Role of Mineral Surfaces on Prebiotic Evolution of Organics in Space

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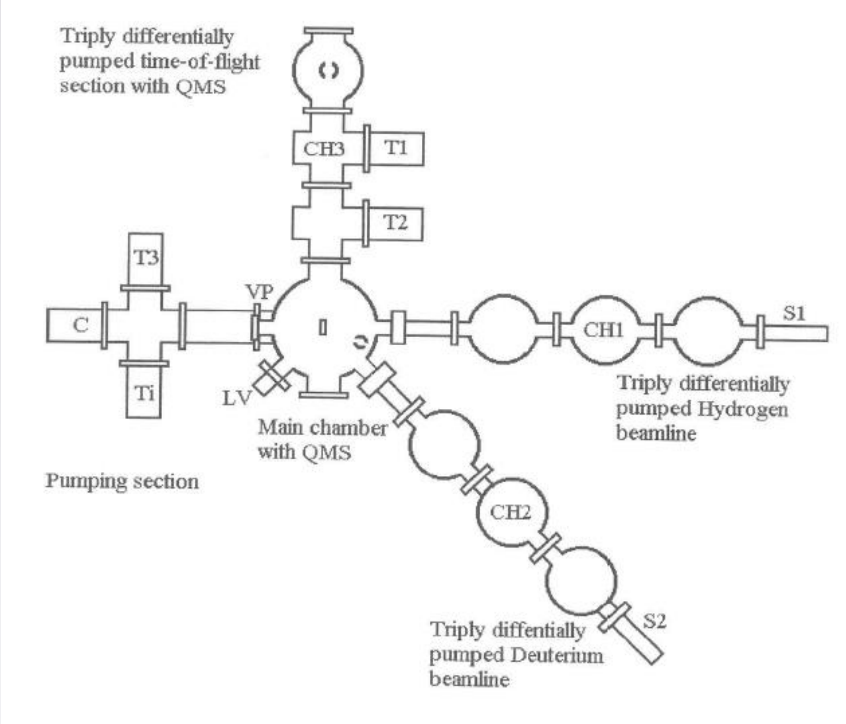
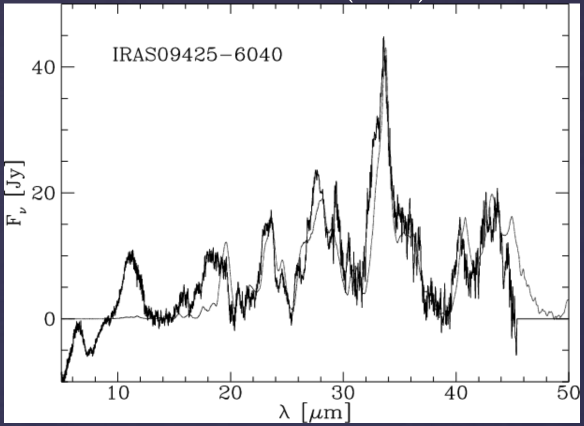


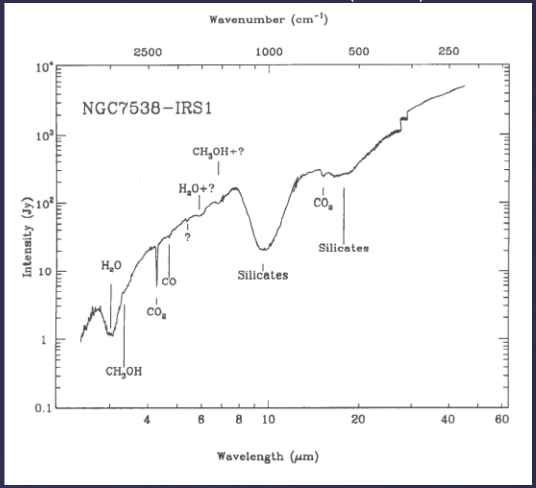
Cristalline silicates in evolved stars

Molster et al. (2002)



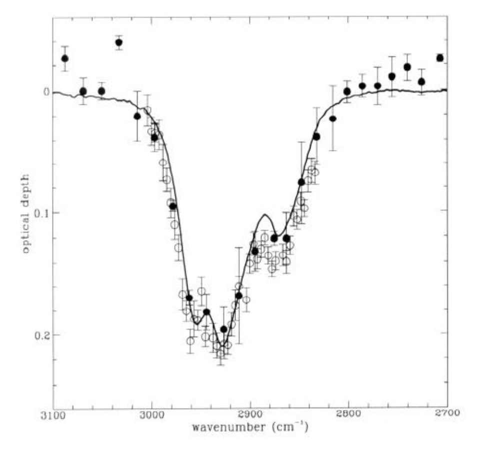
Amorphous silicates in ISM

Strazzulla et al. (1998)



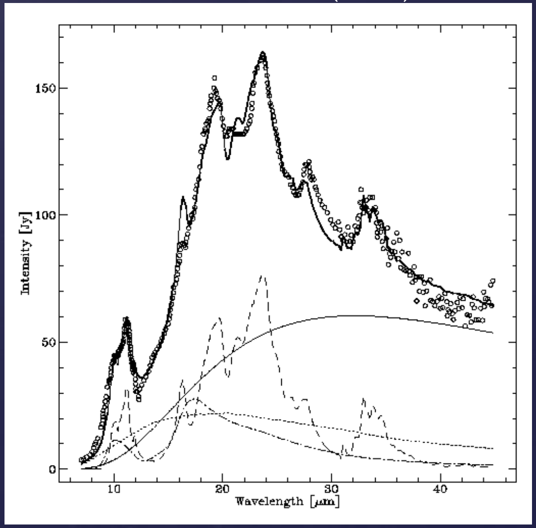
Hydrogenated a-Carbon in ISM

Mennella et al. (1999)

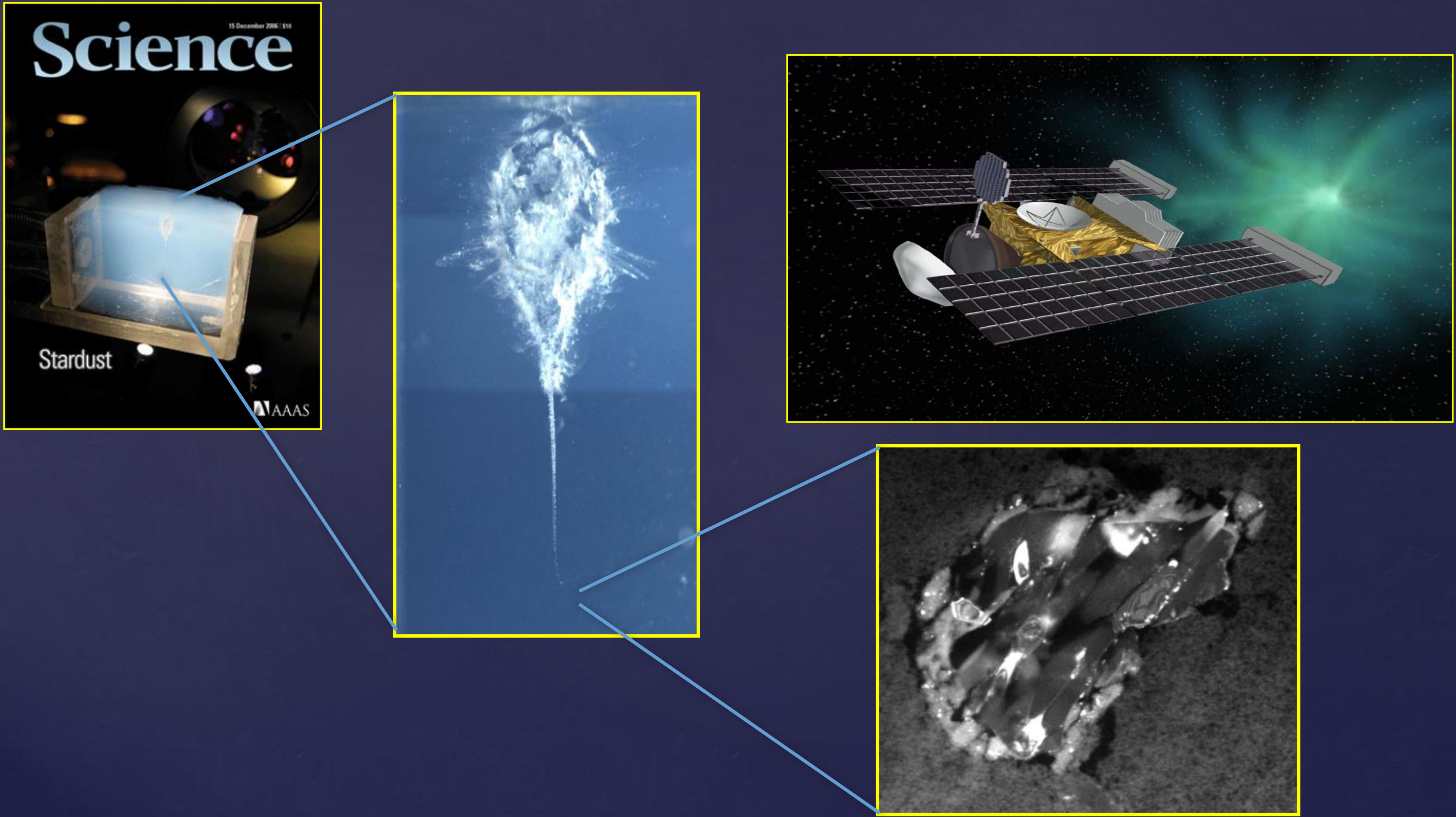


Silicate & a-carbon in comets

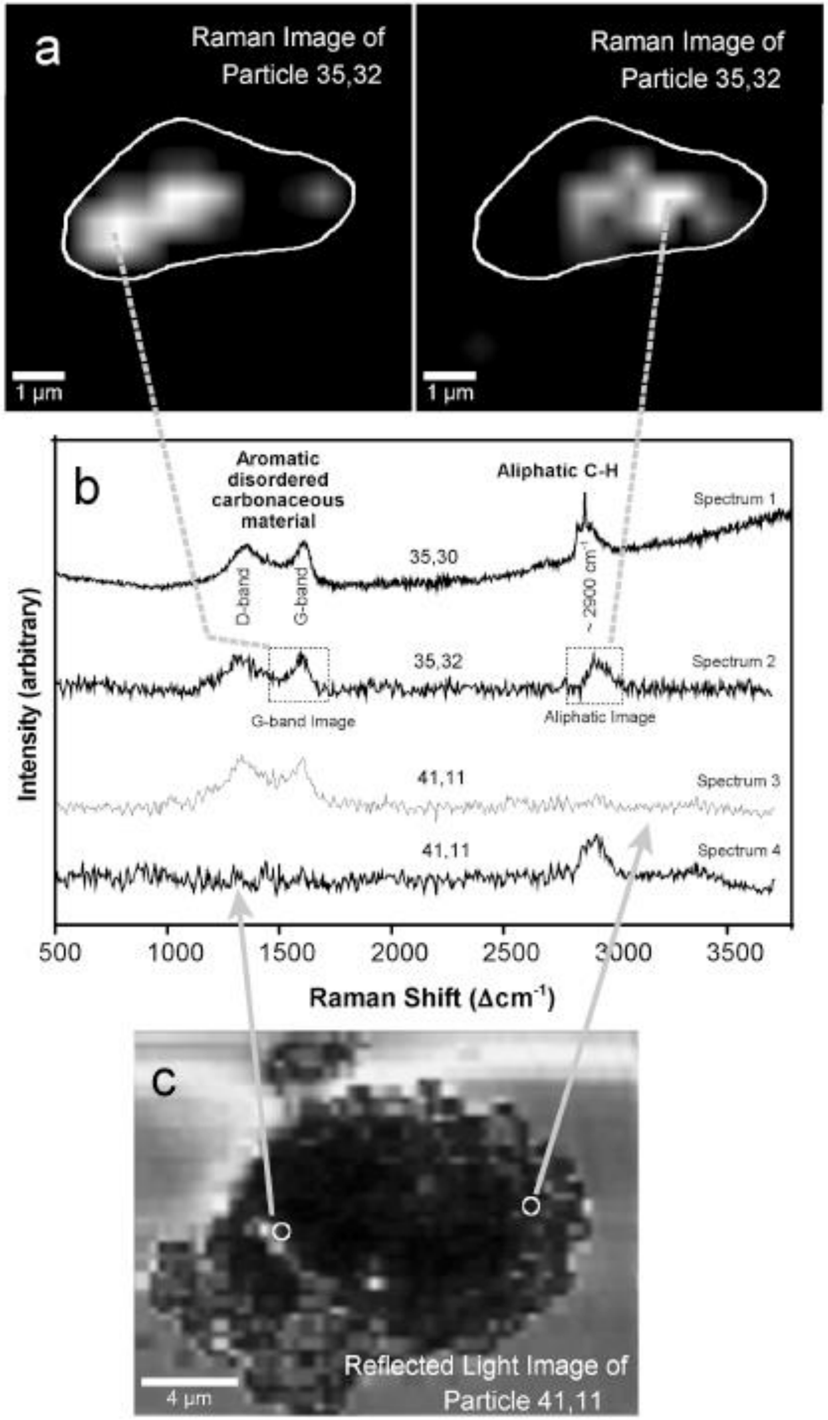
Brucato et al. (1999)

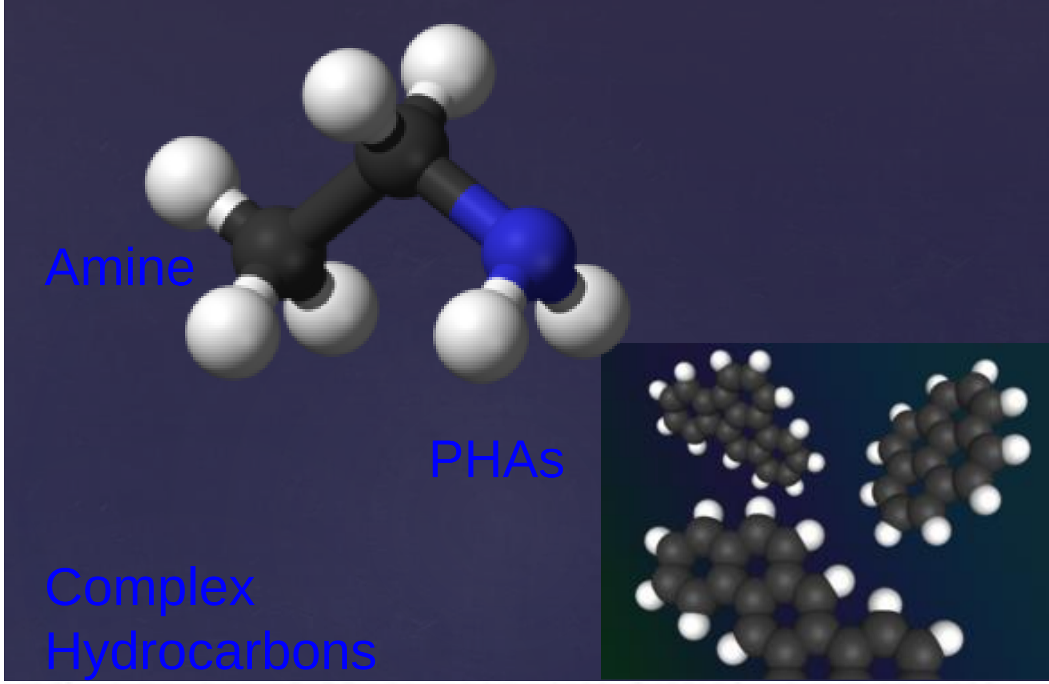


NASA STARDUST Mission
returned on Earth dust grains collected by Wild 2 comet



Brownlee et al. Science 2006

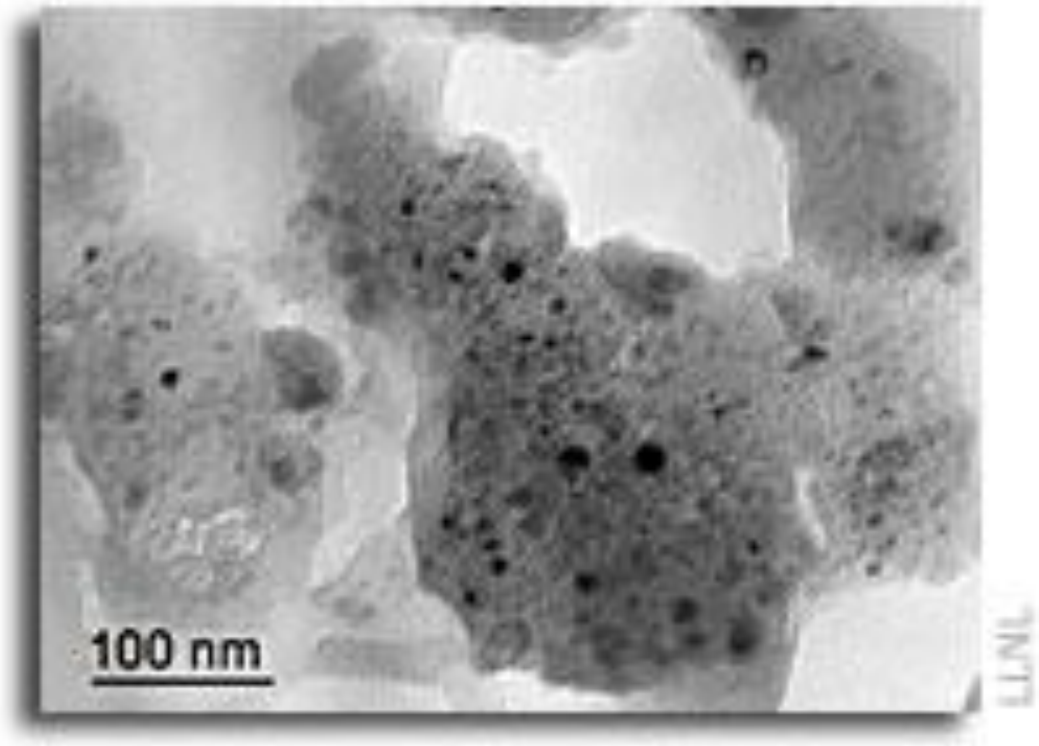


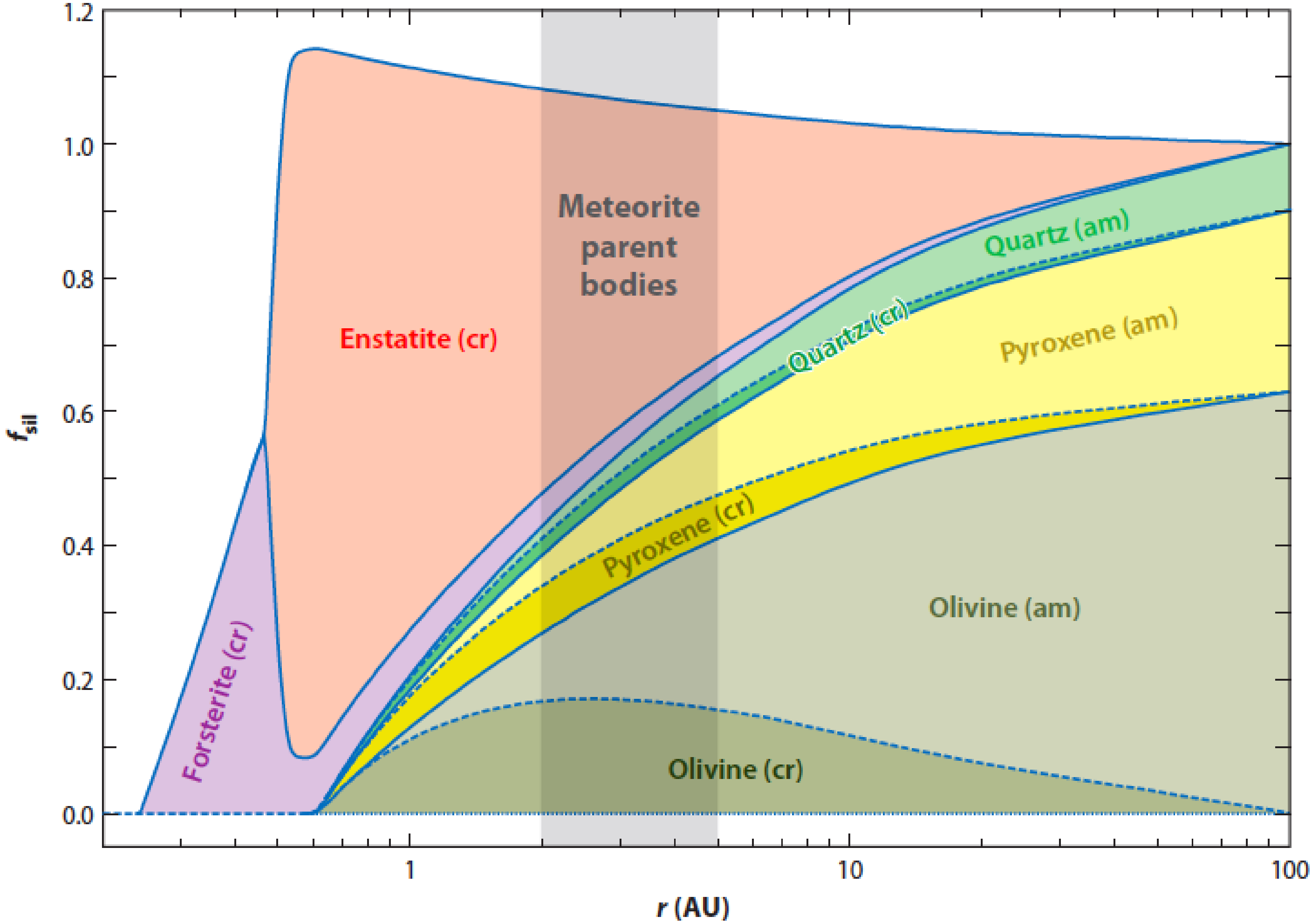


Amine

PHAs

Complex Hydrocarbons




1.2
1.0
0.8
0.6
0.4
0.2
0.0
f_{sil}
1
10
100
r (AU)
Meteorite parent bodies
Enstatite (cr)
Forsterite (cr)
Quartz (am)
Quartz (cr)
Pyroxene (am)
Pyroxene (cr)
Olivine (am)
Olivine (cr)

Gail 2004

ISM, comets and Interplanetary Dust Particles inventory

Oxides:	SiO_2, MgO, FeO, Fe_2O_3, TiO_2, ZrO_2, Al_xO_y
Silicon Carbide:	SiC
a-Carbon	
Sulfides:	FeS, NiS
Silicates	Olivine: $(Mg,Fe)_2SiO_4$ Pyroxene: $(Mg,Fe)SiO_4$ Spinel: $MgAl_2O_4$ Diopsite: $CaMgSi_2O_4$ Melilite: $(Ca,Na)_2(Al,Mg)[(Si,Al)_2O_7]$
Carbonates	Calcite: $CaCO_3$ Dolomite: $CaMg(CO_3)_2$

The role of minerals and metal oxides on prebiotic processes. A general overview

- Minerals can accumulate the prebiotic precursors (concentration effect)
- Minerals can act as catalytic environments, reducing the activation energy for the formation of products
- Minerals can tune the selectivity of prebiotic syntheses
- Minerals may act as a template
- Minerals are benign environments to preserve newly formed biomolecules from degradation

Talk Outline

DUST

Gas

Liquid

Solid

Atoms reaction
10 - 100 K

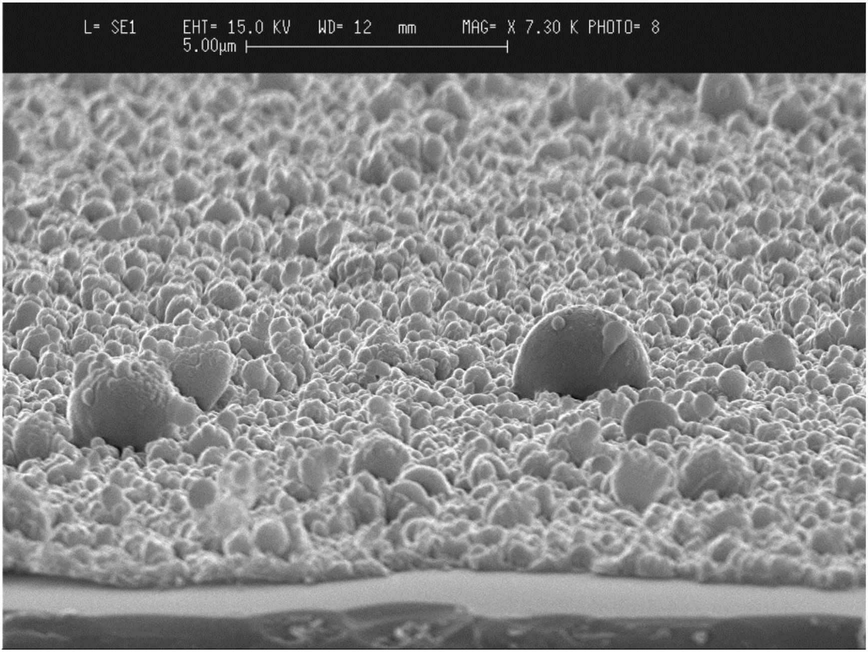
Thermal reaction
UV irradiation
300 - 460 K

Ion & UV irradiation
of ices 20 K

Synthetic Silicate Produced in Laboratory

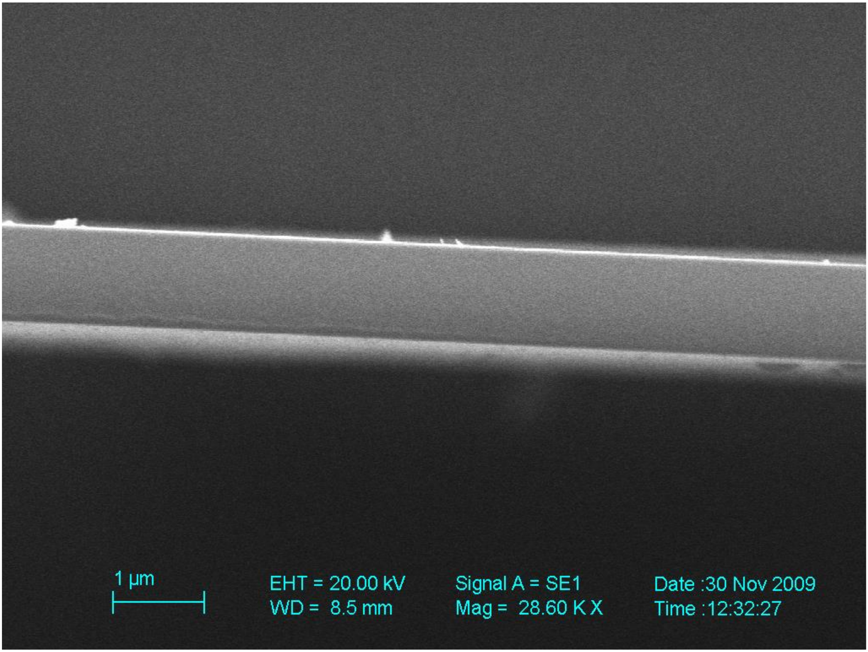
Amorphous olivine & pyroxene

Laser ablation



P= 10 mbar O_2

Electron Beam

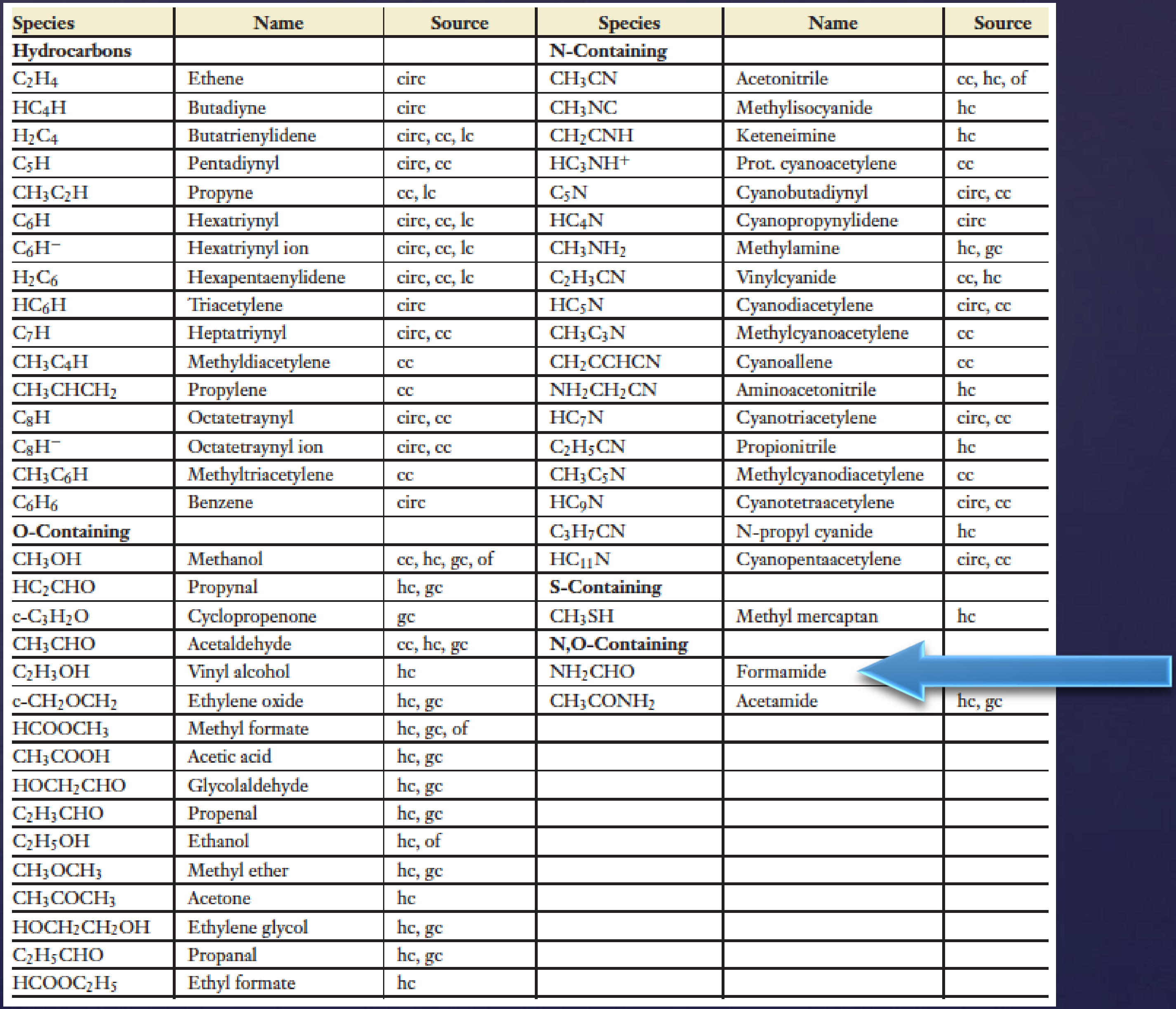


P= 10^{-5} mbar

ENERGY SOURCES IN SPACE

Environment (ice residence time in years)	Ion Processing			Photon Processing		
	Flux, 1 MeV p^+ (eV cm^{-2} s^{-1})	Energy absorbed (eV cm^{-2} s^{-1})^{a}	Dose (eV $molec^{-1}$)	Flux (eV cm^{-2} s^{-1})	Energy absorbed (eV cm^{-2} s^{-1})	Dose (eV $molec^{-1}$)
Diffuse ISM $(10^{5} - 10^{7})^{b}$	$1 \text{ x } 10^{7}$	$1.2 \text{ x } 10^{4}$	<1 - 30	$9.6 \text{ x } 10^{8}$ at 10 eV^{b}	$5 \text{ x } 10^{8}$ 0.02 µm ice	10^{4} - 10^{6}
Dense cloud $(10^{5} - 10^{7})^{b}$	$1 \text{ x } 10^{6}$	$1.2 \text{ x } 10^{3}$ 0.02 µm ice	<< 1 - 3	$1.4 \text{ x } 10^{4}$ at 10 eV	$1.7 \text{ x } 10^{3}$ 0.02 µm ice	< 1 - 4
Protoplanetary nebula $(10^{5} - 10^{7})^{c}$	$1 \text{ x } 10^{6}$	$1.2 \text{ x } 10^{3}$ 0.02 µm ice	<< 1 - 3	$2 \text{ x } 10^{5}$ at 1-10 keV^{d}	$5 \text{ x} 10^{4}$ 0.02 µm ice^{e}	2 – 240
Oort cloud $(4.6 \text{ x } 10^{9})$	$j(E)^{f}$	f	~150 (0.1 m) ~55-5 (1-5 m) <10 (5-15 m)	$9.6 \text{ x } 10^{8}$ at 10 eV	$9.6 \text{ x } 10^{8}$ 0.1 µm ice	$2.7 \text{ x } 10^{8}$
Laboratory $(4.6 \text{ x } 10^{-4})^{g}$	$8 \text{ x } 10^{16}$	$2 \text{ x } 10^{15}$ 1 µm ice	10	$2.2 \text{ x } 10^{15}$ at 7.4 eV	$2.2 \text{ x } 10^{15}$ 1 µm ice	10

COMPLEX ORGANIC INTERSTELLAR MOLECULES



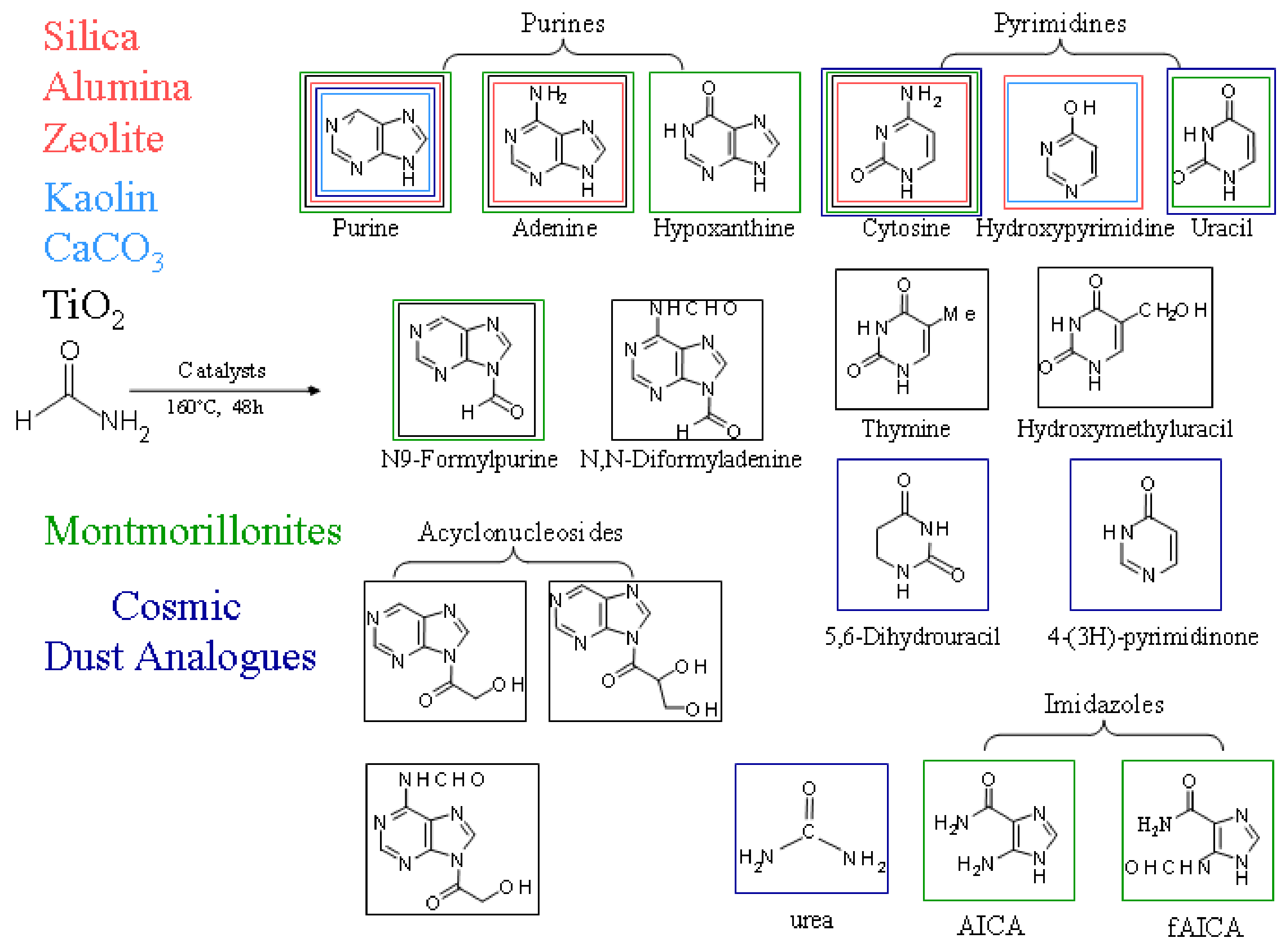
Species	Name	Source	Species	Name	Source
Hydrocarbons			**N-Containing**		
C_2H_4	Ethene	circ	CH_3CN	Acetonitrile	cc, hc, of
HC_4H	Butadiyne	circ	CH_3NC	Methylisocyanide	hc
H_2C_4	Butatrienylidene	circ, cc, lc	CH_2CNH	Keteneimine	hc
C_5H	Pentadiynyl	circ, cc	HC_3NH^+	Prot. cyanoacetylene	cc
CH_3C_2H	Propyne	cc, lc	C_5N	Cyanobutadiynyl	circ, cc
C_6H	Hexatriynyl	circ, cc, lc	HC_4N	Cyanopropynylidene	circ
C_6H^-	Hexatriynyl ion	circ, cc, lc	CH_3NH_2	Methylamine	hc, gc
H_2C_6	Hexapentaenylidene	circ, cc, lc	C_2H_3CN	Vinylcyanide	cc, hc
HC_6H	Triacetylene	circ	HC_5N	Cyanodiacetylene	circ, cc
C_7H	Heptatriynyl	circ, cc	CH_3C_3N	Methylcyanoacetylene	cc
CH_3C_4H	Methyldiacetylene	cc	CH_2CCHCN	Cyanoallene	cc
CH_3CHCH_2	Propylene	cc	NH_2CH_2CN	Aminoacetonitrile	hc
C_8H	Octatetraynyl	circ, cc	HC_7N	Cyanotriacetylene	circ, cc
C_8H^-	Octatetraynyl ion	circ, cc	C_2H_5CN	Propionitrile	hc
CH_3C_6H	Methyltriacetylene	cc	CH_3C_5N	Methylcyanodiacetylene	cc
C_6H_6	Benzene	circ	HC_9N	Cyanotetraacetylene	circ, cc
O-Containing			C_3H_7CN	N-propyl cyanide	hc
CH_3OH	Methanol	cc, hc, gc, of	$HC_{11}N$	Cyanopentaacetylene	circ, cc
HC_2CHO	Propynal	hc, gc	**S-Containing**		
$c\text{-}C_3H_2O$	Cyclopropenone	gc	CH_3SH	Methyl mercaptan	hc
CH_3CHO	Acetaldehyde	cc, hc, gc	**N,O-Containing**		
C_2H_3OH	Vinyl alcohol	hc	NH_2CHO	Formamide	
$c\text{-}CH_2OCH_2$	Ethylene oxide	hc, gc	CH_3CONH_2	Acetamide	hc, gc
$HCOOCH_3$	Methyl formate	hc, gc, of			
CH_3COOH	Acetic acid	hc, gc			
$HOCH_2CHO$	Glycolaldehyde	hc, gc			
C_2H_3CHO	Propenal	hc, gc			
C_2H_5OH	Ethanol	hc, of			
CH_3OCH_3	Methyl ether	hc, gc			
CH_3COCH_3	Acetone	hc			
$HOCH_2CH_2OH$	Ethylene glycol	hc, gc			
C_2H_5CHO	Propanal	hc, gc			
$HCOOC_2H_5$	Ethyl formate	hc			

Herbst & van Dishoeck 2009

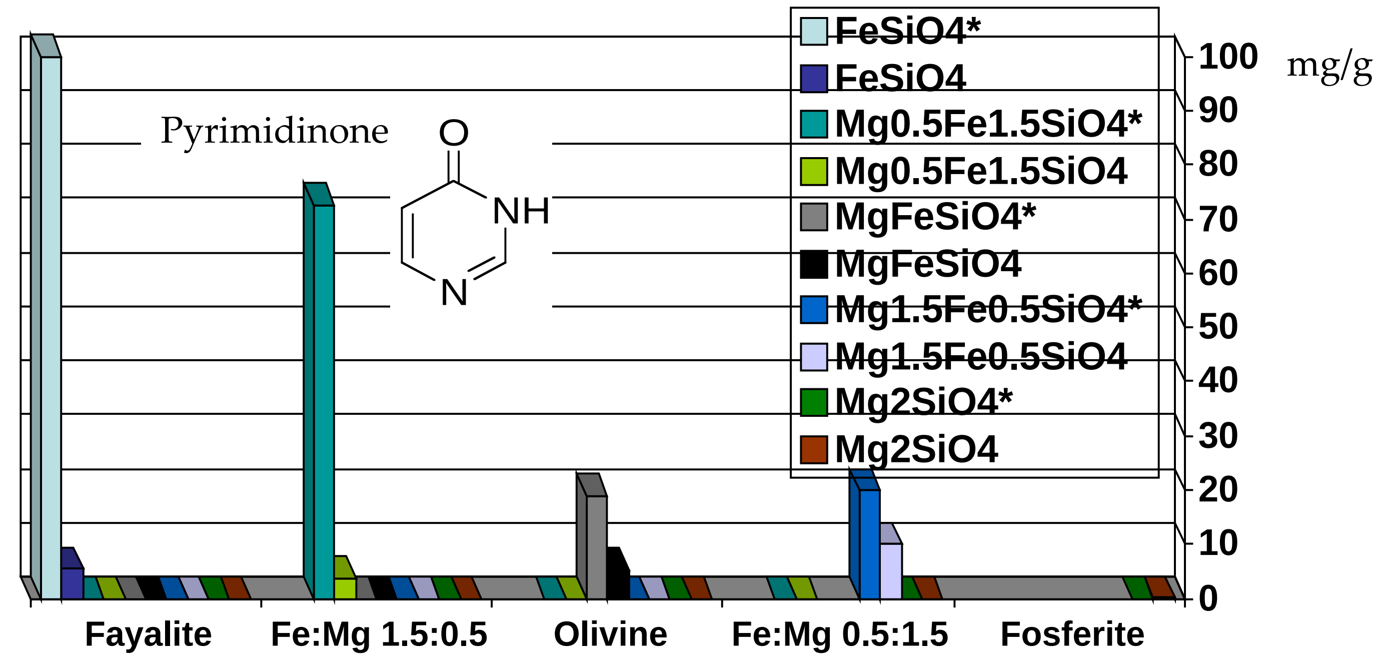
Why Formamide?

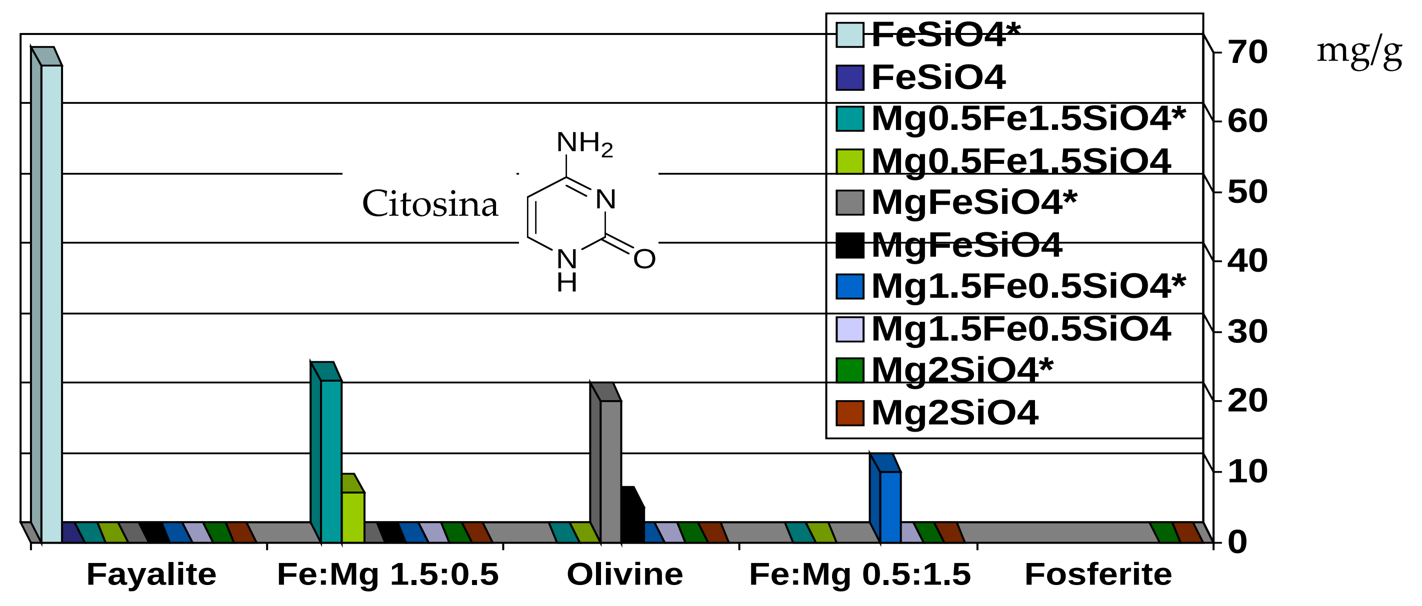
- It's a simple one C-bearing molecule.
- It's formed by hydrolysis of HCN.
- It's active in synthesis of nucleobases.
- It's active in selective degradation of DNA.
- It's observed in:
  - ✓ ISM (Millar 2005);
  - ✓ Hale-Bopp comet (Bockeleé-Morvan et al. 2000);
  - ✓ tentatively in young stellar object W33A (Schutte et al. 1999);
  - ✓ in dense ISM IRS9 (Raunier et al. 2000).

Thermal processing of *liquid* Formamide (160 ° C) with & without dust

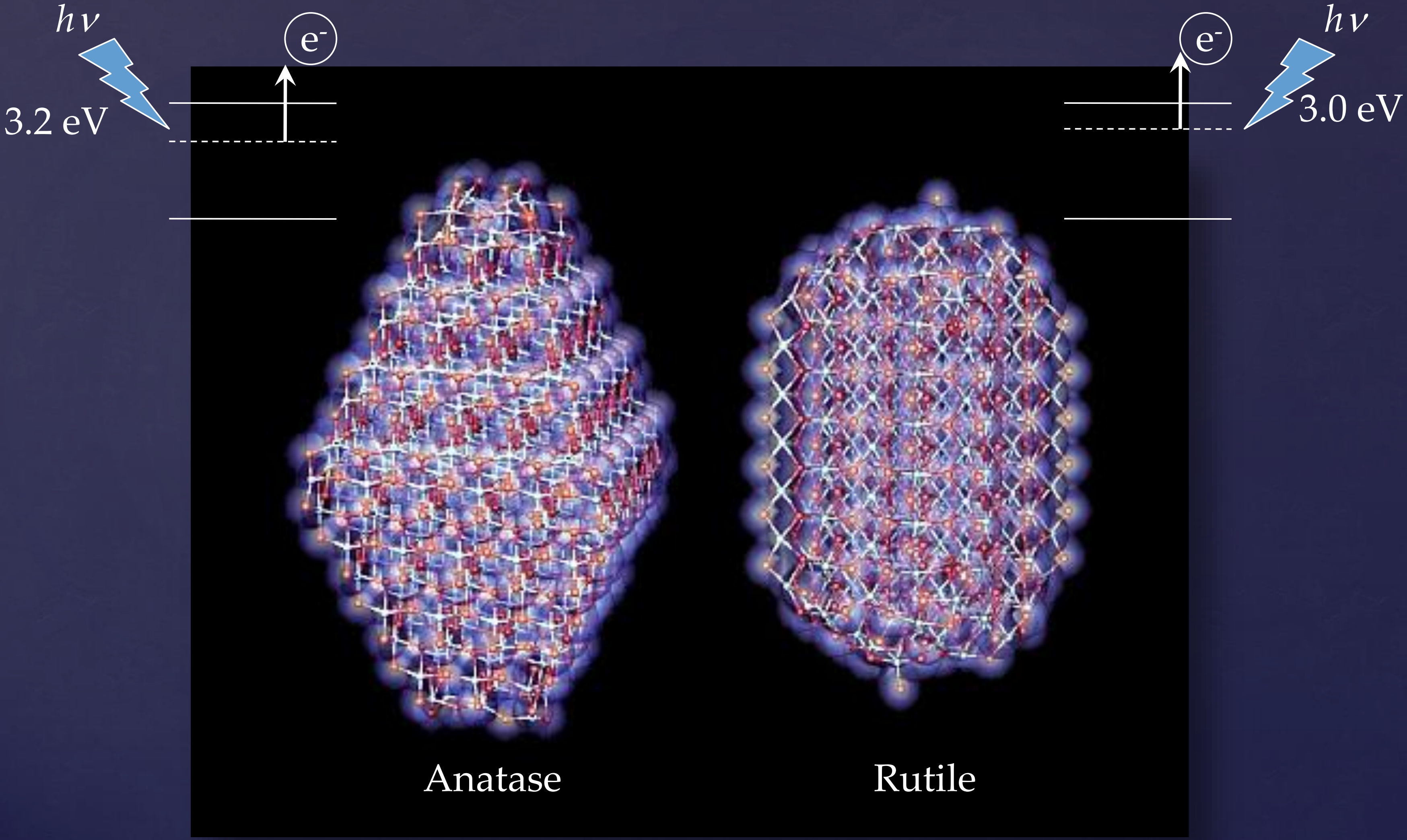


Saladino R., Crestini C., Neri C., Brucato J.R., Colangeli L. Ciciriello F., Di Mauro E., Costanzo G., *ChemBioChem* **6**, 1, 2005

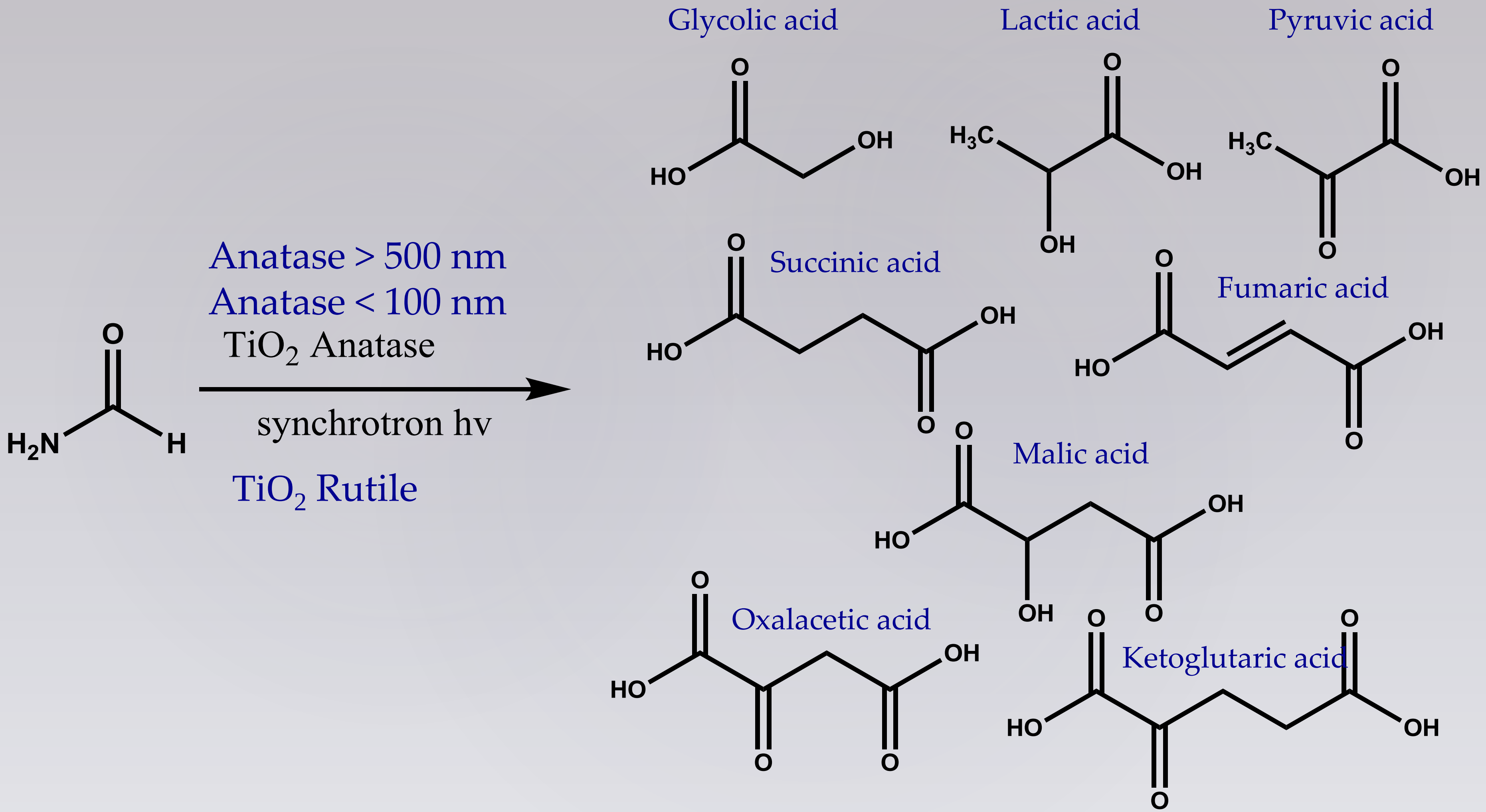

Pyrimidinone
O
NH
N
FeSiO4*
FeSiO4
Mg0.5Fe1.5SiO4*
Mg0.5Fe1.5SiO4
MgFeSiO4*
MgFeSiO4
Mg1.5Fe0.5SiO4*
Mg1.5Fe0.5SiO4
Mg2SiO4*
Mg2SiO4
100
90
80
70
60
50
40
30
20
10
0
mg/g
Fayalite
Fe:Mg 1.5:0.5
Olivine
Fe:Mg 0.5:1.5
Fosferite


Citosina
NH2
N
N
H
O
FeSiO4*
FeSiO4
Mg0.5Fe1.5SiO4*
Mg0.5Fe1.5SiO4
MgFeSiO4*
MgFeSiO4
Mg1.5Fe0.5SiO4*
Mg1.5Fe0.5SiO4
Mg2SiO4*
Mg2SiO4
70
60
50
40
30
20
10
0
mg/g
Fayalite
Fe:Mg 1.5:0.5
Olivine
Fe:Mg 0.5:1.5
Fosferite

Titanium dioxide Photochemistry



Biogenic Carboxylic Acids



Anatase > 500 nm
Anatase < 100 nm
TiO_2 Anatase

synchrotron hv

TiO_2 Rutile

Glycolic acid

Lactic acid

Pyruvic acid

Succinic acid

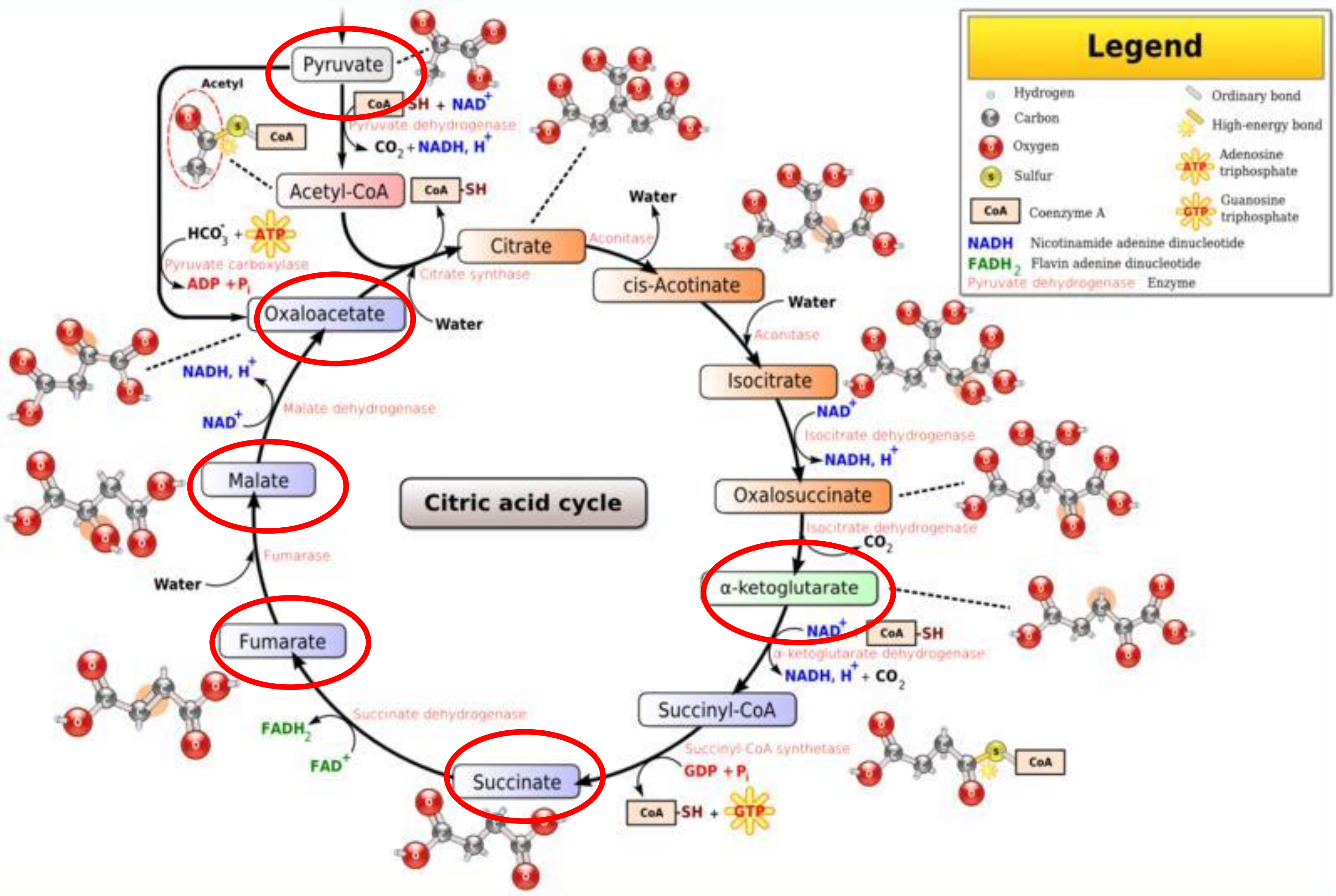
Fumaric acid

Malic acid

Oxalacetic acid

Ketoglutaric acid

R. Saladino, J.R. Brucato, ASTROBIOLOGY 2011



Citric acid cycle

Pyruvate

Acetyl

CoA

CoA -SH + NAD$^+$

Pyruvate dehydrogenase

CO_2 + NADH, H$^+$

Acetyl-CoA

CoA -SH

HCO_3^- + ATP

Pyruvate carboxylase

ADP + P_i

Oxaloacetate

Citrate synthase

Water

Citrate

Aconitase

Water

cis-Acotinate

Water

Aconitase

Isocitrate

NAD$^+$

Isocitrate dehydrogenase

NADH, H$^+$

Oxalosuccinate

Isocitrate dehydrogenase

CO_2

α-ketoglutarate

NAD$^+$

CoA -SH

α-ketoglutarate dehydrogenase

NADH, H$^+$ + CO_2

Succinyl-CoA

Succinyl-CoA synthetase

GDP + P_i

CoA -SH + GTP

Succinate

Succinate dehydrogenase

$FADH_2$

FAD$^+$

Fumarate

Fumarase

Water

Malate

Malate dehydrogenase

NAD$^+$

NADH, H$^+$

Legend

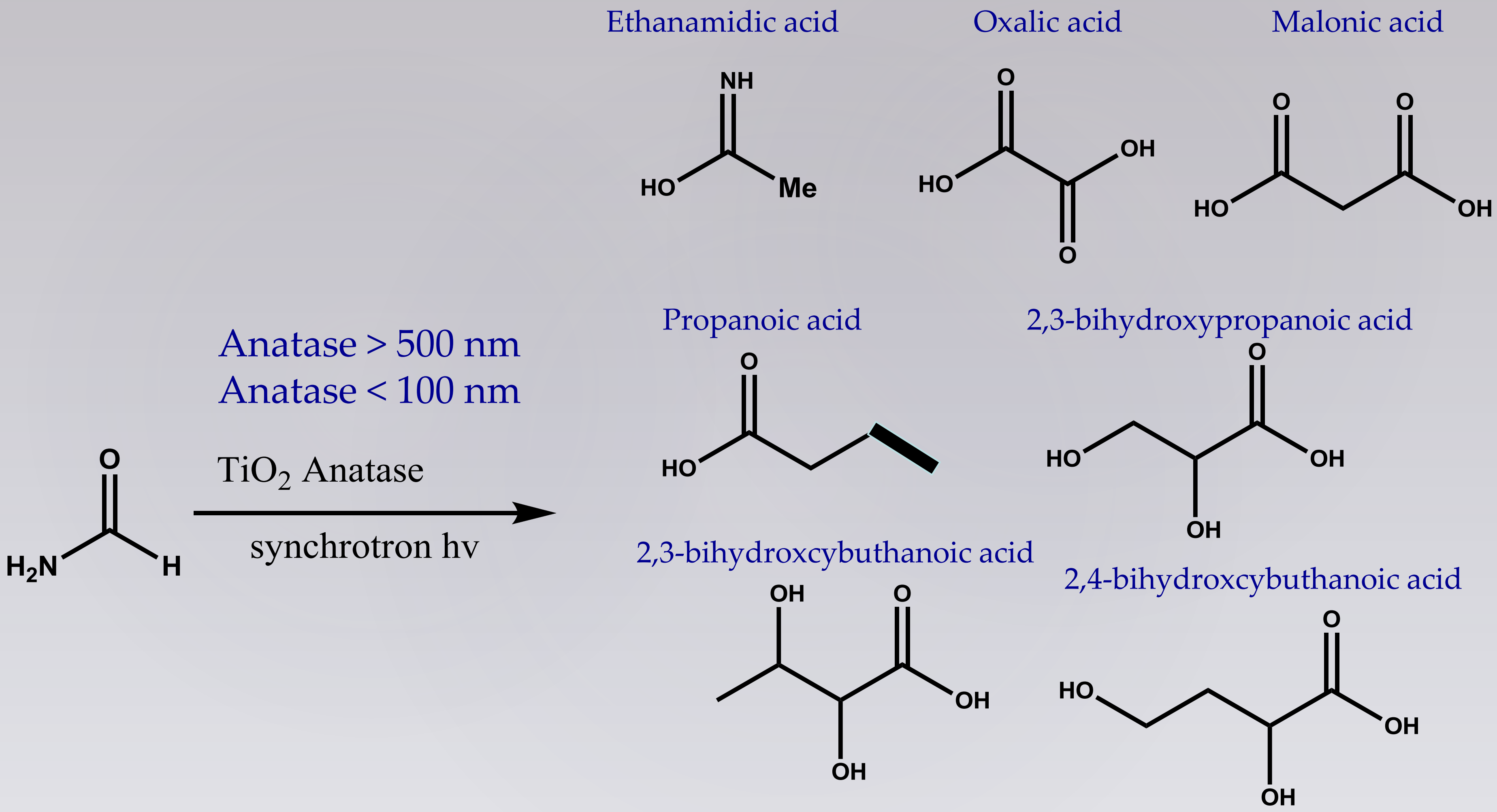
●	Hydrogen	⁄	Ordinary bond
●	Carbon	⁄	High-energy bond
●	Oxygen	ATP	Adenosine triphosphate
S	Sulfur	GTP	Guanosine triphosphate
CoA	Coenzyme A		

NADH Nicotinamide adenine dinucleotide

$FADH_2$ Flavin adenine dinucleotide

Pyruvate dehydrogenase Enzyme

Non-biogenic Carboxylic Acids



Anatase > 500 nm
Anatase < 100 nm

TiO_2 Anatase

synchrotron hv

Ethanamidic acid

Oxalic acid

Malonic acid

Propanoic acid

2,3-bihydroxypropanoic acid

2,3-bihydroxcybuthanoic acid

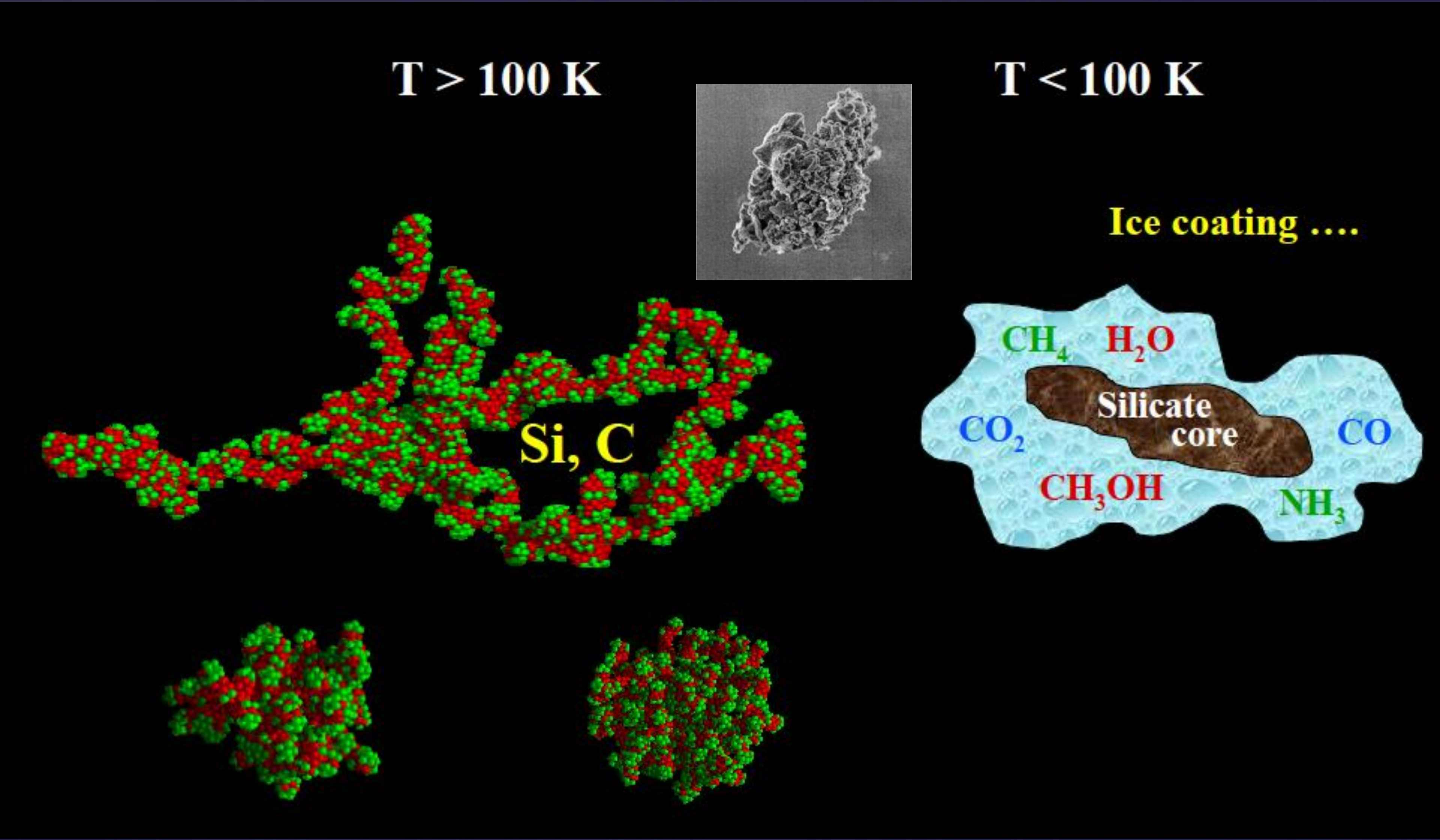
2,4-bihydroxcybuthanoic acid

R. Saladino, J.R. Brucato, A. de Sio, E. Pace 2010

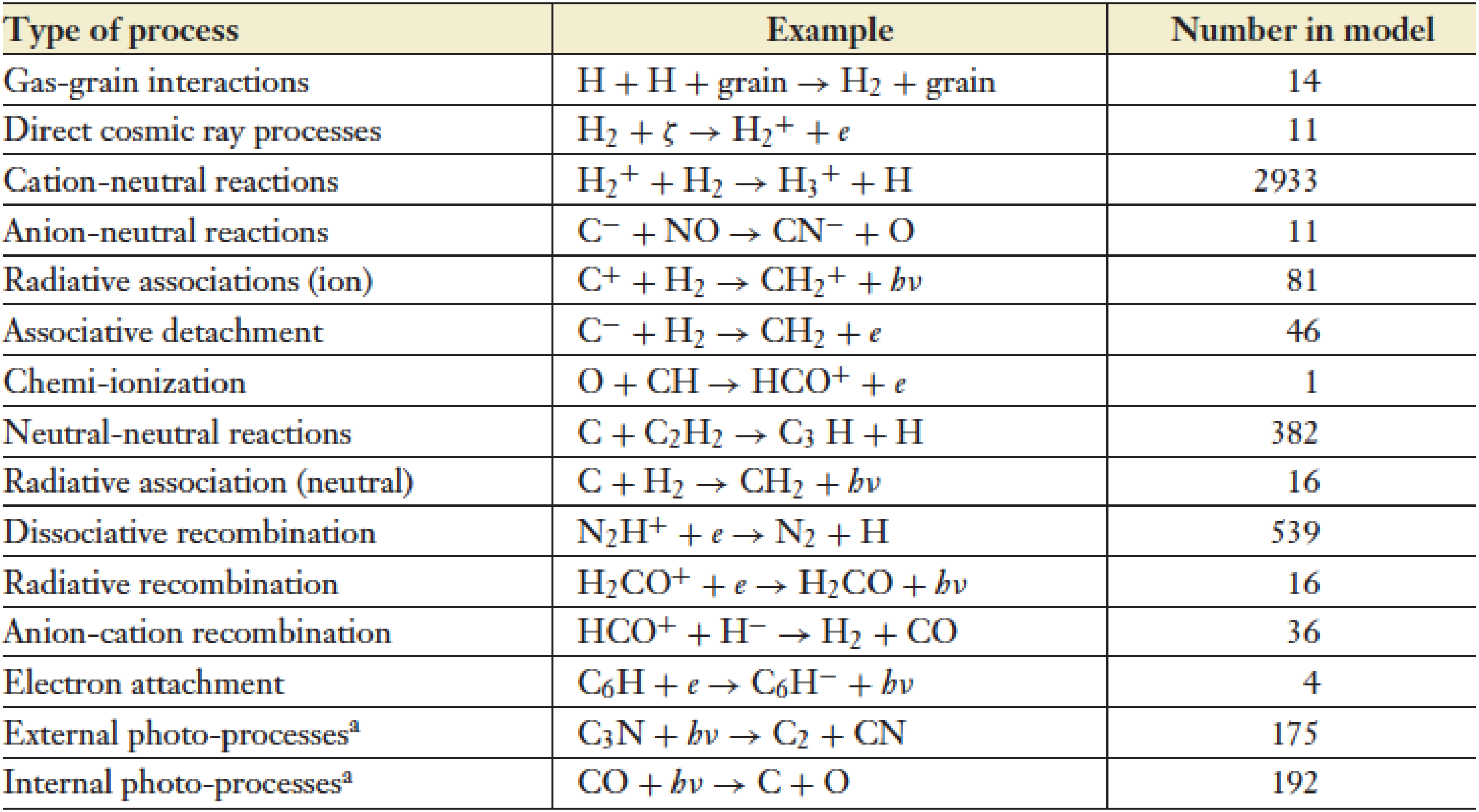
CONCLUSIONS

- Nucleic acid bases ARE NOT produced during the photochemical process
- Biogenic carboxylic acids are synthesized
- Six of ten key intermediates of the Krebs cycle are selectively obtained
- Anatase phase is more reactive than Rutile one

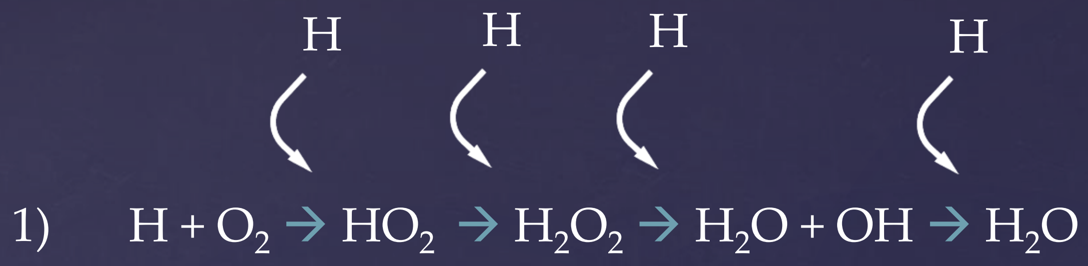
Dust particles: the seeds of planets and molecules



Type of Reactions

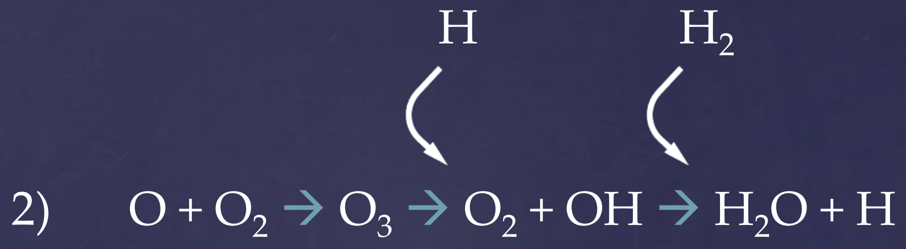


Type of process	Example	Number in model
Gas-grain interactions	$H + H + \text{grain} \rightarrow H_2 + \text{grain}$	14
Direct cosmic ray processes	$H_2 + \zeta \rightarrow H_2^+ + e$	11
Cation-neutral reactions	$H_2^+ + H_2 \rightarrow H_3^+ + H$	2933
Anion-neutral reactions	$C^- + NO \rightarrow CN^- + O$	11
Radiative associations (ion)	$C^+ + H_2 \rightarrow CH_2^+ + h\nu$	81
Associative detachment	$C^- + H_2 \rightarrow CH_2 + e$	46
Chemi-ionization	$O + CH \rightarrow HCO^+ + e$	1
Neutral-neutral reactions	$C + C_2H_2 \rightarrow C_3H + H$	382
Radiative association (neutral)	$C + H_2 \rightarrow CH_2 + h\nu$	16
Dissociative recombination	$N_2H^+ + e \rightarrow N_2 + H$	539
Radiative recombination	$H_2CO^+ + e \rightarrow H_2CO + h\nu$	16
Anion-cation recombination	$HCO^+ + H^- \rightarrow H_2 + CO$	36
Electron attachment	$C_6H + e \rightarrow C_6H^- + h\nu$	4
External photo-processes[a]	$C_3N + h\nu \rightarrow C_2 + CN$	175
Internal photo-processes[a]	$CO + h\nu \rightarrow C + O$	192



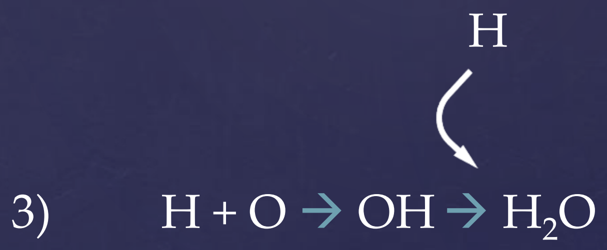
1) $$\mathrm{H + O_2 \xrightarrow{H} HO_2 \xrightarrow{H} H_2O_2 \xrightarrow{H} H_2O + OH \xrightarrow{H} H_2O}$$

(Ioppolo et al. 2008, 2010)



2) $$\mathrm{O + O_2 \rightarrow O_3 \xrightarrow{H} O_2 + OH \xrightarrow{H_2} H_2O + H}$$

(Tielens & Hagen 1982)



3) $$\mathrm{H + O \rightarrow OH \xrightarrow{H} H_2O}$$

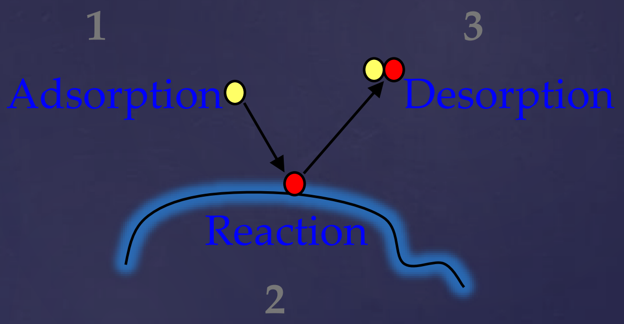
(Dulieu et al. 2010)

Some argues that species formed by these exotermic reactions will immediately desorb (Paoupular 2005). However, models predicts that most (99.1%) of OH and H_2O formed remain on surfaces (Cupper and Herbst 2007).

Surface catalysis

Surface catalysis allow molecules formation that are not possible in the gas phase. It open pathways for the chemical evolution in space.

Eley-Rideal

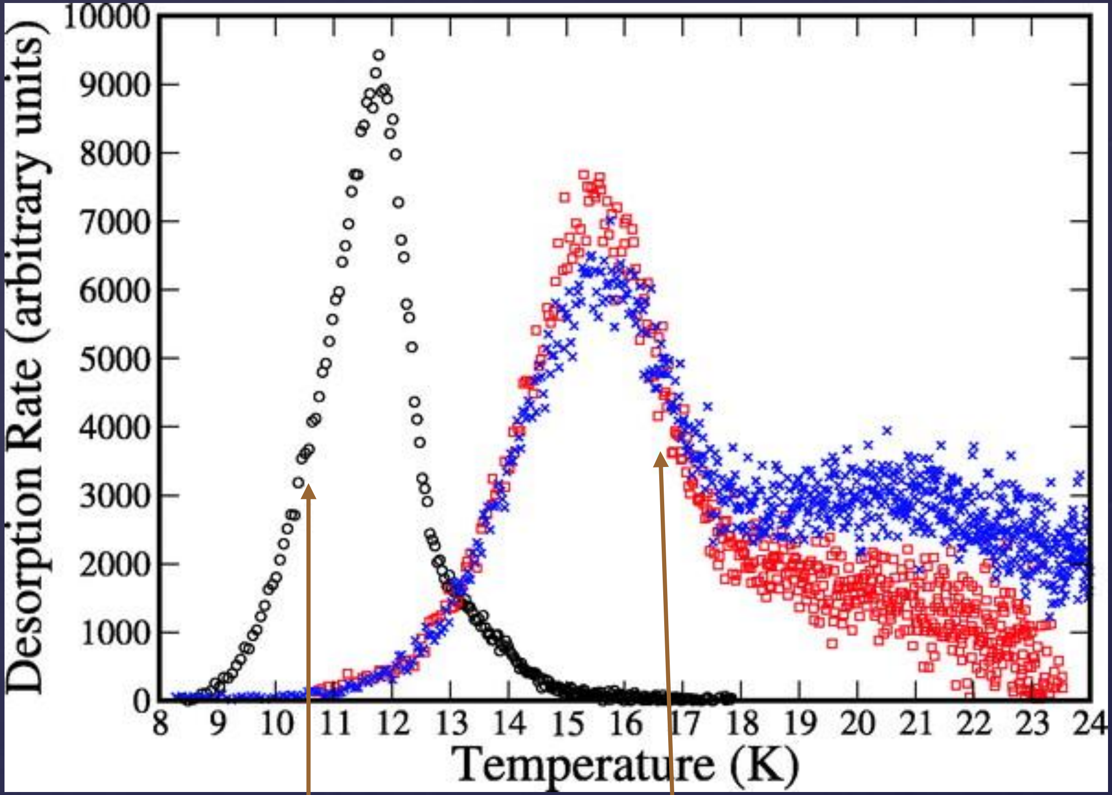

1
Adsorption
3
Desorption
Reaction
2

Langmuir-Hinshelwood

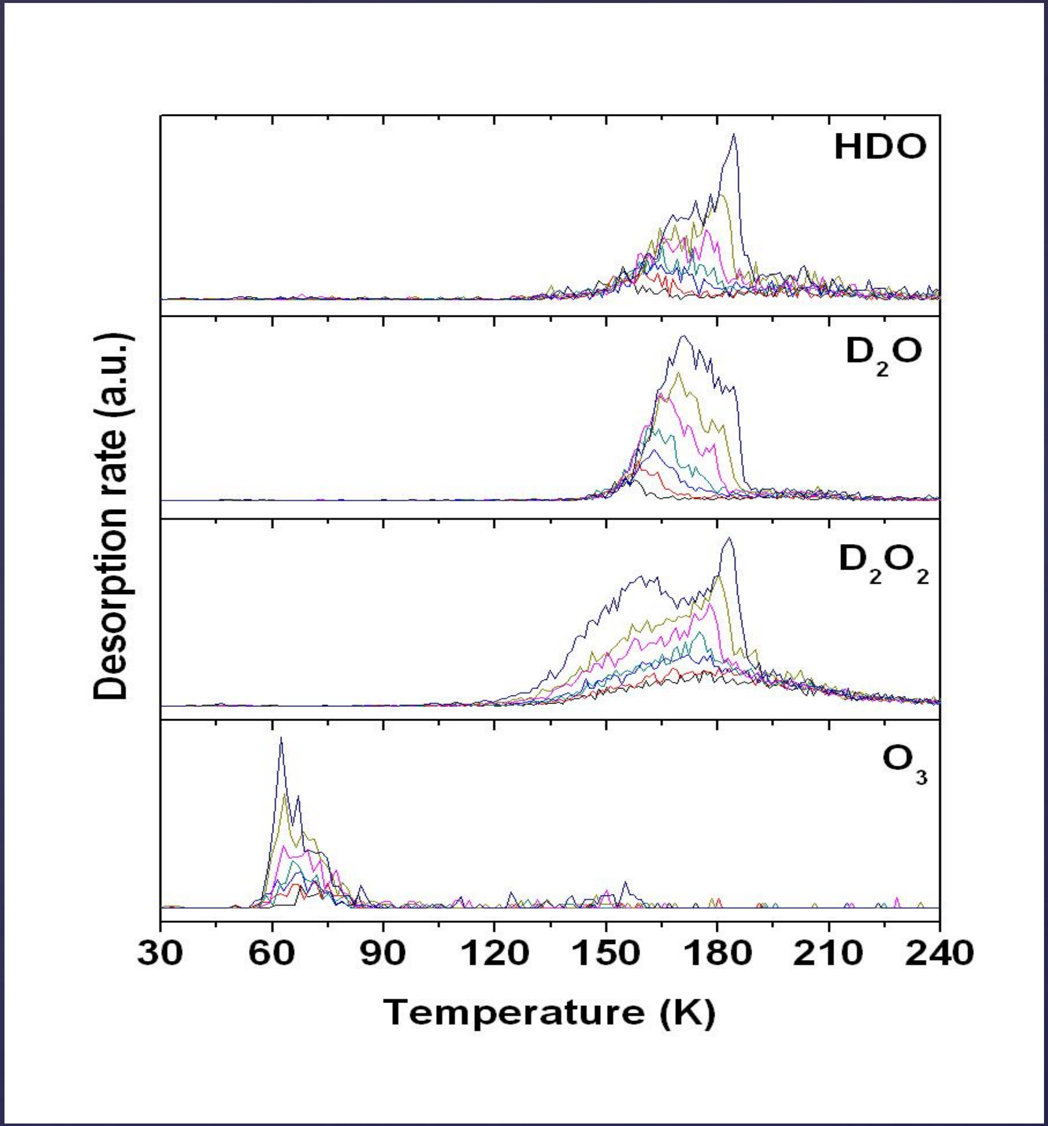

1
Adsorption
4
Desorption
Reaction
Diffusion
3
2

H & D beams irradiation of amorphous olivine silicate (Fe, Mg)SiO$_4$

(Perets et al. 2007)



Desorpion rate of HD molecules vs. surface temperature during TDP on polycrystalline and amorphous silicates



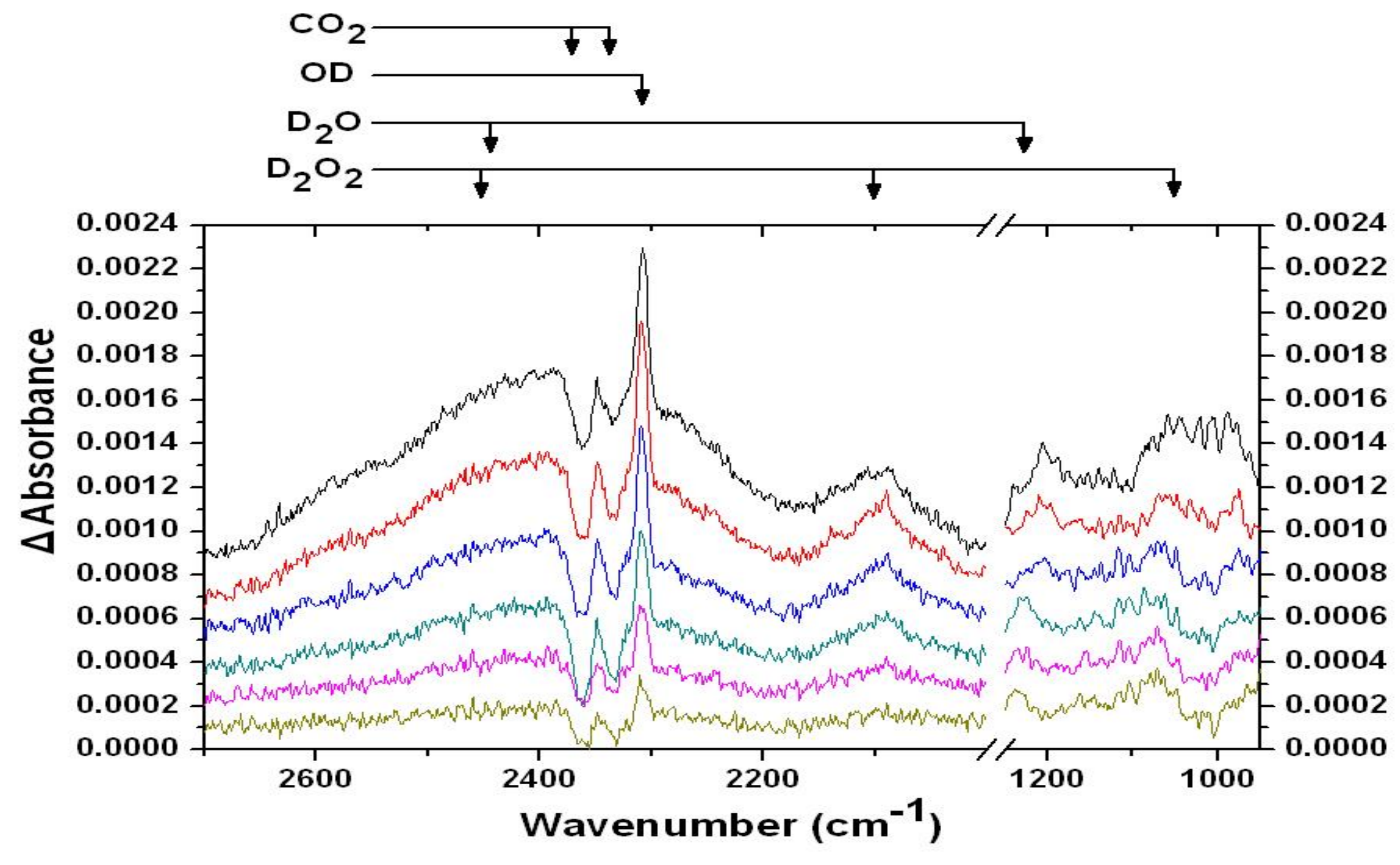
Ed=390 meV

Ed=400 meV

Ed=430 meV

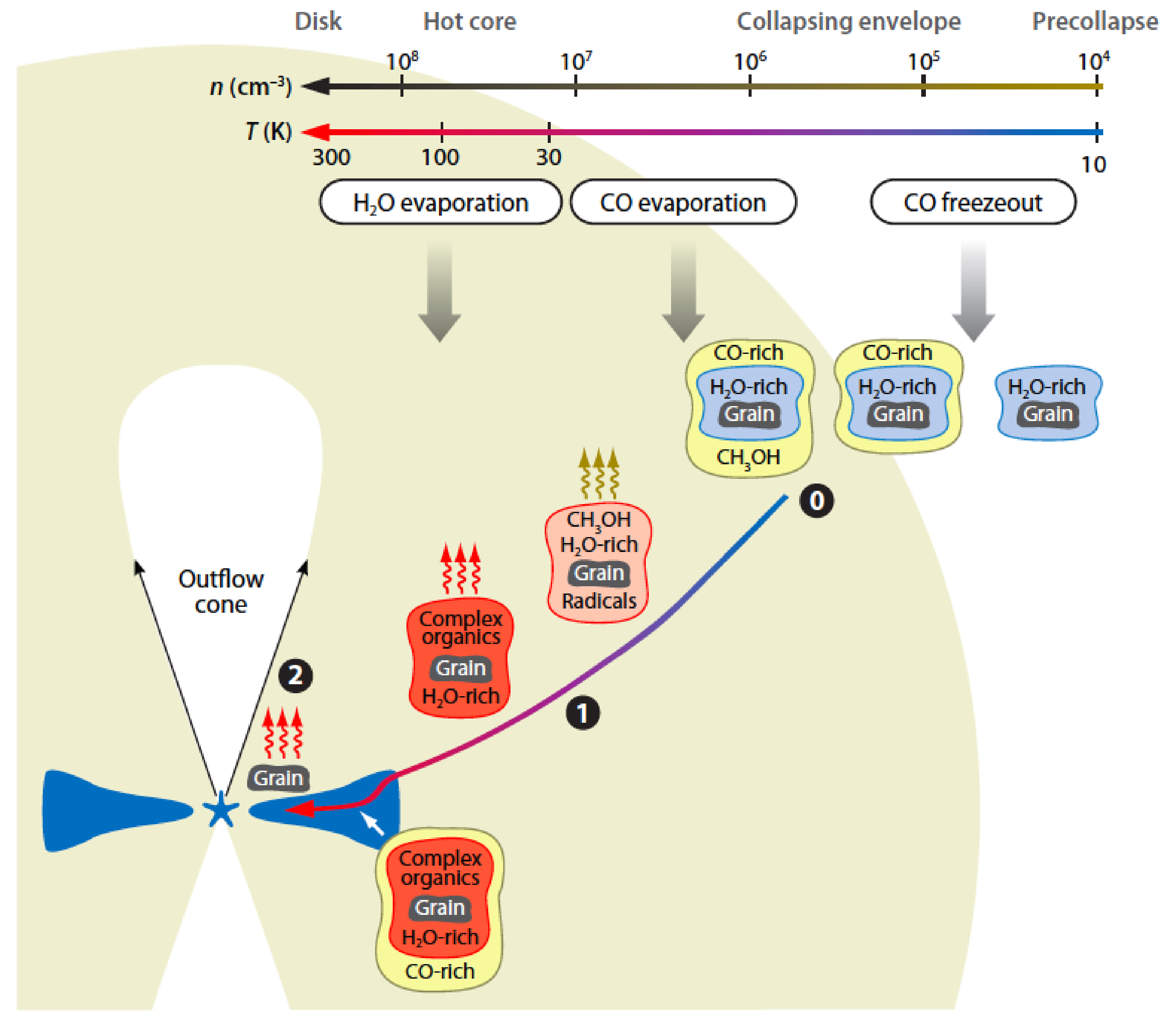
Ed=170 meV

Desorption peaks for various species after D and O co-exposure. From bottom to top: 10 min, 15 min, 22.5 min, 30 min, 45 min, 60 min and 90 min.



The formation of water can follow hydrogenation of both O and O_2 pathways.

Conclusion


Disk
Hot core
Collapsing envelope
Precollapse
n (cm^{-3})
10^8
10^7
10^6
10^5
10^4
T (K)
300
100
30
10
H_2O evaporation
CO evaporation
CO freezeout
CO-rich
H_2O-rich
Grain
CH_3OH
CO-rich
H_2O-rich
Grain
H_2O-rich
Grain
0
CH_3OH
H_2O-rich
Grain
Radicals
Complex organics
Grain
H_2O-rich
1
Outflow cone
2
Grain
Complex organics
Grain
H_2O-rich
CO-rich

Conclusion

Interaction between protons & minerals.

- free protons in the interstitial space
- protons trapped in material defects chemical reactions with oxygen atoms in metal oxides (SiO_2, TiO_2, Al_2O_3) and formation of hydroxyl groups.

Interaction between hydrogen and minerals

- The formation of water can follow hydrogenation of both O and O_2 pathways.

Mars soil analogues

Kaolinite
Smectite
Montmorillonite
Nontronite
Illite
Albite
Andesite
Labradorite
Anorthite
Bytownite
Oligoclase
Anorthoclase
Oligoclase
Labradorite
Nepheline

Natrolite
Fayalite
Forsterite
Enstatite
Ferrosilite
Jadeite
Diopsite
Augite
Serpentine
Apatite
arsenate
Pyrrhotite
Troilite
Pyrite
Oxides

Biomarkers

Extant	*Extinct*	*Meteoritic*
ATP	Generic Isoprenoid	Napthalene
Cyclic AMP	Pristane	Generic amino acid
Pyrimidine base	Phytane	Isovaline
Purine base	Tetramethyl benzenes	Generic aromatic carboxylic acid
DNA	Fatty Acids	
Nicotinamide	Quaternary carbon alkane	
Quinones		
ATP Synthase		
Phytane		
LPS		
Squalene		

Biomarker Selection

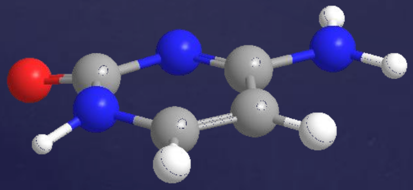
- Expectation of detection in Martian soils (likelihood of preservation and likelihood of existence)

Some Facts

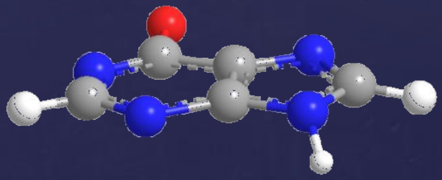
✓ **Minerals:** pivotal role in the prebiotic evolution of complex chemical systems by

- **mediating** the effects of electromagnetic radiation
- **influencing** the photostability of bio-molecules
- **catalyzing** important chemical reactions
- **protecting** molecules against degradation

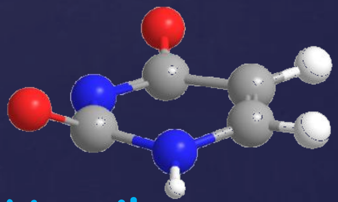
✓ Study the photochemistry and the photophysics of nucleobases in the presence of mineral matrices, to investigate both the **survivability** when exposed to Mars surface and the **physical and chemical processes occurring in extraterrestrial environments.**



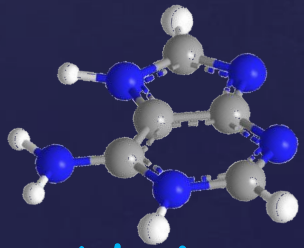
Cytosine



Hypoxanthine



Uracil

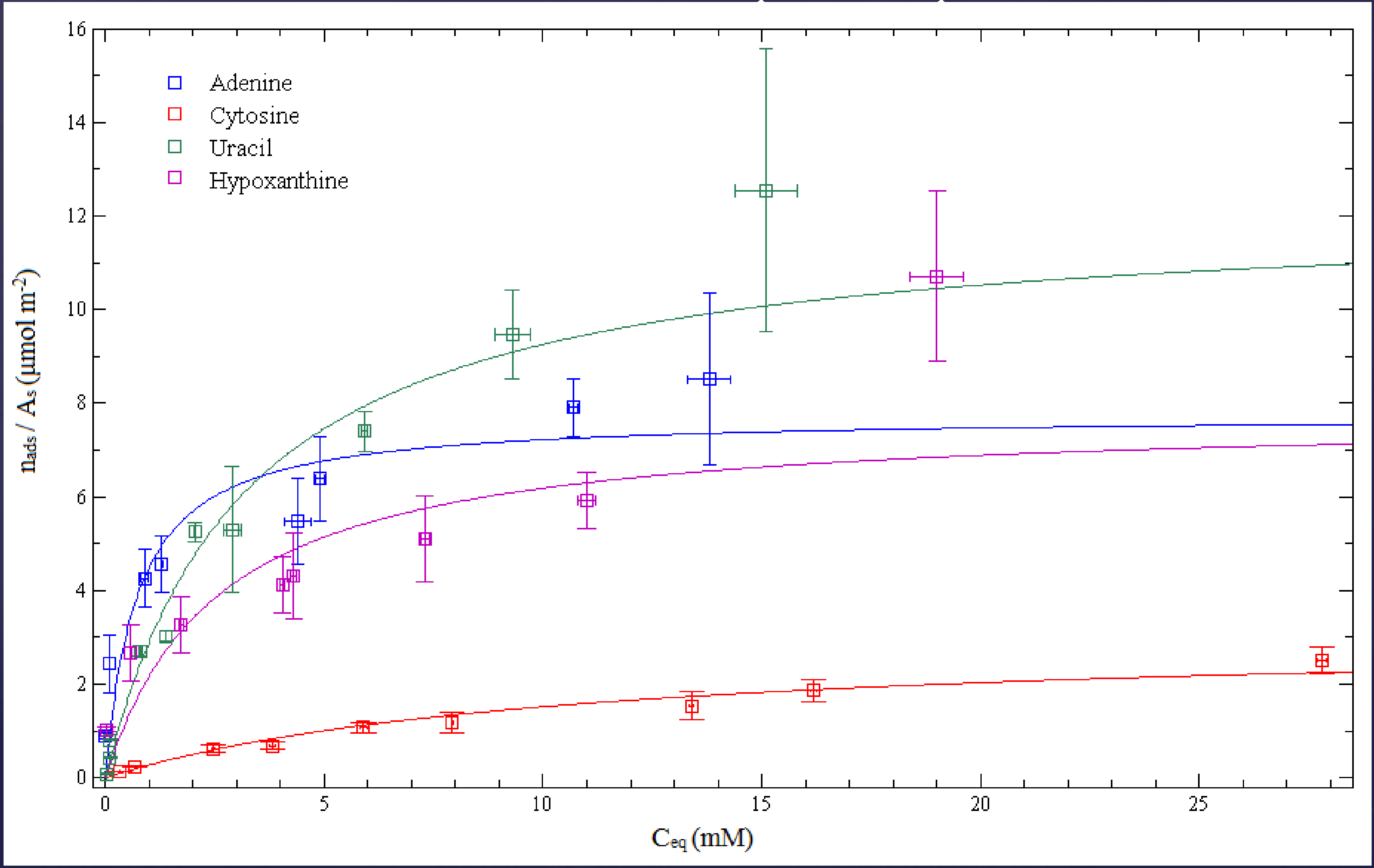


Adenine

Adsorption properties of nucleobases on MgO

LANGMUIR ISOTHERMS OF NUCLEOBASES ONTO MgO AT 298 K

$$n_{ads}/m_{mineral} = KbC_{eq} / (1 + KC_{eq})$$



Adsorption properties of nucleobases on MgO

LANGMUIR ISOTHERMS OF NUCLEOBASES ONTO MgO AT 298 K

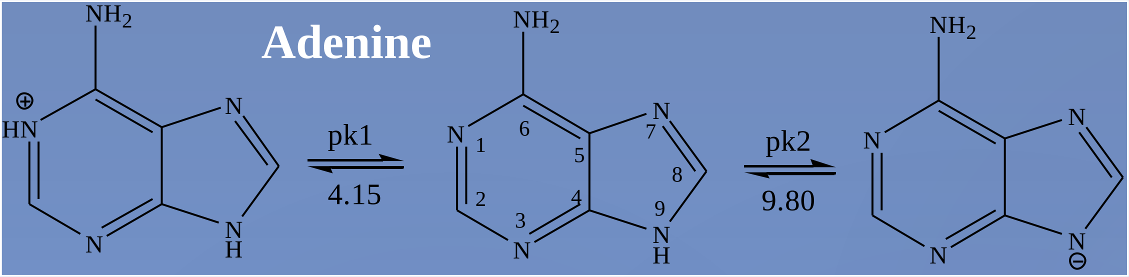
$$n_{ads}/m_{mineral} = KbC_{eq} / (1 + KC_{eq})$$

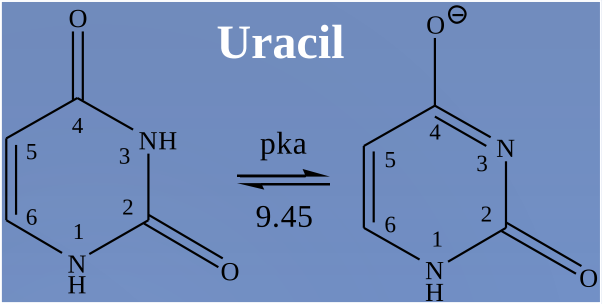
Sample	***K*** **(M^{-1})**	***b*** **(mol g^{-1})**
Adenine	$(1 \pm 1) \cdot 10^{3}$	$(4 \pm 7) \cdot 10^{-4}$
Uracil	$(3.0 \pm 0.9) \cdot 10^{2}$	$(4 \pm 2) \cdot 10^{-4}$
Hypoxanthine	$(3 \pm 5) \cdot 10^{2}$	$(3 \pm 8) \cdot 10^{-4}$
Cytosine	$(1.0 \pm 0.3) \cdot 10^{2}$	$(1.0 \pm 0.4) \cdot 10^{-4}$

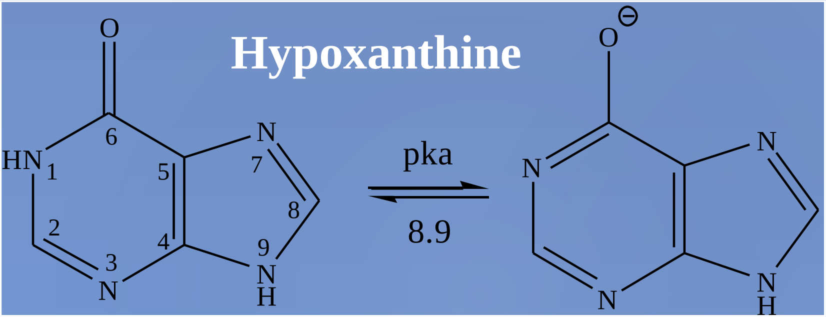
Nucleobases adsorption order:

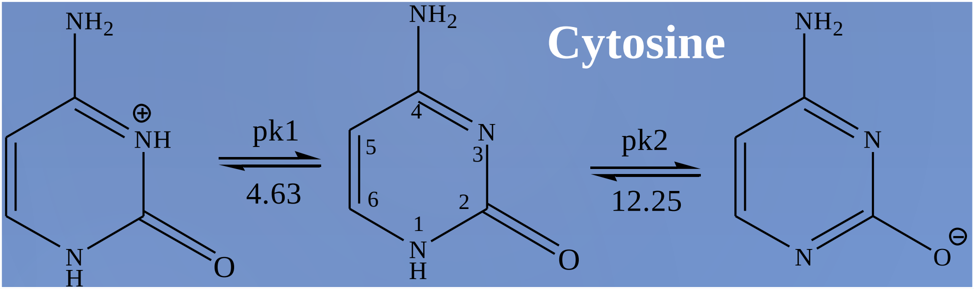
adenine > uracil ≥ hypoxanthine > cytosine

Interpretation of nucleobases adsorption on MgO







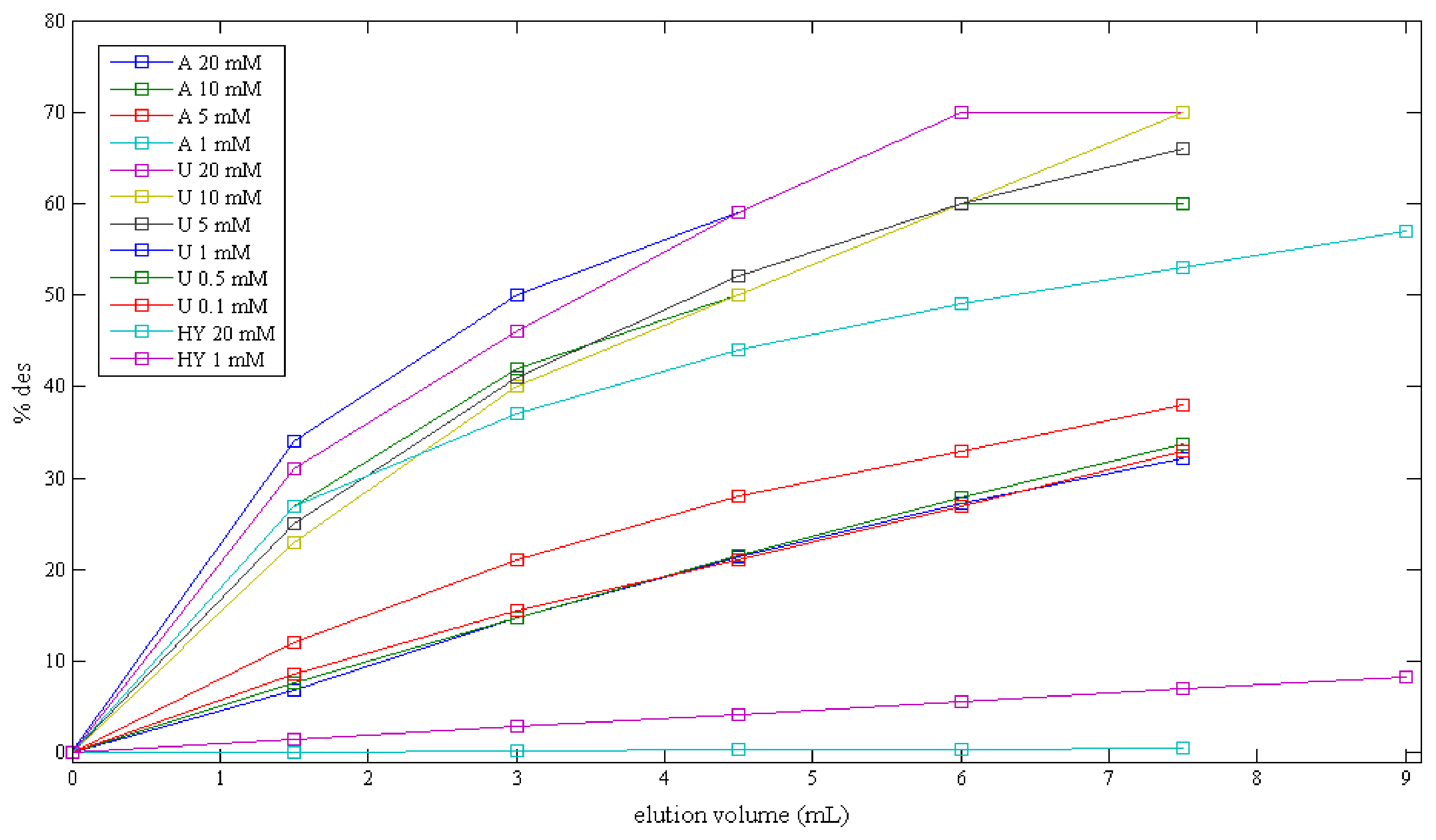


The basicity of MgO causes a pH ≈ 10 at equilibrium

Adenine, uracil, hypoxanthine are largely anionic
Cytosine is neutral

The efficient adsorption of adenine, uracil and hypoxanthine relative to cytosine suggests the involvement of ionic interactions with MgO

Desorption studies of nucleobases from MgO

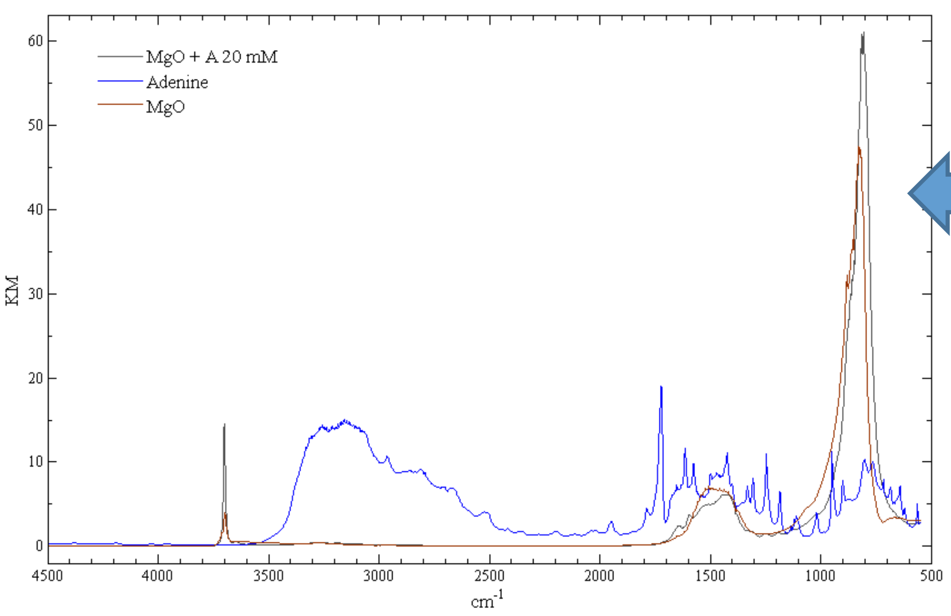


Nucleobases desorption order from MgO:
cytosine >> uracil ≥ adenine > hypoxanthine

The **high reversibility** of the adsorption process and the **decrease in adsorption with increasing temperature** would suggest a **physisorption**

IR-spectroscopy studies of nucleobase-mineral complexes

To better understand, at molecular level, the kind of **interactions between nucleobases and minerals**, IR-spectroscopy studies were carried out, using the diffuse reflectance infrared Fourier transform spectroscopy technique (**DRIFTS**)

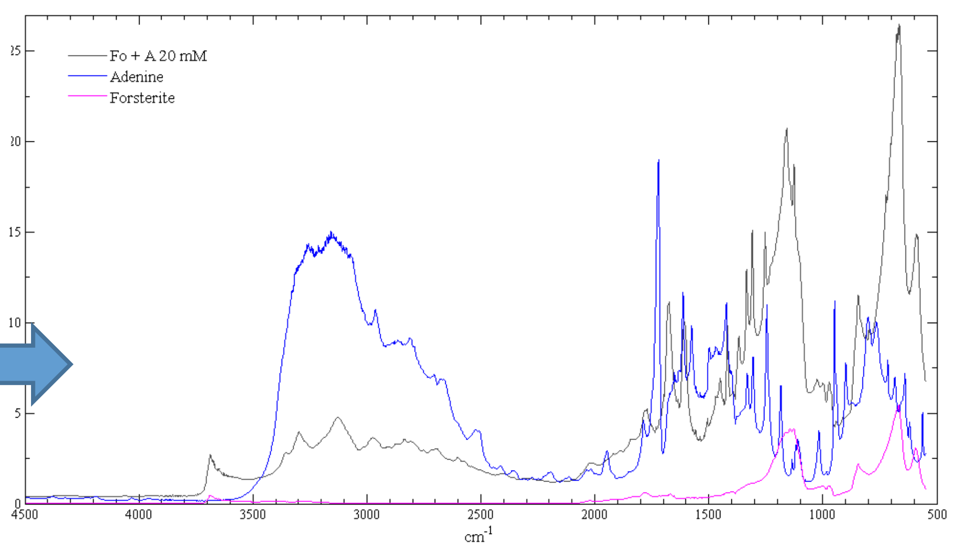


Adenine adsorbed onto MgO

IR bands are **NOT** observed

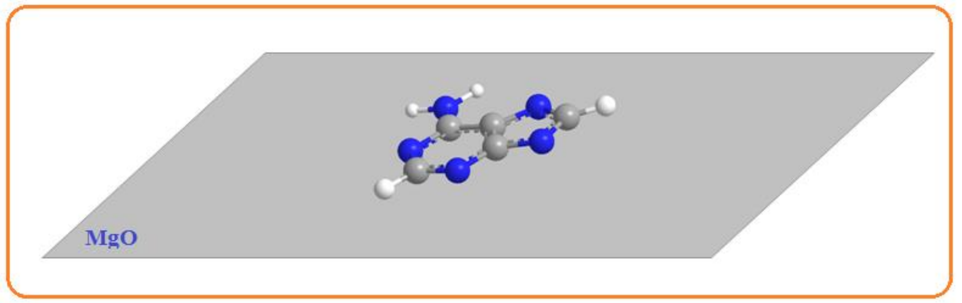
Adenine adsorbed onto forsterite

Detectable IR bands

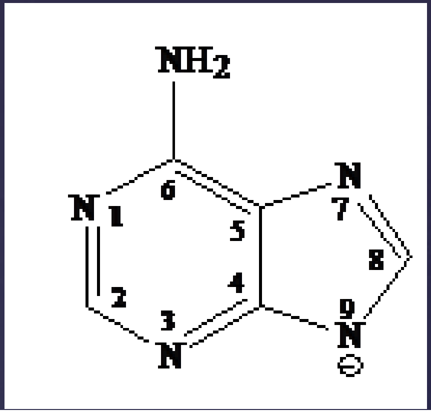


Interpretation of spectroscopic features

Adenine on MgO

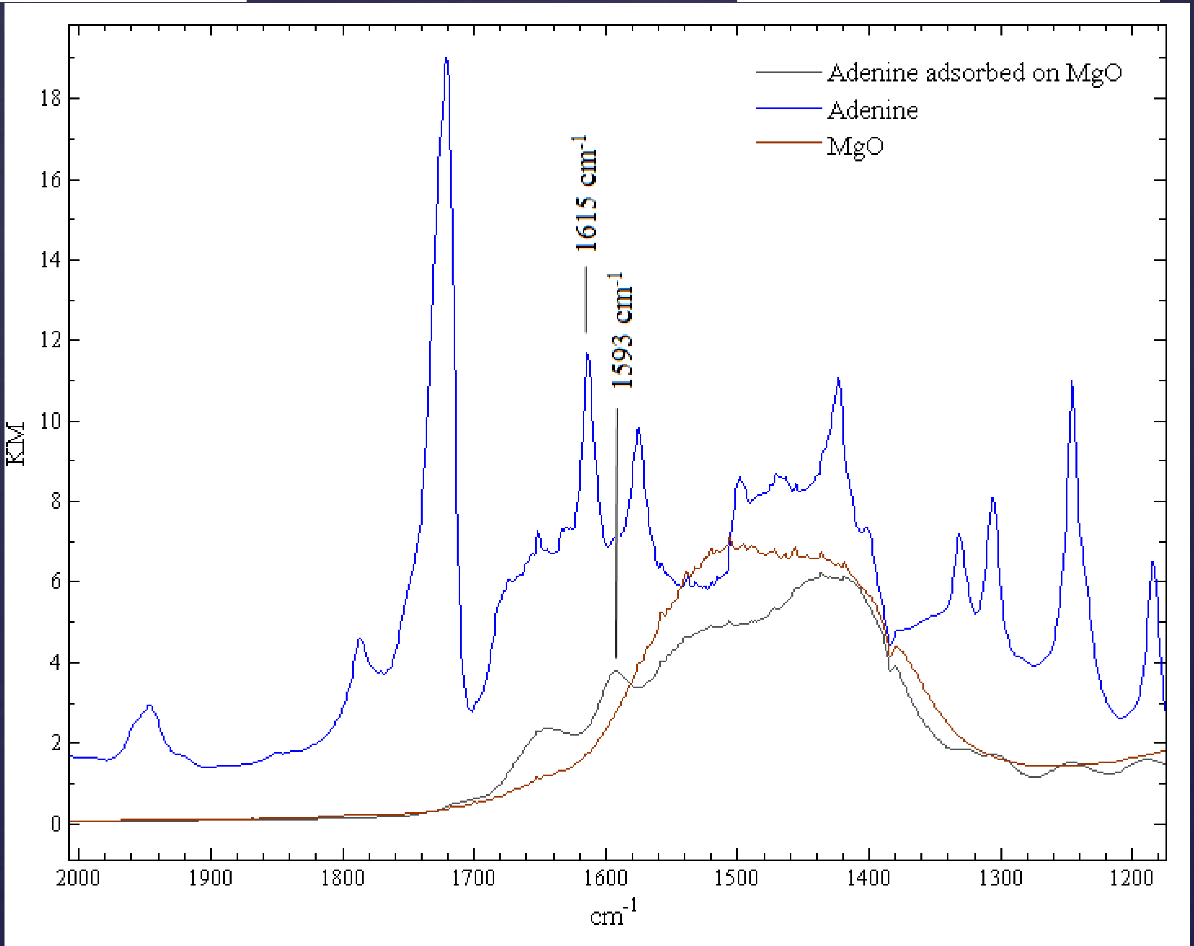


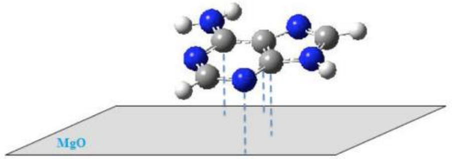
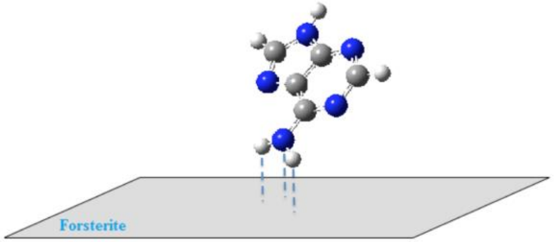
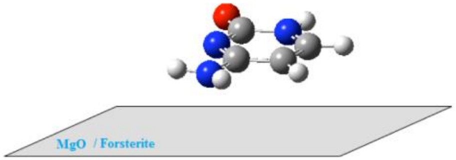
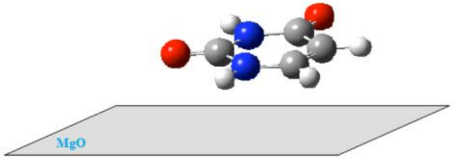
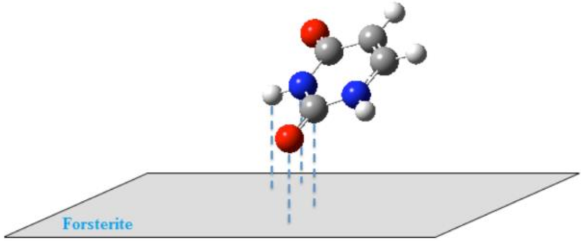
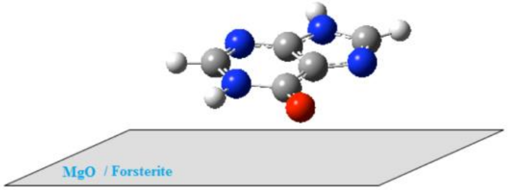
pH ≈ 10

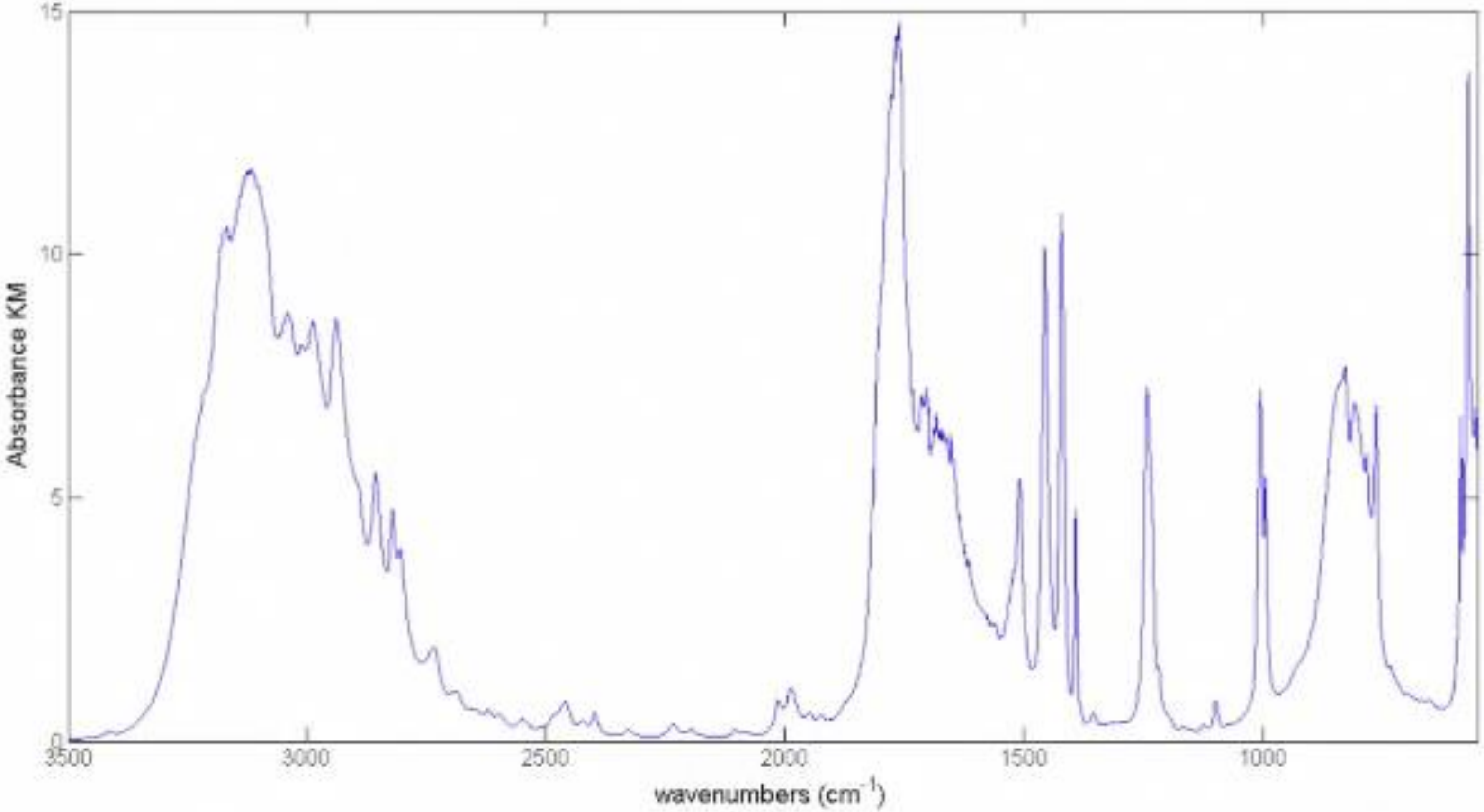


Low frequency shift (-22 cm^{-1}) of the Q_7 vibrational mode: N_3C_4 str, C_5C_6 str

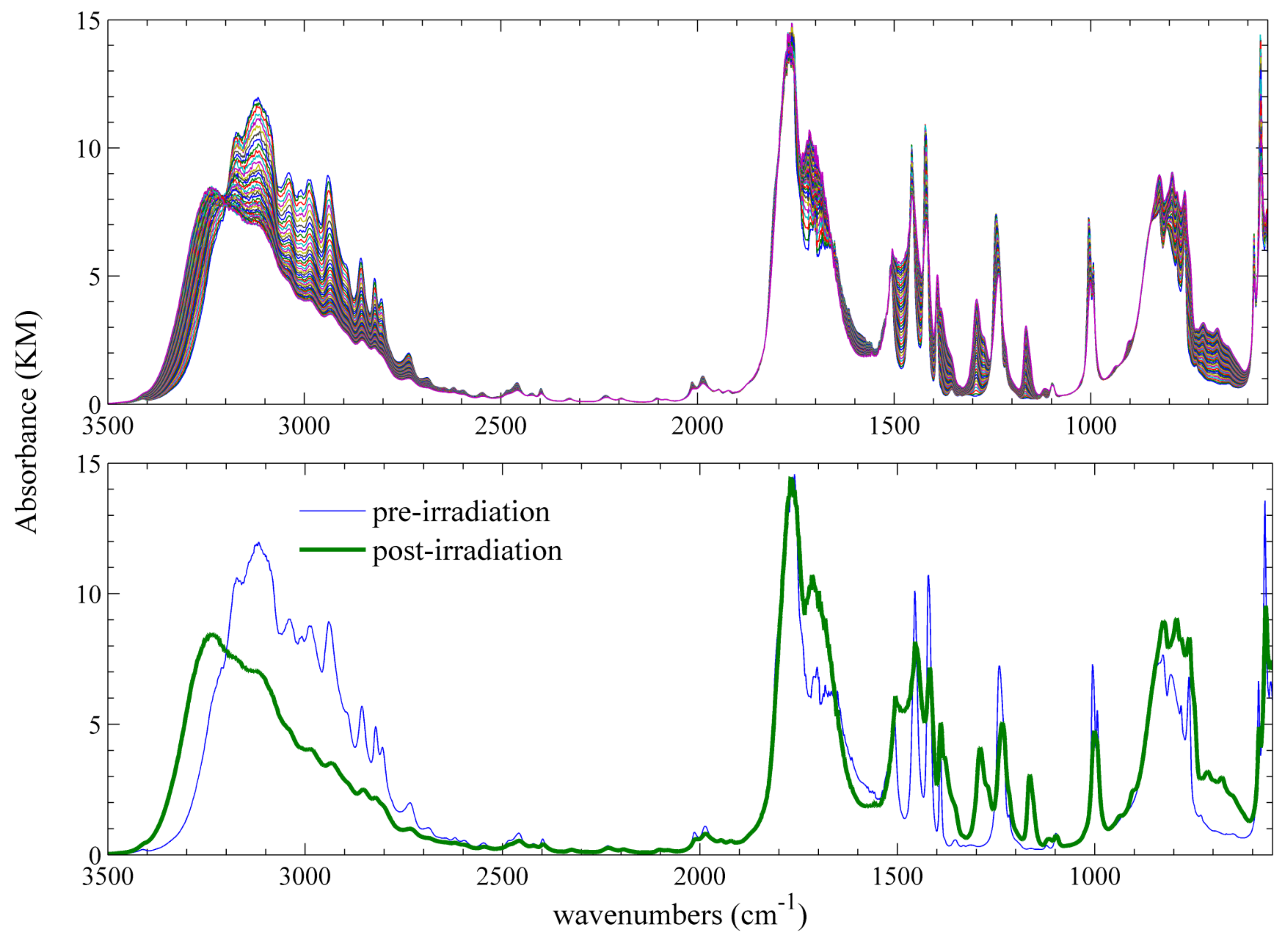
Distorted nearly planar arrangement



 	**Adenine on MgO** **Interaction with the $N_3C_4C_5C_6$ part of the molecule in a distorted nearly planar arrangement.**
 	**Adenine on forsterite** Interaction with the NH_2 group in a tilted arrangement.
 	**Cytosine on MgO and forsterite** Face-to-face configuration.
 	**Uracil on MgO** Face-to-face configuration.
 	**Uracil on forsterite** Interaction with the C_2=O and N_3H groups in a tilted arrangement.
 	**Hypoxanthine on MgO and forsterite** Face-to-face configuration.

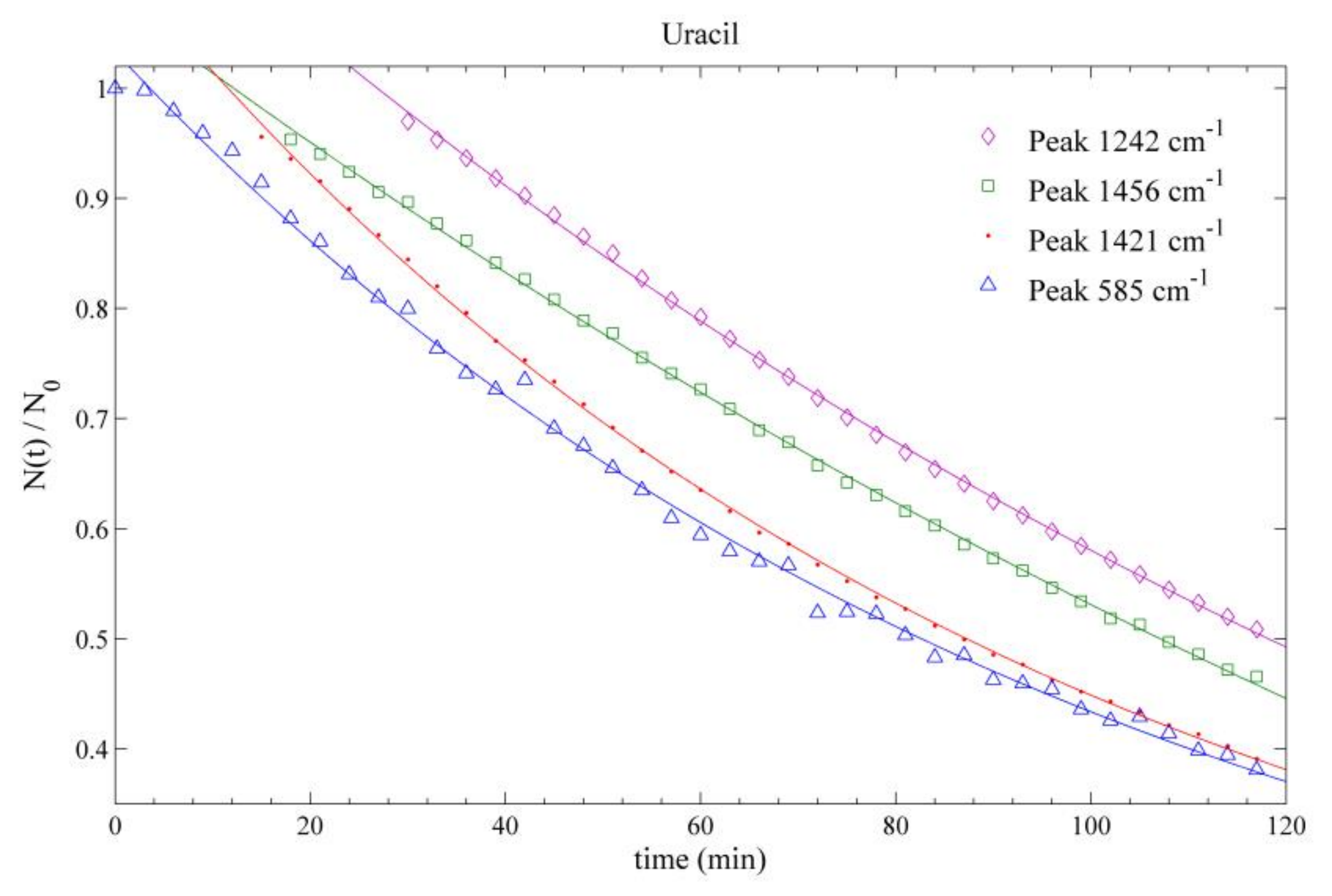

Absorbance KM
15
10
5
0
3500
3000
2500
2000
1500
1000
wavenumbers (cm^{-1})

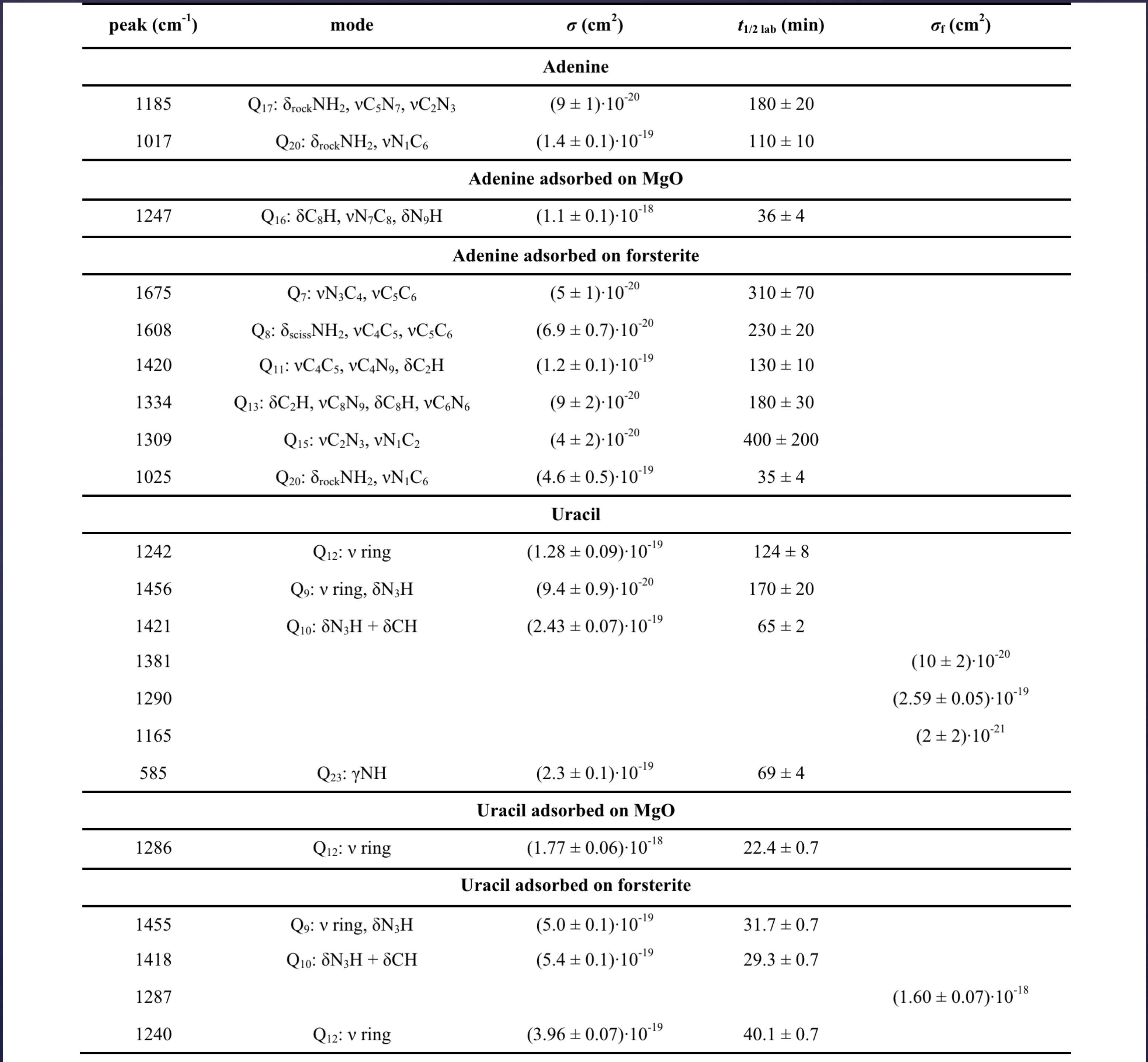
UV degradation kinetics



$$N(t)/N_0 = Be^{-\beta t} + c$$

$N(t)/N_0$ fraction of unaltered molecules
N_0 initial number of molecules
β degradation rate
B fraction of interacting molecules
c fraction of non-interacting molecules





peak (cm^{-1})	mode	σ (cm^2)	$t_{1/2\ lab}$ (min)	σ_f (cm^2)
		Adenine		
1185	Q_{17}: $\delta_{rock}NH_2$, νC_5N_7, νC_2N_3	$(9 \pm 1)\cdot10^{-20}$	180 ± 20	
1017	Q_{20}: $\delta_{rock}NH_2$, νN_1C_6	$(1.4 \pm 0.1)\cdot10^{-19}$	110 ± 10	
		Adenine adsorbed on MgO		
1247	Q_{16}: δC_8H, νN_7C_8, δN_9H	$(1.1 \pm 0.1)\cdot10^{-18}$	36 ± 4	
		Adenine adsorbed on forsterite		
1675	Q_7: νN_3C_4, νC_5C_6	$(5 \pm 1)\cdot10^{-20}$	310 ± 70	
1608	Q_8: $\delta_{sciss}NH_2$, νC_4C_5, νC_5C_6	$(6.9 \pm 0.7)\cdot10^{-20}$	230 ± 20	
1420	Q_{11}: νC_4C_5, νC_4N_9, δC_2H	$(1.2 \pm 0.1)\cdot10^{-19}$	130 ± 10	
1334	Q_{13}: δC_2H, νC_8N_9, δC_8H, νC_6N_6	$(9 \pm 2)\cdot10^{-20}$	180 ± 30	
1309	Q_{15}: νC_2N_3, νN_1C_2	$(4 \pm 2)\cdot10^{-20}$	400 ± 200	
1025	Q_{20}: $\delta_{rock}NH_2$, νN_1C_6	$(4.6 \pm 0.5)\cdot10^{-19}$	35 ± 4	
		Uracil		
1242	Q_{12}: ν ring	$(1.28 \pm 0.09)\cdot10^{-19}$	124 ± 8	
1456	Q_9: ν ring, δN_3H	$(9.4 \pm 0.9)\cdot10^{-20}$	170 ± 20	
1421	Q_{10}: $\delta N_3H + \delta CH$	$(2.43 \pm 0.07)\cdot10^{-19}$	65 ± 2	
1381				$(10 \pm 2)\cdot10^{-20}$
1290				$(2.59 \pm 0.05)\cdot10^{-19}$
1165				$(2 \pm 2)\cdot10^{-21}$
585	Q_{23}: γNH	$(2.3 \pm 0.1)\cdot10^{-19}$	69 ± 4	
		Uracil adsorbed on MgO		
1286	Q_{12}: ν ring	$(1.77 \pm 0.06)\cdot10^{-18}$	22.4 ± 0.7	
		Uracil adsorbed on forsterite		
1455	Q_9: ν ring, δN_3H	$(5.0 \pm 0.1)\cdot10^{-19}$	31.7 ± 0.7	
1418	Q_{10}: $\delta N_3H + \delta CH$	$(5.4 \pm 0.1)\cdot10^{-19}$	29.3 ± 0.7	
1287				$(1.60 \pm 0.07)\cdot10^{-18}$
1240	Q_{12}: ν ring	$(3.96 \pm 0.07)\cdot10^{-19}$	40.1 ± 0.7	

- **Cytosine** and **hypoxanthine** have a greater photostability, both pure and adsorbed on MgO and forsterite.
- For **adenine** and **uracil** degradation was observed both pure and adsorbed onto MgO and forsterite.
- **Minerals** make degradation faster and more probable (the half-lifetimes of degradation decrease and the degradation cross sections increase), but do not promote the formation of new species.
- Comparing the measured cross sections with the molecular dimensions, a rather **low probability of interaction between UV radiation and nucleobases** was estimated (between 0.07 % and 0.0008 %), confirming the high intrinsic photostability of such molecules.

IN DUST WE TRUST