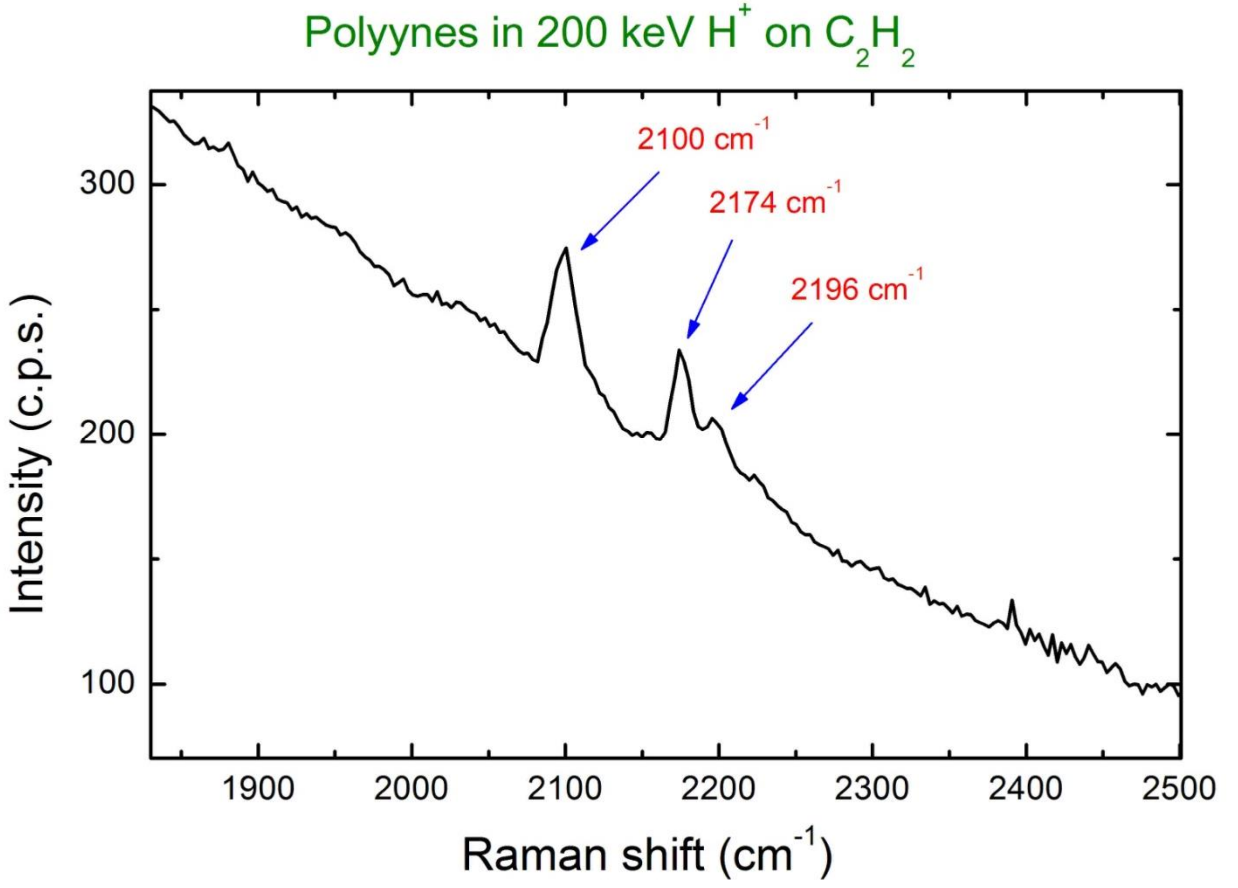


Compagnini et al. 2009, Carbon 47, 1605

Formation of carbon chains



Based on peak position

chains involved should contain 8-12 carbon atoms

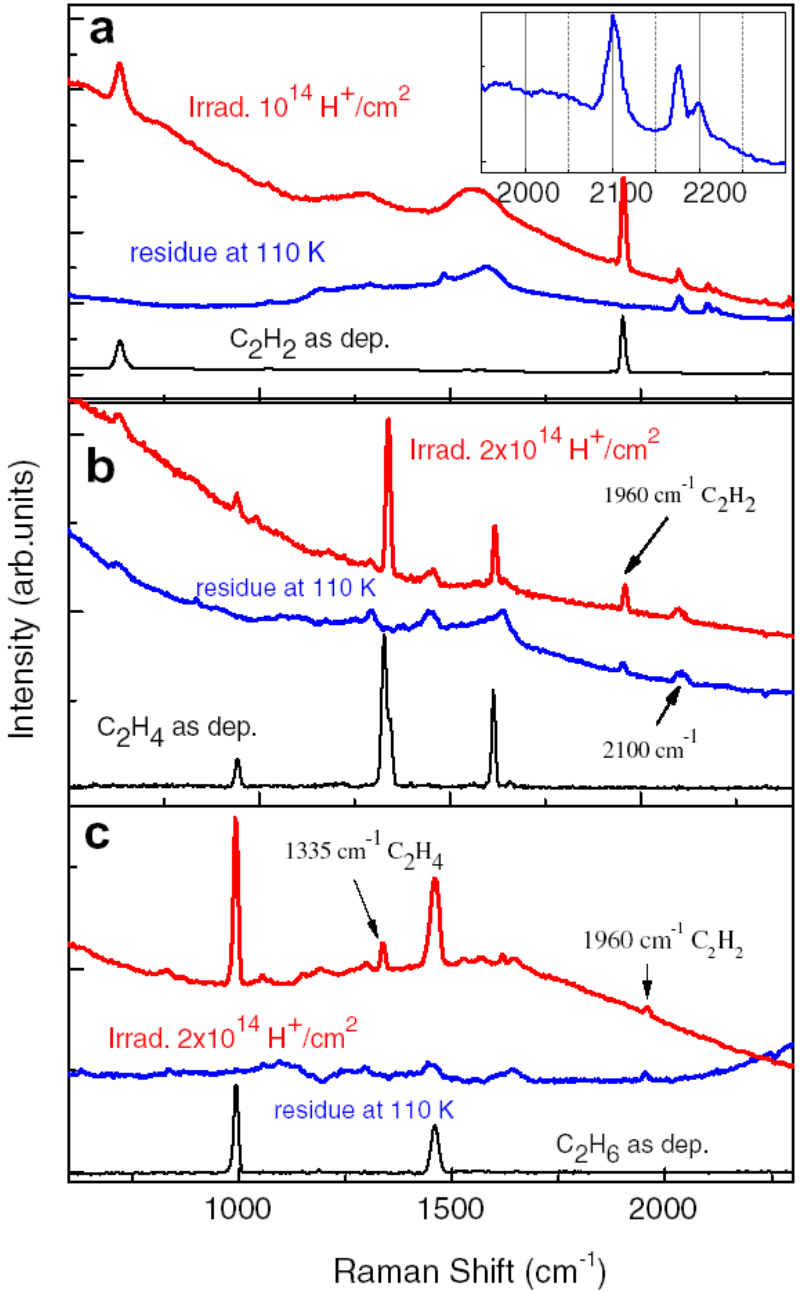
Compagnini et al. 2009, Carbon 47, 1605

Formation of carbon chains

$$C_2H_2 \xrightarrow{irrad.} R{-}(C{\equiv}C)_n{-}R$$

$$C_2H_4 \xrightarrow{irrad.} C_2H_2 + R{-}(C{\equiv}C)_n{-}R$$

$$C_2H_6 \xrightarrow{irrad.} C_2H_4 + C_2H_2 + R{-}(C{\equiv}C)_n{-}R$$



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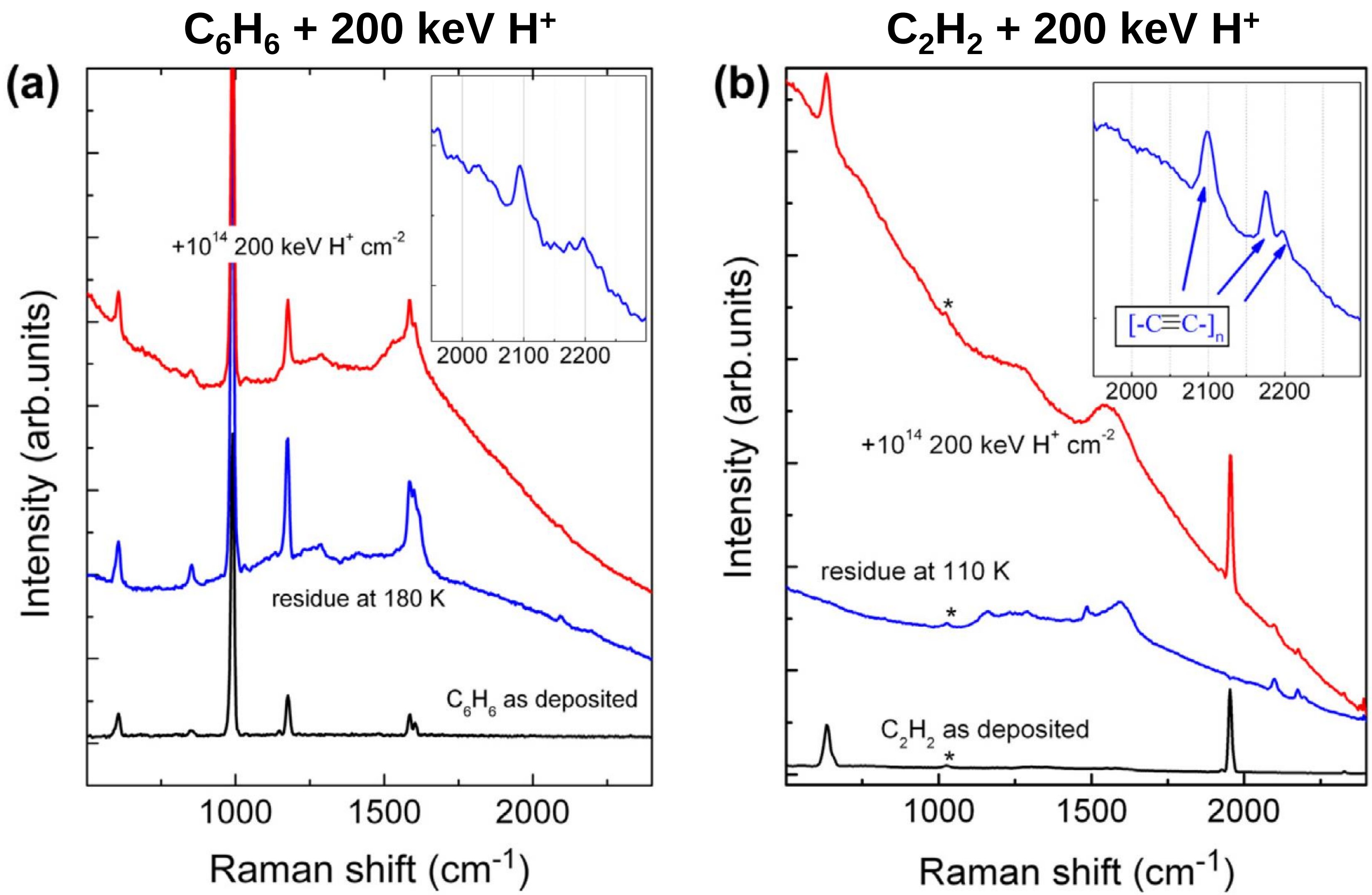
Formation of carbon chains



Puglisi et al. 2014, NIM B 326, 2

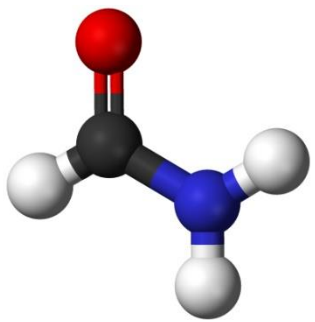
Formamide

is detected in both high and low-mass star forming regions with fractional abuncance ~10^{-10}-10^{-8}

Turner 1991, ApJS, 76, 617; Nummelin et al. 1998, ApJS, 117, 427; Halfen et al. 2011, ApJ, 743, 60;
Kahane et al. 2013, ApJ, 763, L38; Mendoza et al. 2014, MNRAS 445, 151;
López-Sepuclre et al. 2015, MNRAS 449, 2438; Codella et al. 2017, A&A 605, L3

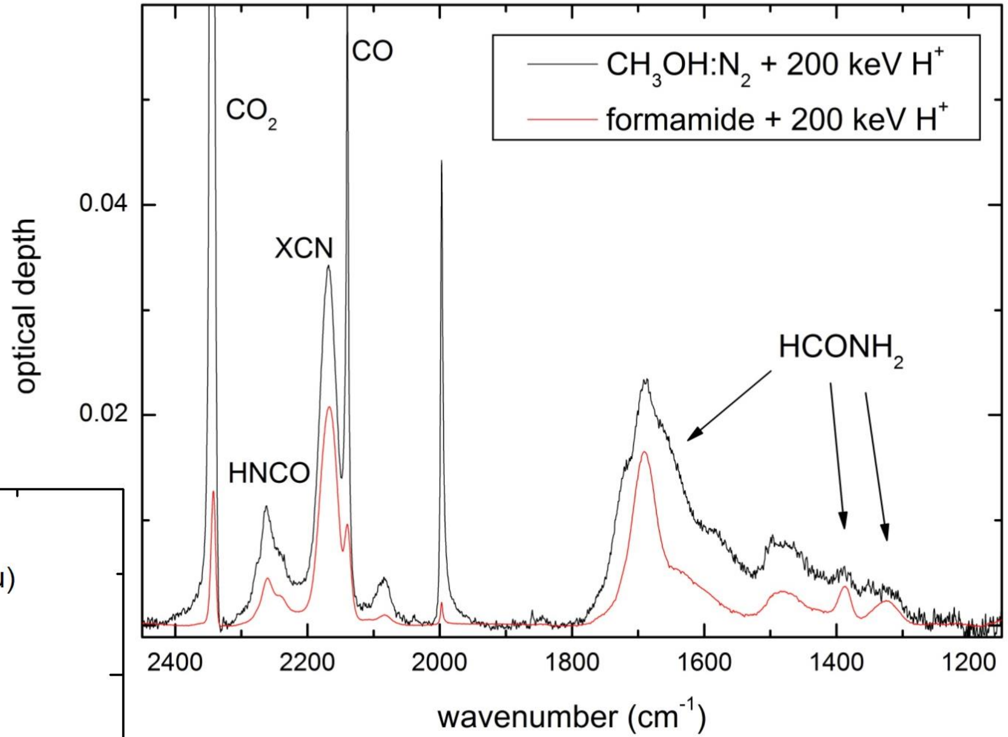
current theories predict its formation by reactions in the gas phase or on interstellar dust grains

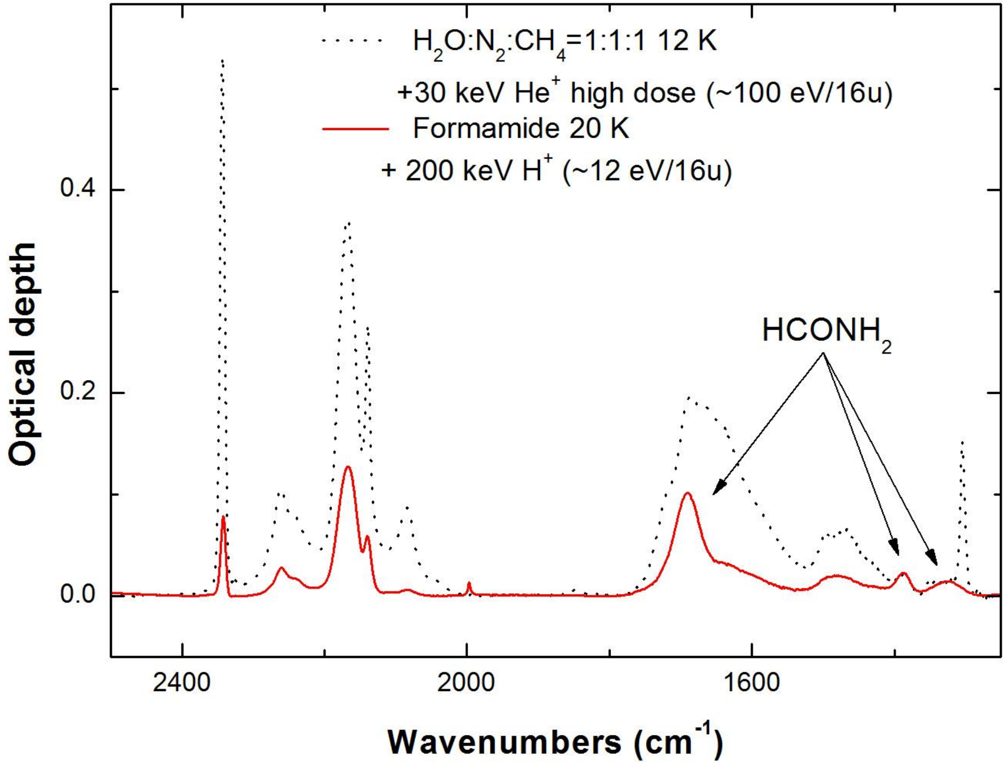
Vasyunin & Herbst 2013, ApJ, 769, 34; Balucani et al. 2015, MNRAS, 449, L16;
Barone et al. 2015, MNRAS, 453, L31; Vazart et al. 2016, J. Chem. Theory, Comput., 12, 5385;
Kanuchova et al. 2016, A&A 585, A155; Fedoseev et al. 2016, MNRAS, 460, 4297;
Vasyunin et al. 2017, ApJ, 842, 33; Urso et al. 2017, PCCP 19, 21759

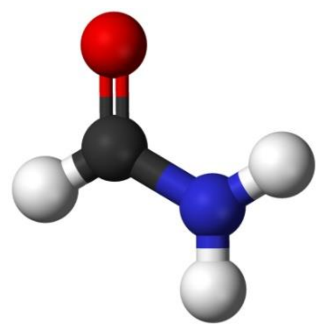


Formation of formamide

Kanuchova et al. 2016, A&A 585, A155;
Urso et al. 2017, PCCP 19, 21759







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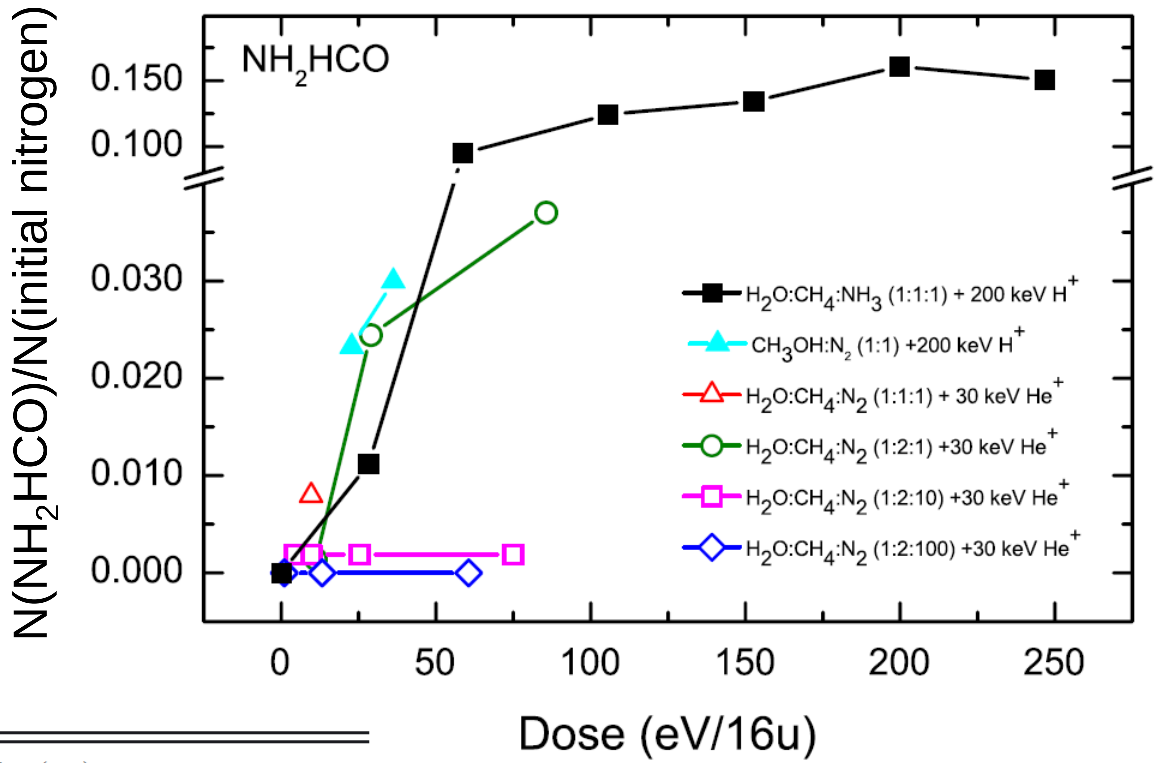
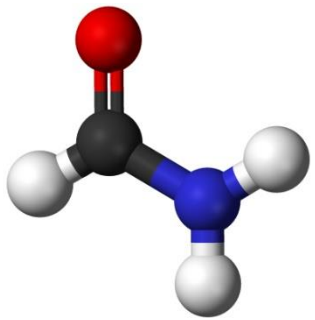
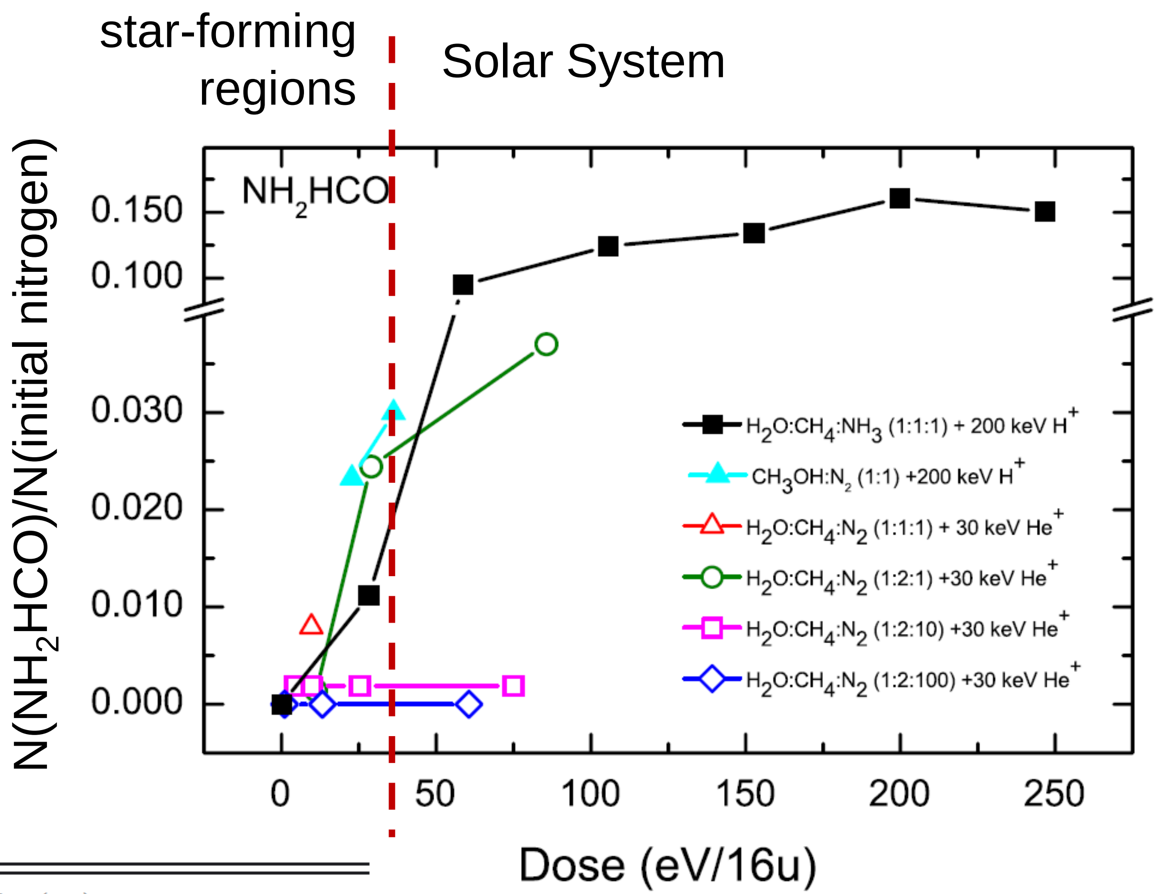


Dose (eV/16u)	Timescale (yr)			
	ionization rate (s^{-1})			
	1.3×10^{-17}	6×10^{-17}	3×10^{-16}	1.3×10^{-15}
1	1.1×10^7	2.5×10^6	5.0×10^5	1.1×10^5
10	1.1×10^8	2.5×10^7	5.0×10^6	1.1×10^6
100	1.1×10^9	2.5×10^8	5.0×10^7	1.1×10^7



Formation of formamide

Kanuchova et al. 2016, A&A 585, A155;
Urso et al. 2017, PCCP 19, 21759



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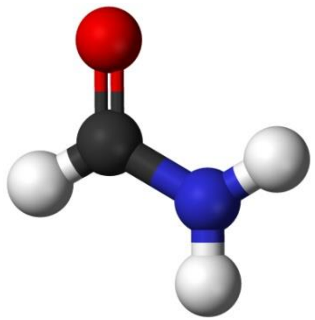


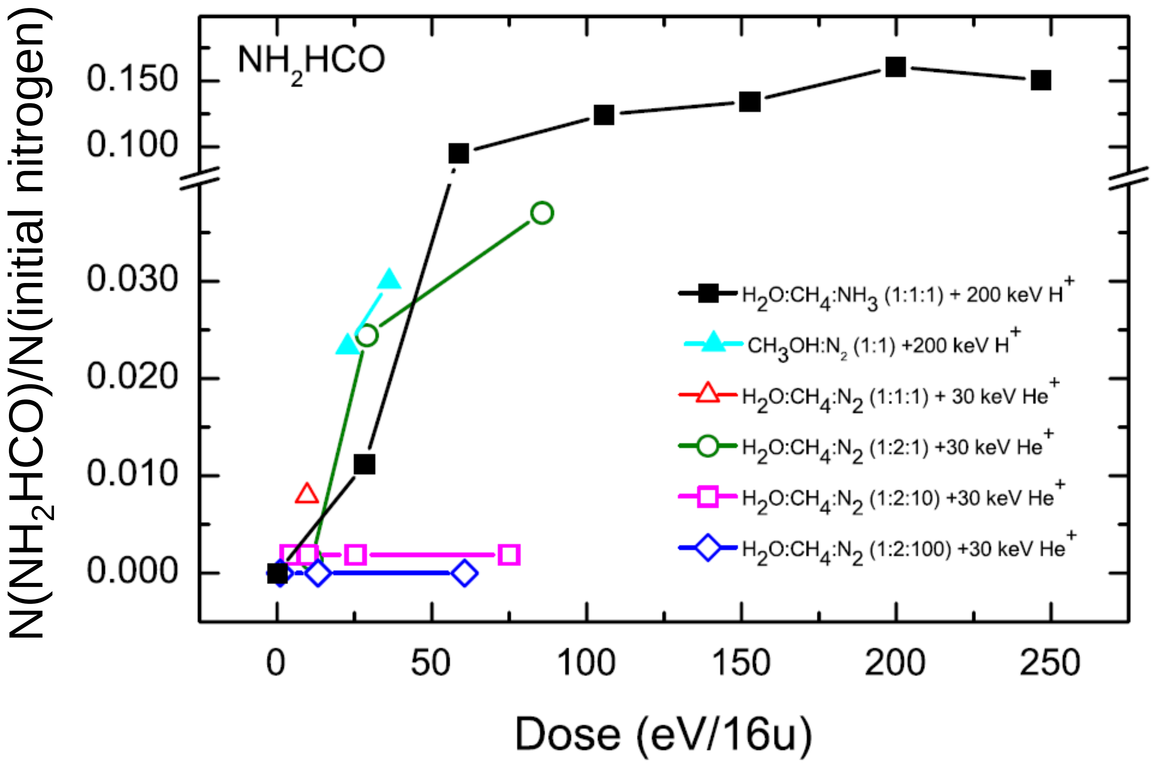
Formation of formamide

Kanuchova et al. 2016, A&A 585, A155;
Urso et al. 2017, PCCP 19, 21759

Experimental results

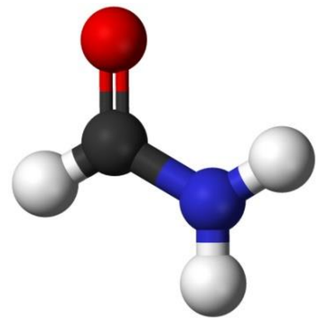
after dose = 10 eV/16u

NH_2HCO/nitrogen ~ 10^{-2}



Nitrogen cosmic abundance ~ $2x10^{-5}$

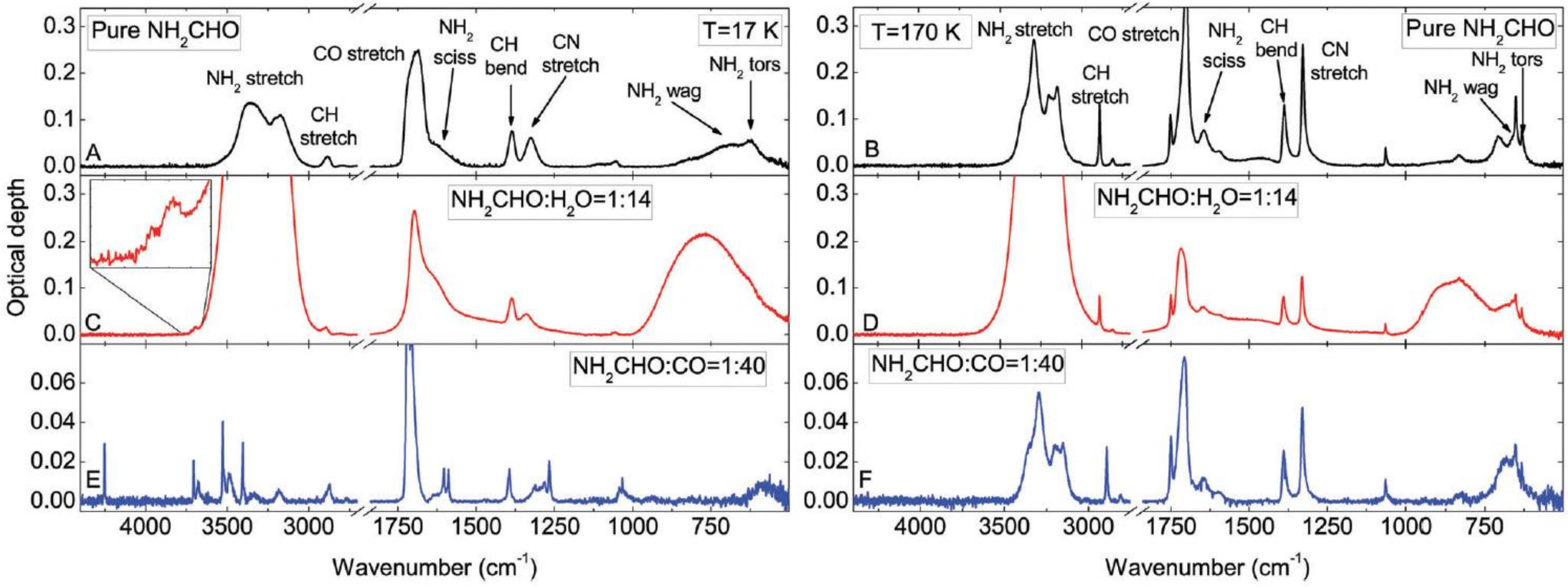
Assuming high N-depletion → NH_2HCO fractional abundance ~ 10^{-7}
comparable to observed values



Thermal desorption of formamide

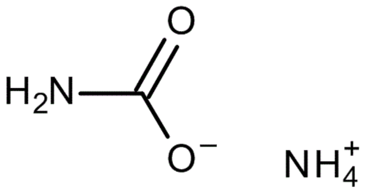
Pure NH_2CHO sublimates at about 220 K (Dawley et al. 2014; Urso et al. 2017)
When diluted in more volatile species NH_2CHO does not sublimate with the matrix

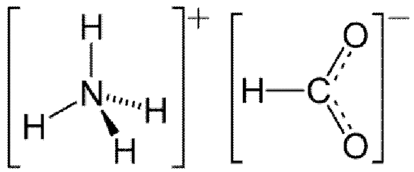
H_2O sublimation temperature ~ 160 K
CO sublimation temperature ~ 32 K

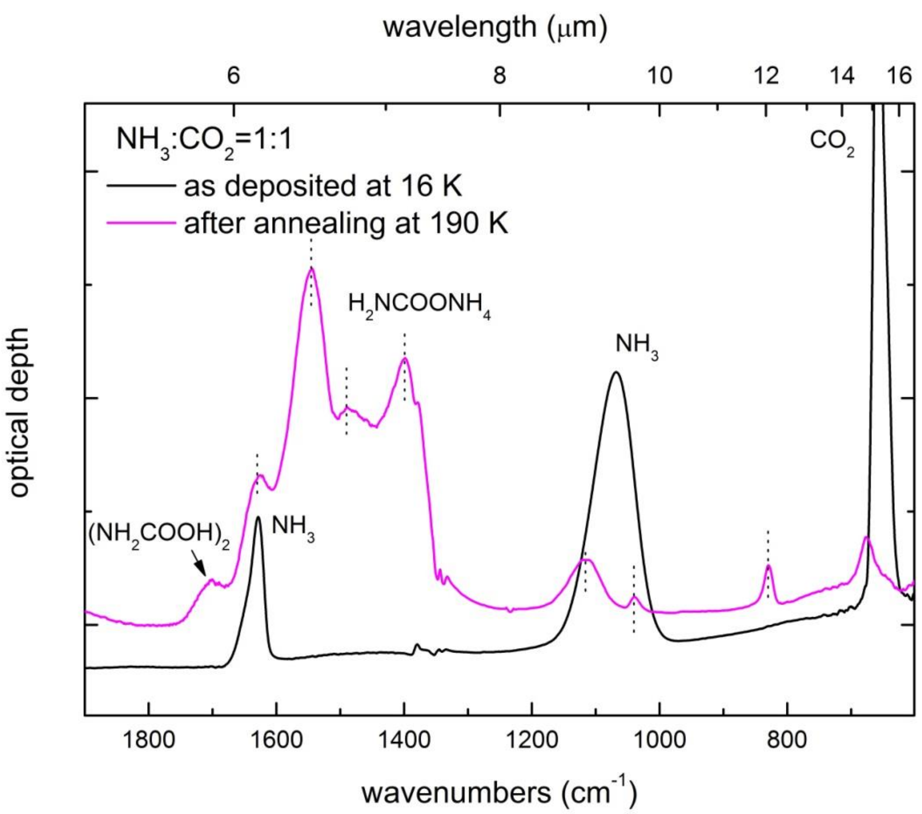


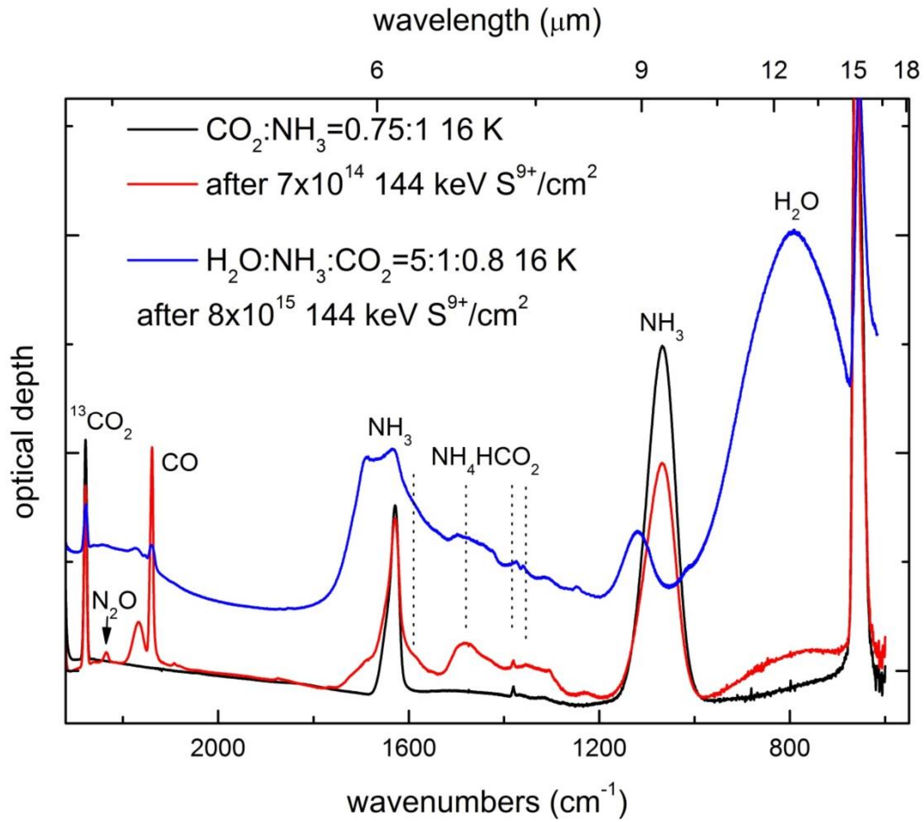
Urso et al. 2017, PCCP 19, 21759

Ammonium carbamate and ammonium formate



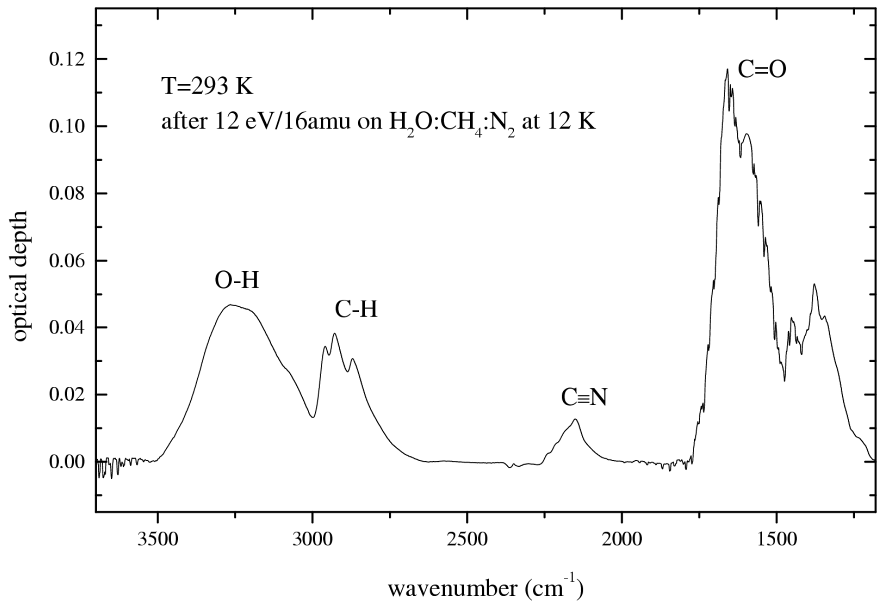






Lv et al. 2014, PCCP 16, 3433

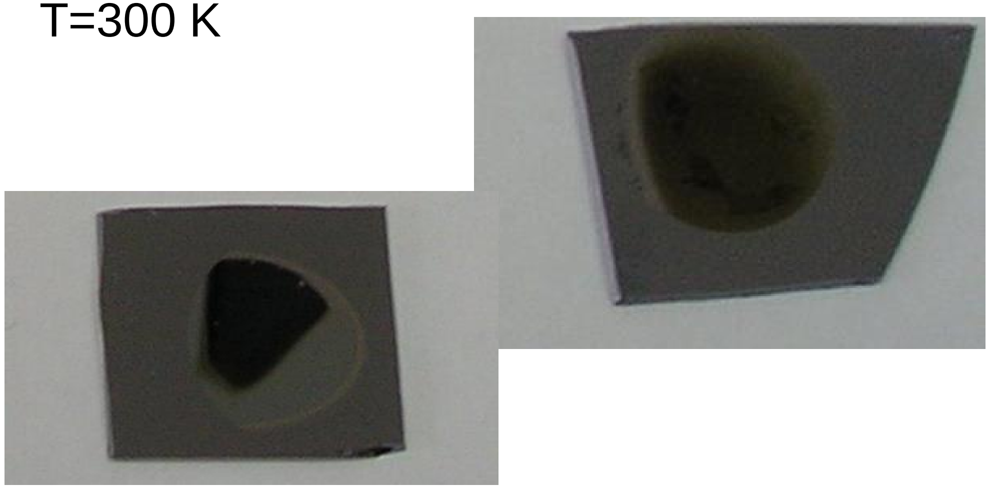
Complex molecules trapped in the residue



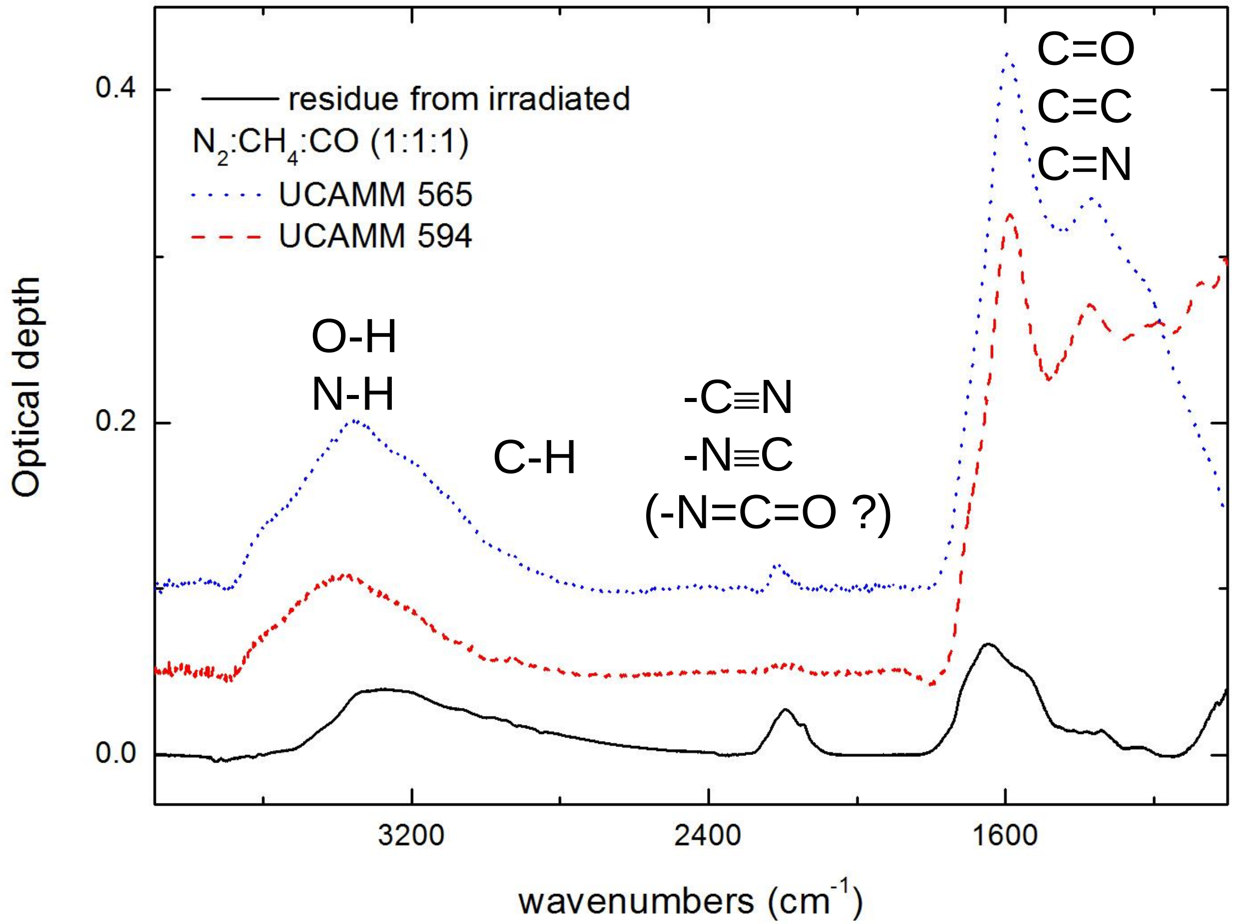
Energetic processing modifies the chemical composition of the sample forming volatile species and a refractory residue

Strazzulla, Baratta, Palumbo 2001, Spectrochim. Acta A 57, 825
Palumbo, Ferini, Baratta, 2004, Ad Sp Res 33, 49

T=300 K



Ultra Carbonaceous Antarctic micrometeorites probing the Solar System beyond the nitrogen snow-line



Dartois et al. 2013, Icarus 224, 243; Baratta et al. 2015, Pl. Sp. Sci., 118, 211
Augé et al. 2016, A&A 592, A99; Dartois et al. 2018, A&A 609, A65

Do complex molecules survive in the interplanetary medium?

- ✓Complex molecules formed after cosmic-ray bombardment of simple ices remain trapped in the refractory residue;

- ✓Infrared spectra of micrometeorites show the presence of astrobiologically relevant chemical bonds;

- ✓Formation of organic refractory material could have occurred in comets and TNOs and/or during the protostellar phase;

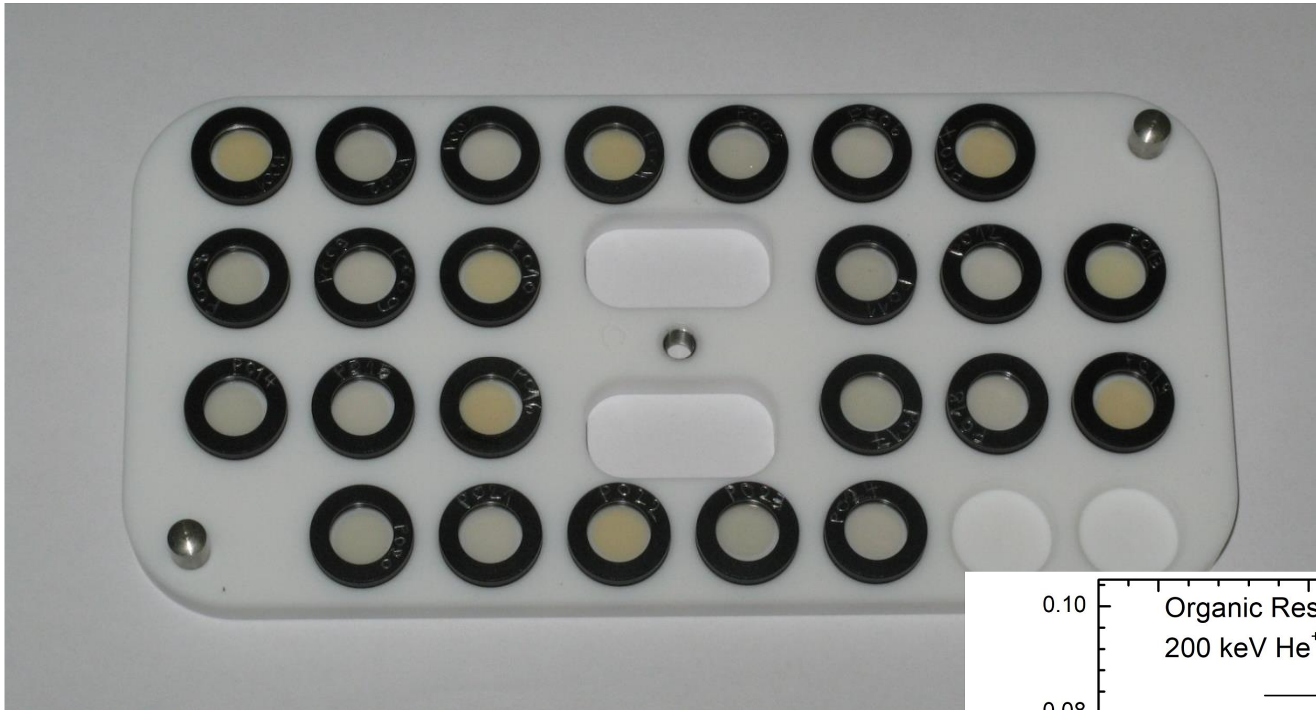
- ✓It has been suggested that comets, asteroids, and micrometeorites could have delivered organic material on the early Earth;

How long complex molecules trapped in the residue survive in the interplanetary medium exposed to UV solar photons?

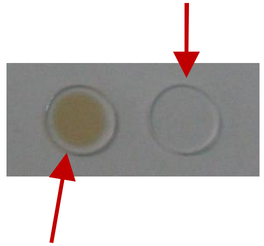
Photochemistry on the Space Station

This is an international project (P.I. H. Cottin) related to ASTROBIOLOGY
This project is approved by ESA (European Space Agency)
The Italian participation (P.I. G.A. Baratta) is funded by ASI (Agenzia Spaziale Italiana)
The aim is to study the survival of organic material exposed to solar UV radiation
We prepared organic refractory residues that remained exposed for about 16 months

Photochemistry on the Space Station



MgF_2 substrate



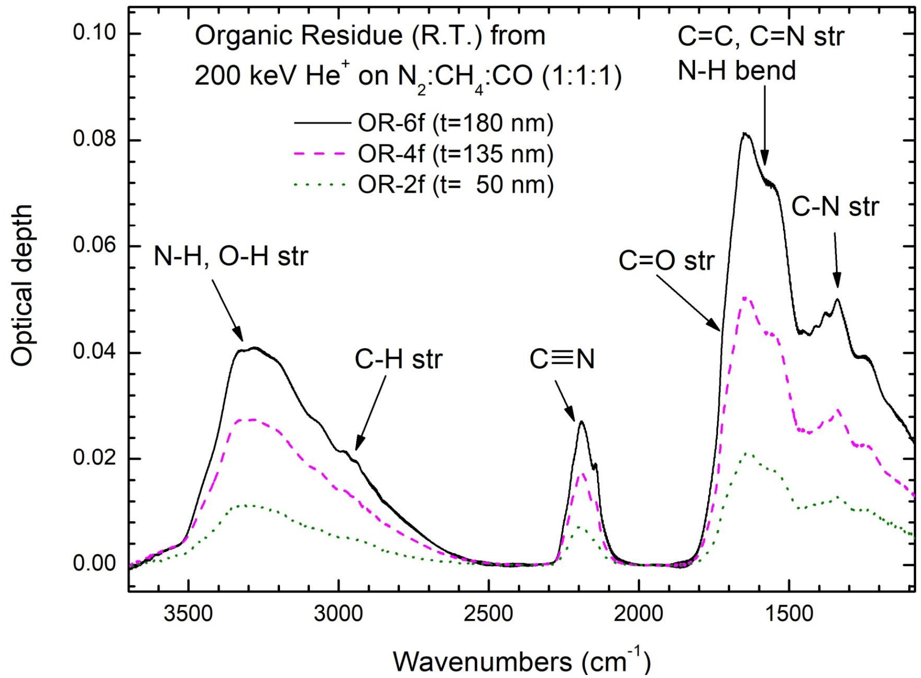
Residue on MgF_2

Residues after 200 keV He^+ on N_2:CH_4:CO at 16 K

3 different thicknesses of the residue
(180 nm; 135 nm; 50 nm)

10 samples for each thickness

Baratta et al. 2015, Planet. Space Science, 118, 211
Baratta et al. 2018, Astrobiology, submitted



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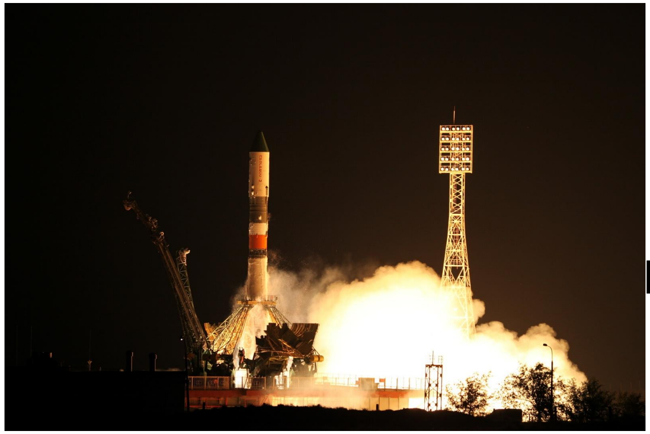
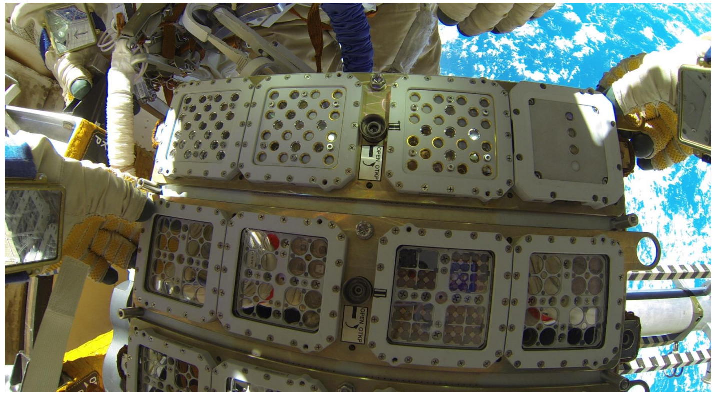


24 July 2014 launch of rocket "Soyuz-U" to transport cargo ship "Progress M-24Mñ from Baikonur (Kazakhstan)

18 August 2014
Expose-R facility placed outside the ISS on the Universal Platform D of the Russian module Zvezda



22 October 2014
Removal of protective cover

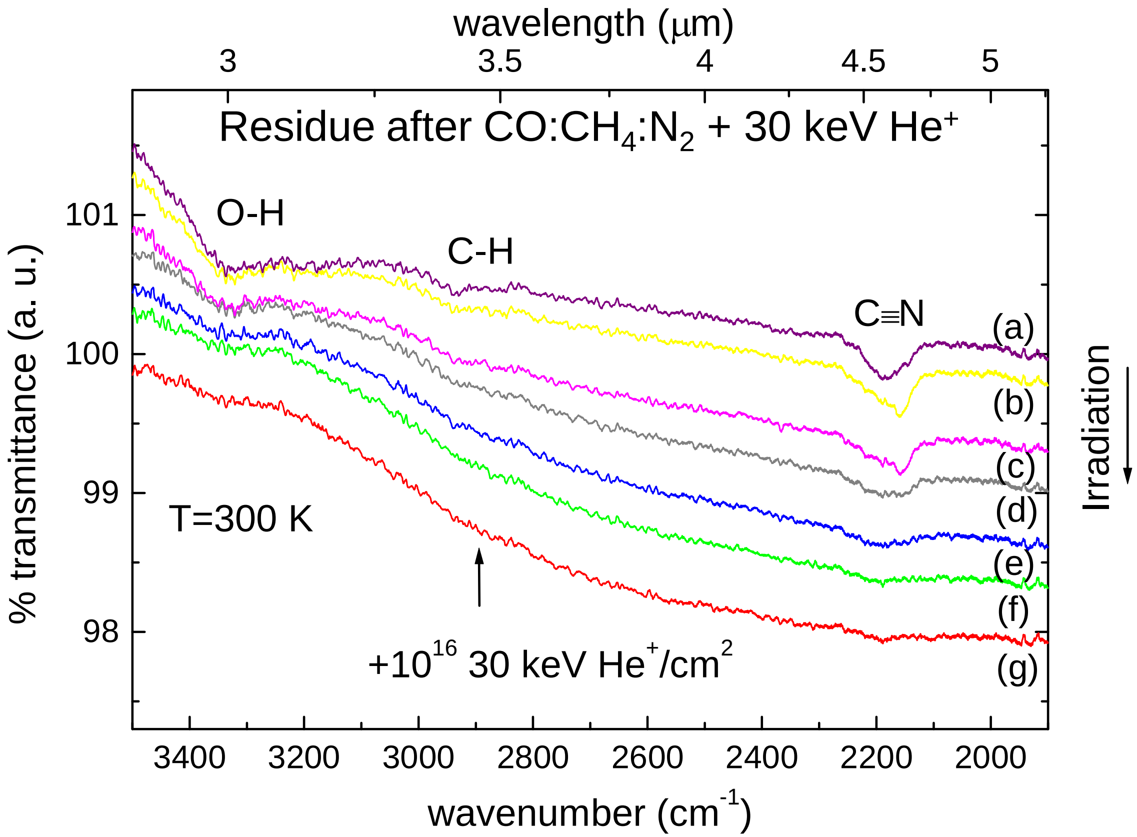
3 February 2016
Expose-R facility returned inside the ISS

2 March 2016 samples landed at Karaganda (Kazakhstan), on-board the Soyuz 44S return capsule

Exposure to space vacuum lasted **531 days**
Exposure to solar UV photons lasted **469 days**

Work in progress

Investigate the effects of solar wind ions and solar energetic particles (SEP)



Palumbo M.E., Ferini G., Baratta G.A., 2004, Adv. Space Res. 33, 49

Ferini G., Baratta G.A., Palumbo M.E., 2004, A&A 414, 757

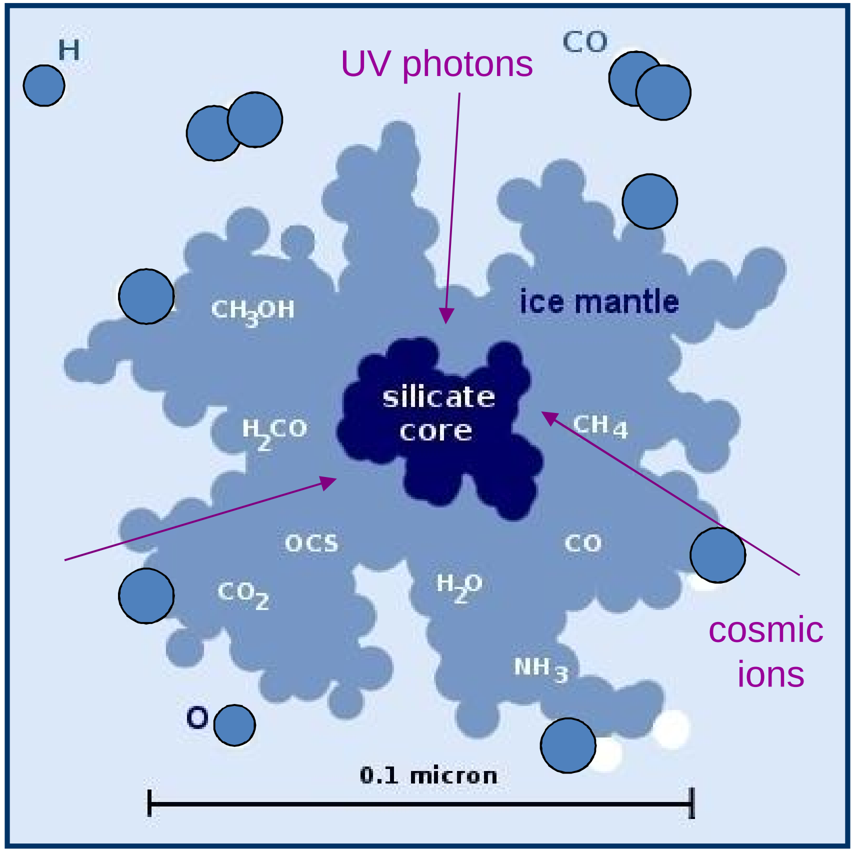
In summary

Cosmic-rays

- ✓ **modify the chemical composition of icy grain mantles;**

- ✓ **give a significant contribution to the formation of complex molecules;**

- ✓ **could have contributed to the synthesis of the organic material from which life originated.**



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Riccardo Urso

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MIUR PRIN
VAMDC Virtual Atomic and Molecular Data Centre
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LASSIE
Vamos Seguro
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