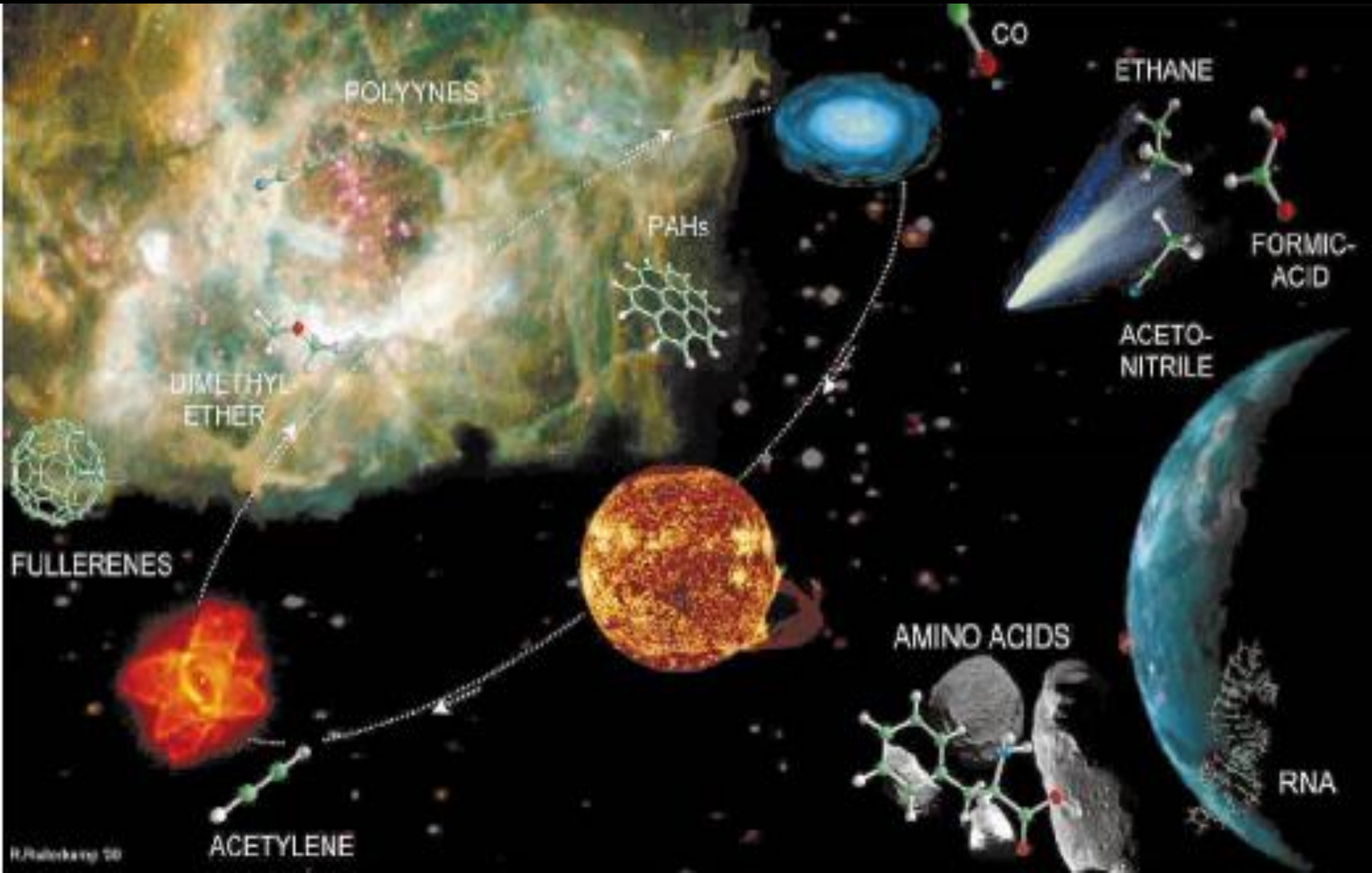
ASTROCHEMISTRY & ASTROBIOLOGY



FOLLOW THE LIFE

- Solvent
- ⇒ Biogenic elements
- Source of Free Energy

searches for life within our solar system commonly retreat from a search for life to a search for "life as we know it," meaning life based on liquid water, a suite of so-called "biogenic" elements (most famously carbon), and a usable source of free energy.

(Chyba & Hand, 2005, p. 34)

SIGA A VIDA

- Siga a água (Follow the water)
- ⇒ Siga o carbono
- Siga o nitrogênio
- Siga o fósforo
- Siga a energia
- Siga a entropia
- Siga a informação
- Siga o significado

Universo Orgânico!

- 0.5 % da matéria bariônica “visível” está na forma molecular. (Fraser, McCoustra & Willians, 2002, A&G, 43, 2.11).
- **~170 Moléculas detectadas no espaço** **(~50% orgânicas: CHON).**

Como são encontradas as biomoléculas ?

IR-Telescopes (vibrational lines)

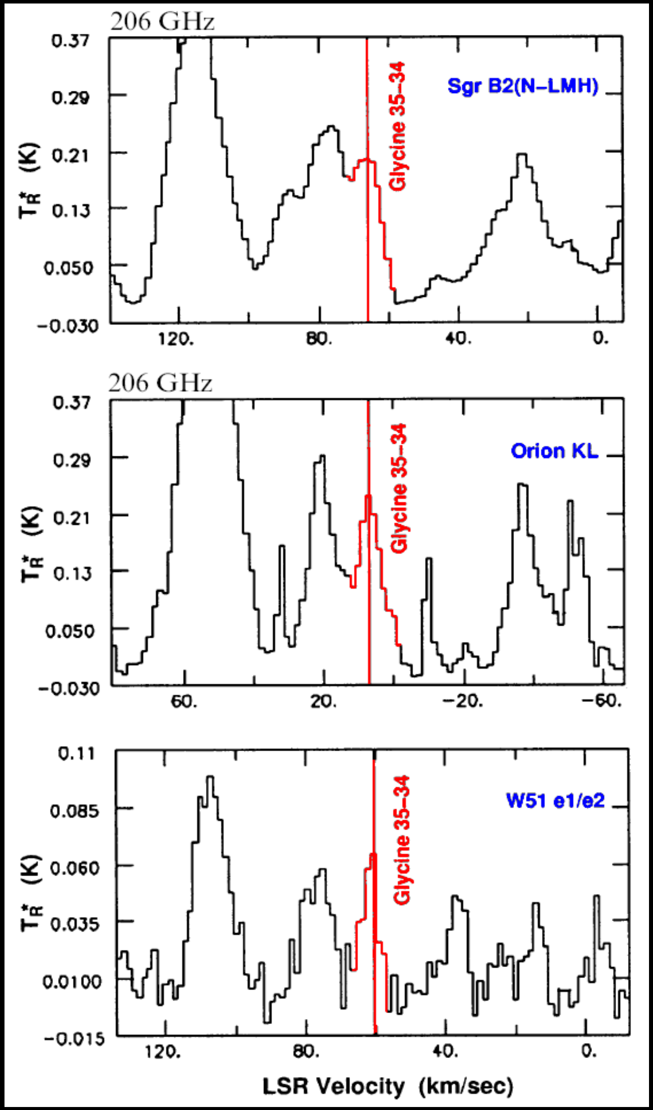
GEMINI Sul (8.1m)

SOAR (4.2m)

Radiotelescopes (rotational lines)

VLA

Itapetinga, SP



Onde são encontradas as biomoléculas?

Gaseous Pillars – Eagle Nebula

Key hole Nebula

Titan

Hale-Bopp

Murchinson

Molecules in Space

338 Molecules

as if May 2024

2 atoms	H_2	AlF	AlCl	C_2	CH	CH^+
	CN	CO	CO^+	CP	SiC	HCl
	KCl	NH	NO	NS	NaCl	OH
	PN	SO	SO^+	SiN	SiO	SiS
	CS	HF	HD	FeO (?)	O_2	CF^+
	SiH (?)	PO	AlO	OH^+	CN^-	SH^+
	LiH	SH	N_2	S_2†	N_2^+†	CN^+†
3 atoms	C_3	C_2H	C_2O	C_2S	CH_2	HCN
	HCO	HCO^+	HCS^+	HOC^+	H_2O	H_2S
	HNC	HNO	MgCN	MgNC	N_2H^+	N_2O
	NaCN	OCS	SO_2	$c-SiC_2$	CO_2	NH_2
	H_3^+	H_2D^+	HD_2^+	SiCN	AlNC	SiNC
	HCP	CCP	AlOH	H_2O^+	H_2Cl^+	KCN
	FeCN	OCN^-	CO_2^+	H_2S^+	CN_2	HDO
	CS_2†					
4 atoms	$c-C_3H$	$l-C_3H$	C_3N	C_3O	C_3S	C_2H_2
	NH_3	HCCN	$HCNH^+$	HNCO	HNCS	$HOCO^+$
	H_2CO	H_2CN	H_2CS	H_3O^+	$c-SiC_3$	CH_3
	C_3N^-	PH_3(?)	HCNO	HOCN	HSCN	H_2O_2
	C_4 (??)					
5 atoms	C_5	C_4H	C_4Si	$l-C_3H_2$	$c-C_3H_2$	H_2CCN
	CH_4	HC_3N	HC_2NC	HCOOH	H_2CNH	H_2C_2O
	H_2NCN	HNC_3	SiH_4	H_2COH^+	C_4H^-	HC(O)CN
6 atoms	C_5H	$l-H_2C_4$	C_2H_4	CH_3CN	CH_3NC	CH_3OH
	CH_3SH	HC_3NH^+	HC_2CHO	NH_2CHO	C_5N	$l-HC_4H$
	$l-HC_4N$	$c-H_2C_3O$	H_2CCNH(?)	C_5N^-		
7 atoms	C_6H	CH_2CHCN	CH_3C_2H	HC_5N	CH_3CHO	CH_3NH_2
	$c-C_2H_4O$	H_2CCHOH	C_6H^-			
8 atoms	CH_3C_3N	$HC(O)OCH_3$	CH_3COOH	C_7H	H_2C_6	CH_2OHCHO
	$l-HC_6H$	CH_2CHCHO(?)	CH_2CCHCN	H_2NCH_2CN	C_2H_6†	$(NH_2)_2CO$(??)
9 atoms	CH_3C_4H	CH_3CH_2CN	$(CH_3)_2O$	CH_3CH_2OH	HC_7N	C_8H
	$CH_3C(O)NH_2$	C_8H^-	C_3H_6			
10 atoms	CH_3C_5N	$(CH_3)_2CO$	$(CH_2OH)_2$	CH_3CH_2CHO	NH_2CH_2COOH(??)†	
11 atoms	HC_9N	CH_3C_6H	C_2H_5OCHO			
12 atoms	C_6H_6	$C_2H_5OCH_3$?	$n-C_3H_7CN$	$CO(CH_2OH)_2$(??)		
> 12 atoms	$HC_{11}N$	$C_{10}H_8^+$	$C_{14}H_{10}^+$(??)	C_{24}(??)	C_{60}	C_{70}

Abundâncias relativas dos elementos químicos

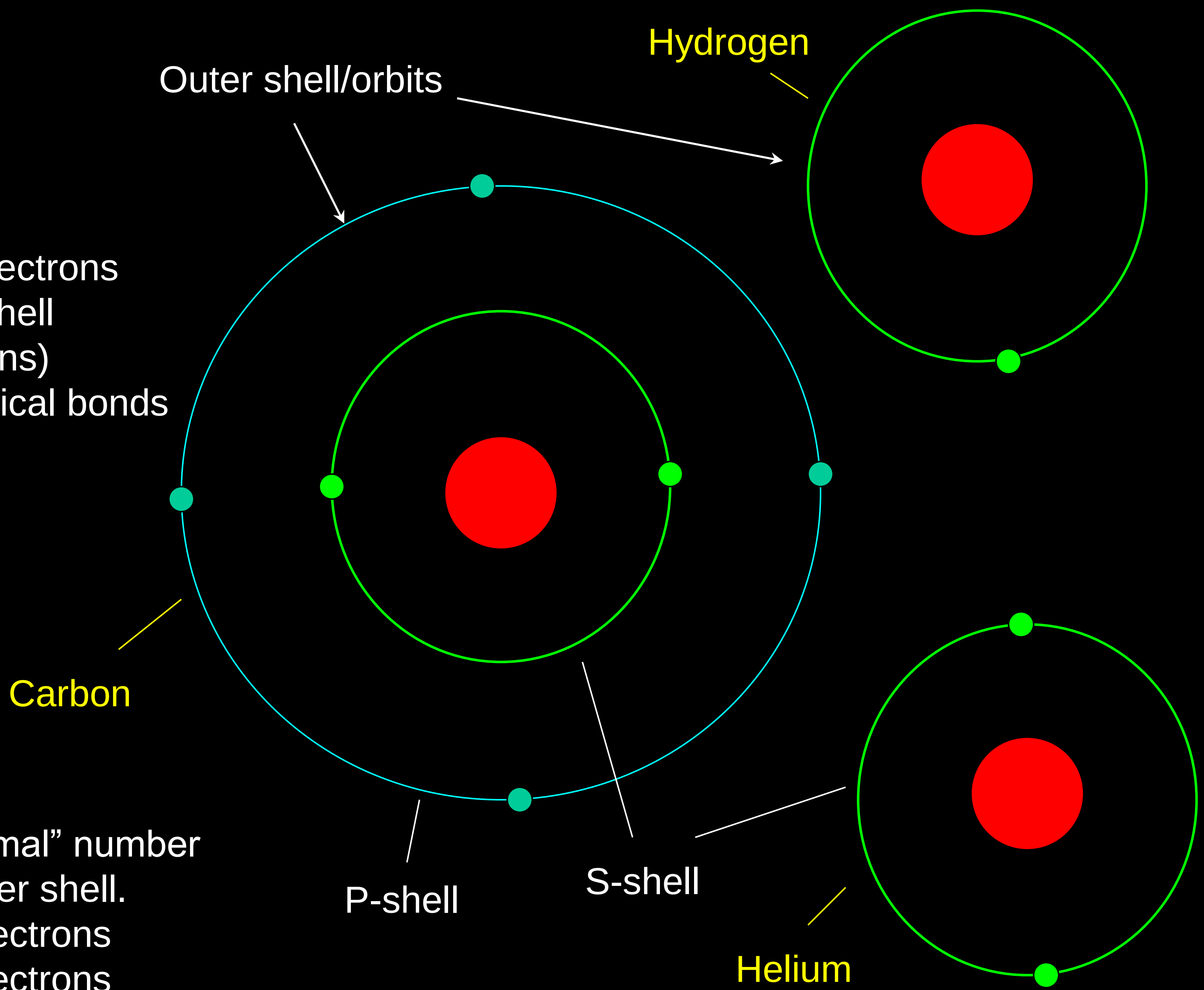
Relative number abundances of chemical elements (O=100)
The abundances are in number (decreasing order)
Sources: Lehninger 2000 (human body and Earth crust abundances); Asplund, Grevesse & Sauval 2004 (C, N, and O are solar photospheric values; the other elements are Solar System meteoritic values)

Human Body	Earth Crust	Cosmic
H 247	O 100	H 21 900
O 100	Si 59.6	O 100
C 37.3	Al 16.8	C 53.7
N 5.49	Fe 9.6	N 13.2
Ca 1.22	Ca 7.5	Mg 7.41
P 0.86	Na 5.3	Si 7.10
Cl 0.31	K 5.3	Fe 6.17
K 0.24	Mg 4.7	S 3.16
S 0.20	Ti 1.1	Al 0.58
Na 0.12	H 0.4	Ca 0.43
Mg 0.04	C 0.4	Na 0.41

Why Carbon?

- Carbon atom can form up to 4 chemical bonds with many other atoms – can form long and complex molecules
- Carbon can form compounds that readily dissolve in water.

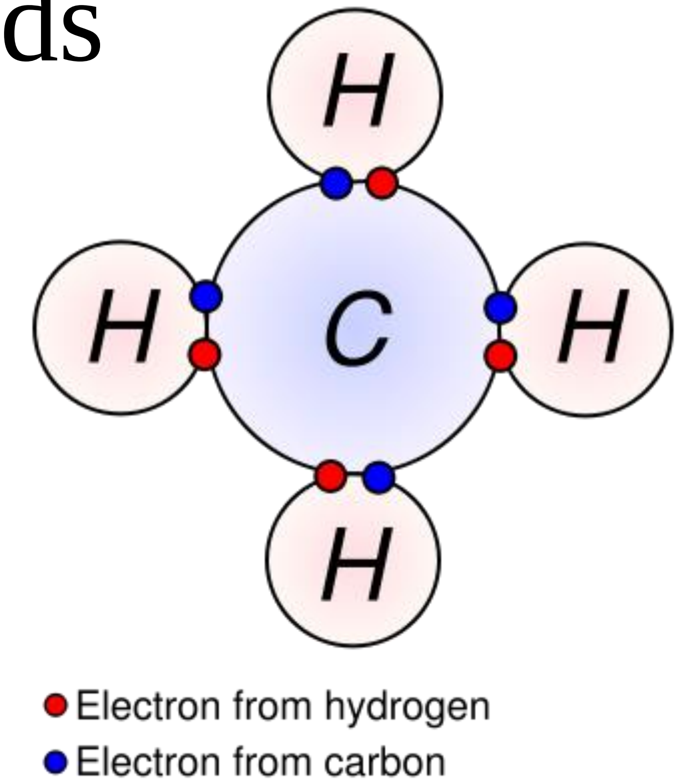
Typically only electrons from the outer shell (valence electrons) engage in chemical bonds

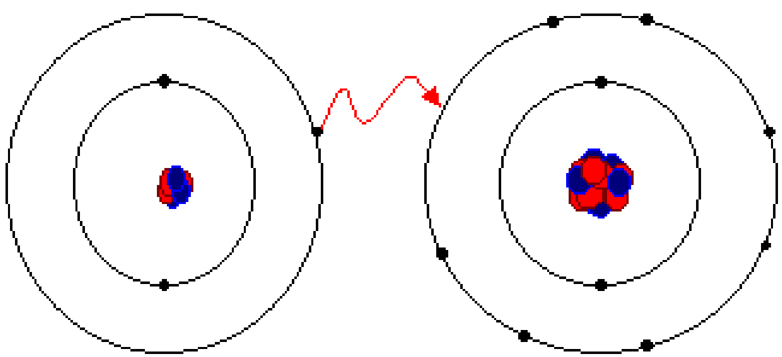


There is “optimal” number of electrons per shell.
S-shell = 2 electrons
P-shell = 8 electrons

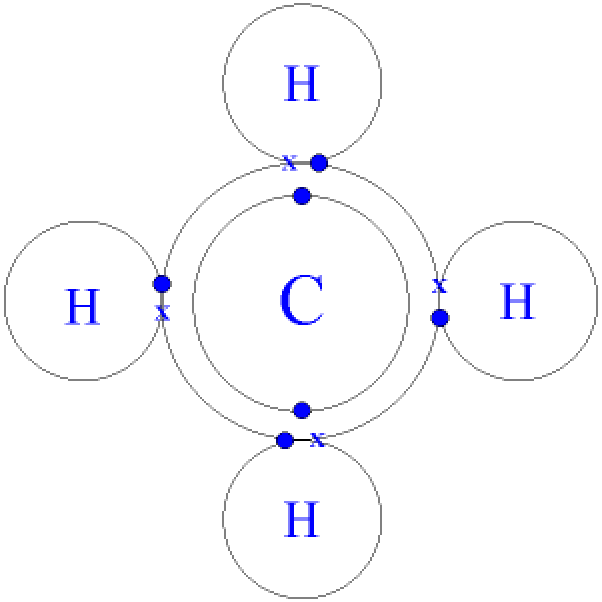
Chemical bonds

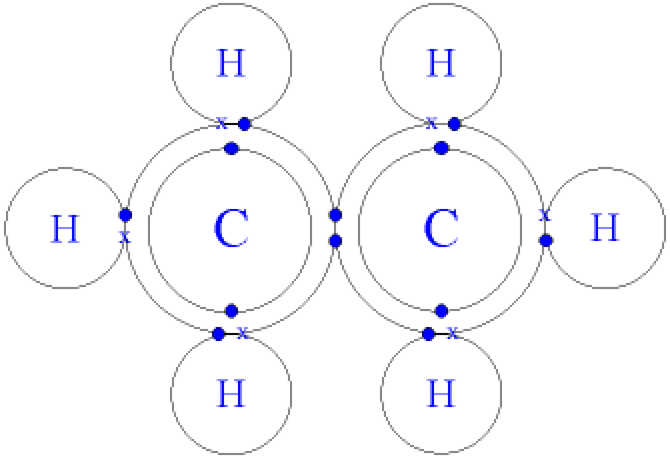
- Covalent
- Ionic
- Hydrogen





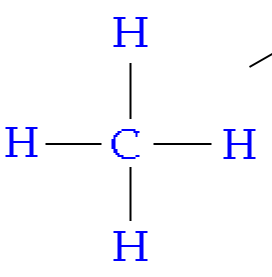
Carbon has 4 valence electrons – can form up to 4 bonds

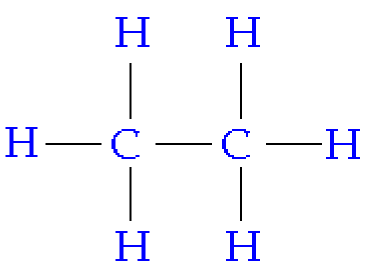


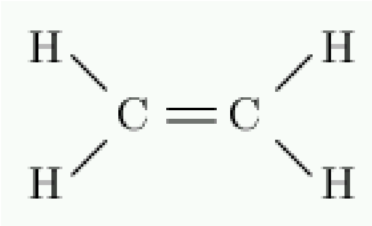


Methane

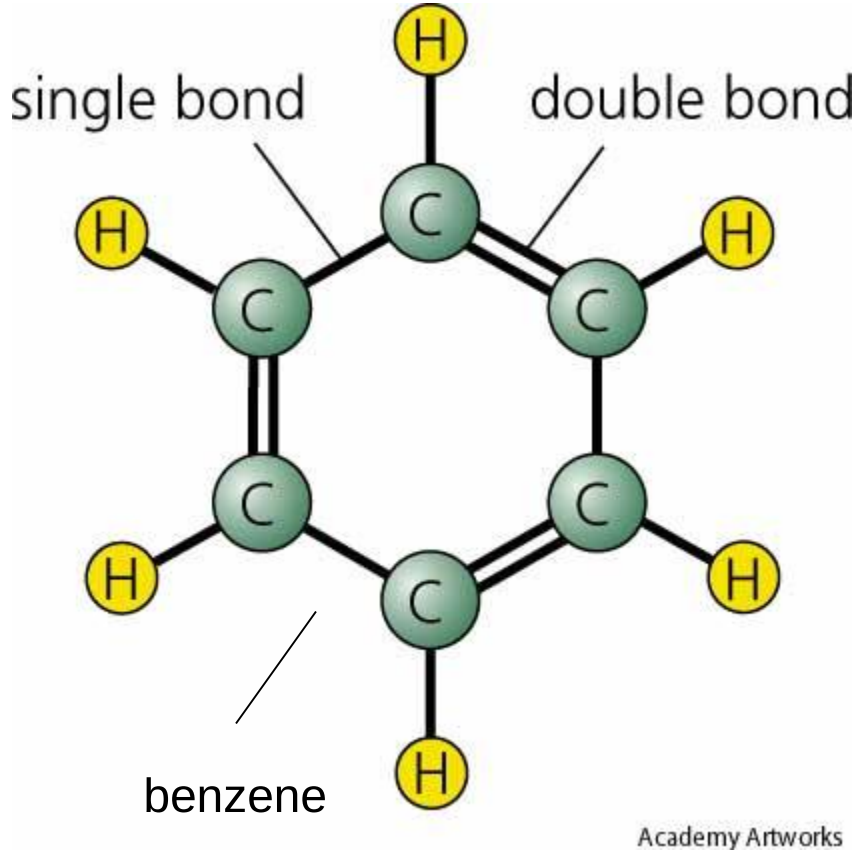
Ethane



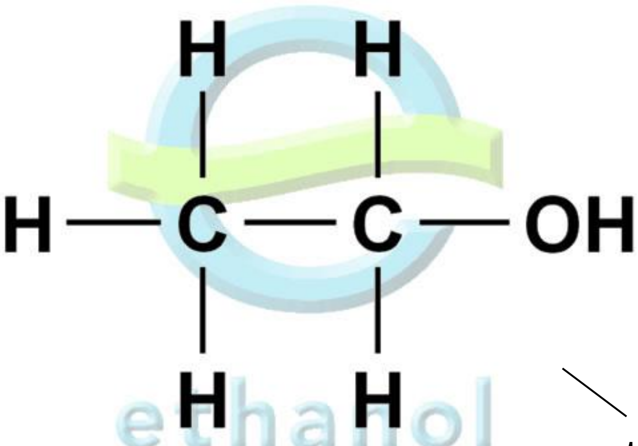




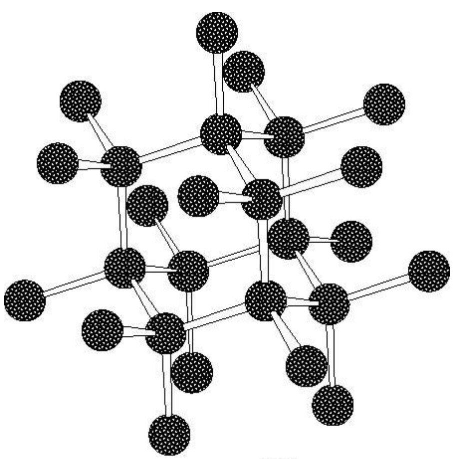
ethene



benzene

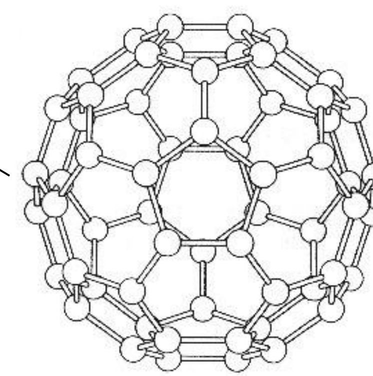


ethanol



diamond

fullerene



Polymerization

- A **polymer** is a substance composed of molecules with large molecular mass composed of repeating structural units, or monomers, connected by covalent chemical bonds. Well known examples of polymers include plastics and DNA.

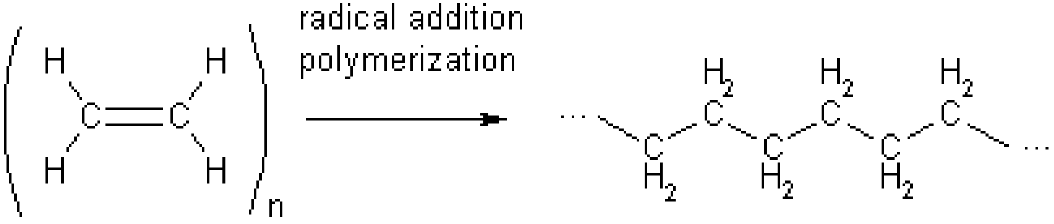
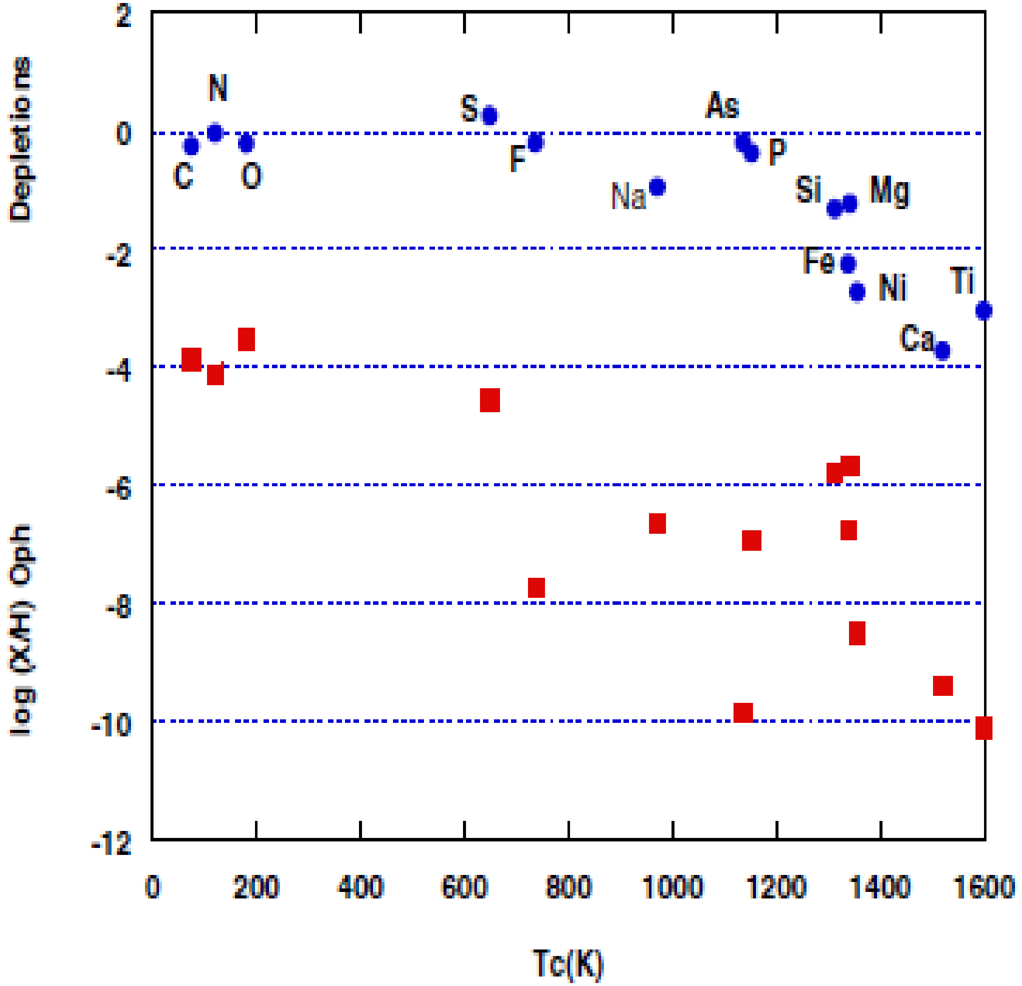


Fig 1: The polymerisation of ethene in to poly(ethene)

Silicon life?

- Si is abundant and also can form four bonds at once (like C). But!
- Si bonds are much weaker – complex molecules based on Si will be fragile
- Si does not form double bonds – less variety



Depletions
log (X/H) Oph
Tc(K)
C
N
O
S
F
Na
As
P
Si
Mg
Fe
Ni
Ti
Ca
2
0
-2
-4
-6
-8
-10
-12
0
200
400
600
800
1000
1200
1400
1600

Organic and Inorganic Carbon

C can be in <u>reduced</u> or <u>oxidized</u> forms.

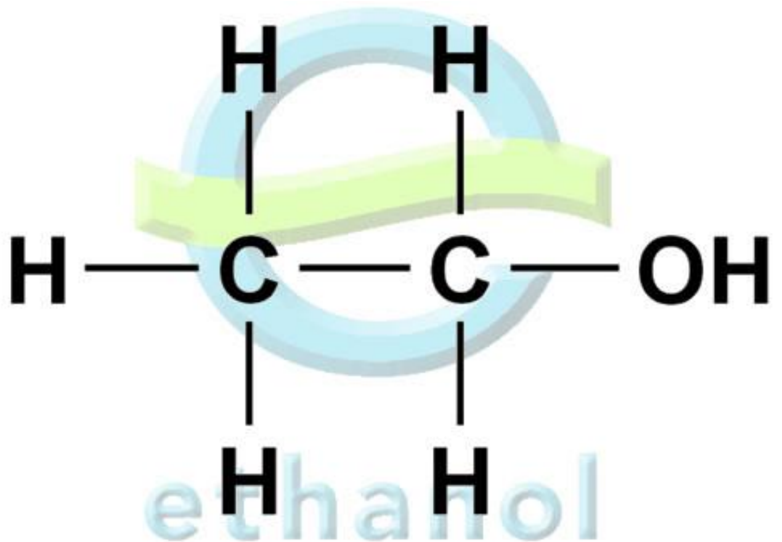
Organic carbon
(reduced)

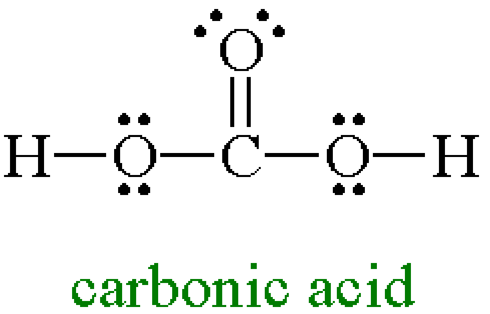
'CH_2O'

Example:
Glucose -- $C_6H_{12}O_6$

Inorganic carbon
(oxidized)

CO_2 carbon dioxide
H_2CO_3 carbonic acid
HCO_3^- bicarbonate ion
CO_3^{2-} carbonate ion





Inorganic carbon
(C-O bonds only)

Organic carbon
(has C-H and C-C bonds)

Coal

Oil

Organic carbon

Inorganic carbon

Seashells

http://www.summerclouds.com/Vero/Sea%20Shells.jpg

http://www.cmas-md.org/Images/Sanjay/UnivTop4.jpg

Coral

http://educate.si.edu/lessons/currkits/ocean/

Four types of organic macromolecules in living systems.

Most of the molecules in the living systems are water (H_2O) and large organic macromolecules:

- Carbohydrates
- Lipids
- Proteins
- Nucleic Acids

Carbohydrates (sugars, starches)

- Representatives:

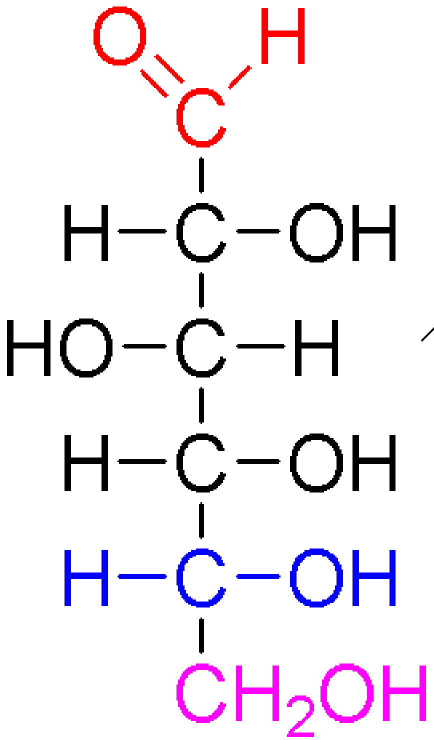
Glucose, Fructose

- Many hydroxyl

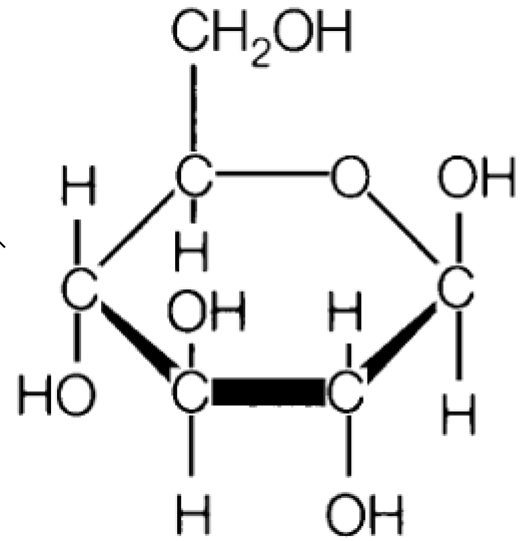
groups (-OH)

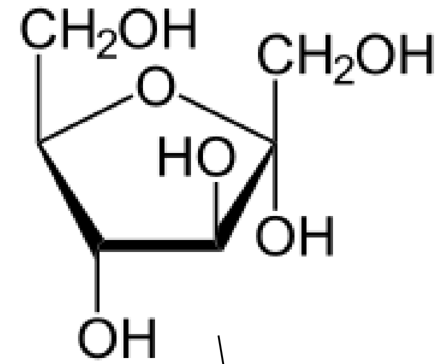
- Soluble in water
- Form Polysaccharides
- Good energy source
- Structural support for

organisms (cellulose
- the main constituent of wood)



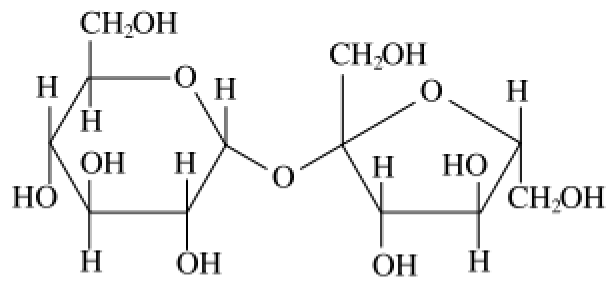
Glucose



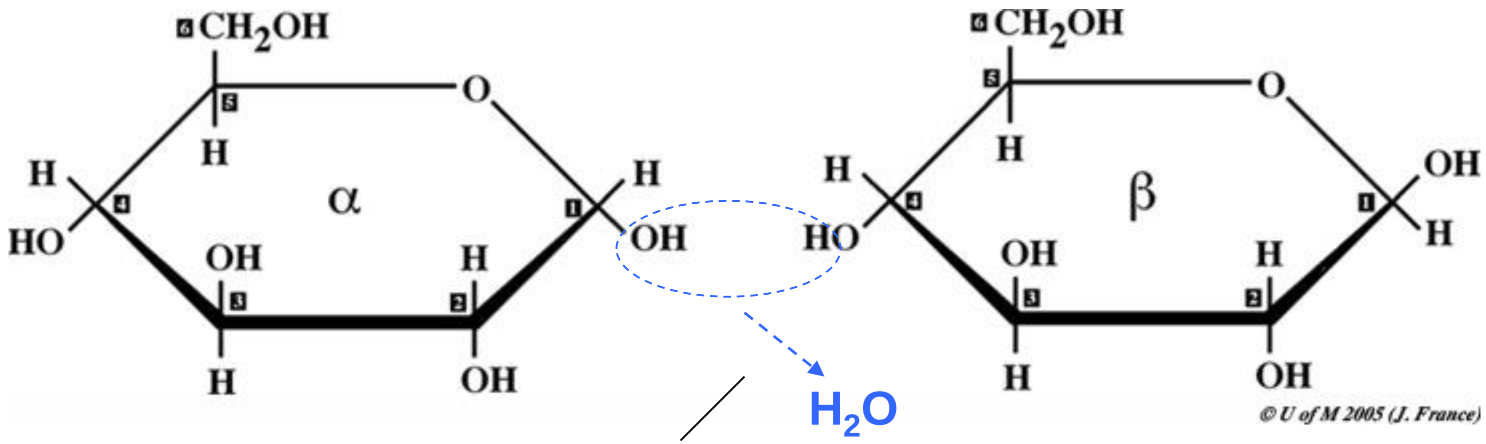


Fructose

Table sugar

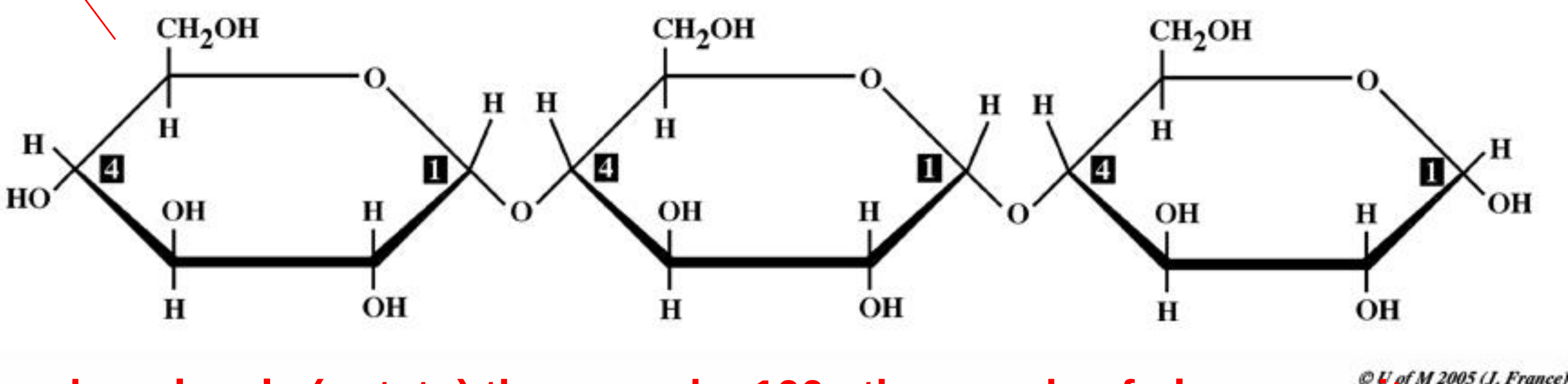


Glucose polymerization



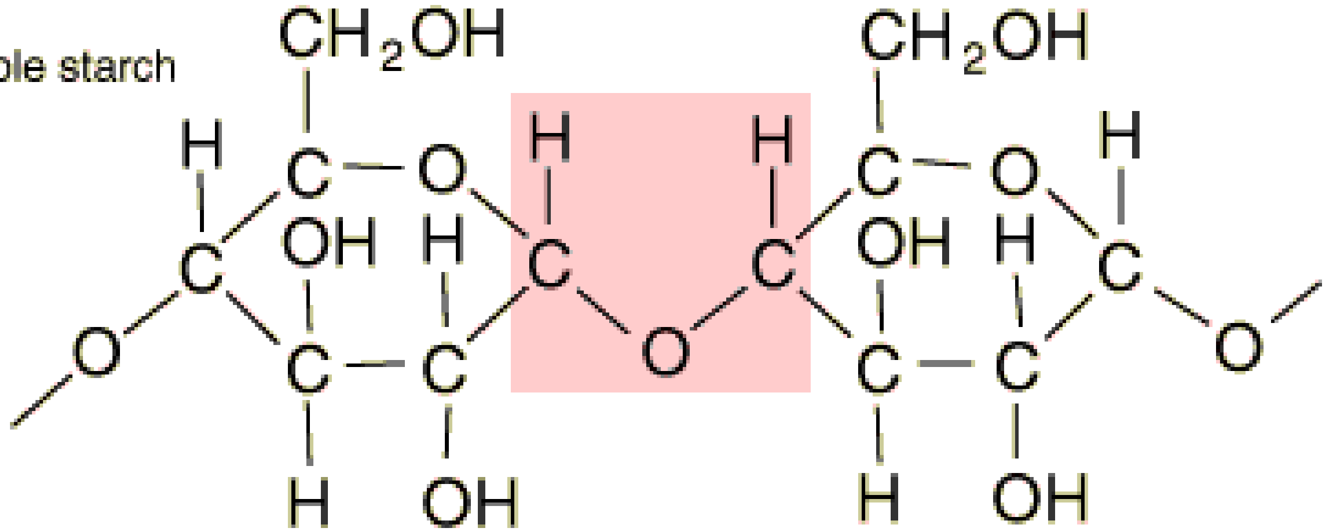
Linked by dehydration reaction

Polysaccharides

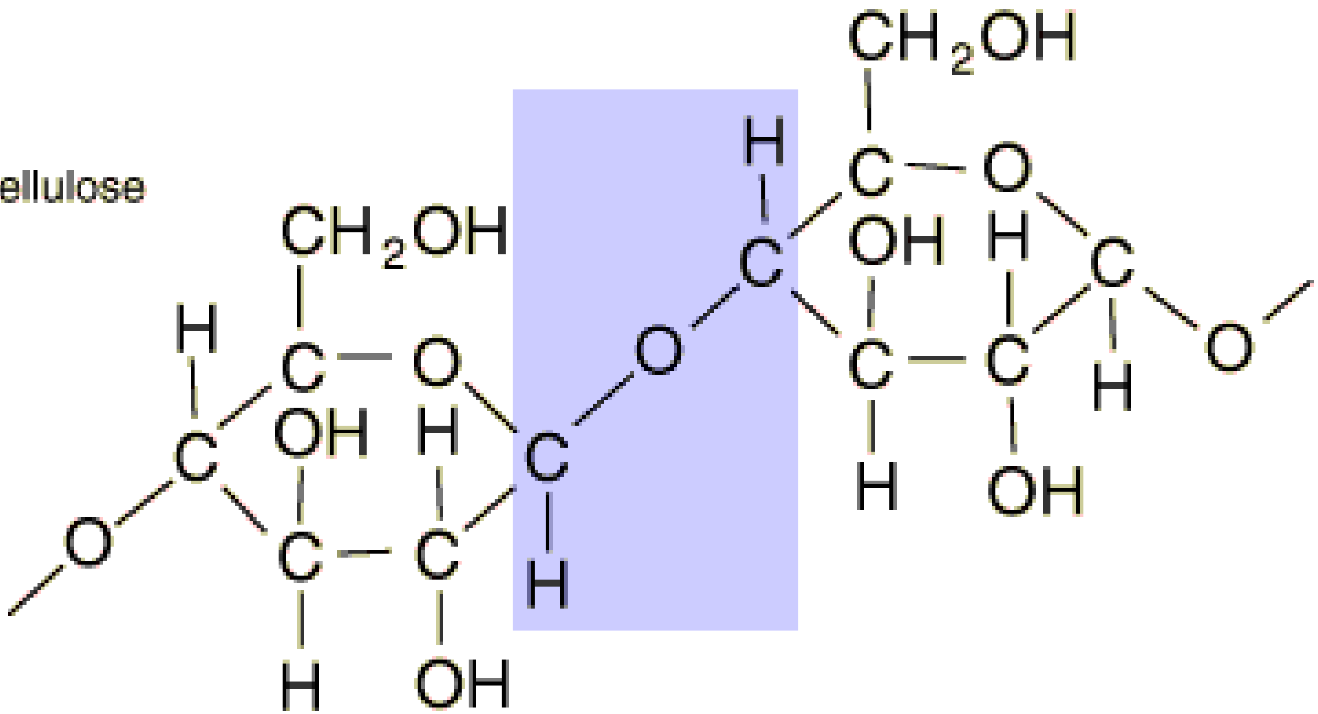


In starch molecule (potato) there can be 100s thousands of glucose units

Simple starch



Cellulose



Carbohydrates are important as a source of energy for life

- Respiration

$CH_2O + O_2 \rightarrow CO_2 + H_2O + \text{Energy}$

In reality:

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{Energy}$

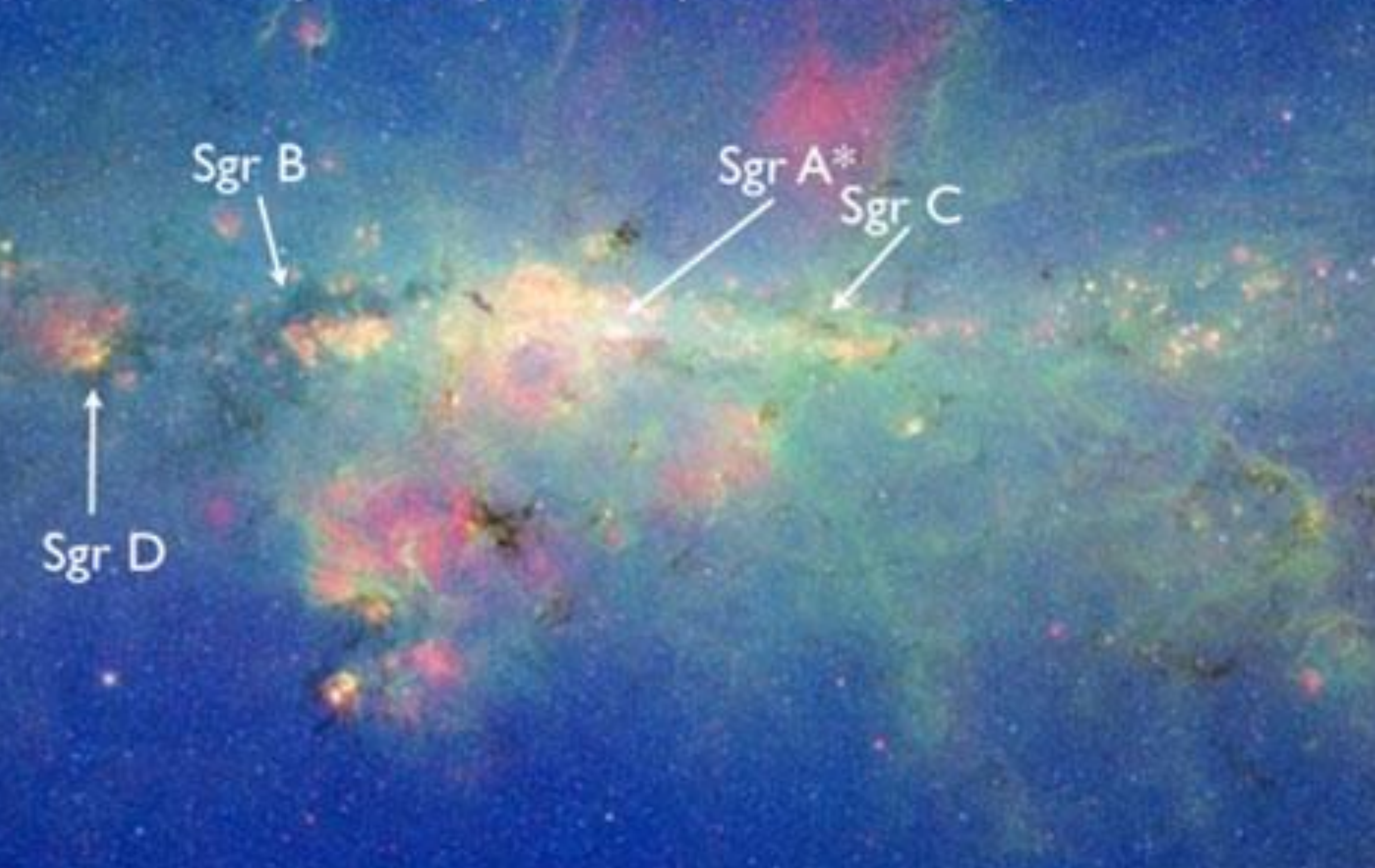
- Fermentation

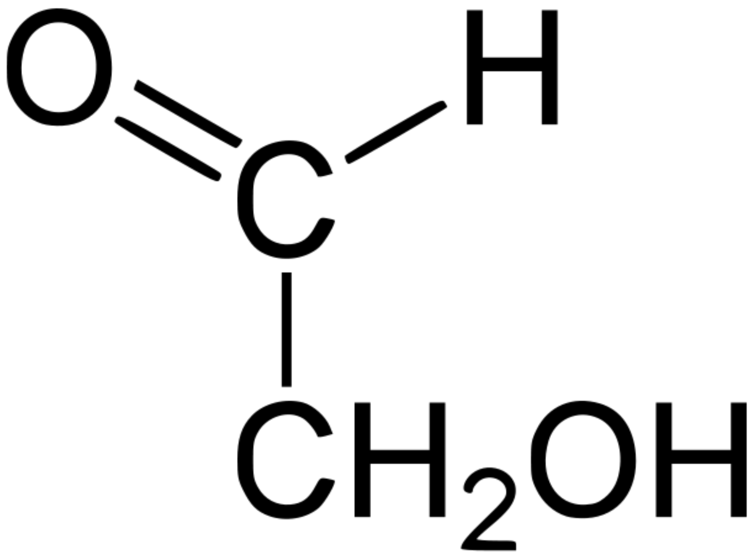
$C_6H_{12}O_6 \rightarrow 2CO_2 + 2C_2H_6O + \text{Energy}$

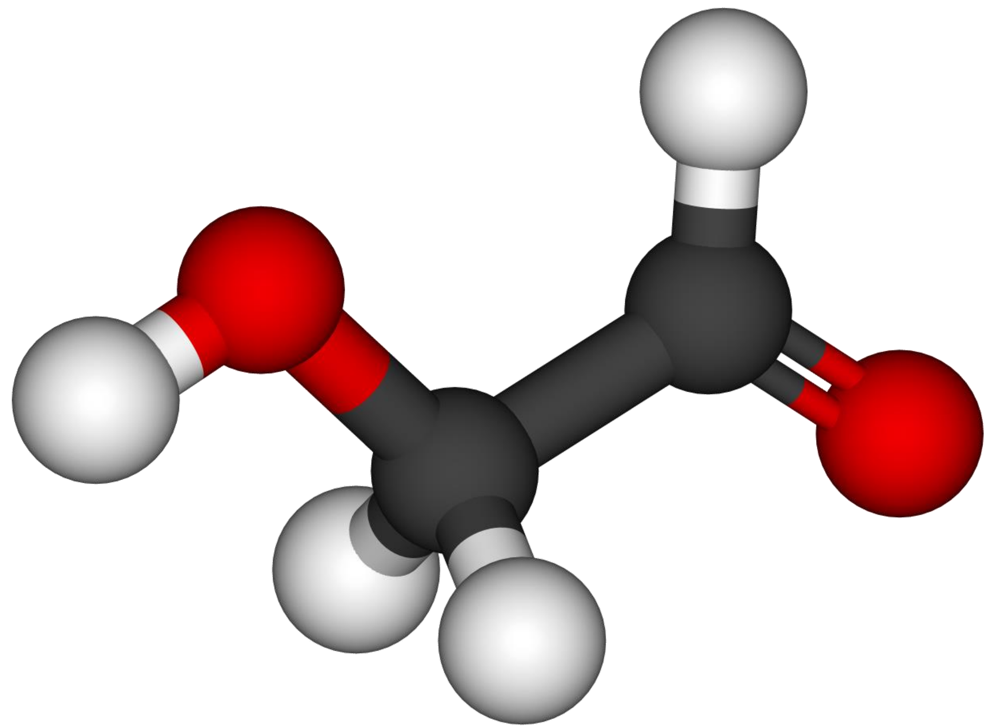
O Universo é úmido

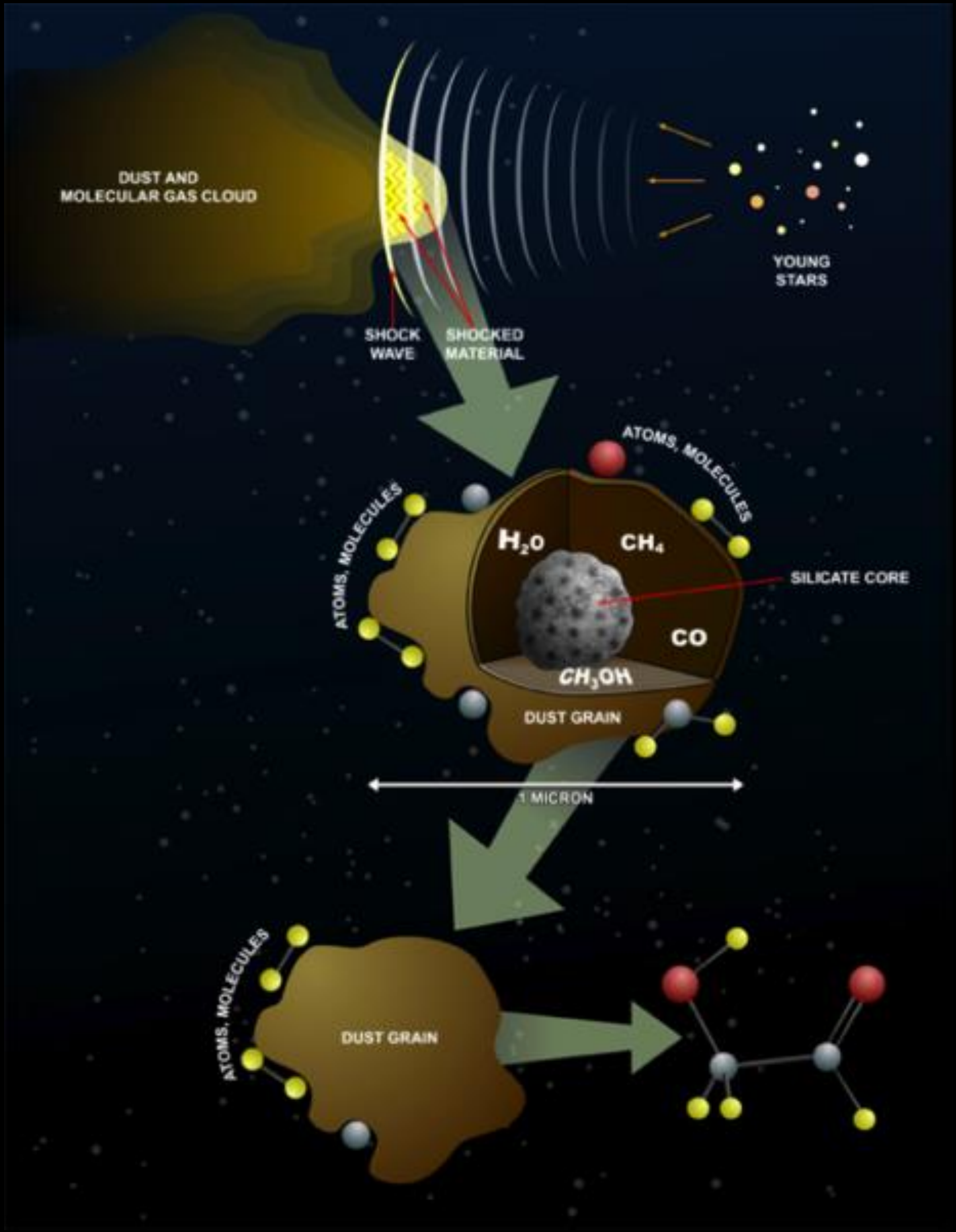

O Universo é doce

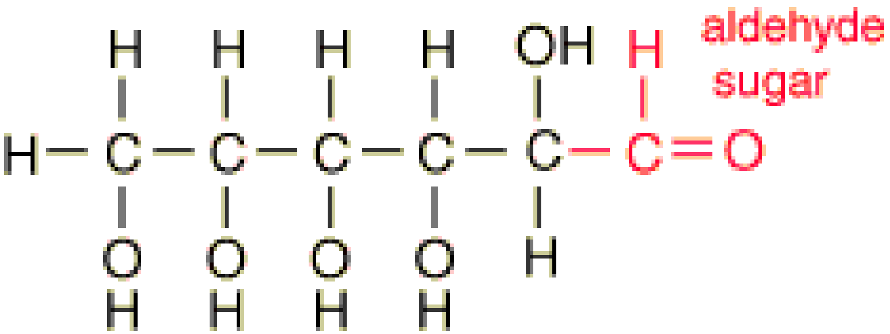
Center of the Milky Way as seen by the Spitzer Space Telescope



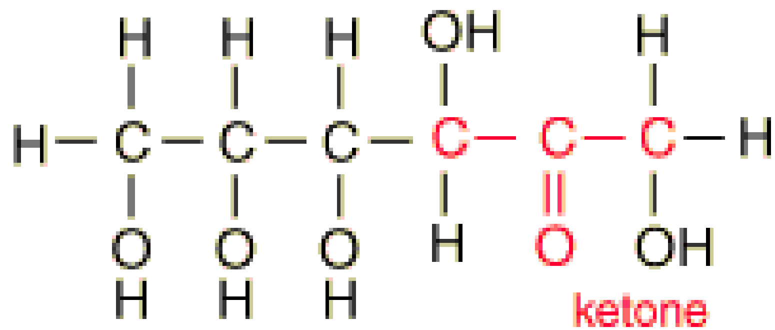




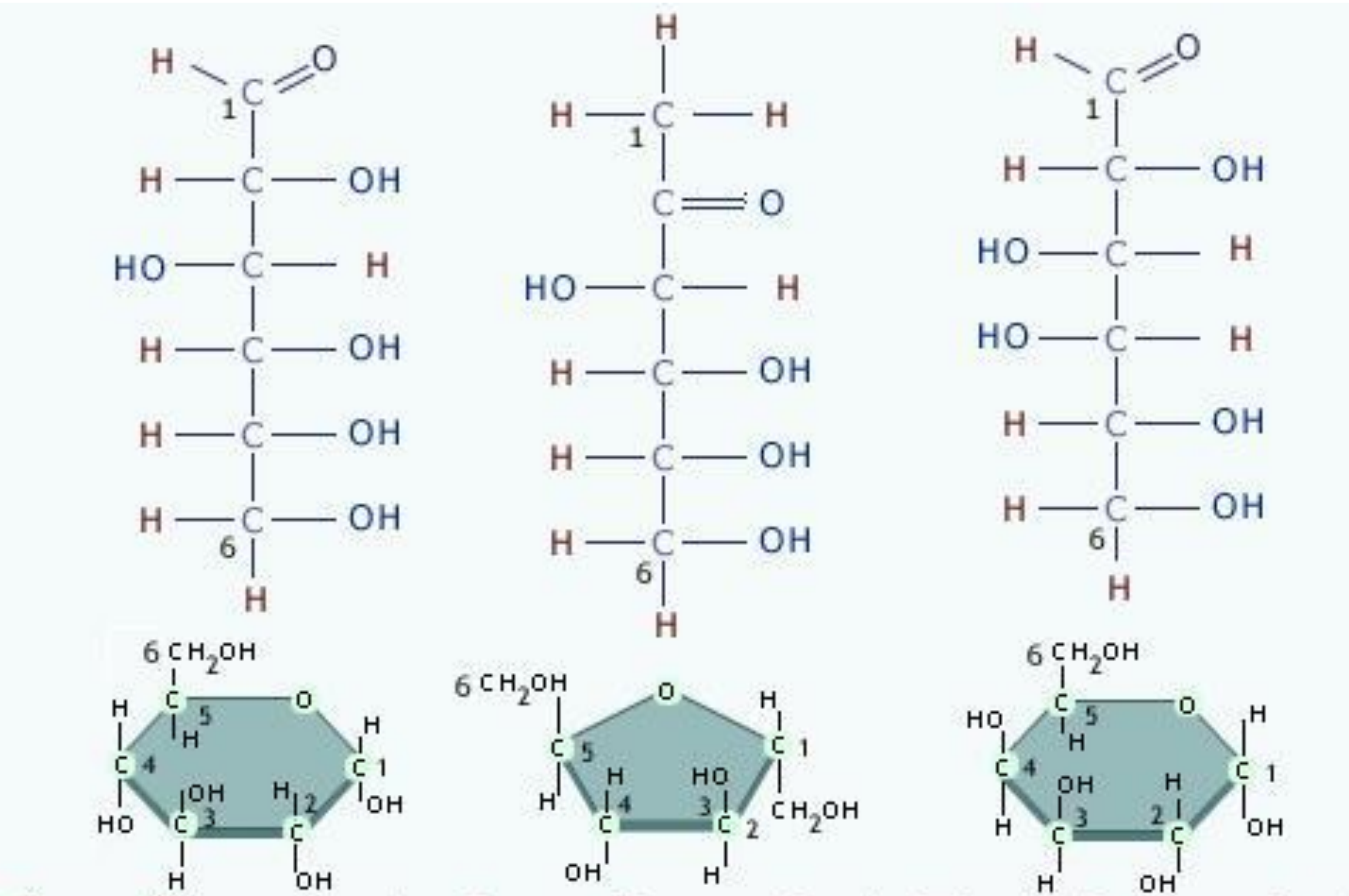

DUST AND
MOLECULAR GAS CLOUD
SHOCK
WAVE
SHOCKED
MATERIAL
YOUNG
STARS
ATOMS, MOLECULES
ATOMS, MOLECULES
H_2O
CH_4
SILICATE CORE
CO
CH_3OH
DUST GRAIN
1 MICRON
ATOMS, MOLECULES
DUST GRAIN



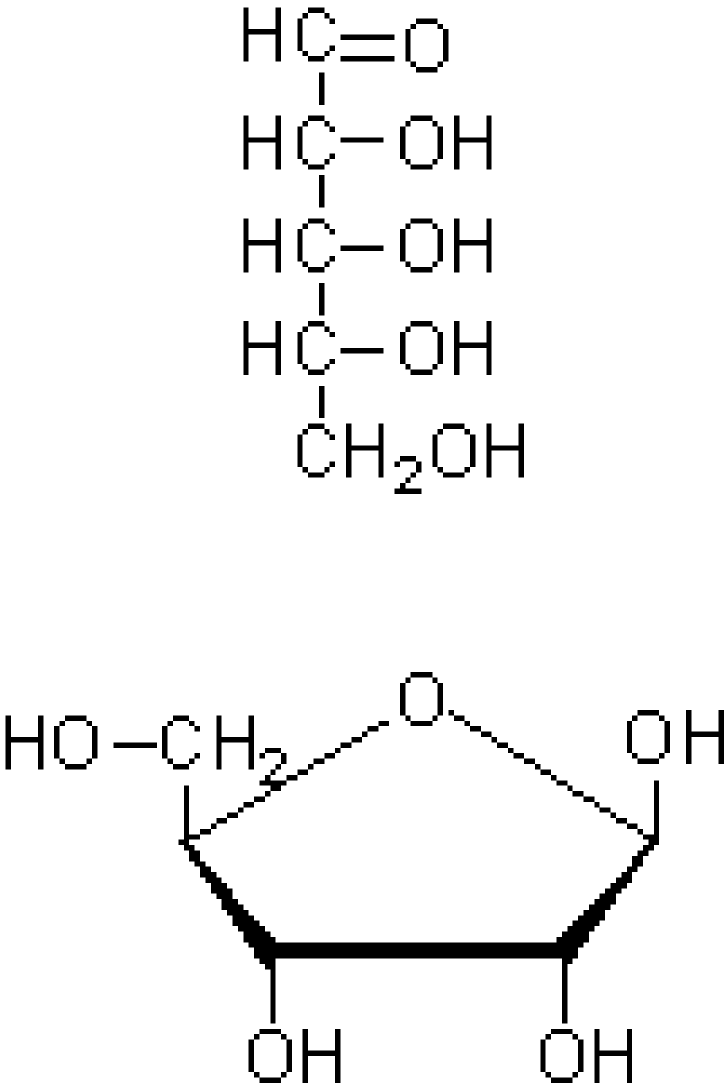
Glucose



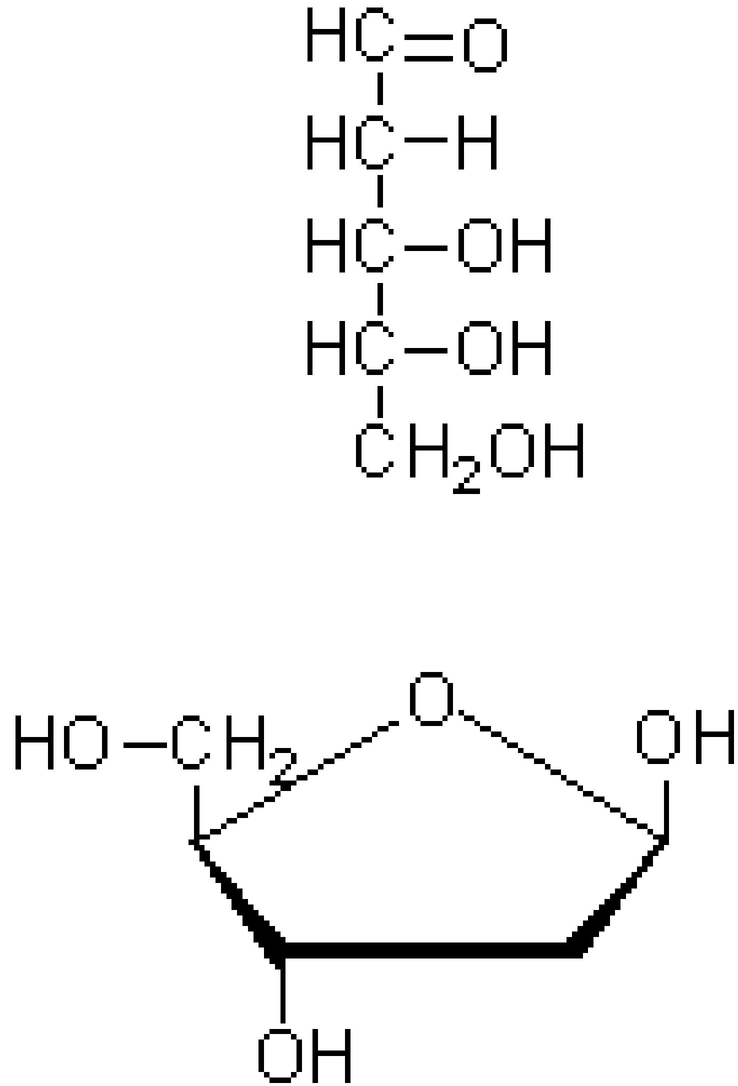
Fructose



Glucose(Pyranose form) Fructose(Furanose form) Galactose(Pyaranose form)



ribose



deoxyribose

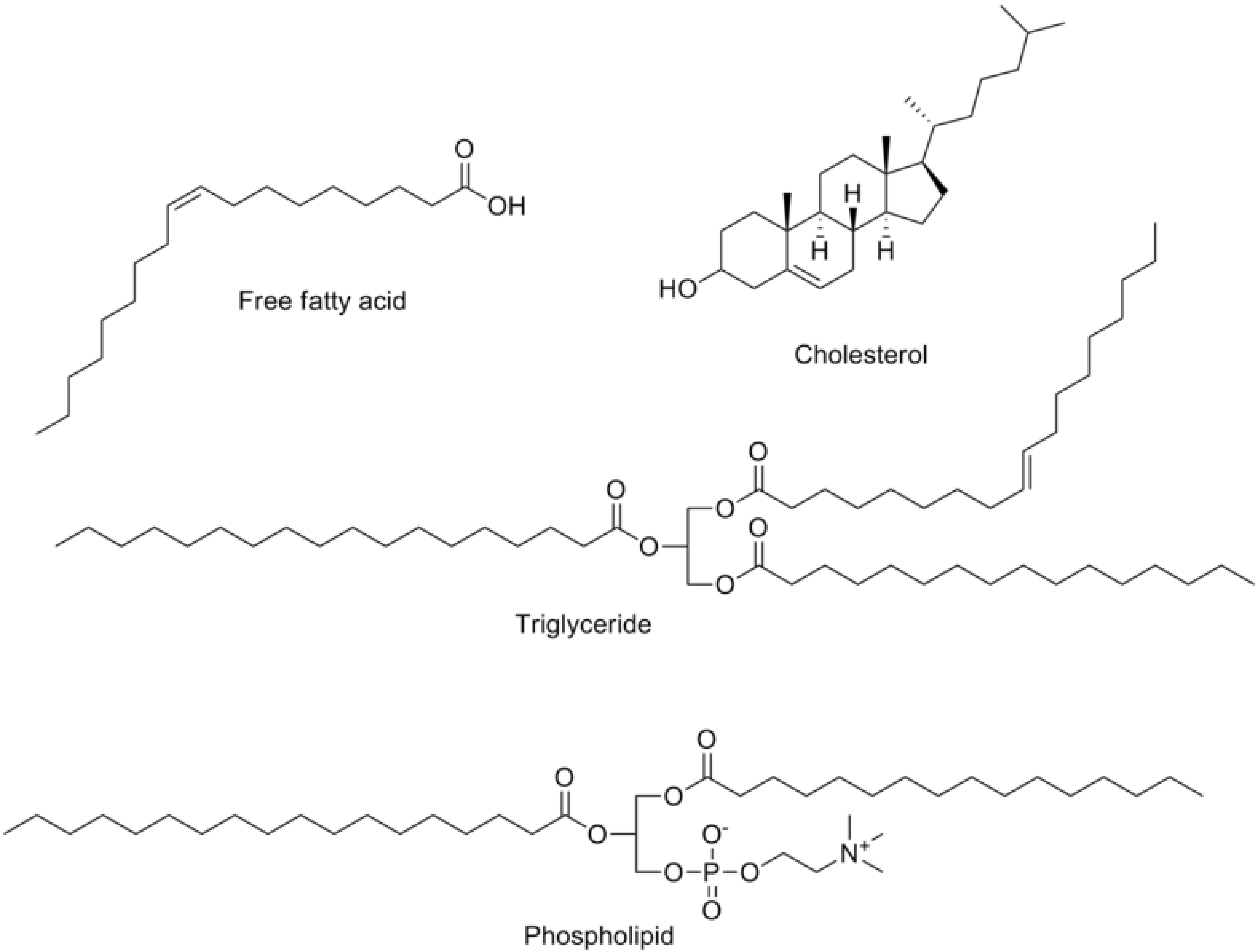
Lipids (fats and oils)

- Representatives: fatty acids and cholesterol
- Poorly soluble in water
- Good (concentrated)

energy source

- Flexible

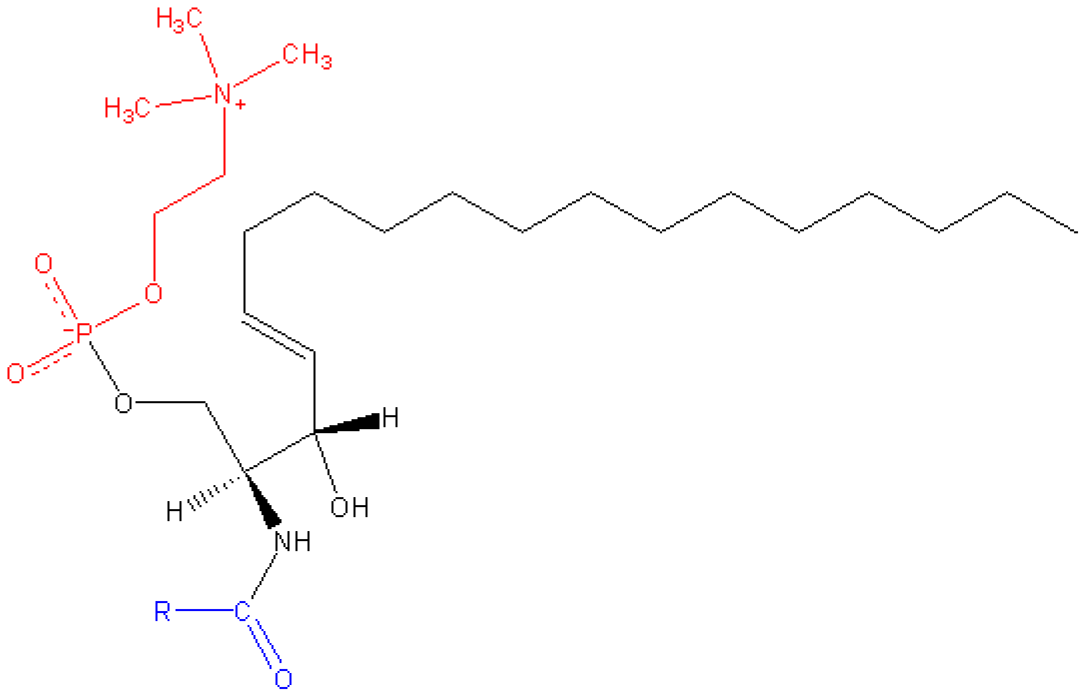
(cell membrane material)



Free fatty acid
Cholesterol
Triglyceride
Phospholipid

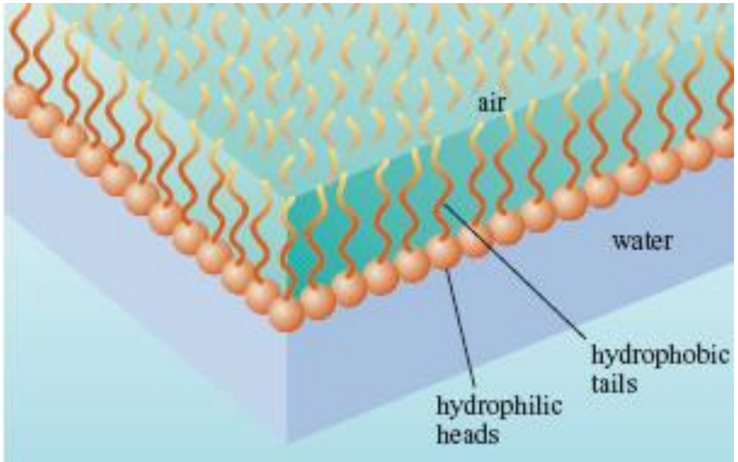
Lipids are important for the formation of the cell membrane

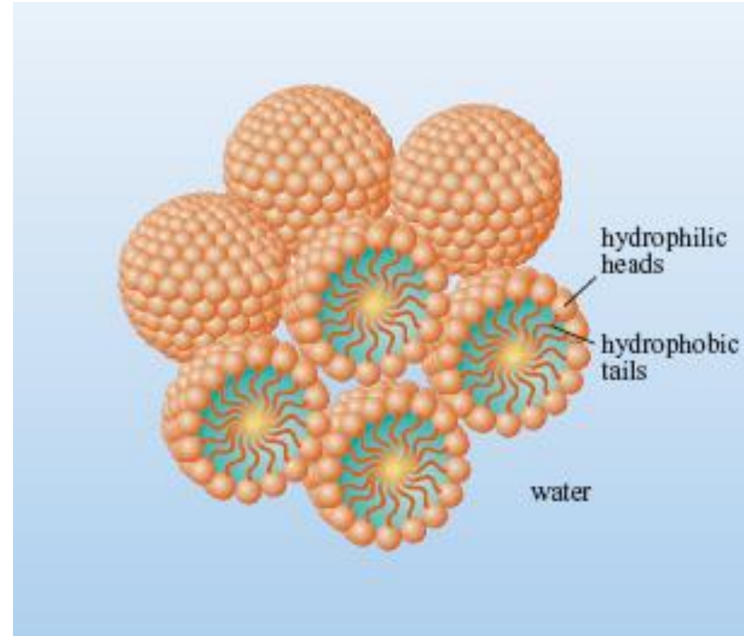
- Some lipids have hydrophilic (love water) head and hydrophobic tail



- In solution these lipids can form monolayers, bilayers and bilayer vesicles spontaneously – pre-cells.

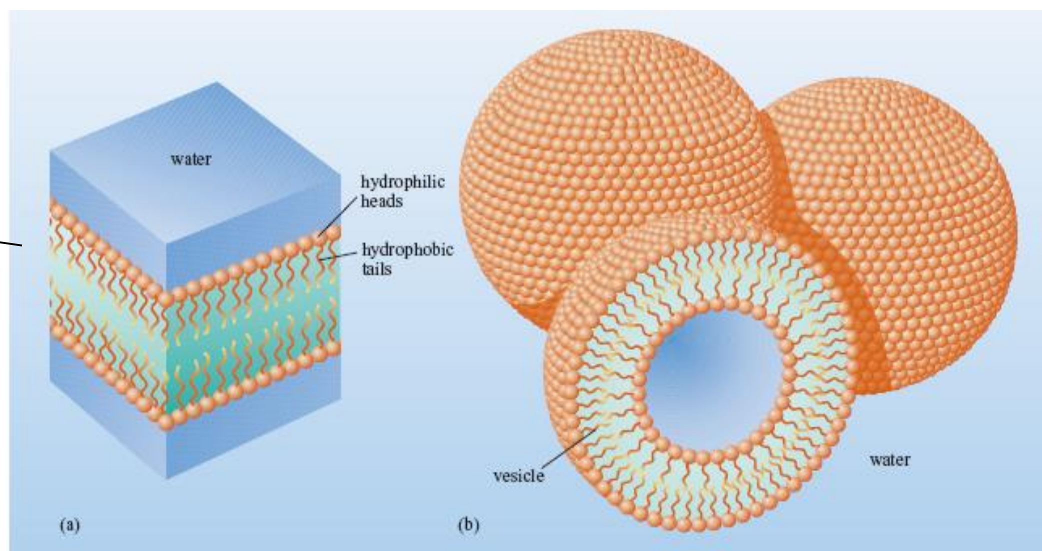
Monolayer





Micells

Bilayer



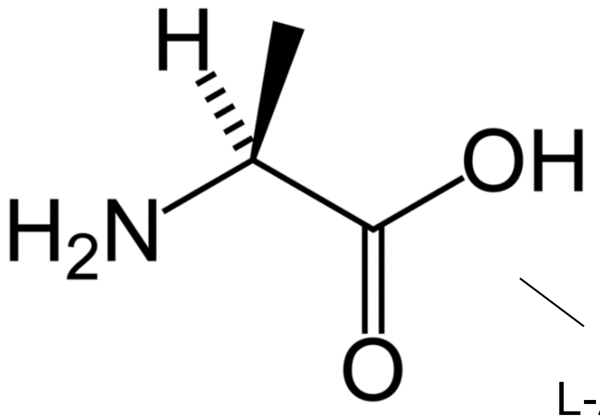
Bilayer vesicle

SIGA A VIDA

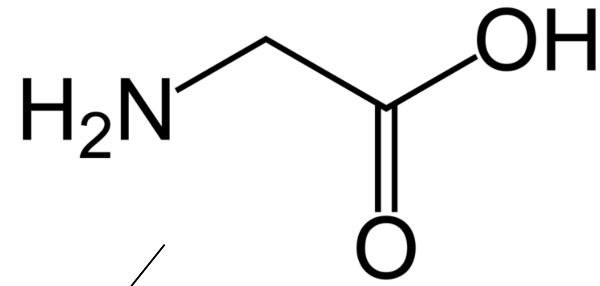
- Siga a água (Follow the water)
- Siga o carbono
- ⇒ Siga o nitrogênio
- Siga o fósforo
- Siga a energia
- Siga a entropia
- Siga a informação
- Siga o significado

Proteins

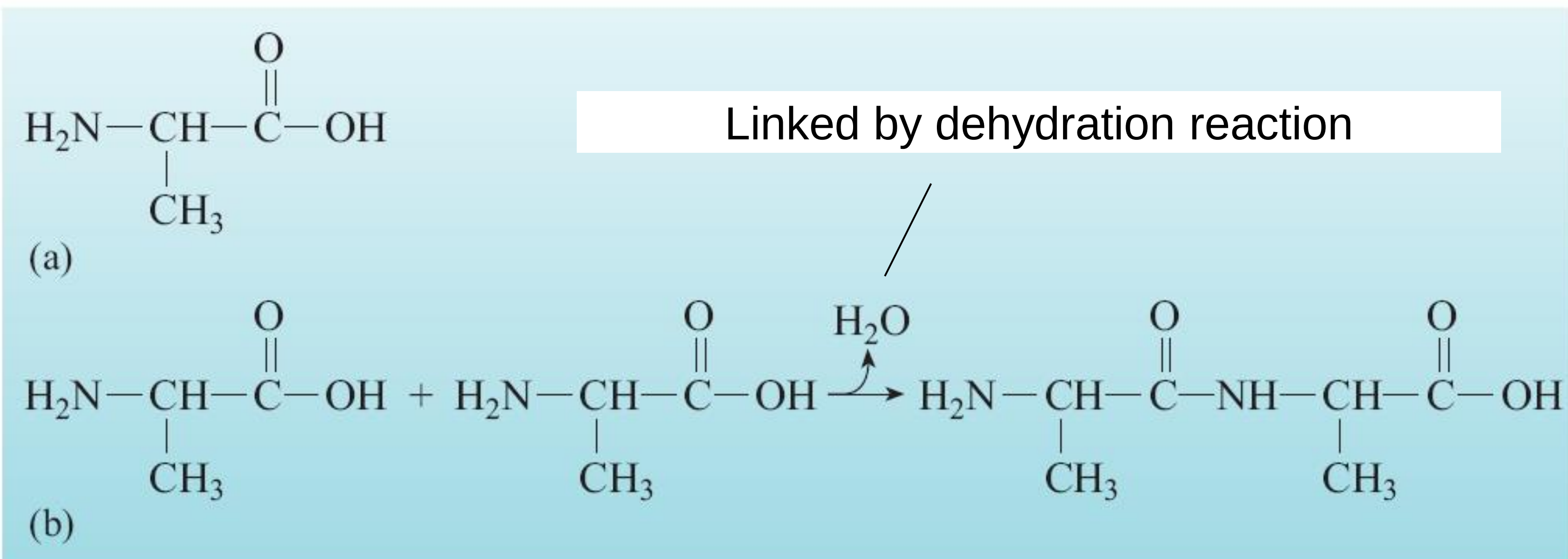
- “Proteios” – primary
- Long “trains” of amino acids
- Different proteins have different sequence of amino acids
- 20 amino acids used in any organism
- Some provide structure (fingernails, hair)
- Some serve as catalysts
- Enzymes – proteins with catalitic properties



L-Alanine



Glycine



Catalysts in Chemistry

- Suppose chemical reaction:

A + B → AB   is a slow reaction

- The same reaction can be accelerated with catalyst (D):

A + D → AD   fast step

B + AD → AB + D fast step

The net result is still:

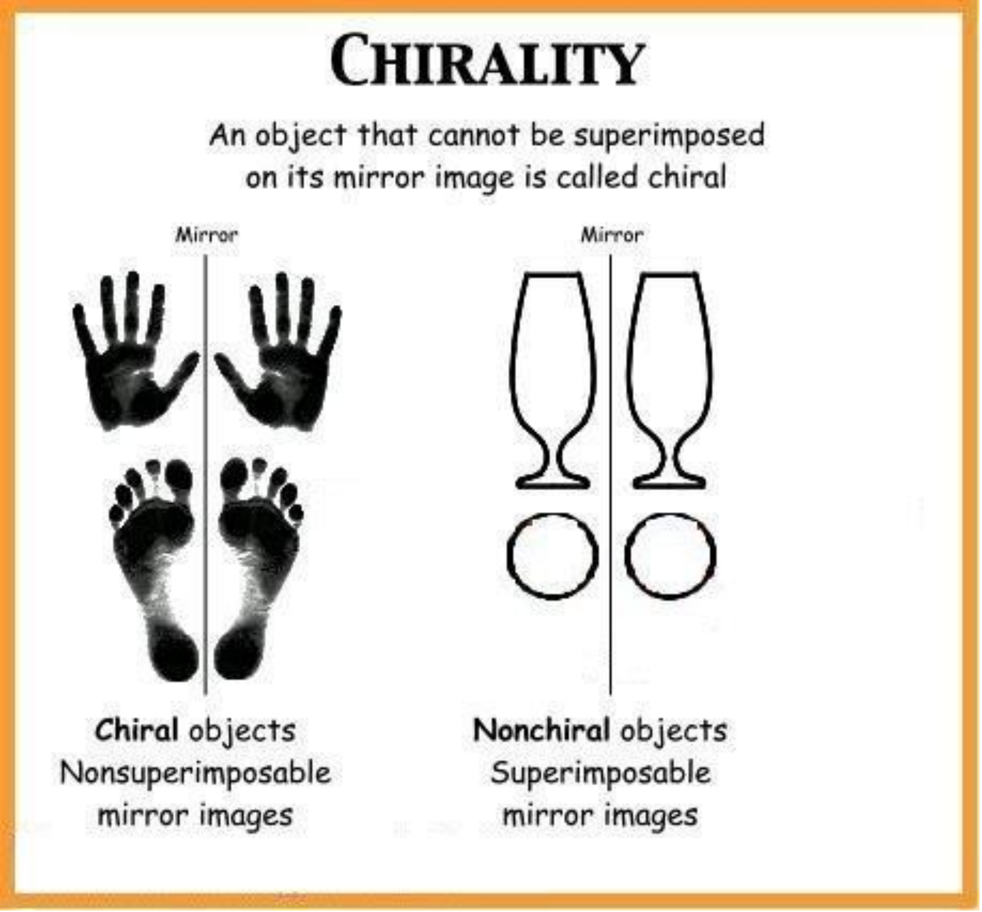
A + B → AB but it is much faster

Proteins (continued)

- Even though there are ~70 amino acids any known life uses only 20
- Amino acids derived abiotically are a mix of both “left-handed” and “right-handed” ones. Biological amino acids are only left-handed.

Chirality

- Was there a common ancestor for all life?



Biology uses only
left-handed Alanine

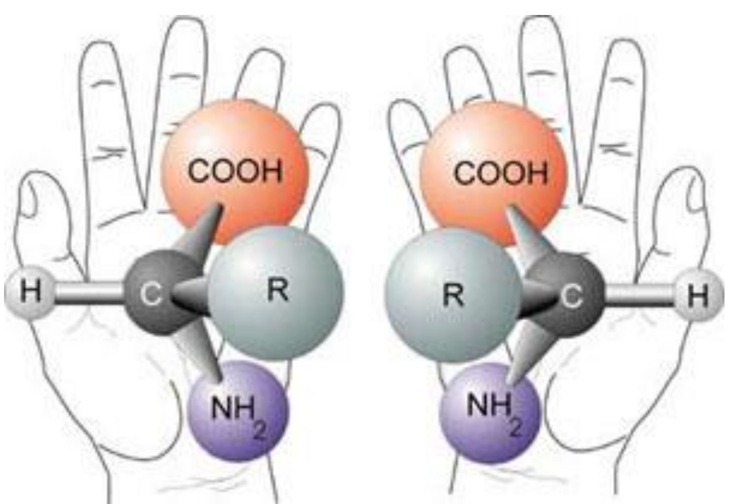


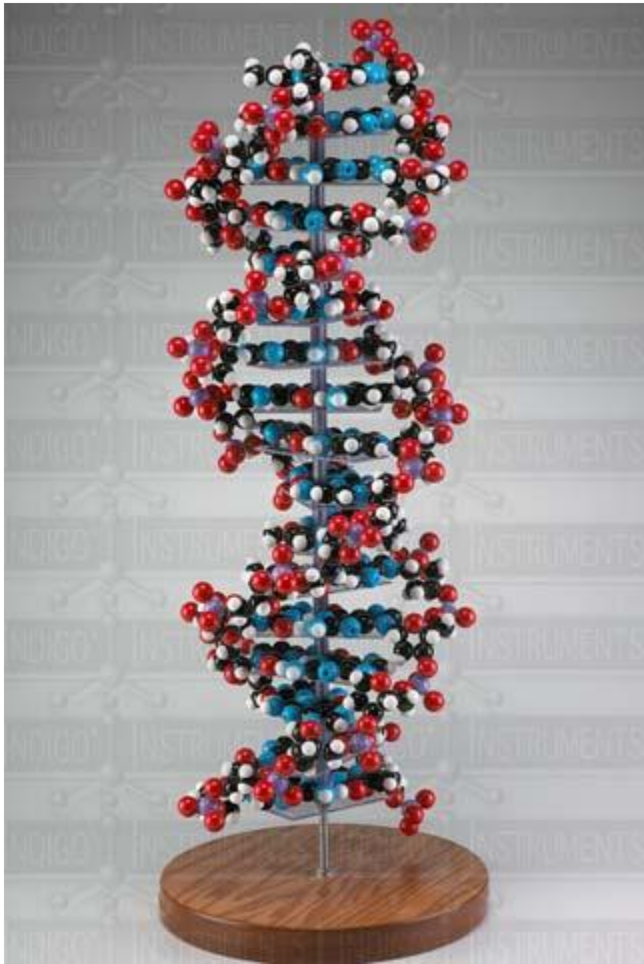
Table 1.5 Abundances of amino acids synthesized in the Miller–Urey experiment and those found in the Murchison meteorite. The number of dots represents relative abundance. Those amino acids used by life (i.e. in proteins) are indicated.

Amino acid	Abundance of amino acids		Found in proteins on Earth
	synthesized in the Miller–Urey experiment	Found in the Murchison meteorite	
glycine	●●●●	●●●●	yes
alanine	●●●●	●●●●	yes
α-amino-*N*-butyric acid	●●●	●●●●	no
α-aminoisobutyric acid	●●●●	●●	no
valine	●●●	●●	yes
norvaline	●●●	●●●	no
isovaline	●●	●●	no
proline	●●●	●	yes
pipecolic acid	●	●	no
aspartic acid	●●●	●●●	yes
glutamic acid	●●●	●●●	yes
β-alanine	●●	●●	no
β-amino-*N*-butyric acid	●●	●●	no
β-aminoisobutyric acid	●	●	no
γ-aminobutyric acid	●	●●	no
sarcosine	●●	●●●	no
N-ethylglycine	●●	●●	no
N-methylalanine	●●	●●	no

Nucleic acids (DNA/RNA)

- Deoxyribonucleic acid (DNA), is a nucleic acid that contains the (genetic) instructions used in the development and functioning of all known living organisms.

- Collection of nucleotides linked together in long polymers – the largest macromolecule



Nucleotide

Each nucleotide:
1) Five-carbon sugar molecule
2) One or more phosphate groups
3) Nitrogen-containing compound – nitrogenous base

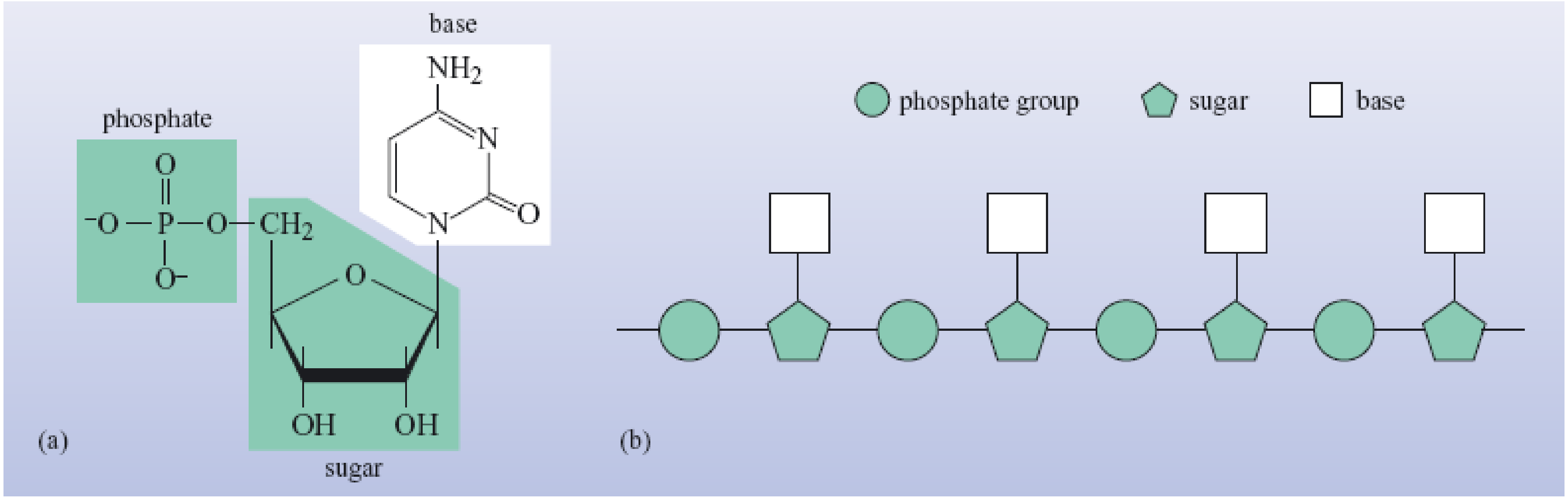


Figure 1.7 (a) The structure of a nucleotide consisting of a phosphate group, sugar molecule and nitrogenous base (cytosine in this instance). (b) Nucleotides polymerize by simple reactions that involve the loss of water to form nucleic acids. ((a) Zubay, 2000)

Watson and Crick (1953) realized that DNA have a double helix.

Strand

DNA strand	DNA strand
A	T
T	A
G	C
C	G

Hydrogen bond (weak)

A can link only with T
G can link only with C

Two DNA strands are “complimentary” to each other

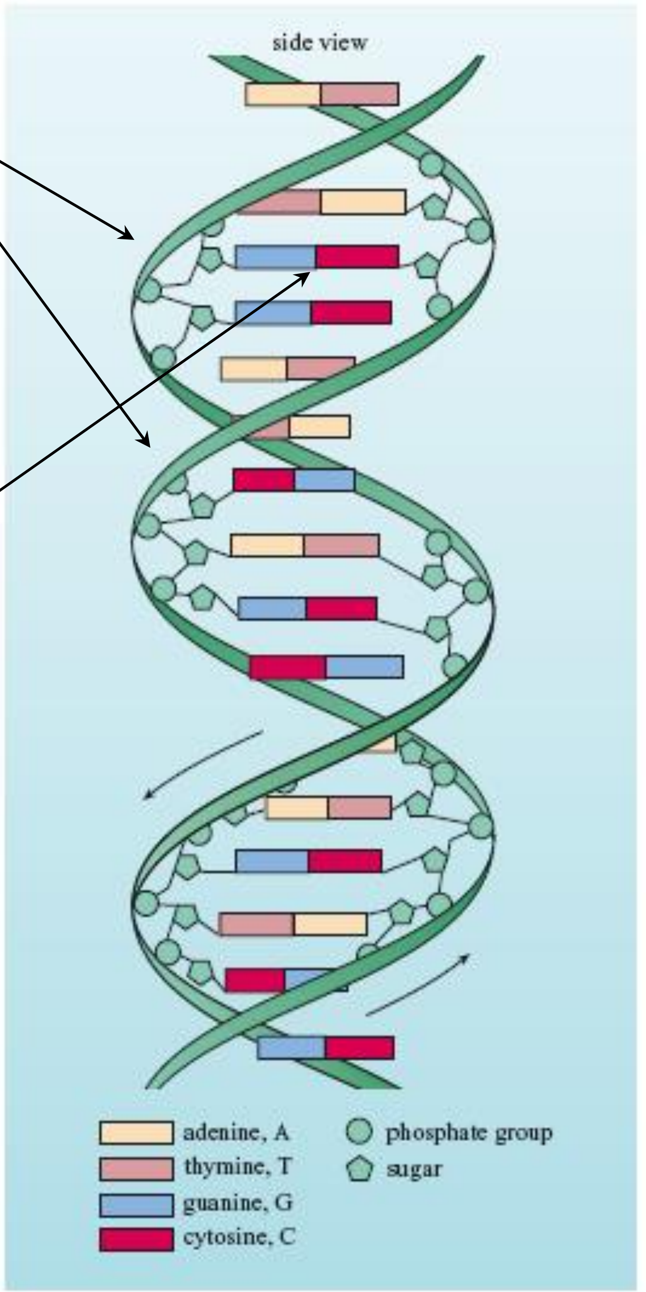
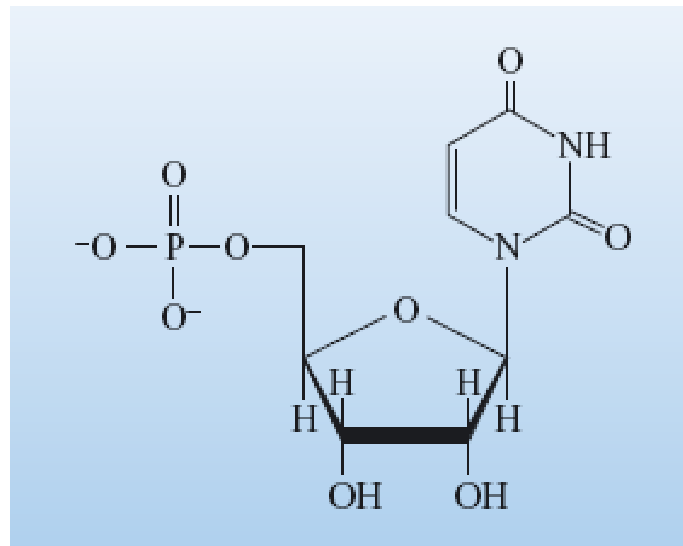


Figure 1.9 The DNA double helix. Note that the ‘ribbons’ are not real, but are there to illustrate the nature of the double helix.

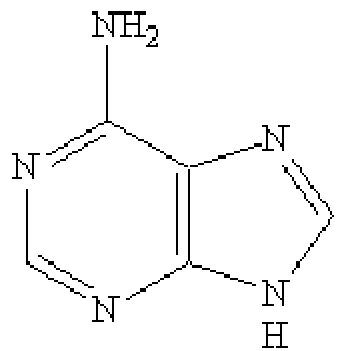
DNA vs. RNA

- Deoxyribonucleic acid (DNA) – deoxyribose sugar
- Ribonucleic acid (RNA) – ribose sugar

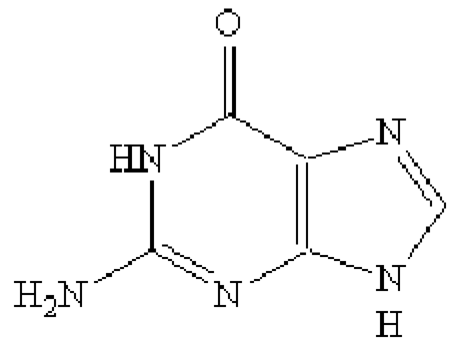


Four bases:

DNA	RNA
A – adenine –	A
G – guanine –	G
C – cytosine –	C
T – thymine	U – uracil

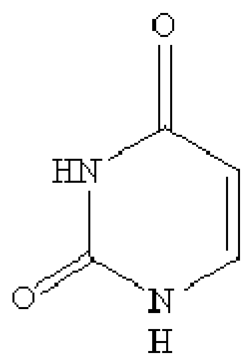


Adenine

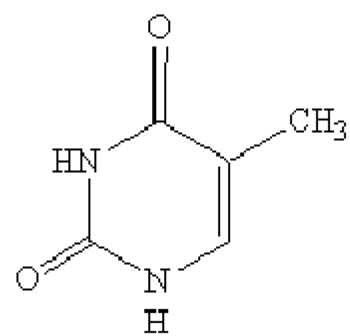


Guanine

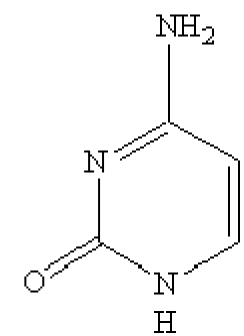
Purines



Uracil

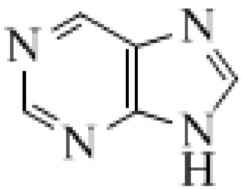


Thymine

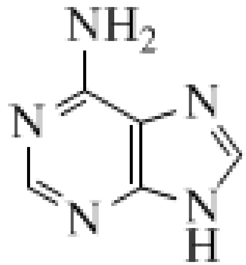


Cytosine

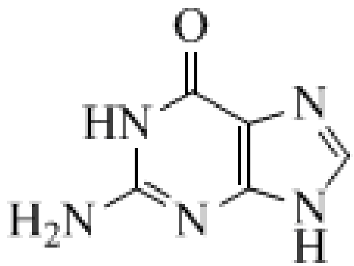
Pyrimidines



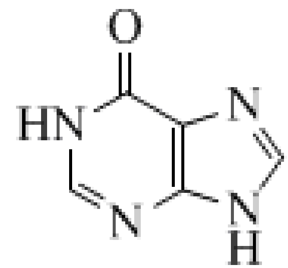
purine
1



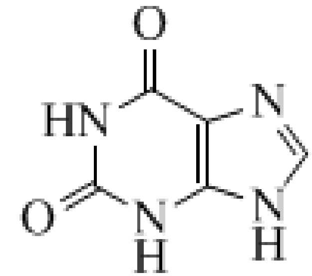
adenine
2



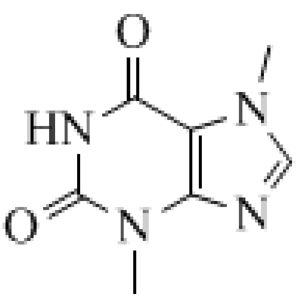
guanine
3



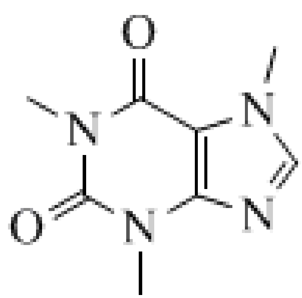
hypoxanthine
4



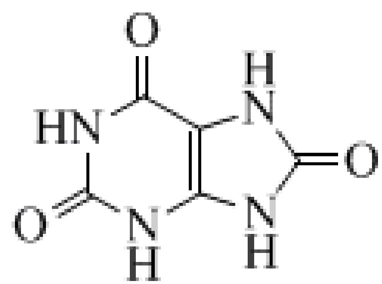
xanthine
5



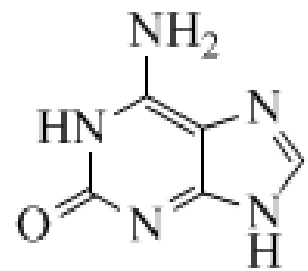
theobromine
6



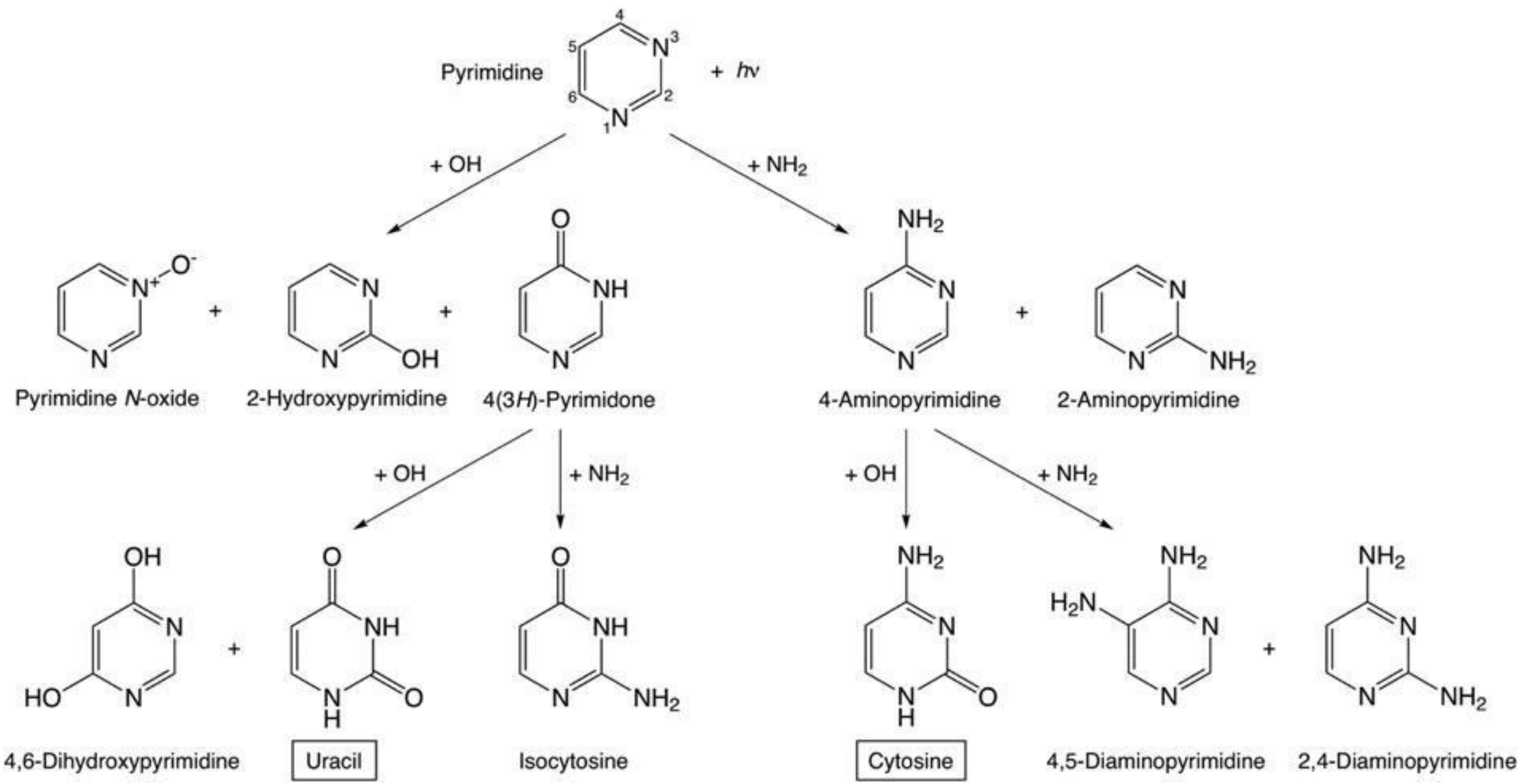
caffeine
7



uric acid
8



isoguanine
9

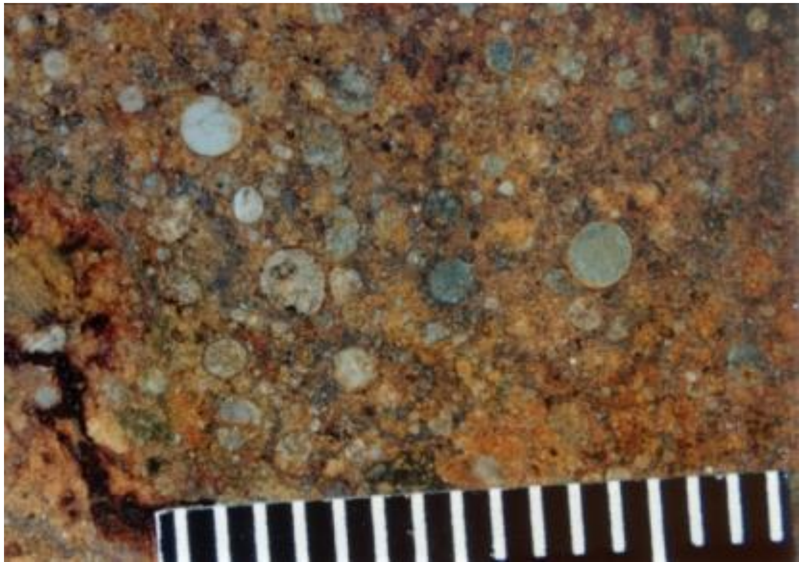

Pyrimidine
+ hν
+ OH
+ NH2
Pyrimidine N-oxide
2-Hydroxypyrimidine
4(3H)-Pyrimidone
4-Aminopyrimidine
2-Aminopyrimidine
+ OH
+ NH2
+ OH
+ NH2
4,6-Dihydroxypyrimidine
Uracil
Isocytosine
Cytosine
4,5-Diaminopyrimidine
2,4-Diaminopyrimidine

Meteorites

- A **meteorite** is a natural object originating in outer space that survives an impact with the Earth's surface without being destroyed.
- Chondrites – 86%

(5% Carbonaceous Chondrites)

- Achondrites – 8%
- Iron meteorites – 5%



TYPES OF METEORITES

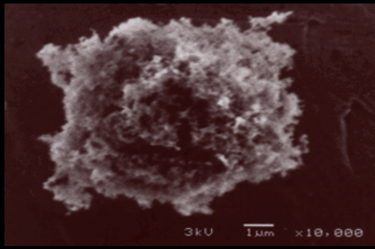
TYPE	SUBTYPE	FREQUENCY	COMPOSITION	FORMATION
Stones	Carbonaceous Chondrites	5 %	Water, carbon silicates, metals	Primitive
	Chondrites	81 %	Silicates	Heated under pressure
	Achondrites	8 %	Silicates	Heated
Stony irons		1 %	50 % silicates, 50 % free metal	Differentiated
Irons		5 %	90 % iron 10 % nickel	Differentiated

Meteorites represent extraterrestrial material which can be studied on Earth !

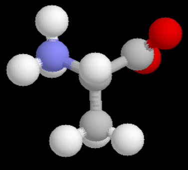
Murchison (1969, Australia)

<u>Insoluble C-fraction:</u>

60-80 % aromatic carbon highly substituted small aromatic moieties branched by aliphatic chains



<u>Volatile fraction:</u>



Organics Found in Meteorites

Total Carbon Content: > 3% (by weight); Soluble Fraction: < 30% of total C

COMPONENTS:

ACIDS:
- Amino acids
- Carboxylic acids
- Hydroxycarboxylic acids
- Dicarboxylic acids
- Hydroxydicarboxylic acids
- Sulfonic acids
- Phosphonic acids

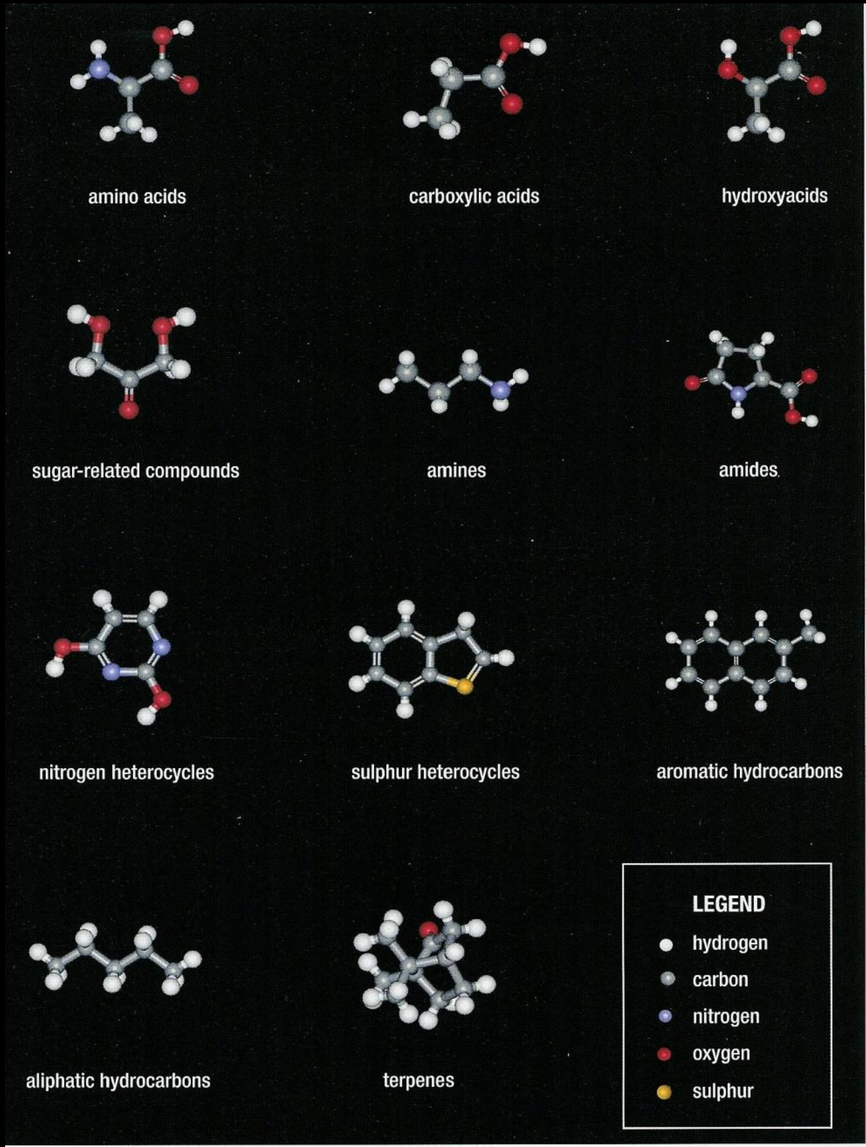
HYDROCARBONS:
- non-volatile: aliphatic
  - aromatic (PAH)
  - polar
- volatile

FULLERENES:
- C_{60}, C_{70}
- $He@C_{60}$
- Higher Fullerenes

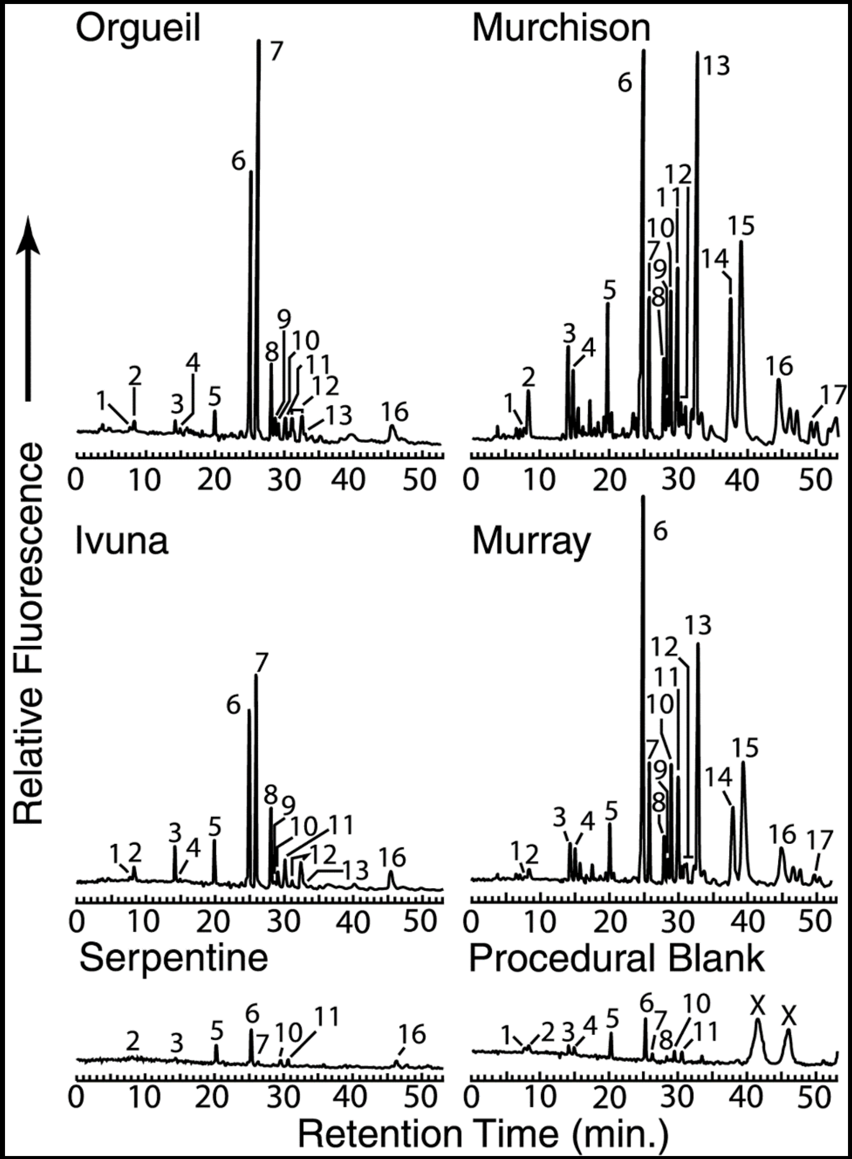
OTHERS:
- N-Heterocycles
- Amides
- Amines
- Alcohols
- Carbonyl compounds

Abundances of soluble organic compounds in the Murchison meteorite (Botta & Bada 2002, Sephton 2002, 2004)

Compound Class		Concentration(ppm)
Amino Acids	CM	17-60
	CI	~5
Aliphatic hydrocarbons		>35
Aromatic hydrocarbons		3.3
Fullerenes		> 1
Carboxylic acids		> 300
Hydroxycarboxylic acids		15
Dicarboxylic acids & Hydroxydicarboxylic acids		14
Purines & Pyrimidines		1.3
Basic N-heterocycles		7
Amines		8
Amides	linear	> 70
	cyclic	> 2
Alcohols		11
Aldehydes & Ketones		27
Sulphonic acids		68
Phosphonic acids		2



Chromatograms of Meteorite Extracts



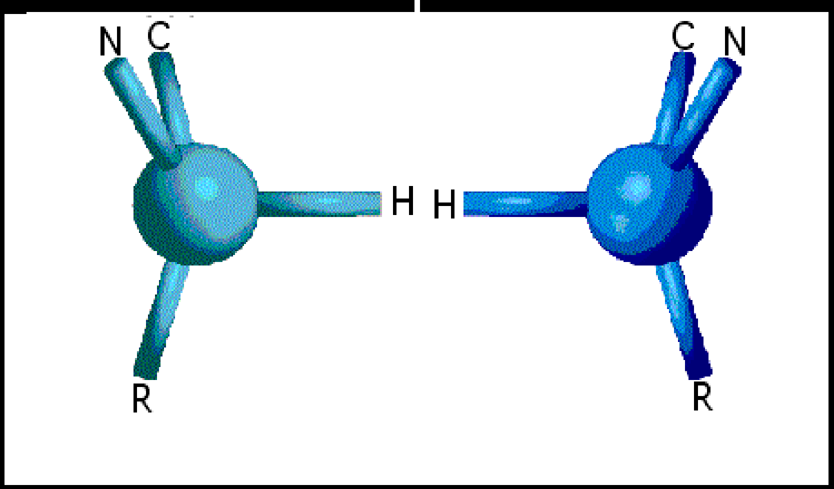
1 D-Aspartic Acid
2 L-Aspartic Acid
3 L-Glutamic Acid
4 D-Glutamic Acid
5 D,L-Serine
6 Glycine
7 β-Alanine
8 γ-Amino-*n*-butyric Acid (g-ABA)
9 D,L-b-Aminoisobutyric Acid (b-AIB)
10 D-Alanine
11 L-Alanine
12 D,L-β-Amino-n-butyric Acid (b-ABA)
13 α-Aminoisobutyric Acid (AIB)
14 D,L-α-Amino-n-butyric Acid (a-ABA)
15 D,L-Isovaline
16 L-Valine
17 D-Valine
X: unknown

Ehrenfreund *et al.*, 2001

Amino Acids in Carbonaceous Chondrites

- Amino acids are readily synthesized under a variety of plausible prebiotic conditions (e.g. in the Miller-Urey Experiment).
- Amino acids are the building blocks of proteins and enzymes in life on Earth.
- Chirality (handedness) can be used to distinguish biotic vs. abiotic origins.
- Most of the amino acids found in meteorites are very rare on Earth (AIB, isovaline).

Chirality



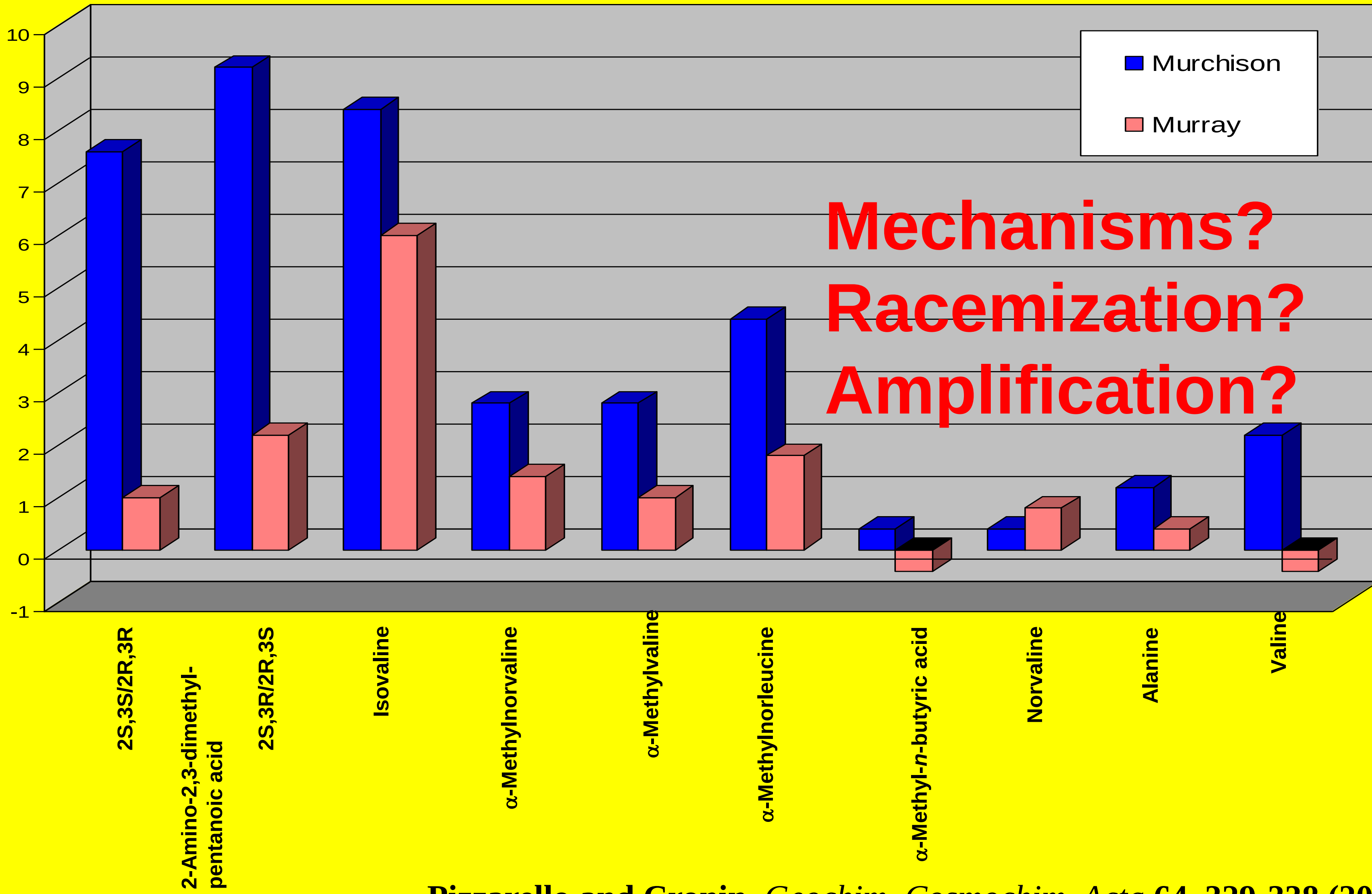
- **Left- and right-handed mirror molecules are called enantiomers.**
- **Enantiomers possess identical physical properties (melting point *etc*.).**
- **They rotate the plane of planar-polarized light in opposite directions.**
- **They cannot be chromatographically separated on a non-chiral column.**

Separation on chiral column

or

Derivatization to form diastereoisomers, separation on non-chiral column

Enantiomeric Excesses in Meteoritic Amino Acids



Pizzarello and Cronin, *Geochim. Cosmochim. Acta* **64, 329-338 (2000)**

Racemic amino acids from the ultraviolet photolysis of interstellar ice analogues

Max P. Bernstein*†, Jason P. Dworkin*†, Scott A. Sandford†, George W. Cooper† & Louis J. Allamandola†

** The Center for the Study of Life in the Universe, SETI Institute, 2035 Landings Drive, Mountain View, California 94043, USA*
† NASA-Ames Research Center, Mail Stop 245-6, Moffett Field, California 94035-1000, USA

The delivery of extraterrestrial organic molecules to Earth by meteorites may have been important for the origin and early evolution of life[1]. Indigenous amino acids have been found in meteorites[2]—over 70 in the Murchison meteorite alone[3]. Although it has been generally accepted that the meteoritic amino acids formed in liquid water[4] on a parent body, the water in the Murchison meteorite is depleted in deuterium[5] relative to the indigenous organic acids[6,7]. Moreover, the meteoritical evidence[8] for an excess of laevo-rotatory amino acids is hard to understand in the context of liquid-water reactions on meteorite parent bodies. Here we report a laboratory demonstration that glycine, alanine and serine naturally form from ultraviolet photolysis of the analogues of icy interstellar grains. Such amino acids would naturally have a deuterium excess similar to that seen in interstellar molecular clouds, and the formation process could also result in enantiomeric excesses if the incident radiation is circularly polarized. These results suggest that at least some meteoritic amino acids are the result of interstellar photochemistry, rather than formation in liquid water on an early Solar System body.

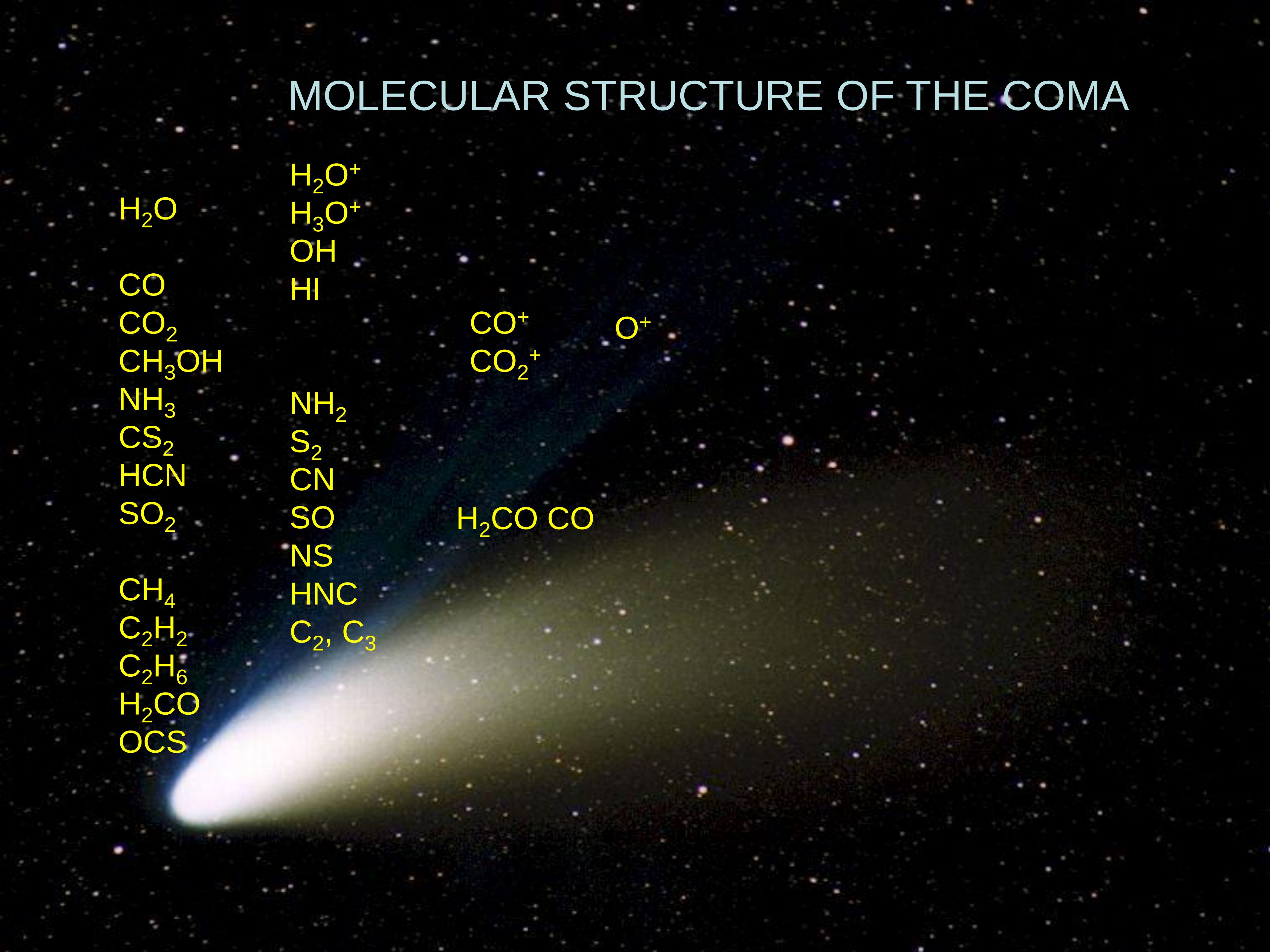
As the most ancient and pristine bulk material studied in the laboratory, primitive meteorites are the clearest windows to the birth of the Solar System. Planetary systems such as our own are believed to form from the collapse of an interstellar dense molecular cloud composed of gas and sub-micrometre sized grains. In such 'dark' clouds the temperatures are low ($T < 50$ K), and all but the most volatile species (that is, H_2, He, Ne) condense onto grains, coating them with a thin layer of ice[9]. This ice is composed primarily of amorphous H_2O, but usually also contains a variety of other simple molecules[9,10], such as CO_2, CO, CH_3OH, and NH_3. Laboratory studies[11] and astronomical observations[10,12] indicate that radiation processing of such ices can create complex organic compounds[13]. Many of the organic molecules that are present in carbonaceous chondrites (primitive carbon-rich meteorites) and comet and asteroid dust are thought to come, at least in part, from the ice and complex compounds constructed in the interstellar medium (ISM).

Perhaps the most convincing molecular evidence for the interstellar heritage of meteoritic molecules is their high deuterium (D) enrichment[3,14]. At the low temperatures in dense molecular clouds deuterium fractionation is efficient and elevated D/H ratios are seen in grain mantles[15]; such increased ratios are also found in several gas-phase interstellar molecules, including amino acid precursors, such as formaldehyde and ammonia[16]. Although it had been accepted that the deuterium in meteoritic organics indicated that their precursors formed in the ISM, the actual hydroxy and amino acids are still commonly believed to have formed on the asteroid or comet parent body from reactions in liquid water[4] that, at least in Murchison, was apparently deuterium poor[5]. It is difficult to explain how these compounds retain relatively high amounts of deuterium, let alone how it is distributed. For example, it seems contradictory that the hydroxy acids in the Murchison meteorite have one-third as much deuterium as the amino acids, and yet have a lower rate of deuterium exchange in water than amino acids[3,7]. If, however, the hydroxy and amino acids had formed in the ISM their deuterium enrichment would be a logical consequence of the photochemistry of already deuterium-enriched pre-solar ices.

The laboratory experiments described here were designed to elucidate potential pathways from interstellar chemistry to the organic molecules extracted from meteorites. We have conducted laboratory experiments at temperatures, pressures and radiation conditions that are representative of the interstellar clouds from which planetary systems form. In a series of experiments, gases were vapour deposited onto a substrate at 15 K forming an ice film consisting primarily of amorphous H_2O with other compounds over a range of concentrations (0.5–5% NH_3, 5–10% CH_3OH and 0.5–5% HCN, relative to H_2O). These solid mixtures are

Comets & Astrobiology

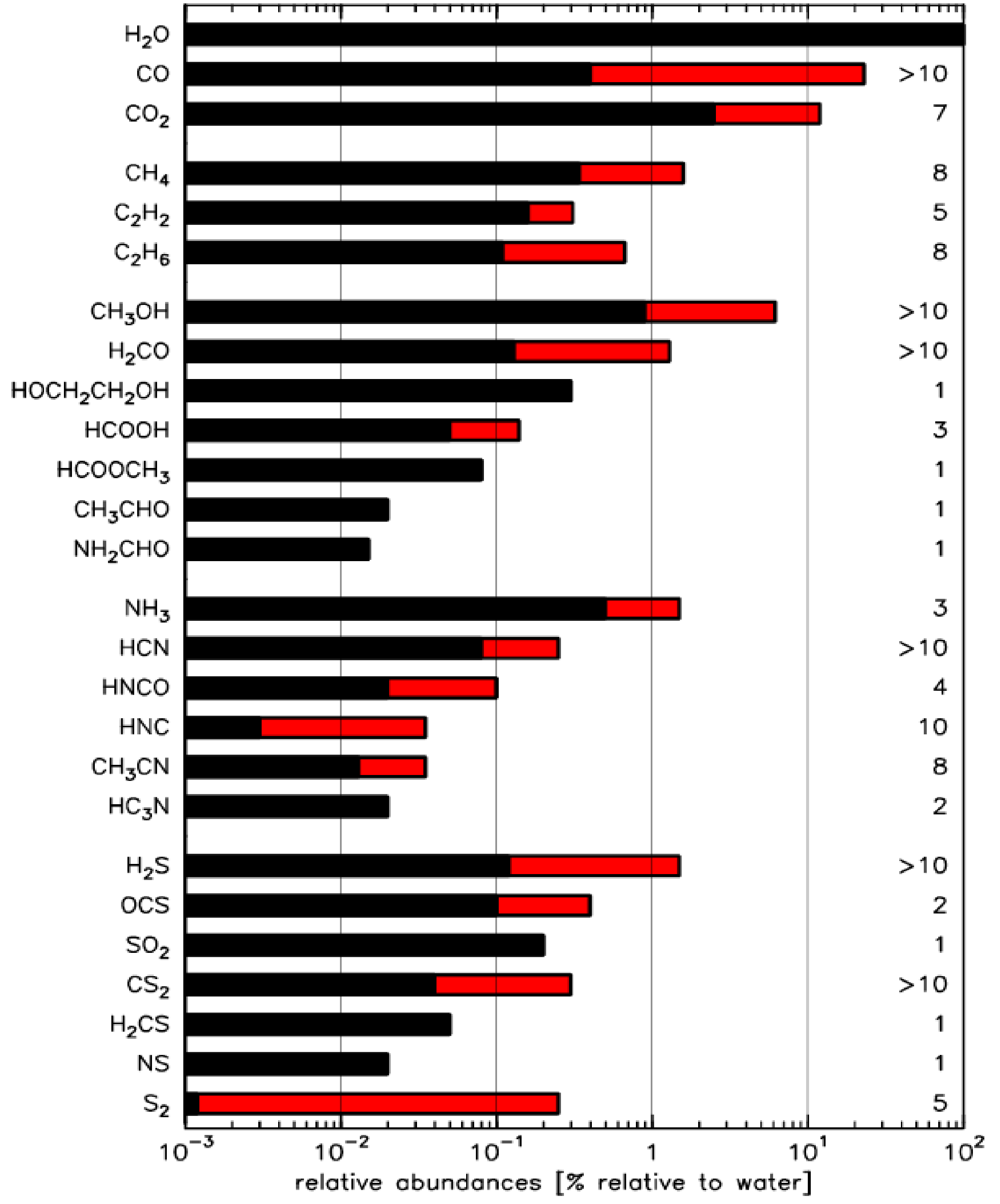
- Comets are the key to understanding the Solar Nebula & its evolution.
- Comets could serve as probes of chemical processes occurring in the midplanes of astronomical disks
- Comets may have provided key organic nutrients required to jump start life on Earth.


MOLECULAR STRUCTURE OF THE COMA
H_2O
CO
CO_2
CH_3OH
NH_3
CS_2
HCN
SO_2
CH_4
C_2H_2
C_2H_6
H_2CO
OCS
H_2O^+
H_3O^+
OH
HI
NH_2
S_2
CN
SO
NS
HNC
C_2, C_3
CO^+
CO_2^+
O^+
H_2CO CO

Evidence for chemical diversity

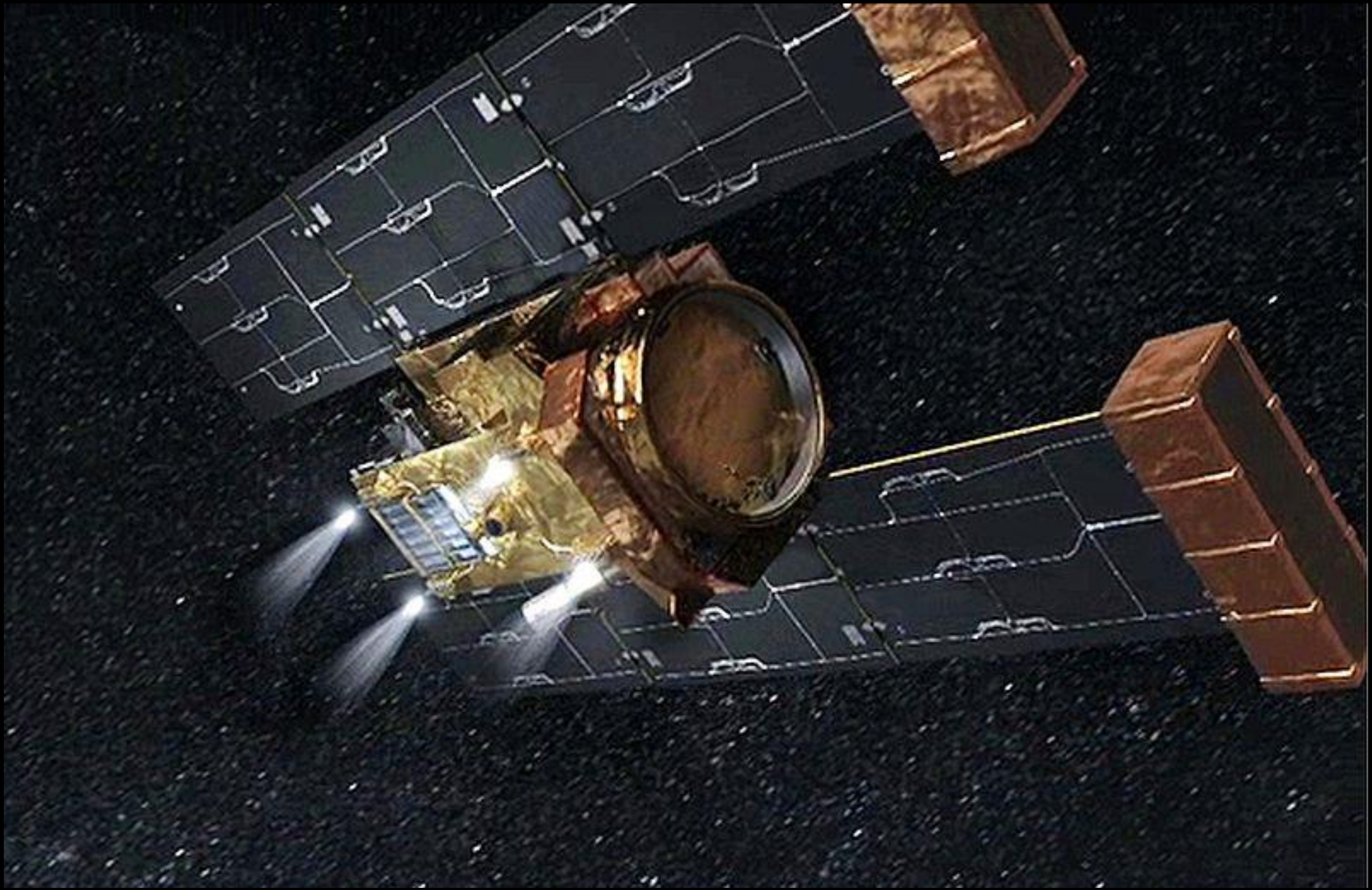
Diversity among Oort cloud comets

No systematic differences between Oort cloud and « Kuiper belt » comets

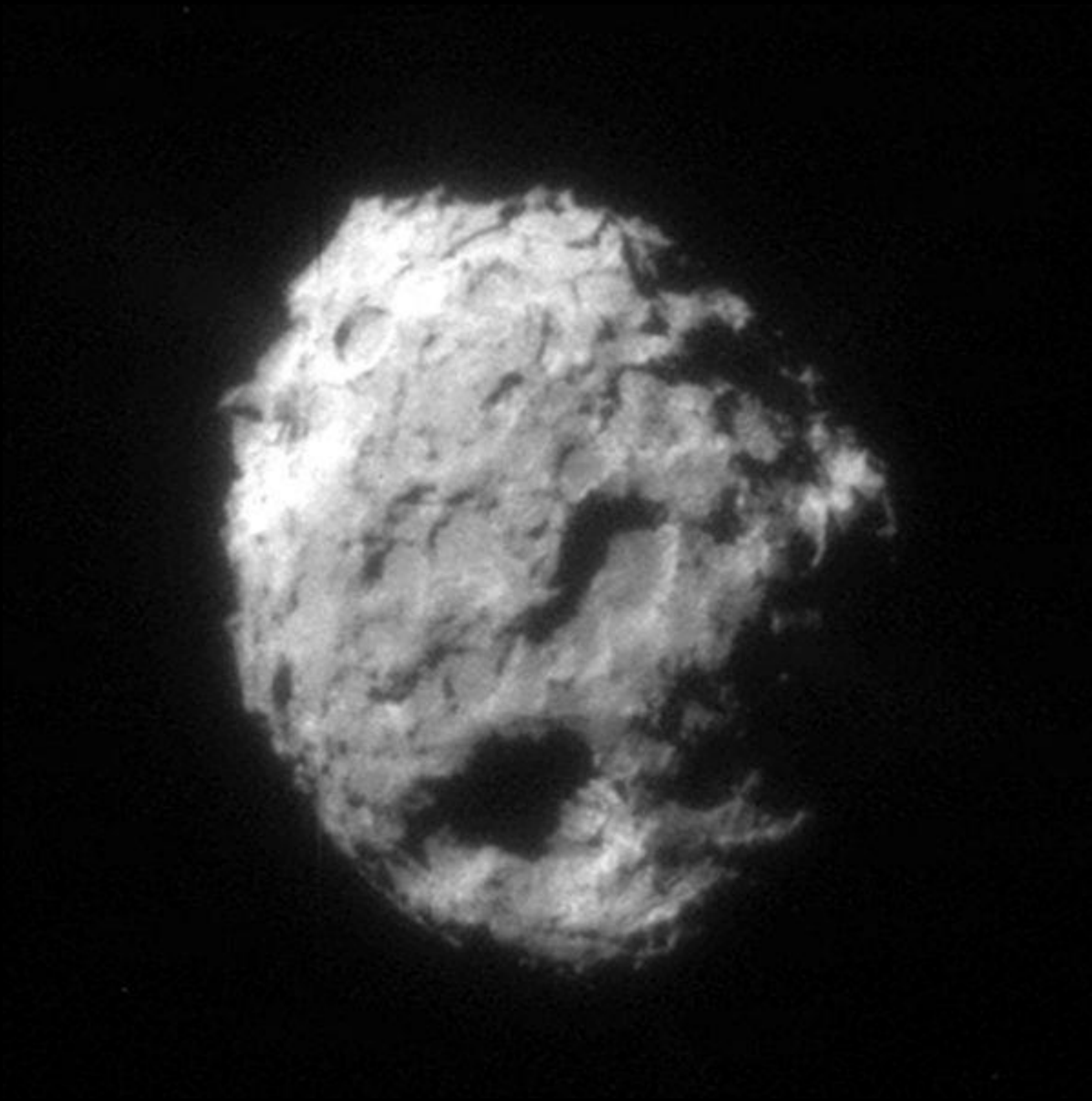


Crovisier 2005

Wild 2 (Jan 17, 2010)

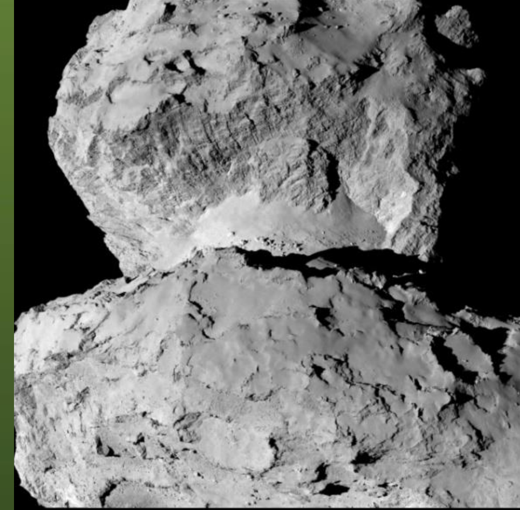


Stardust (launched Feb 7, 1999)



Wild 2 (Stardust, January 2, 2004)

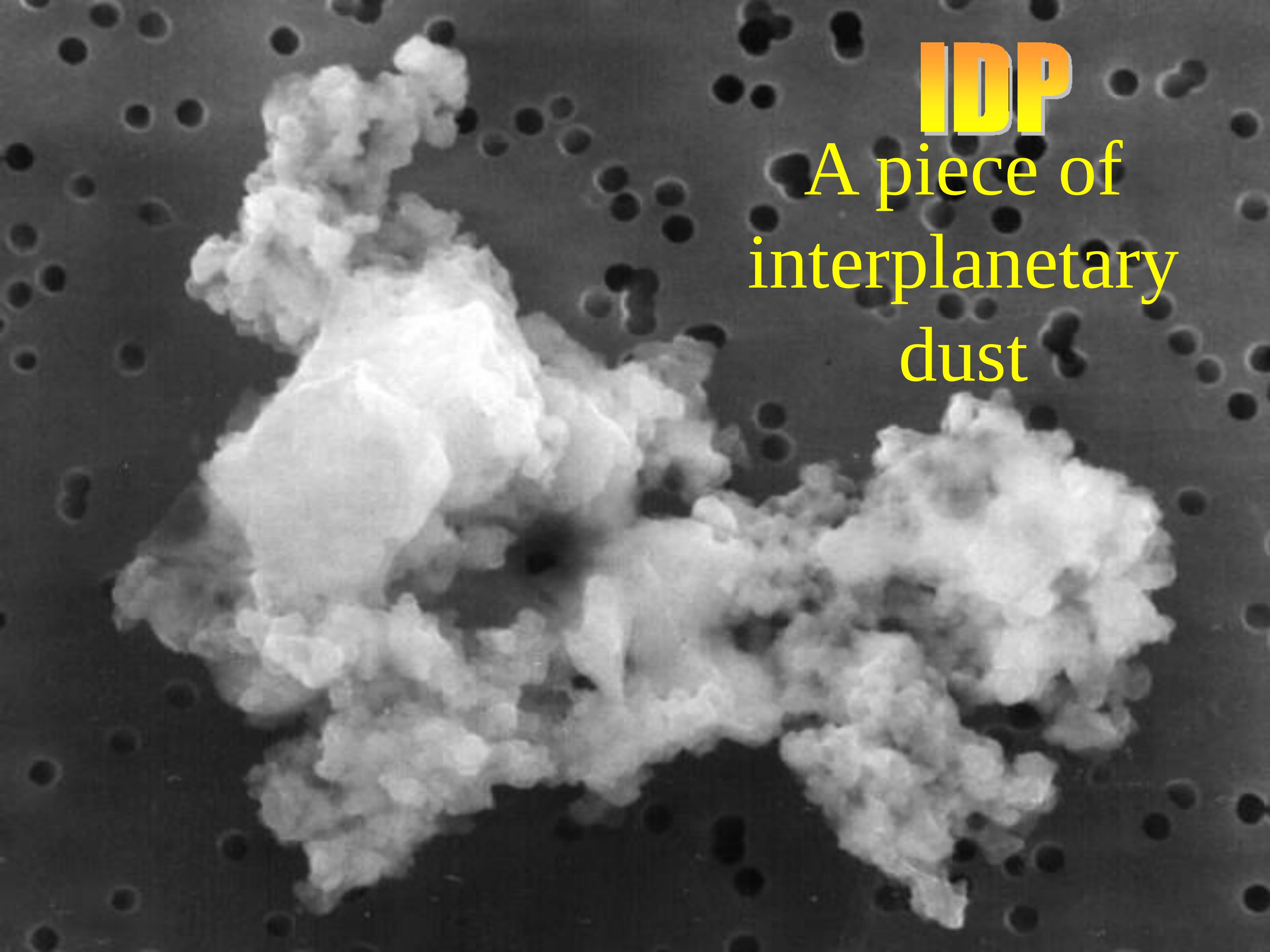
Stardust Sample Return (Jan 16, 2006)



TOUCHDOWN

2014/11/23 16:03 GMT

TELEMETRY OK 16:09 GMT


IDP
A piece of interplanetary dust

NITROGEN ISOTOPE RATIOS

(TERRESTRIAL $^{14}N/^{15}N \sim 270$)

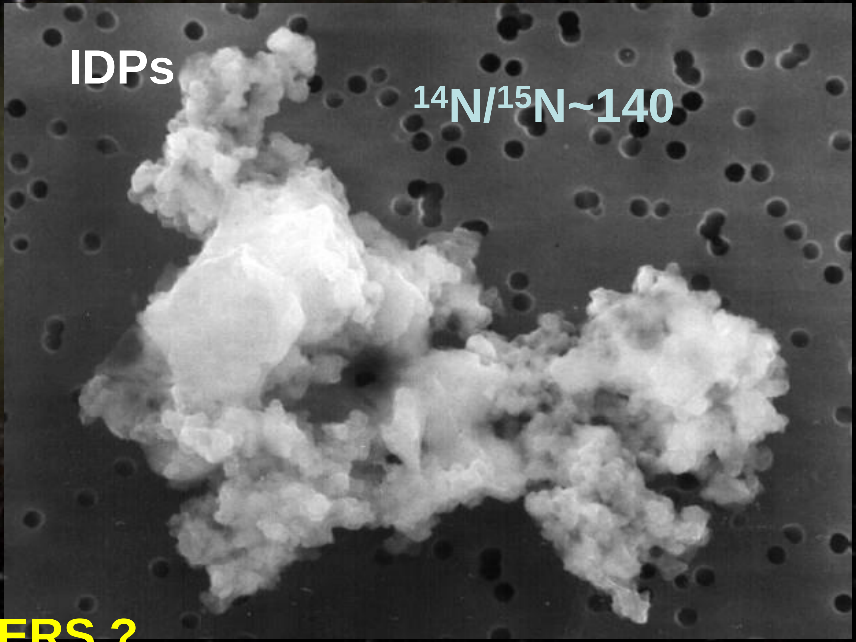
PROTOSOLAR $^{14}N/^{15}N \sim 400$

ISM DEPLETION CORES
$^{14}NH_3/^{15}NH_3 \sim 140$

COMETS:

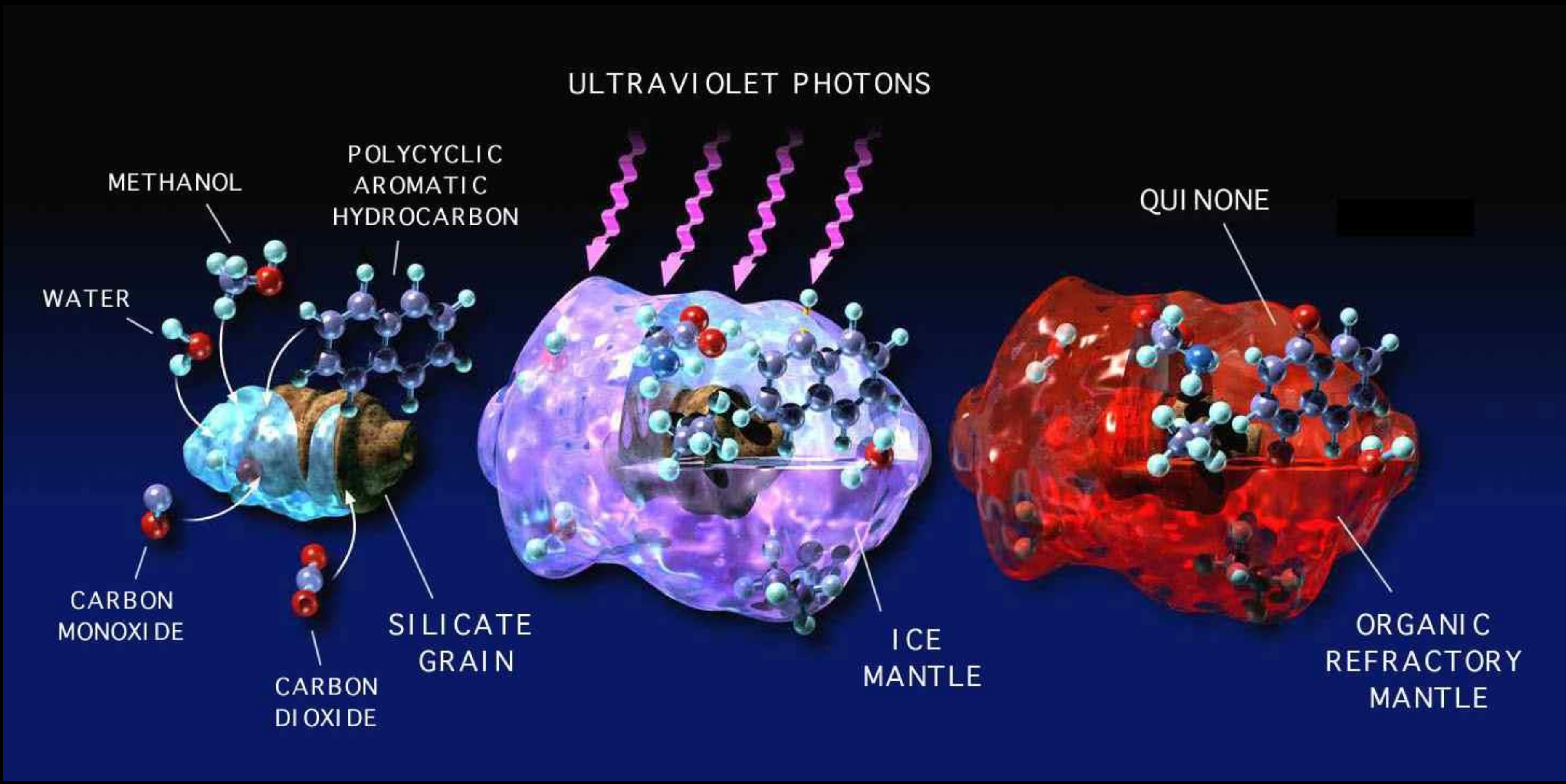
$HC^{14}N/HC^{15}N \sim 400$

$C^{14}N/C^{15}N \sim 140$



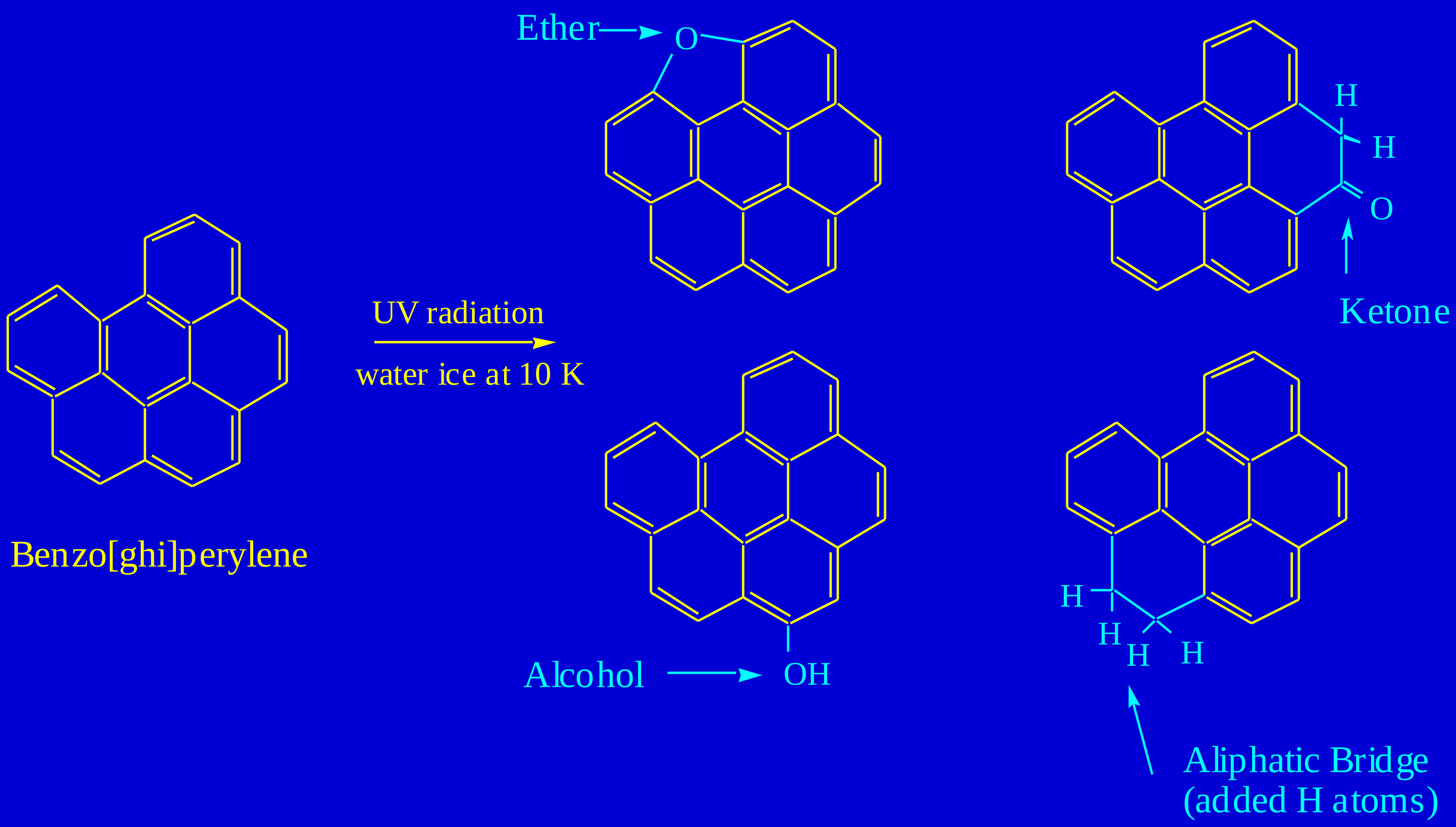
PROCESSING ISM TO ORGANIC POLYMERS ?

Interstellar Dust: ice mantle evolution



Bernstein, Sandford, Allamandola , Sci. Am. 7,1999, p26

Photolysis of PAHs in Water Ice Produces Alkanes, Ketones, Ethers, and Alcohols.

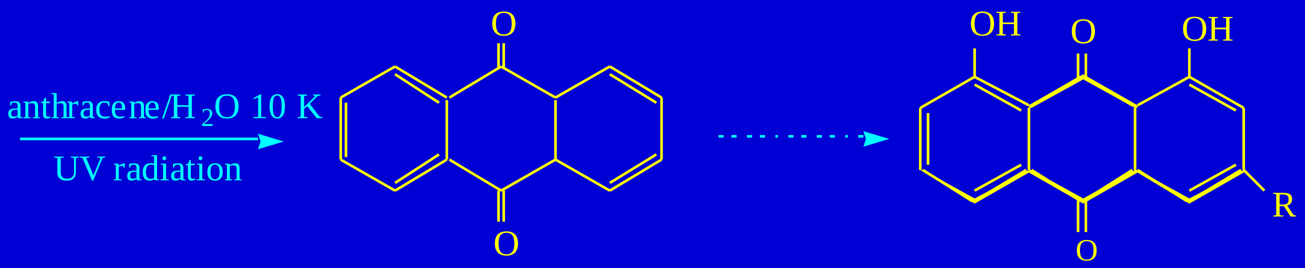


Both oxidation (alcohol, ether and ketone formation) and reduction (addition of hydrogen) reactions occur on photolysis of water ices containing PAHs. These are the same kinds of compounds observed in meteorites, fit spectra of emission objects and, in some cases, have biochemical significance.

Bernstein et al.Science 283, 1135 (1999)

Photochemistry of PAHs in Ice: Abiotic Synthesis of Biogenic Compounds

Juglone (in walnut & pecan shells)
Bull. Soc. Chim. 1, 800 (1907)



Aloe-Emodin (extract of Aloe)
Arch. Pharm. **247**, 81 (1909)

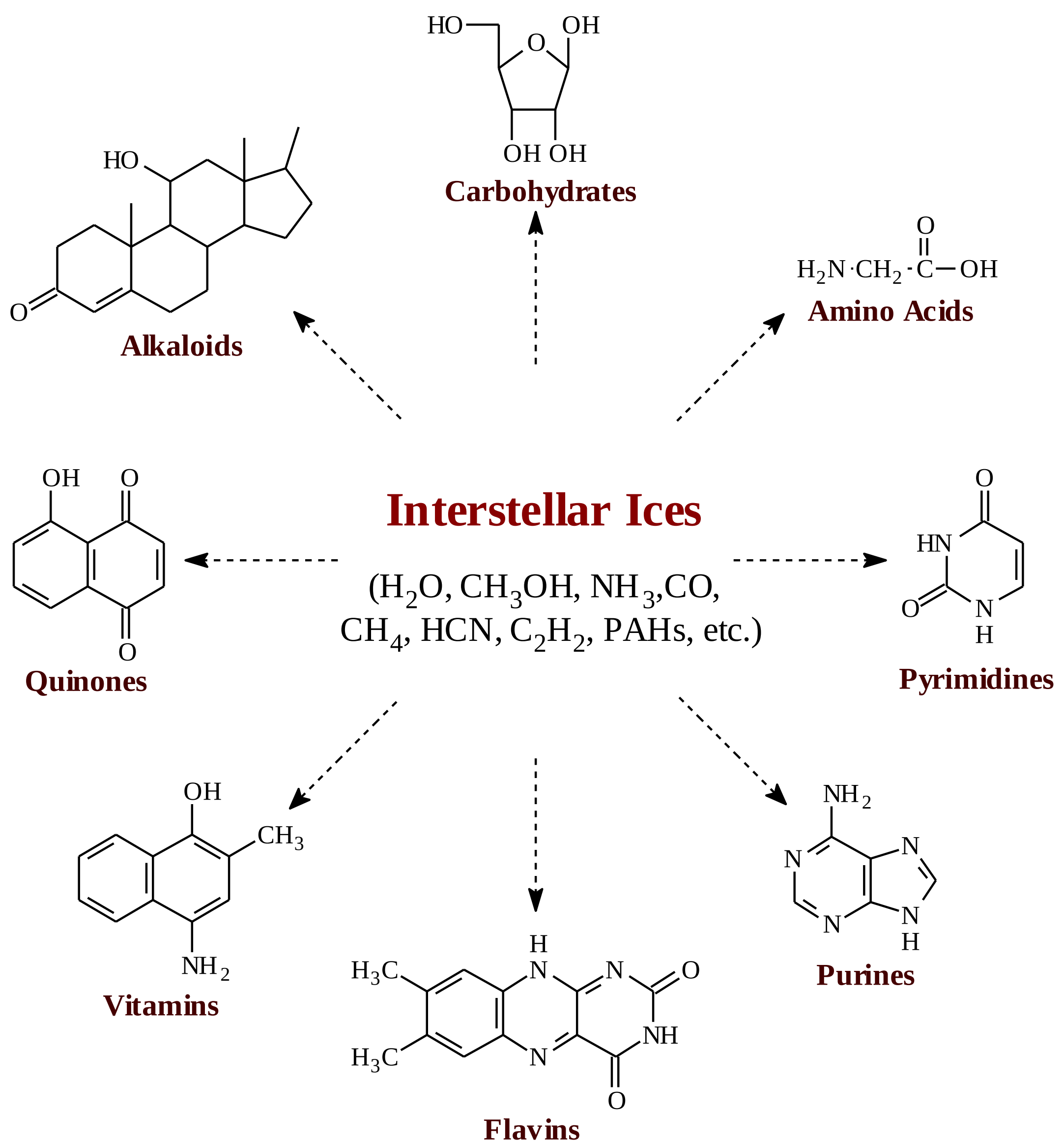
Rhein (extract of chinese rhubarb)
Ann. **50**, 196 (1844)

These quinone type structures are very important in many living systems. For example, naphthaquinones (like juglone above) are essential for electron transport in simple organisms.

Juglone: Bernstein et al.Met. & Planet. Sci. 36, 351 (2001)

Anthroquinone: Ashbourne et al. in prep

Abiotic Synthesis of Biogenically Useful Molecules in Cometary and Interstellar Ices



Courtesy Jason Dworkin