Formation of complex molecules after cosmic ion bombardment and UV photolysis of interstellar ice analogues

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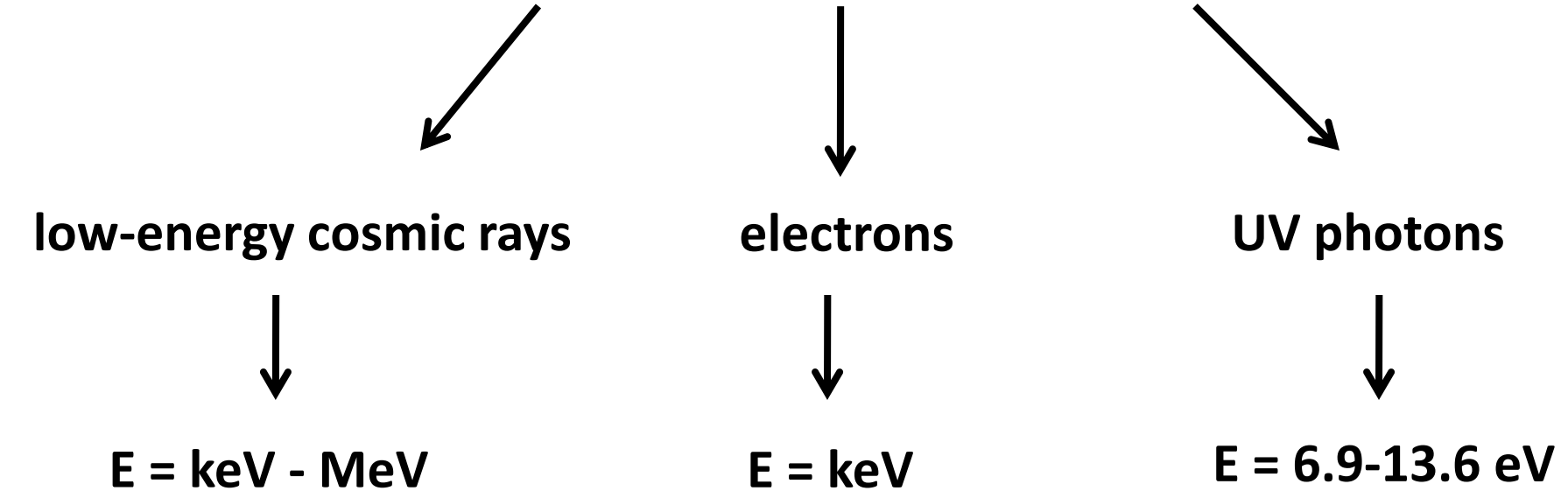
Energetic processing in dense molecular clouds

High density and high extinction → stellar radiation does not penetrate molecular clouds

Interaction of cosmic rays with molecular clouds

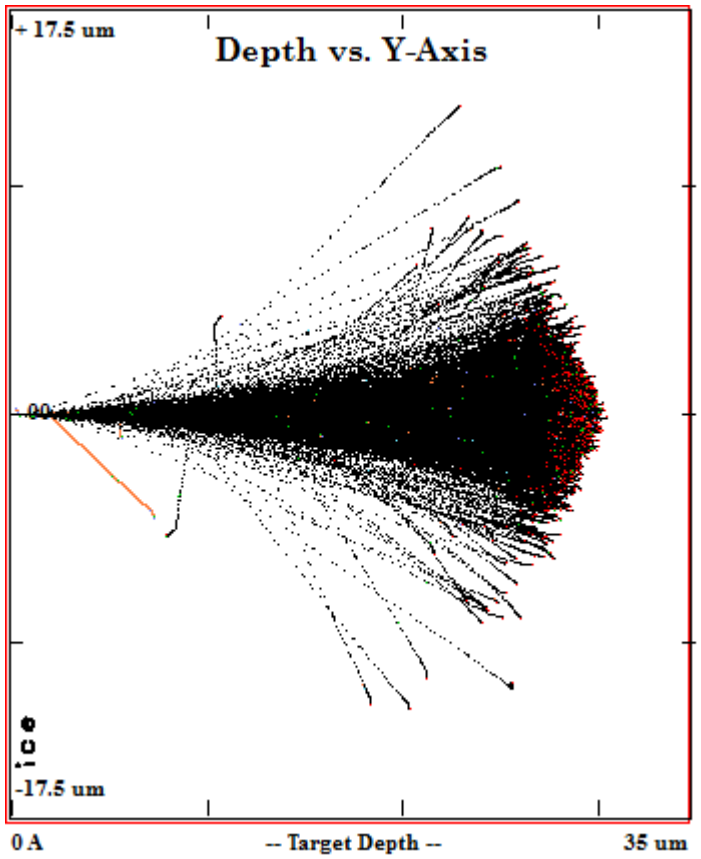


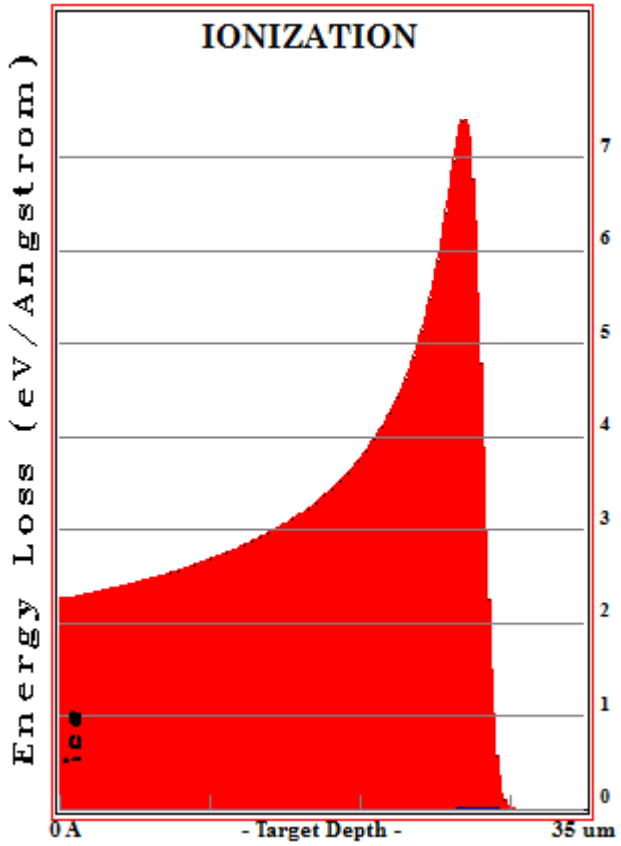
Energetic processing in the Solar System

	Energy		Fluxes (cm^{-2} s^{-1})
Solar Photons	2 eV	Visible	$2.0 \cdot 10^{17}$
	4 eV	NUV	$1.5 \cdot 10^{16}$
	6 eV	FUV	$3.0 \cdot 10^{13}$
Solar Wind (1 AU)			
	1keV	H^+	$3.0 \cdot 10^{8}$
	4keV	He^{2+}	
Solar Flares (1 AU)			
	>1 MeV	H^+	10^{10} (cm^{-2} yr^{-1})
	>1 MeV	He^{2+}	
Galactic cosmic rays			
	>1 MeV	H^+	1-10
	>1 MeV	He^{2+}	

Interaction of ions with matter

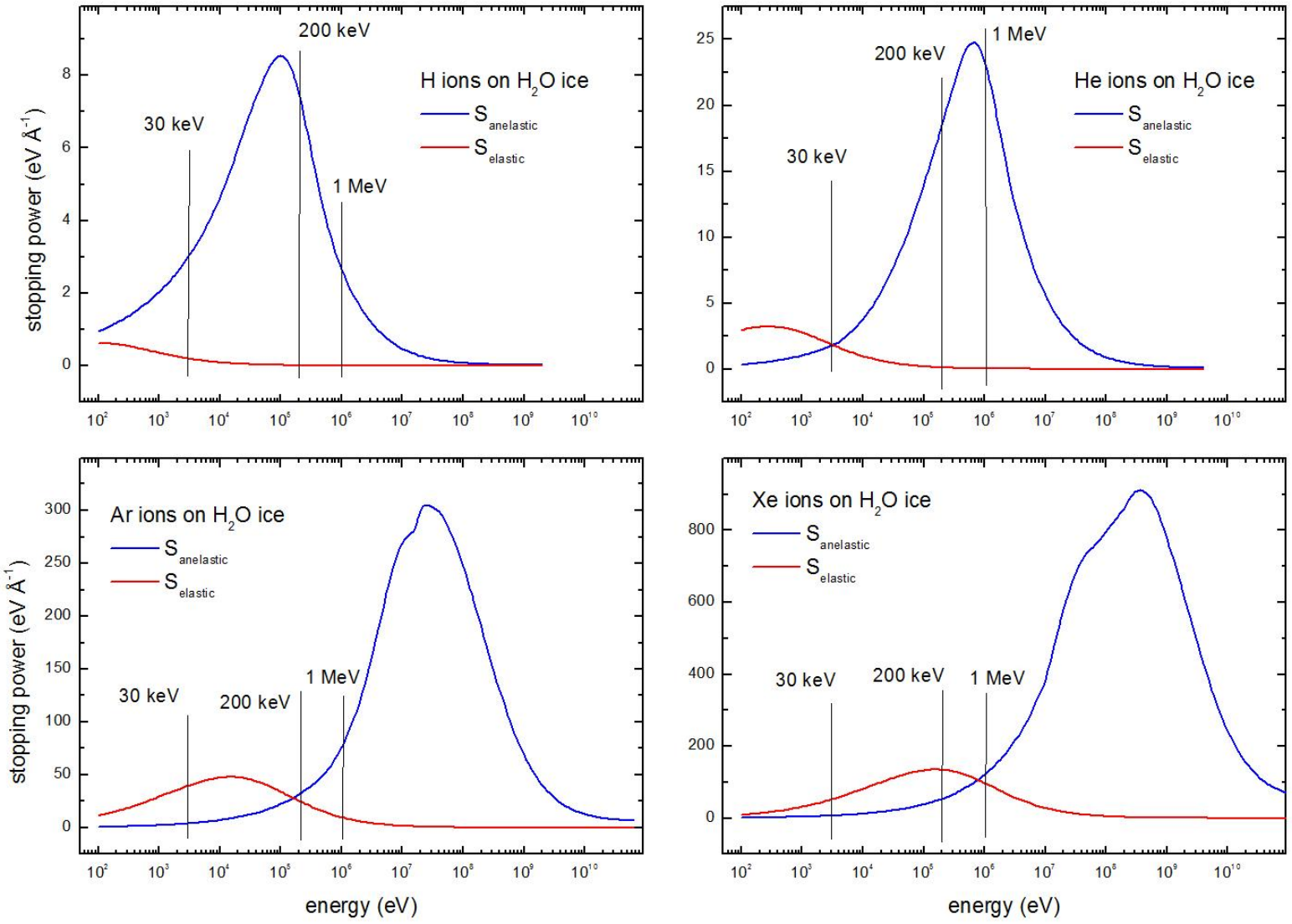
1 MeV protons on H_2O





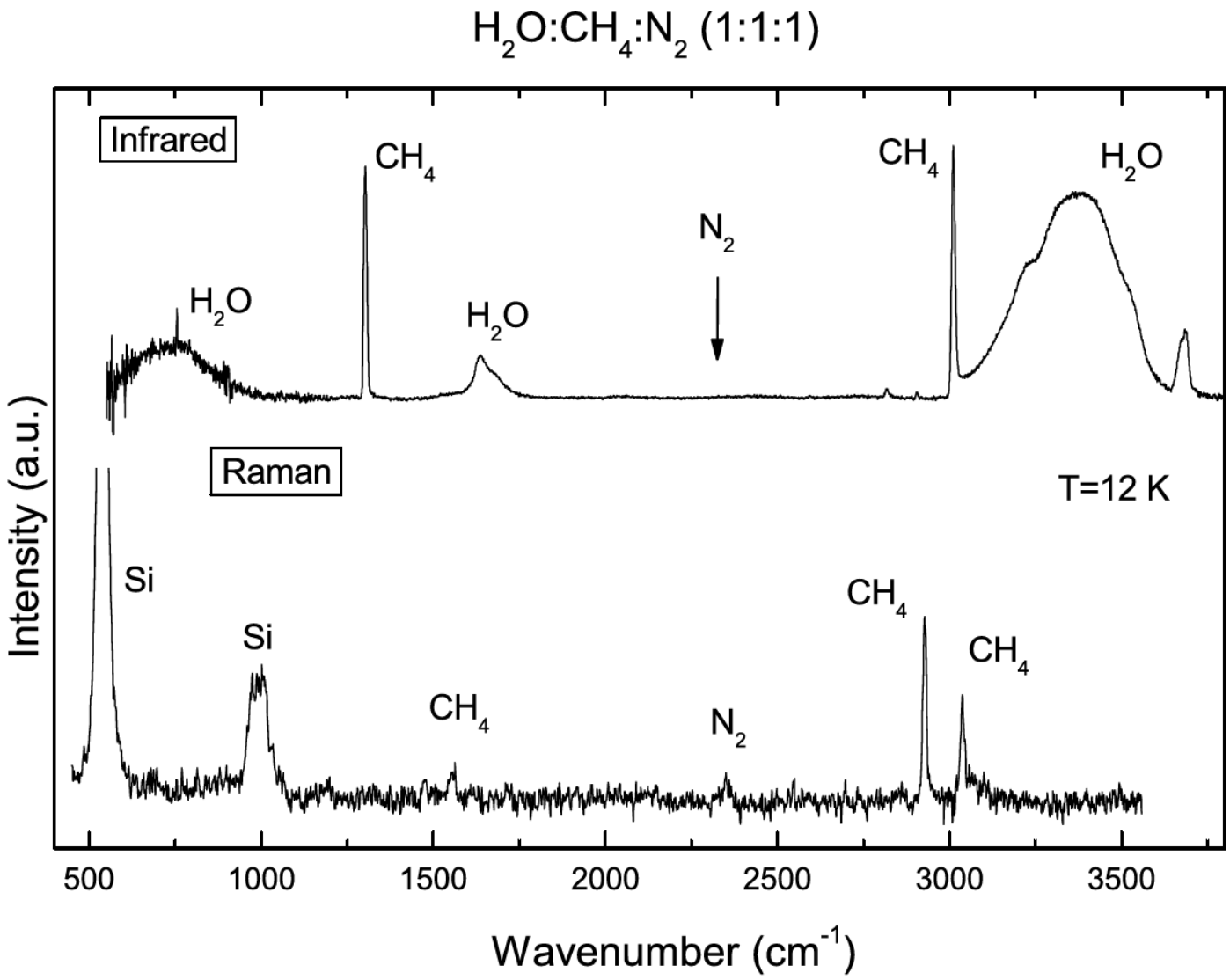
J.F. Ziegler: SRIM (Stopping and Range of Ions in Matter); TRIM (TRansport of Ions in Matter)

Interaction of ions with matter



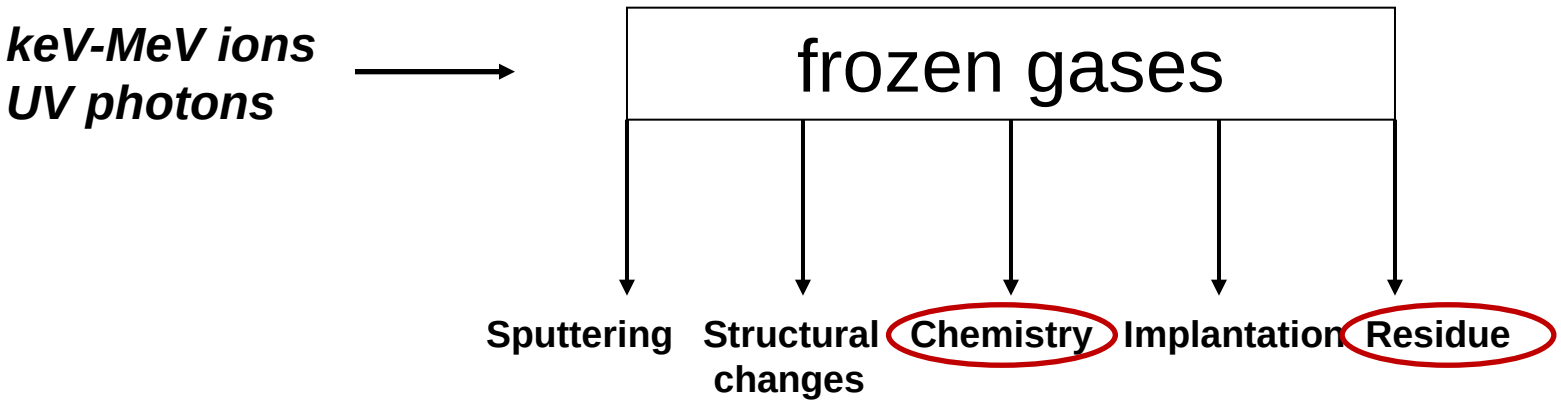
J.F. Ziegler: SRIM (Stopping and Range of Ions in Matter); TRIM (TRansport of Ions in Matter)

IR and Raman spectroscopy



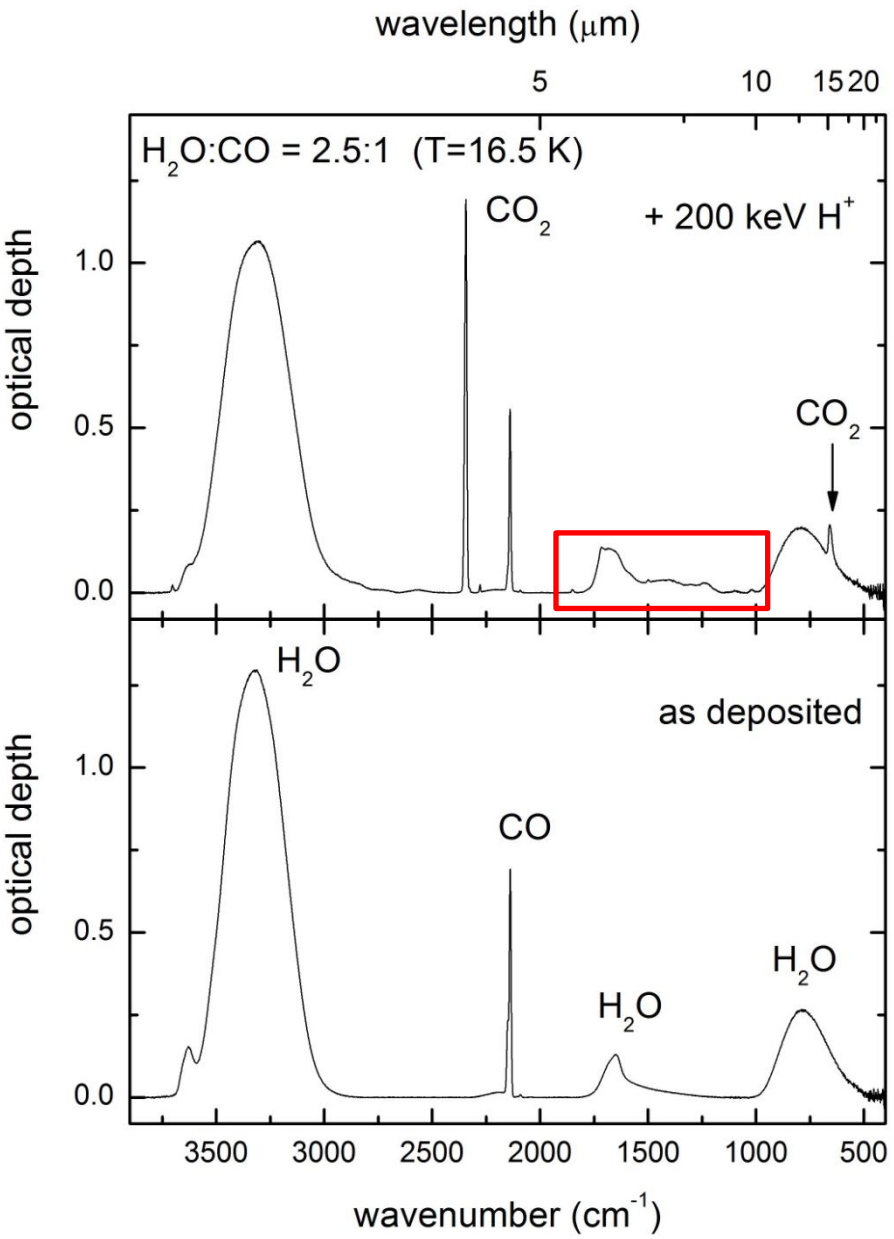
Palumbo M.E., Ferini G., Baratta G.A., 2004, Adv. Sp. Res. 33, 49

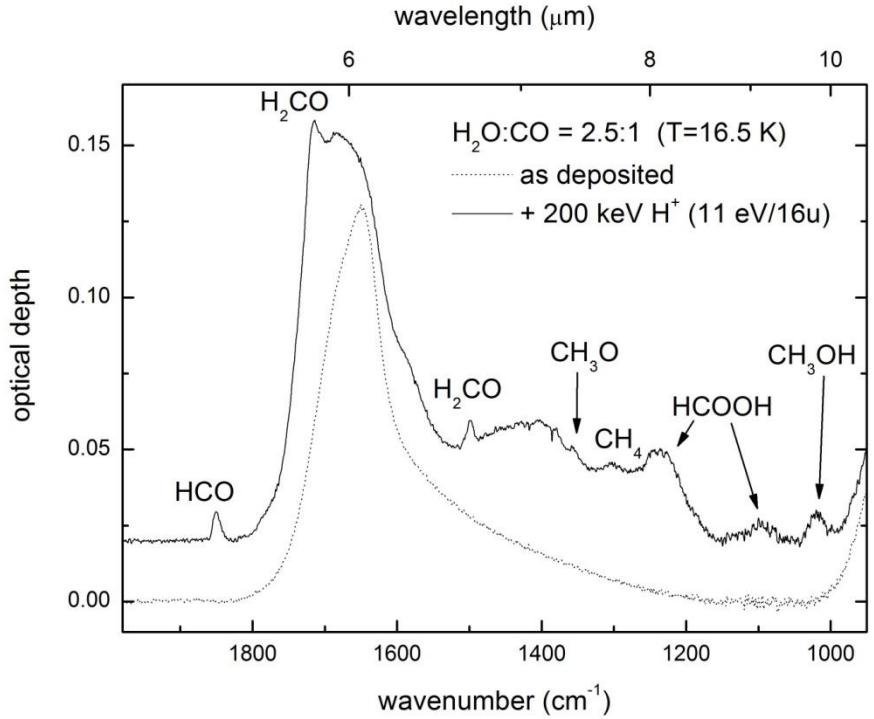
Effects of energetic processing



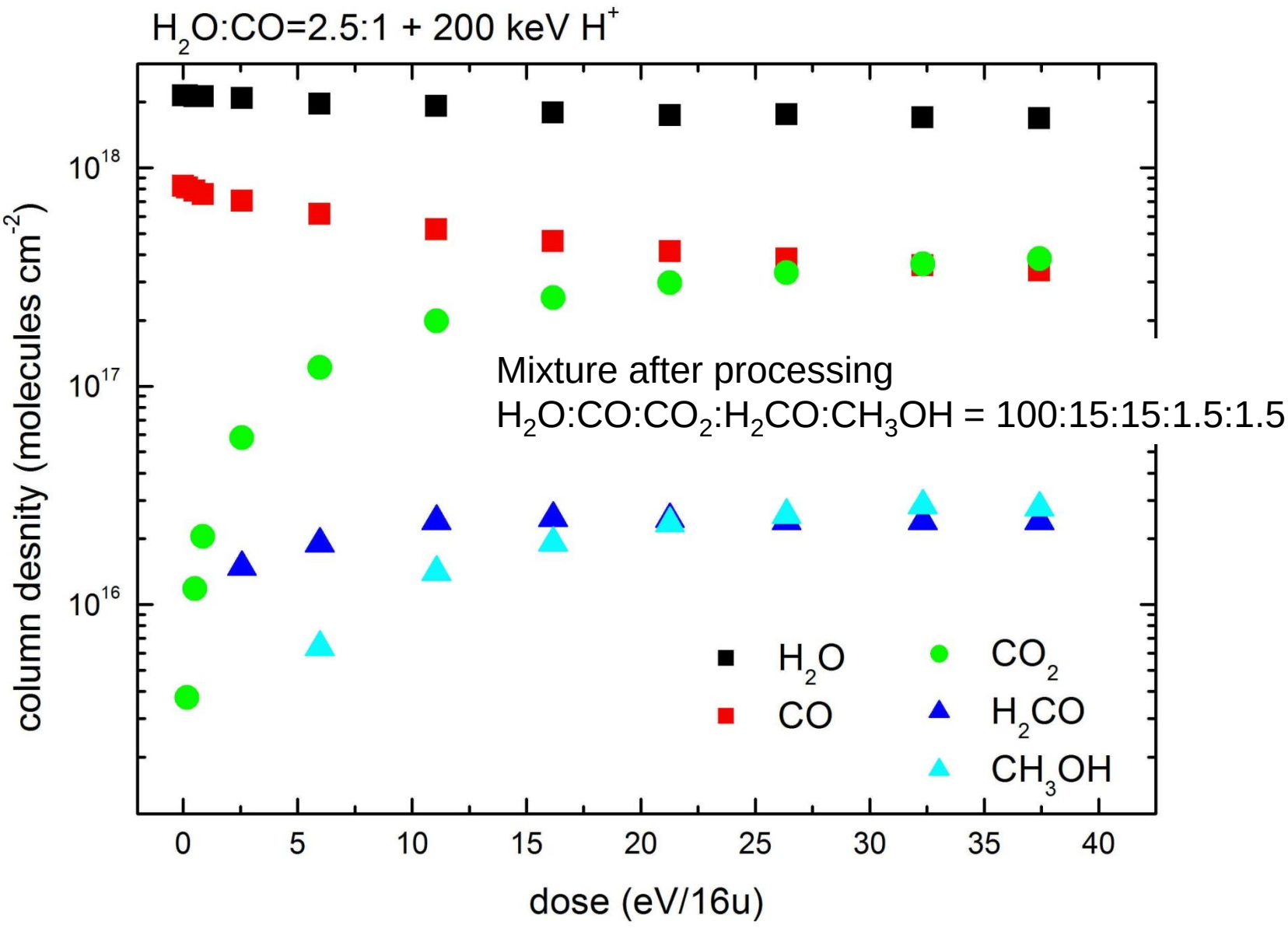
Laboratory experiments

H_2O:CO

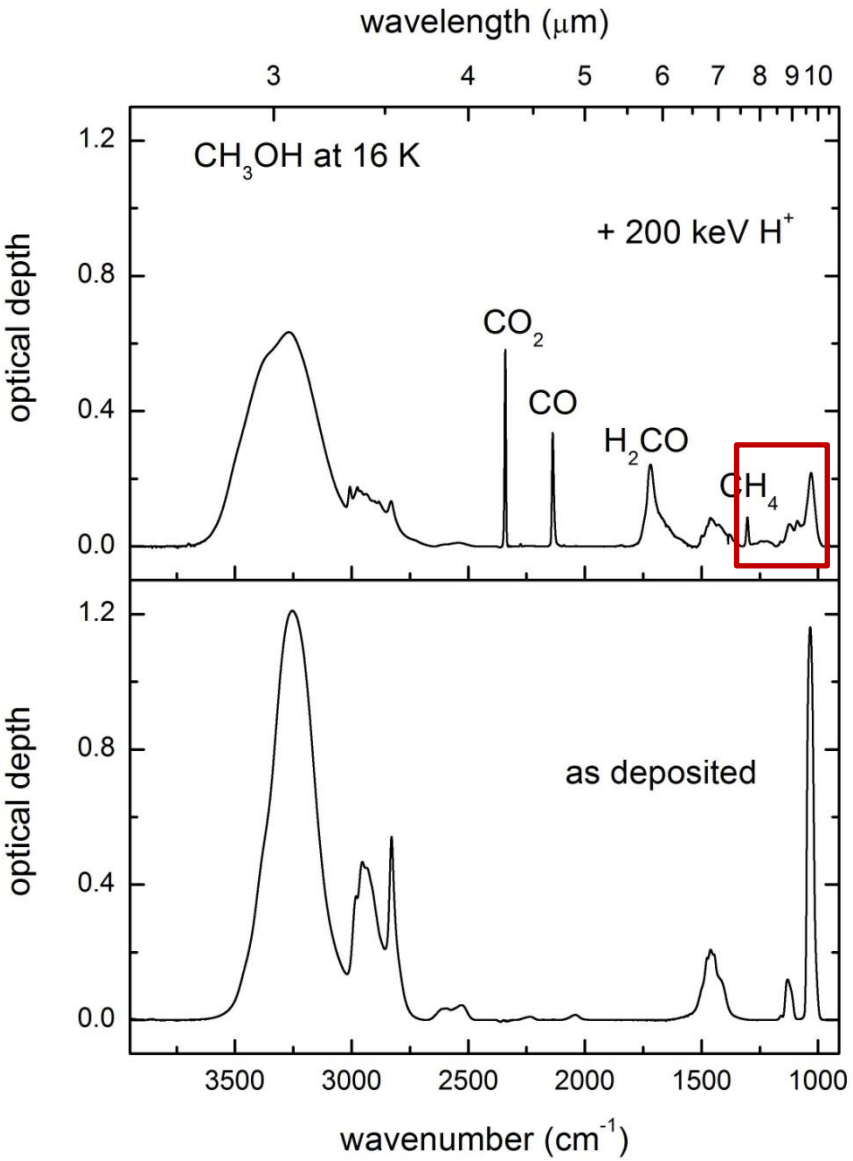

wavelength (μm)
5
10
15
20
H2O:CO = 2.5:1 (T=16.5 K)
+ 200 keV H+
CO2
CO2
optical depth
1.0
0.5
0.0
H2O
as deposited
CO
H2O
H2O
3500
3000
2500
2000
1500
1000
500
wavenumber (cm-1)


wavelength (μm)
6
8
10
H2CO
H2O:CO = 2.5:1 (T=16.5 K)
as deposited
+ 200 keV H+ (11 eV/16u)
optical depth
0.15
0.10
0.05
0.00
CH3O
CH3OH
H2CO
HCOOH
CH4
HCO
1800
1600
1400
1200
1000
wavenumber (cm-1)

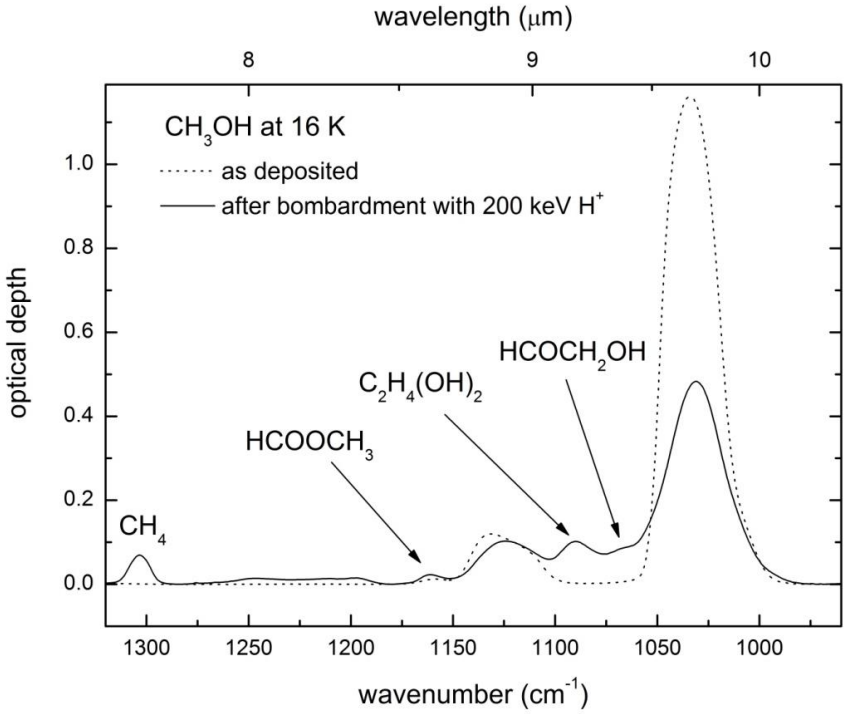
H_2O:CO

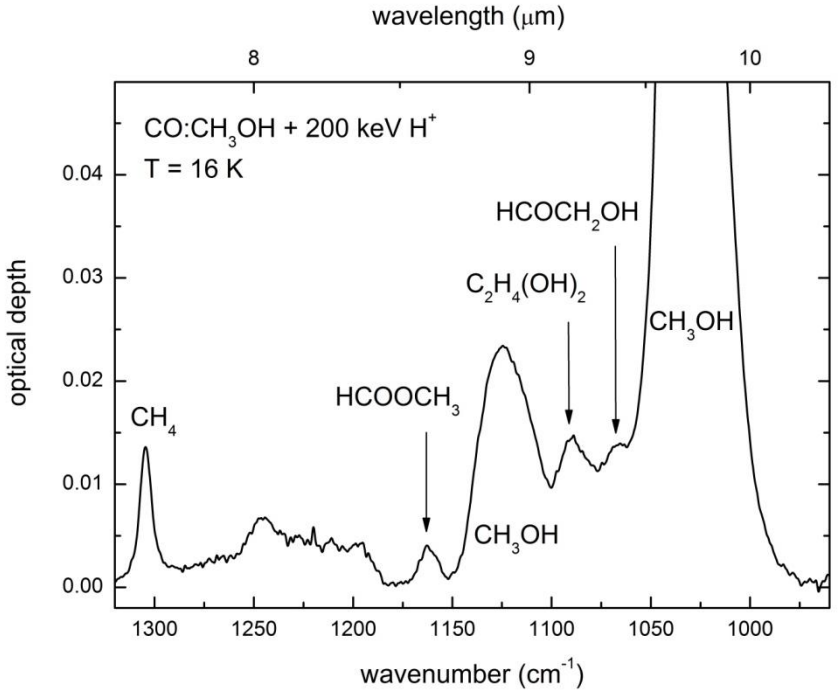

H2O:CO=2.5:1 + 200 keV H+
column desnity (molecules cm-2)
10^18
10^17
10^16
0
5
10
15
20
25
30
35
40
dose (eV/16u)
Mixture after processing
H2O:CO:CO2:H2CO:CH3OH = 100:15:15:1.5:1.5
H2O
CO
CO2
H2CO
CH3OH

CH_3OH

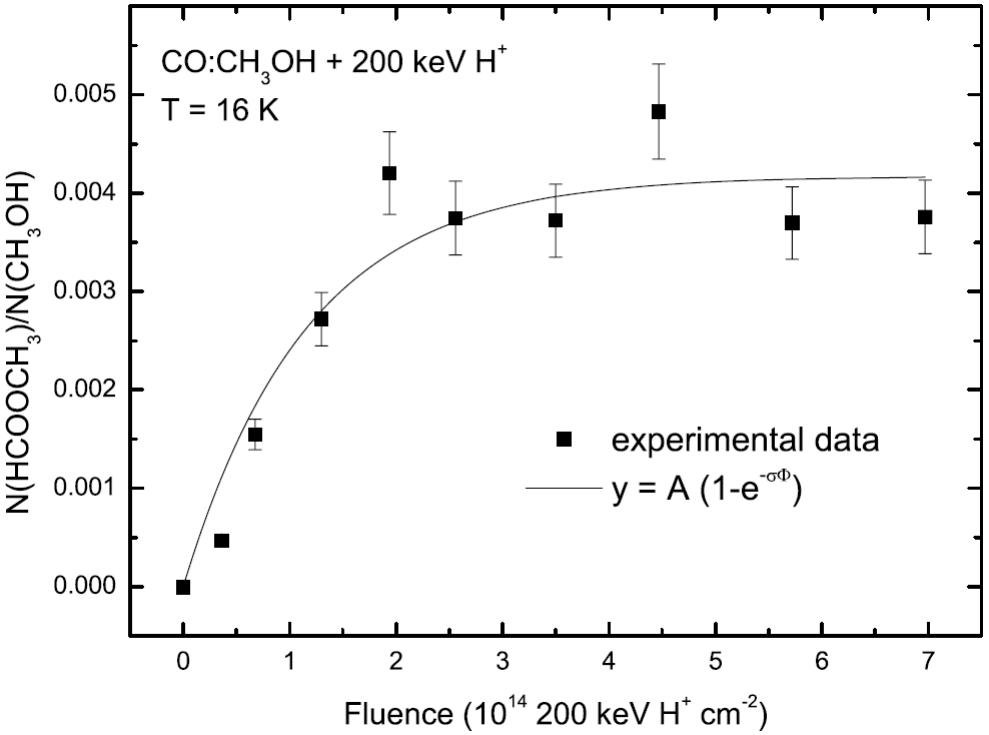


Modica and Palumbo 2010, A&A 519, A22





Formation rates



$$\zeta_0 = 3 \times 10^{-17}\ s^{-1}$$

$$R(\zeta_0) = 6.2 \times 10^{-18}\ s^{-1}$$

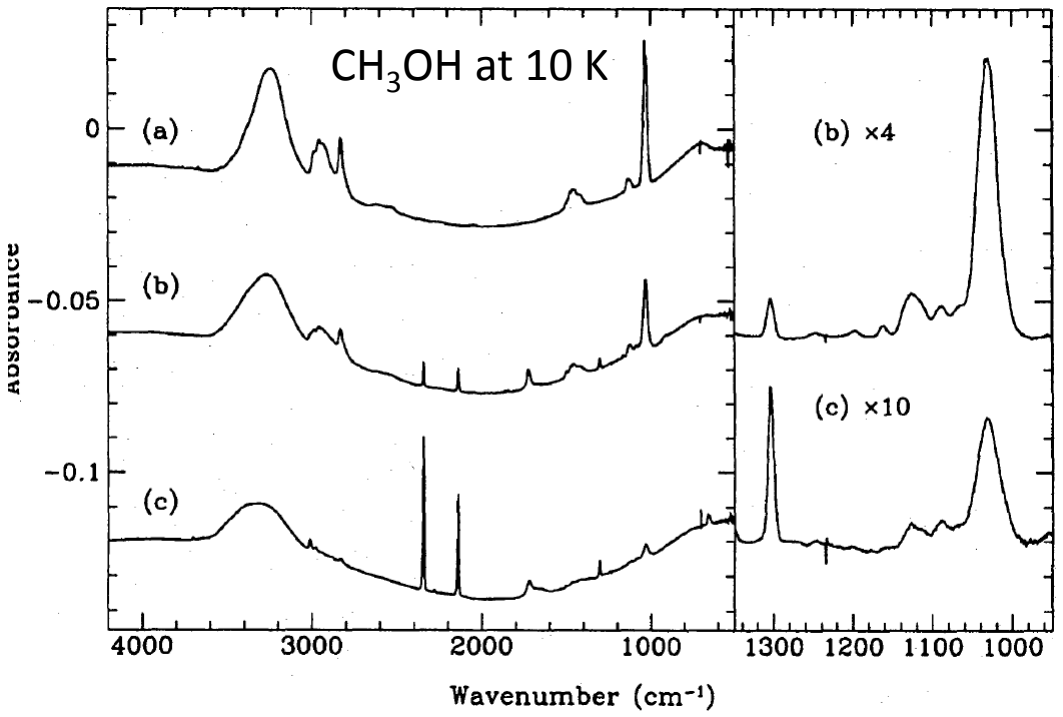
$$R(\zeta) = \frac{R(\zeta_0) \times \zeta}{\zeta_0}$$

Occhiogrosso, A., Viti, S., Modica, P., Palumbo, M.E. 2011, MNRAS 418, 1923

Table 2. Observed and predicted column densities towards Orion KL hot core, G31.41+0.31, NGC 1333–IRAS2 and B1-b core.

Source	Type	Distance (pc)	T_{rot} (K)	Observations (cm^{-2})	Model (cm^{-2})
Orion KL Hot Core	High mass	480	250	6.9×10^{16} *a*	3.5×10^{14}
G31.41+0.31 HMC	High mass	7900	300	6.8×10^{18} *b*	9.3×10^{15}
NCG 1333-IRAS2	Low mass	220	38	5.8×10^{14} *c*	6.4×10^{12}
B1-b	Dark core	350	<30	8.3×10^{12} *d*	1.2×10^{12}

UV photolysis

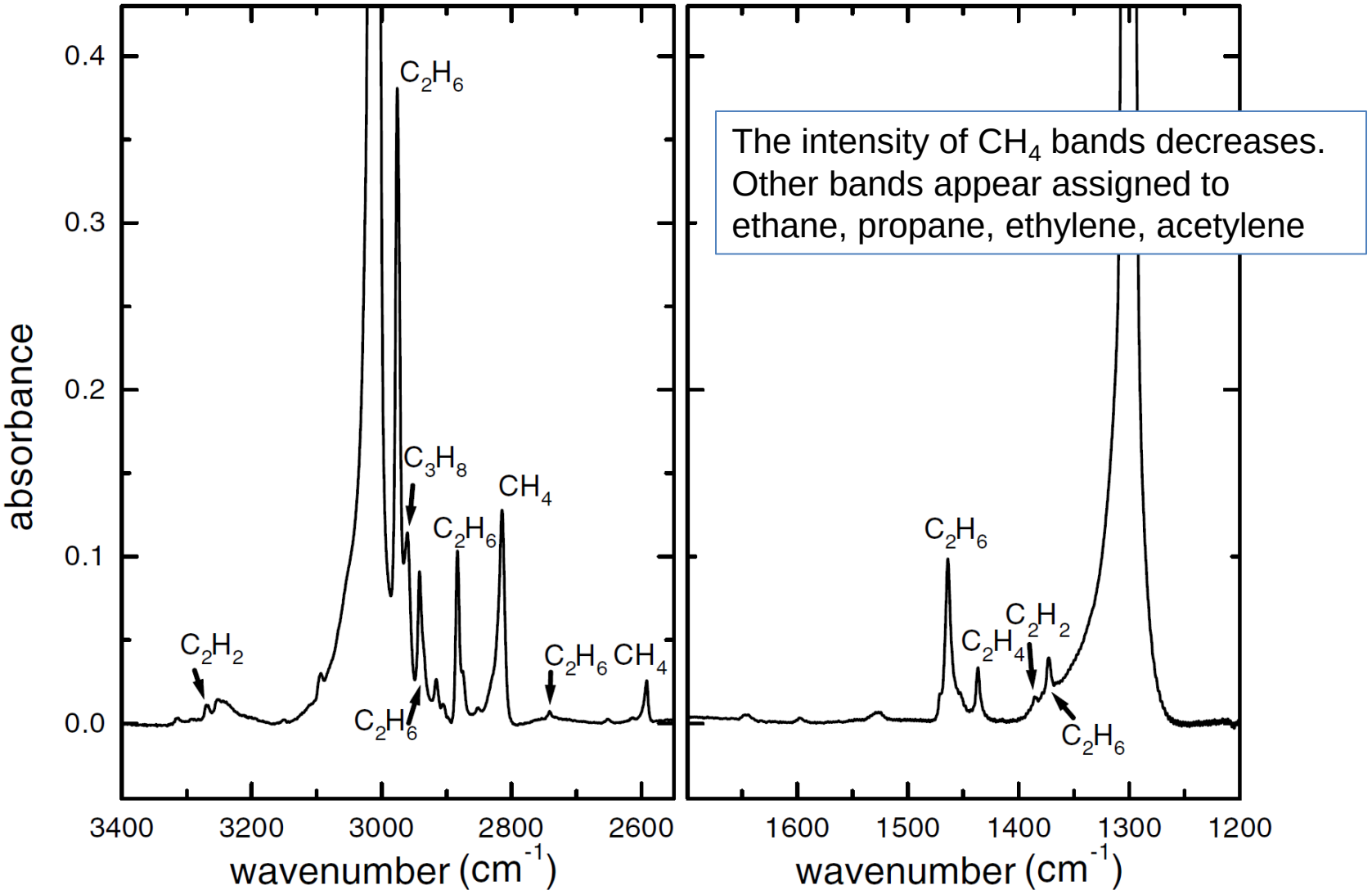


Gerakines et al. 1996, A&A 312, 289
Munoz Caro and Schutte 2003, A&A 412, 121
Oberg et al. 2009, A&A 504, 891
Islam et al. 2014, A&A 561, A73

New bands observed during the photolysis of CH_3OH at 10 K

ν (cm^{-1})	Assignment
655	CO_2
910	H_3COHCO
1088	C-OH stretch (alcohols)
1160	H_3COHCO; ν(C-O)
1197	CH_2OH
1244[a]	H_2CO
1304[a]	CH_4
1352	CH_2OH
1497	H_2CO
1718[a]	H_3COHCO
1719	H_2CO
1850[b]	HCO
1863[b]	HCO
2092	^{13}CO
2138[a]	CO
2278	$^{13}CO_2$
2342[a]	CO_2
3011	CH_4
4140[a]	H_2

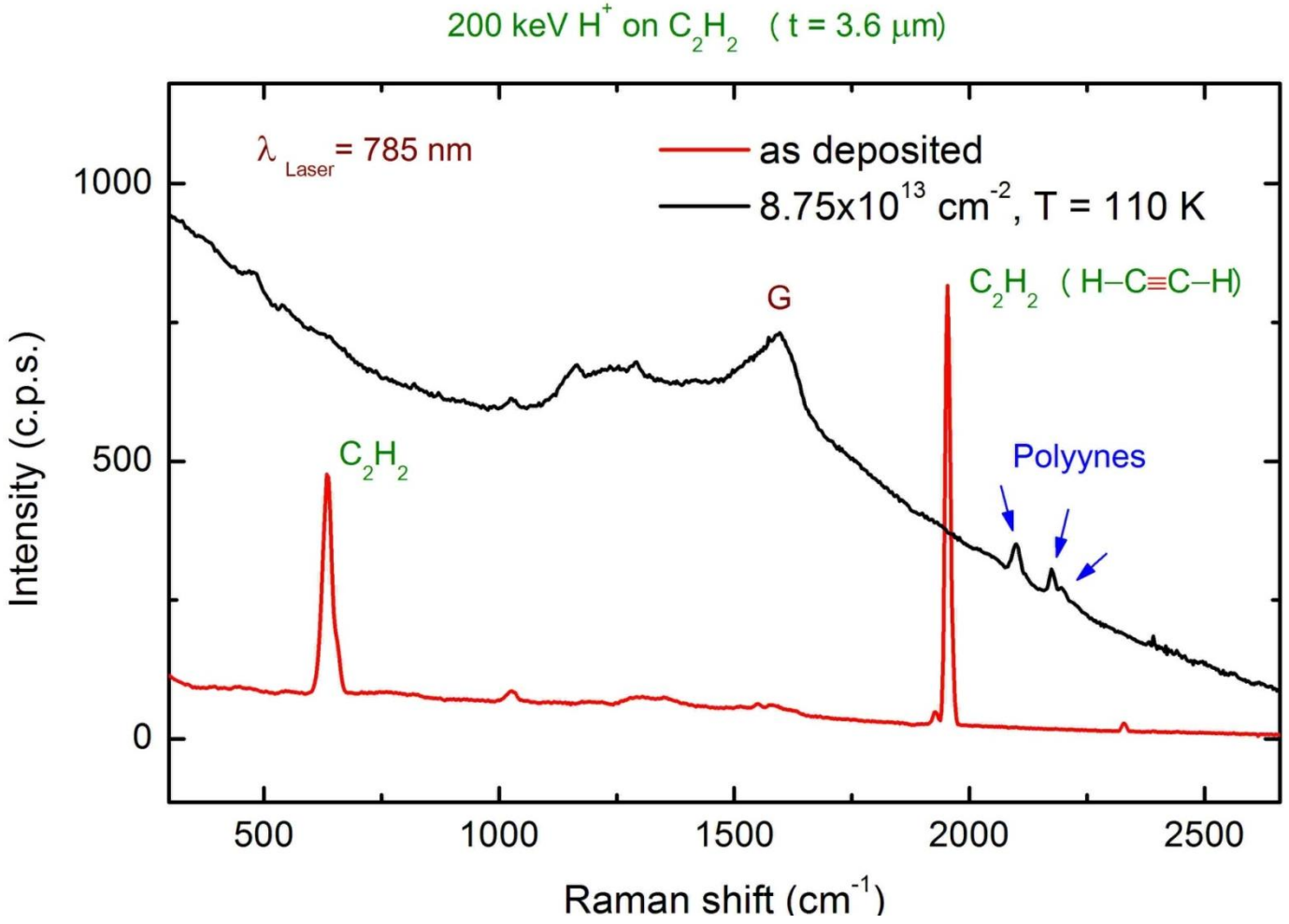
CH_4 + 60 keV Ar^{++} at 12 K



The intensity of CH_4 bands decreases. Other bands appear assigned to ethane, propane, ethylene, acetylene

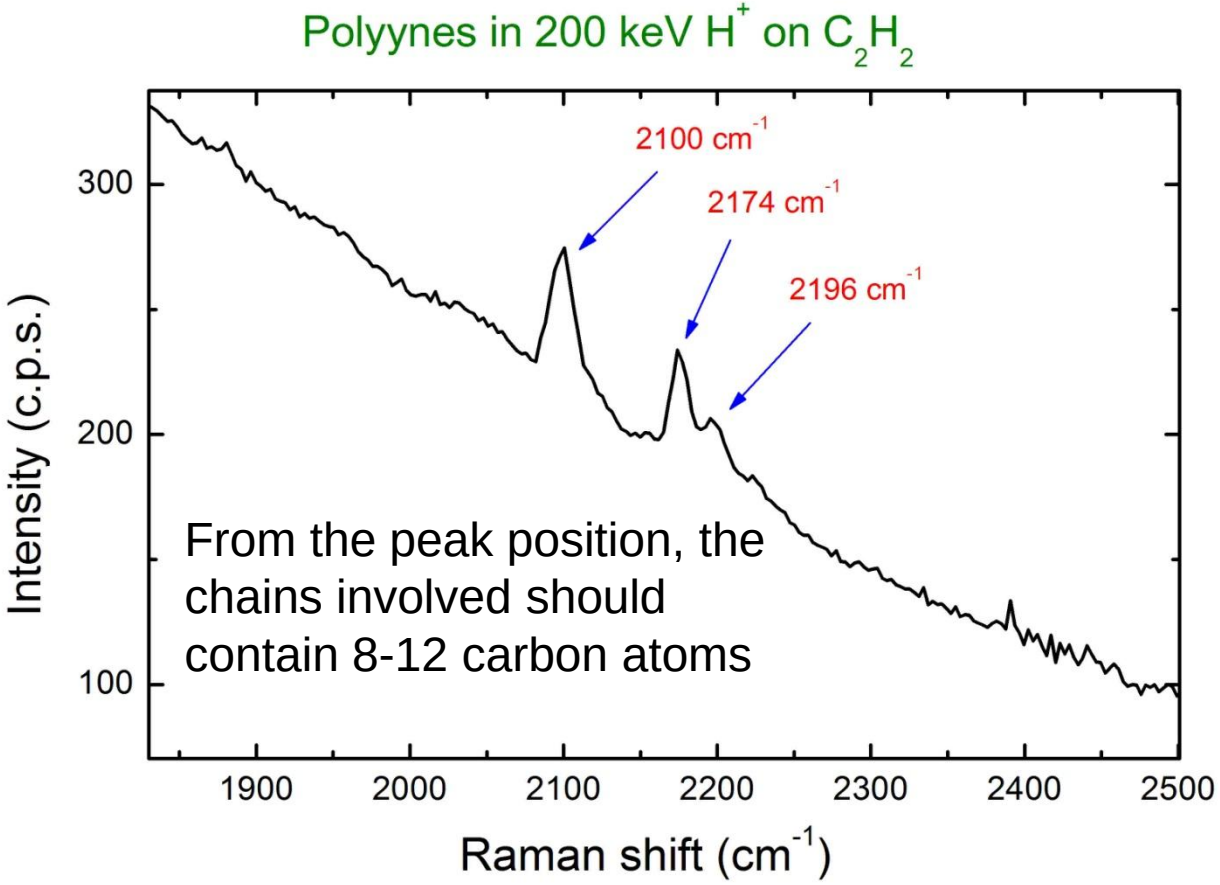
Baratta et al. 2003, NIMB 209, 283

Formation of linear carbon chains



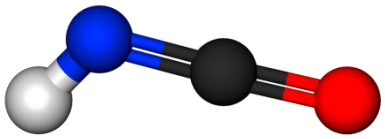
Compagnini et al. 2009, Carbon 47, 1605
Puglisi et al. 2014, NIMB 326, 2

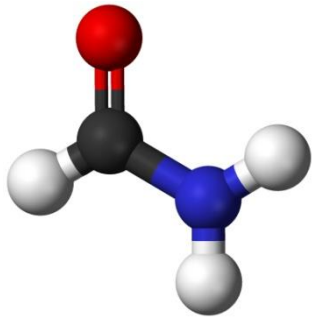
Formation of linear carbon chains



Compagnini et al. 2009, Carbon 47, 1605
Puglisi et al. 2014, NIMB 326, 2

Formation of formamide (NH_2CHO) and isocyanic acid (HNCO)





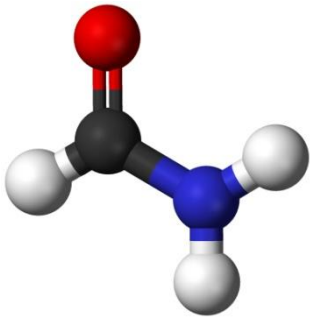
Studied mixtures

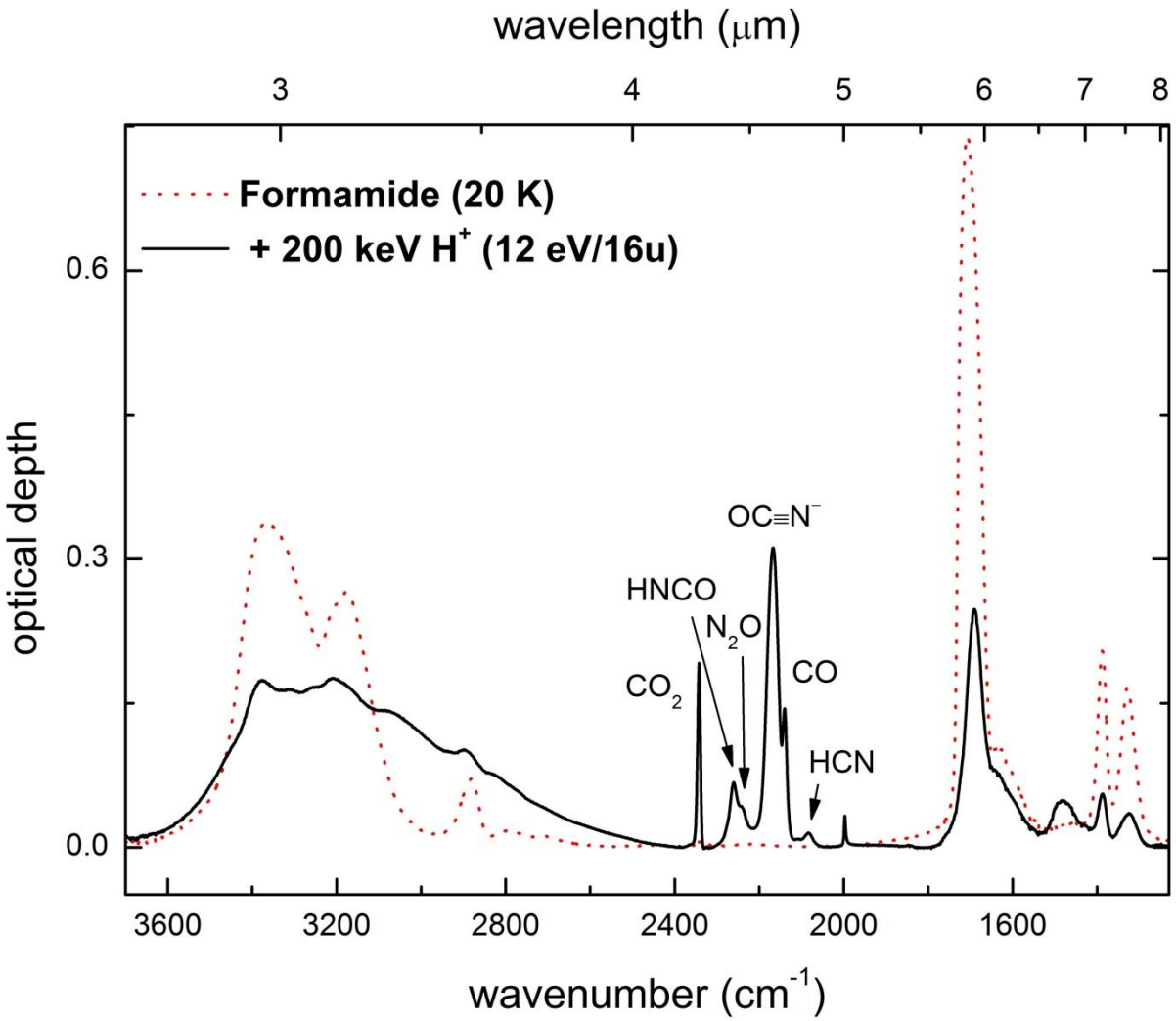
See poster presented by Riccardo Urso

H_2O:CH_4:NH_3 = 1:1:1 + 200 keV H^+
CH_3OH:N_2 = 1:1 + 200 keV H^+
H_2O:CH_4:N_2 = 1:1:1 + 30 keV He^+
H_2O:CH_4:N_2 = 1:2:1 + 30 keV He^+
H_2O:CH_4:N_2 = 1:2:10 + 30 keV He^+
H_2O:CH_4:N_2 = 1:2:100 + 30 keV He^+

Kanuchova Z., Urso, R.G., Baratta, G.A, Brucato J.R., Palumbo M.E., Strazzulla G. 2016, A&A 585, A155

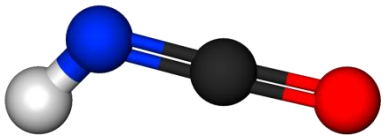
Formamide (NH_2CHO)

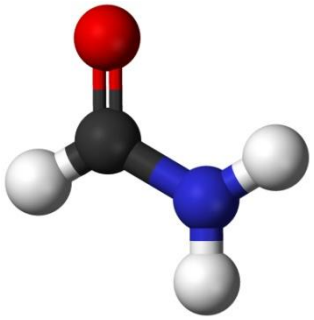


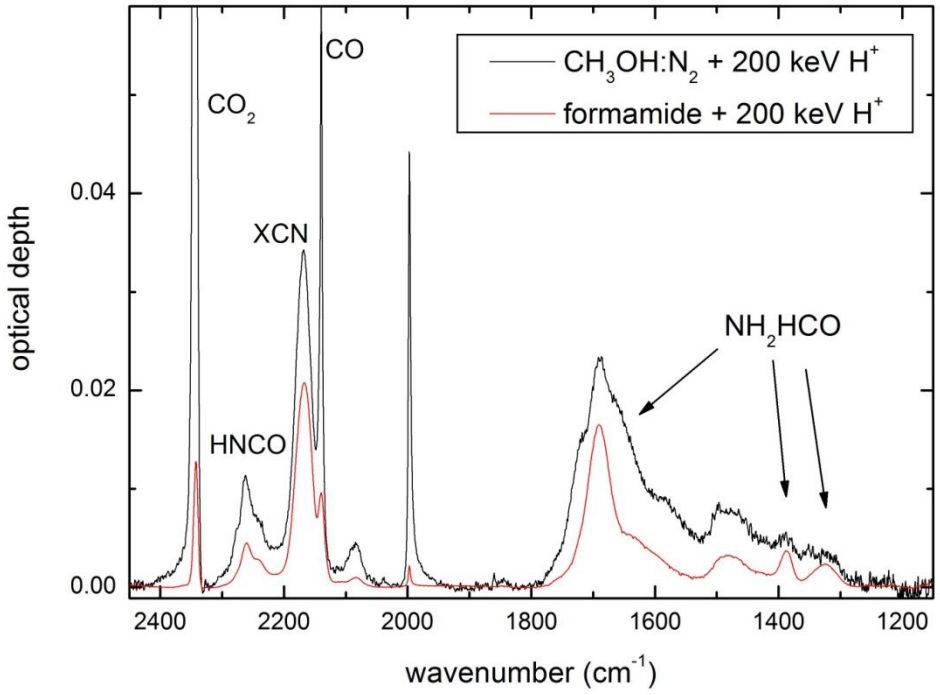


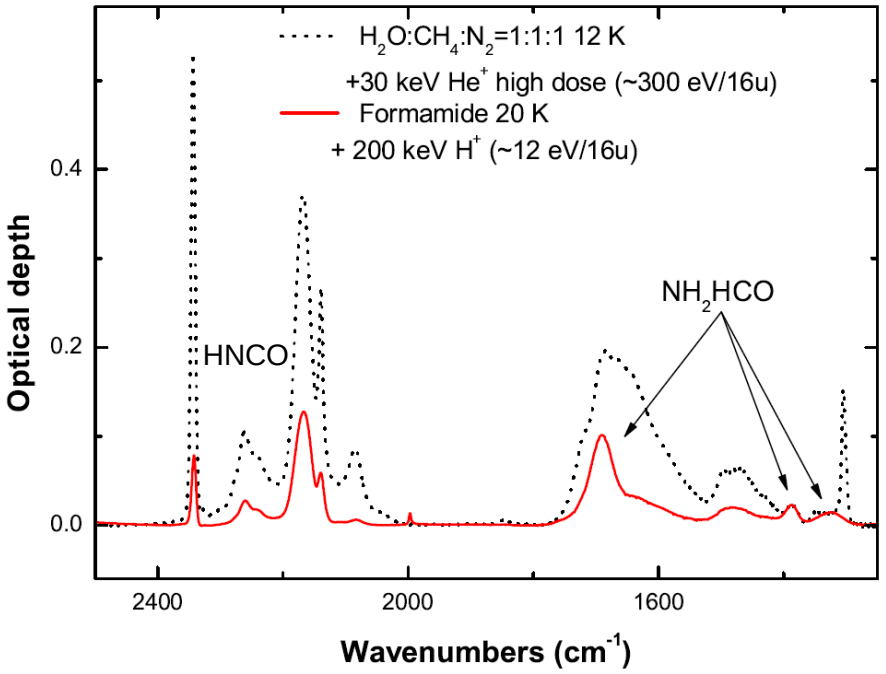
Brucato, Baratta, Strazzulla, 2006, A&A 455, 395

Formation of formamide (NH_2CHO) and isocyanic acid (HNCO)



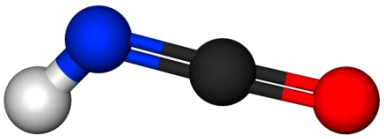


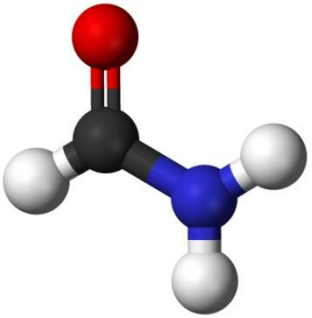


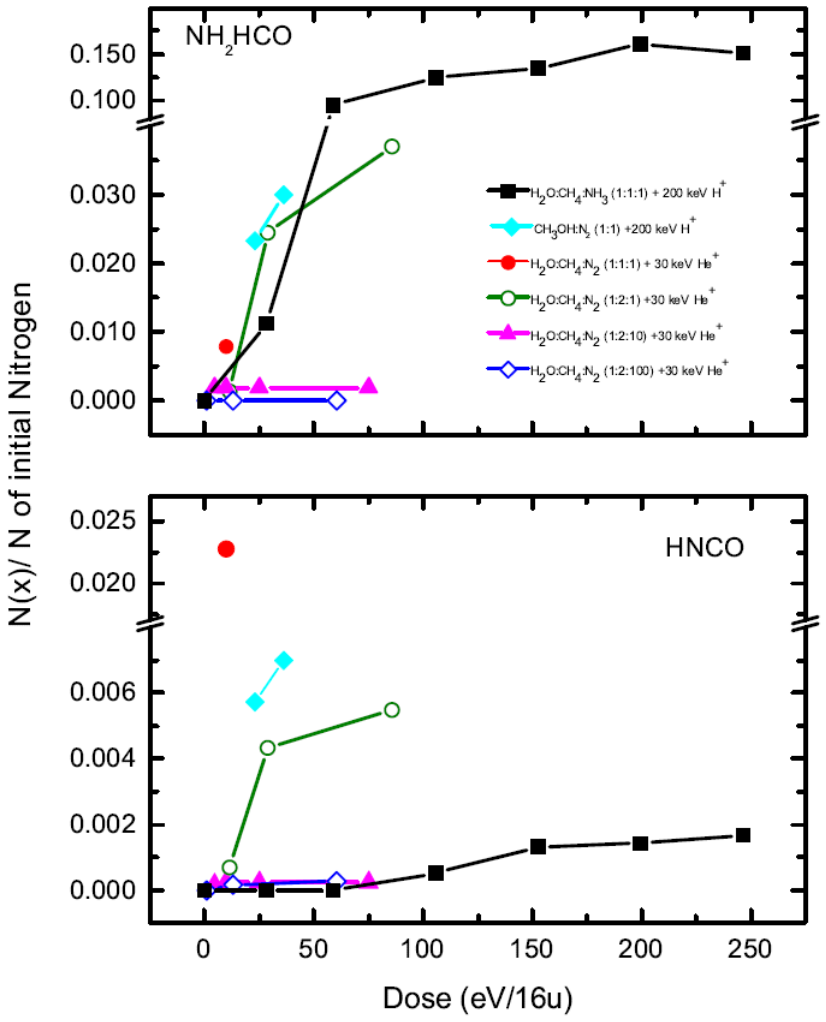


Kanuchova Z., Urso, R.G., Baratta, G.A, Brucato J.R., Palumbo M.E., Strazzulla G. 2016, A&A 585, A155

Formation of formamide (NH_2CHO) and isocyanic acid (HNCO)







Experimental results

after dose = 10 eV/16u

NH_2CHO/nitrogen ~ 10^{-2}

HNCO/nitrogen ~ 10^{-3}

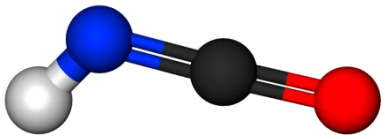
Nitrogen cosmic abundance ~ 2×10^{-5}

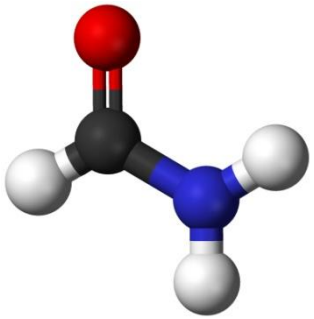
Assuming high N-depletion
NH_2CHO fractional abundance ~ 10^{-7}
comparable to observed values

HNCO fractional abundance ~ 10^{-8}
lower than observed values

Kanuchova Z., Urso, R.G., Baratta, G.A, Brucato J.R., Palumbo M.E., Strazzulla G. 2016, A&A 585, A155

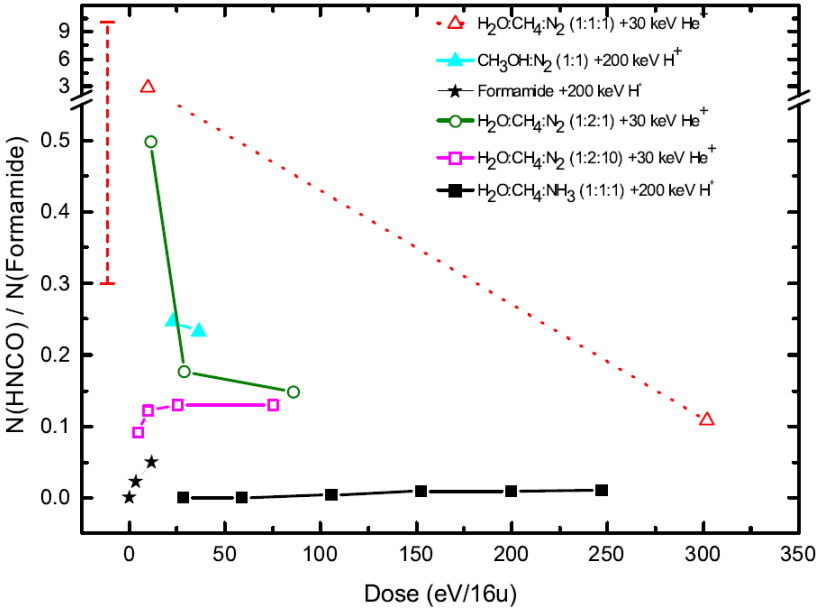
Formation of formamide (NH_2CHO) and isocyanic acid (HNCO)





dose (eV/16u)	timescale (years)			
	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}

While the observed amount of formamide can be accounted for by cosmic-ray bombardment of icy grain mantles, other processes (such as gas-phase and grain-surface reactions) have to be invoked to explain the observed gas-phase abundance of HNCO.



Kanuchova Z., Urso, R.G., Baratta, G.A, Brucato J.R., Palumbo M.E., Strazzulla G. 2016, A&A 585, A155

Formation of formamide (NH_2CHO)

A&A 576, A91 (2015)
DOI: 10.1051/0004-63

Result

The hydrogenation of HNCO does not produce detectable amounts of formamide

Hydrogenation at low temperatures does not always lead to saturation: the case of HNCO

J. A. Noble[1], P. Theule[1], E. Congiu[2], F. Dulieu[2], M. Bonnin[2], A. Bassas[1], F. Duvernay[1], G. Danger[1], and T. Chiavassa[1]

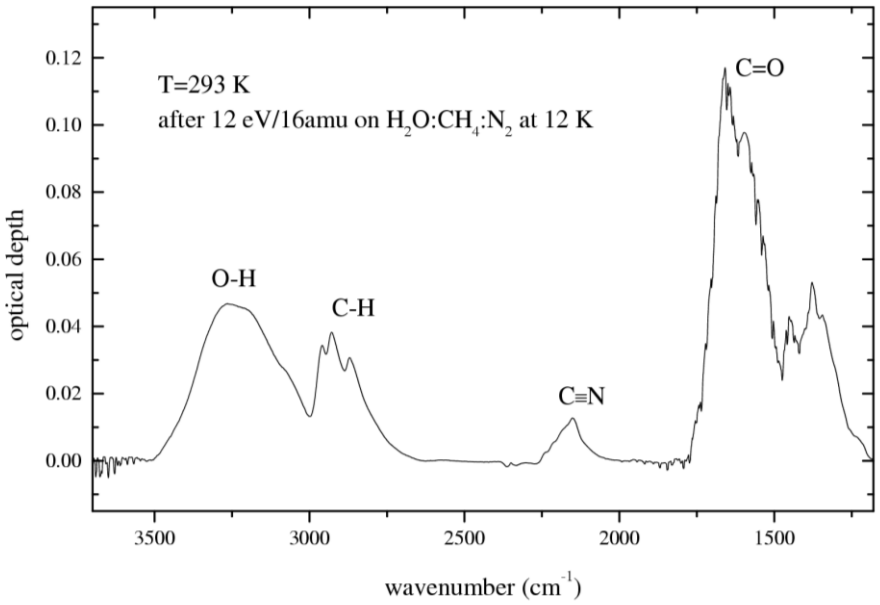
MNRAS 453, L31–L35 (20

The major conclusion of this Letter is that there is no need to invoke grain-surface chemistry to explain the presence of formamide provided that its precursors, NH_2 and H_2CO, are available in the gas phase

Gas-phase formation of the prebiotic molecule formamide: insights from new quantum computations

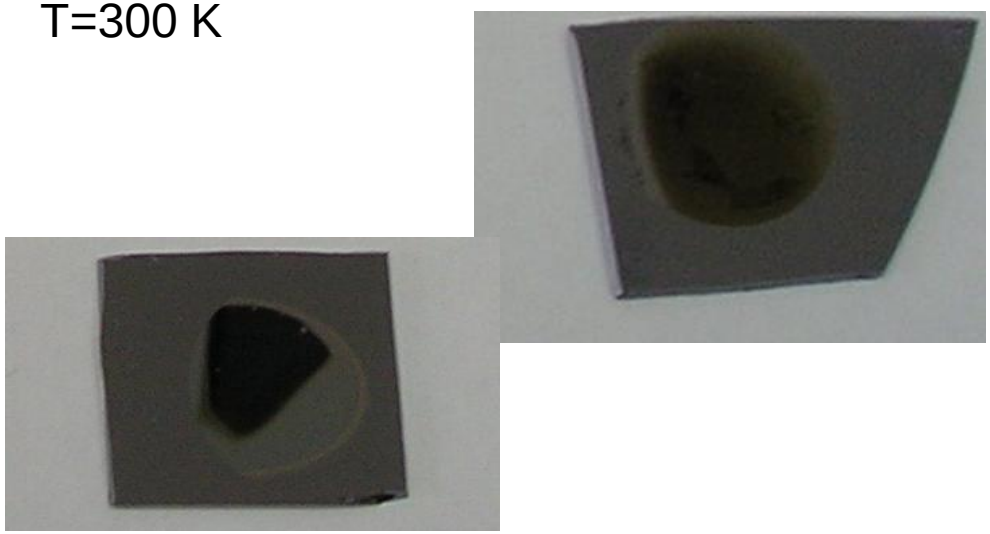
V. Barone,[1★] C. Latouche,[1] D. Skouteris,[1★] F. Vazart,[1] N. Balucani,[2,3,4]
C. Ceccarelli[3,4★] and B. Lefloch[3,4]

Infrared and Raman spectroscopy of residues

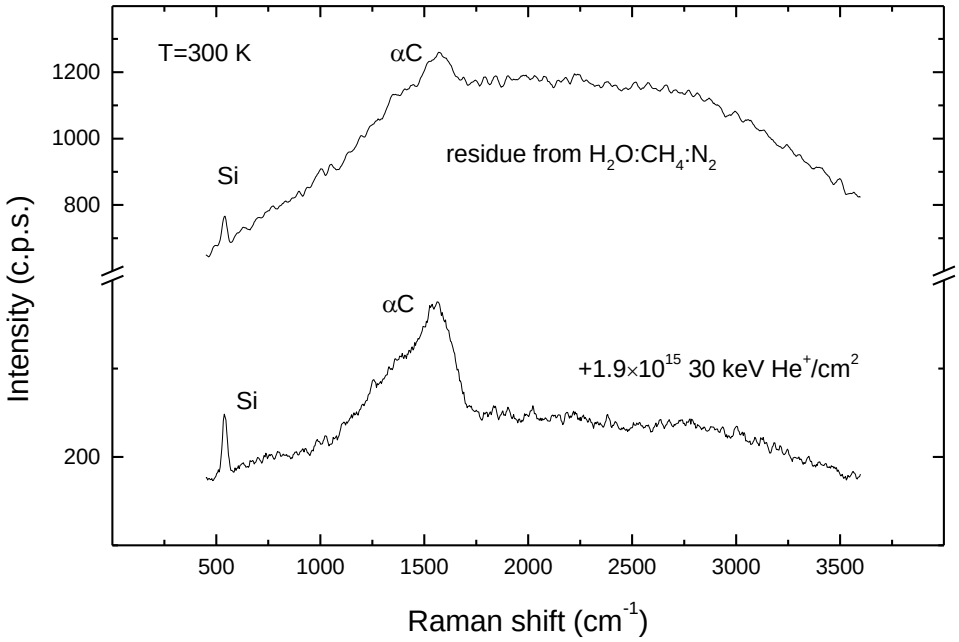


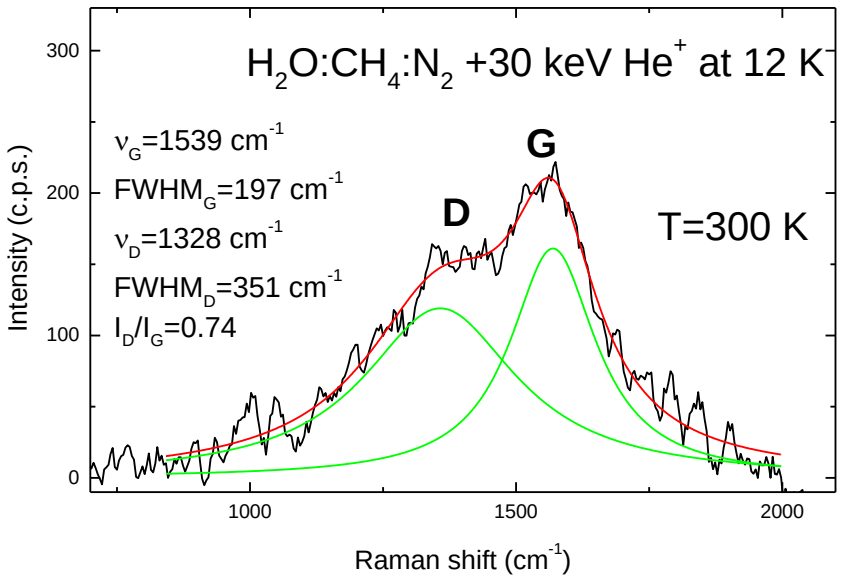
Strazzulla, Baratta, Palumbo 2001, Spectrochim. Acta A 57, 825
Palumbo, Ferini, Baratta, 2004, Ad Sp Res 33, 49

T=300 K



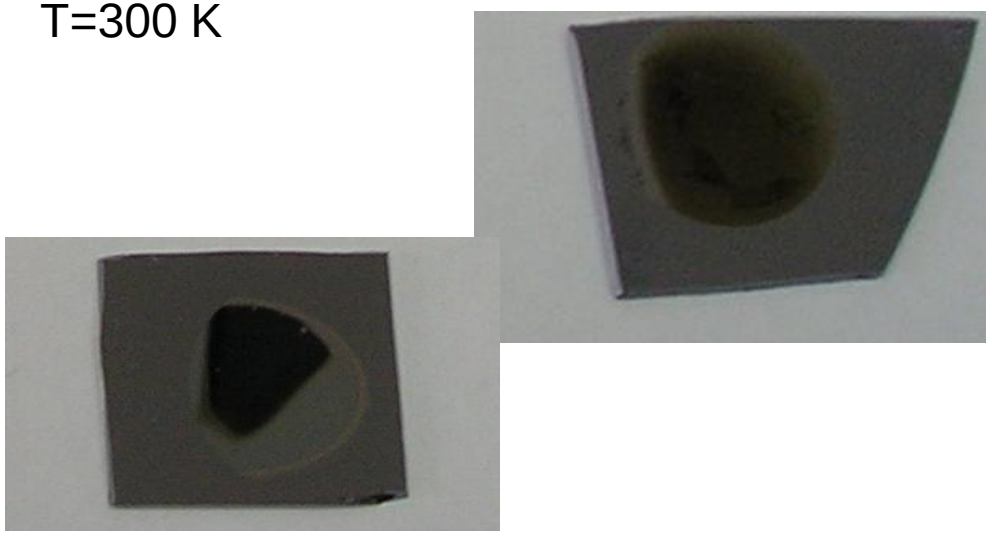
Infrared and Raman spectroscopy of residues



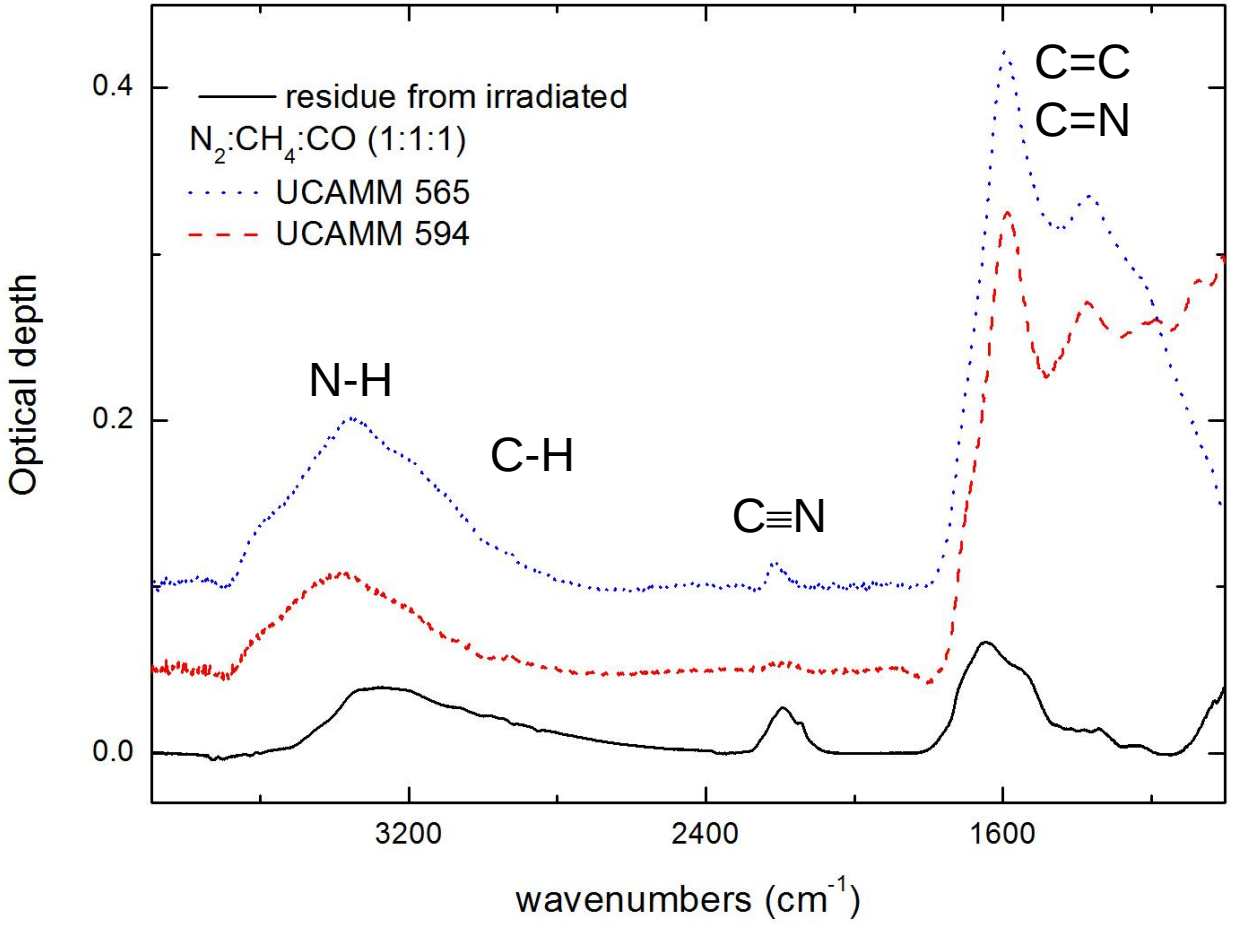


Ferini G., Baratta G.A., Palumbo M.E., 2004, A&A 414, 757

T=300 K

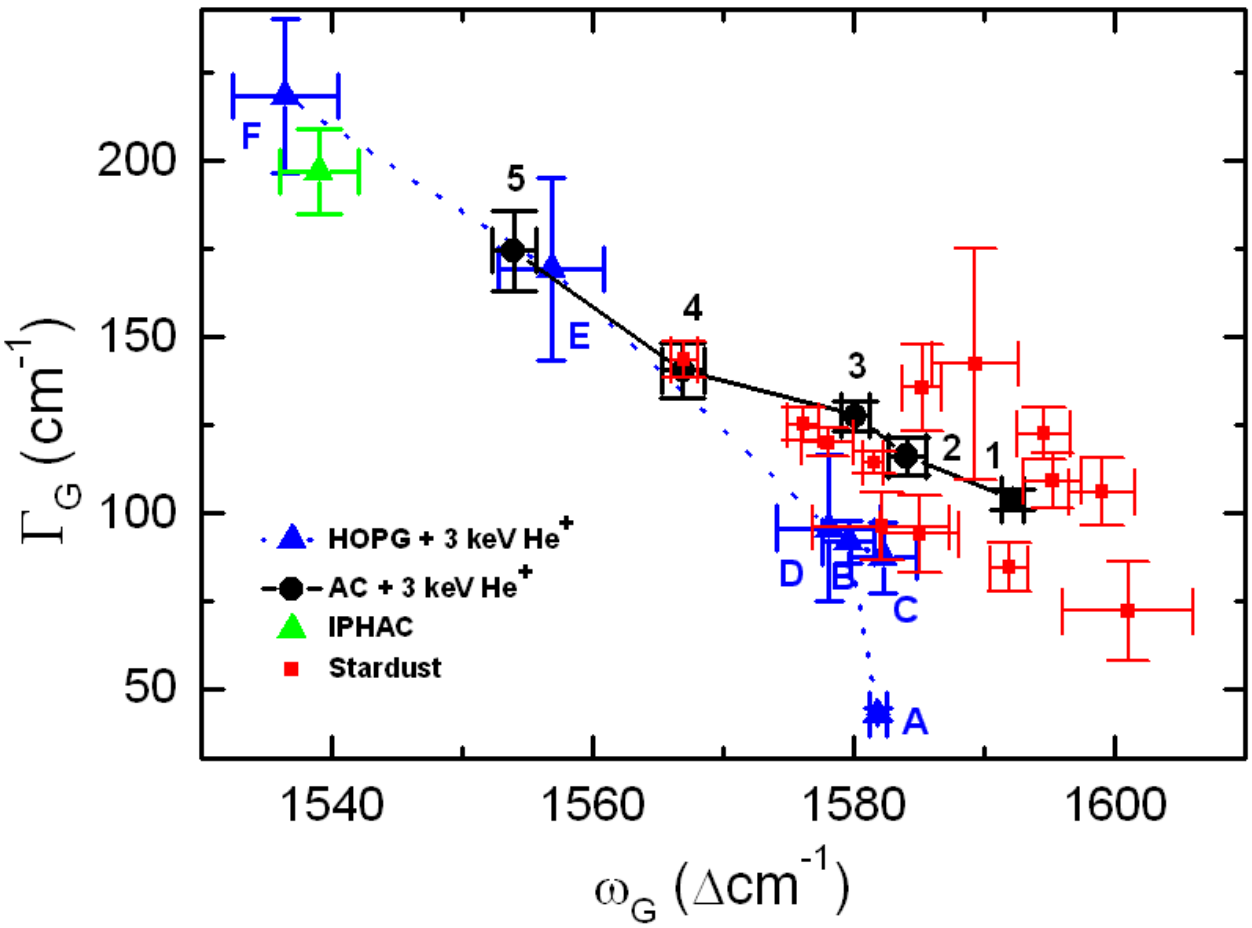


Ultra Carbonaceous Antarctic micrometeorites probing the Solar System beyond the nitrogen snow-line



Dartois et al. 2013, Icarus 224, 243
Baratta et al. 2015, Planet. Space Science, 118, 211

Comet Wild2 grains collected by Stardust



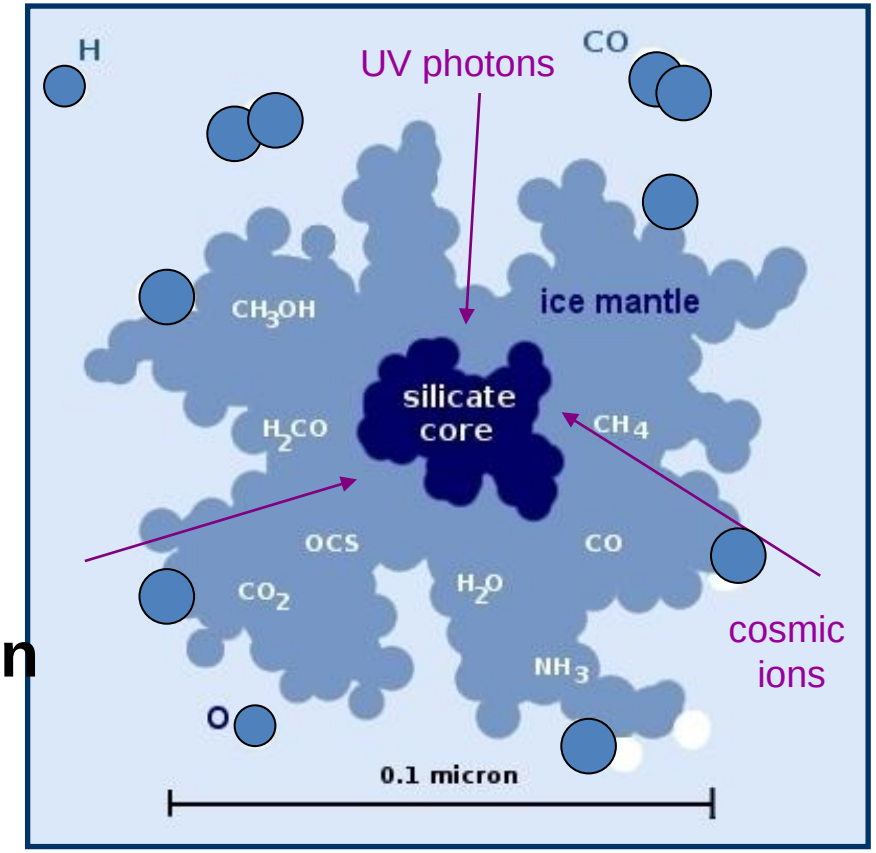
The most disordered amorphous carbon detected by Raman spectroscopy in some Stardust grains could be indicative of ion irradiation of carbon containing ices or of pre-existing more ordered carbons.

Rotundi A., Baratta G.A., … Brucato J.R., … Colangeli L., … Ferrini G., … Mennella V., … Palumbo M.E., et al. Meteoritics & Planetary Science 2008, 43, 367

Summary

Energetic processing

- ✓ **modifies the chemical composition of icy grain mantles;**
- ✓ **gives a significant contribution to the formation of complex molecules in the solid phase.**



Molecules formed in the solid phase are released to the gas phase after desorption of ice mantles or are incorporated in planets, satellites and comets

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