Lezione Astrobiologia

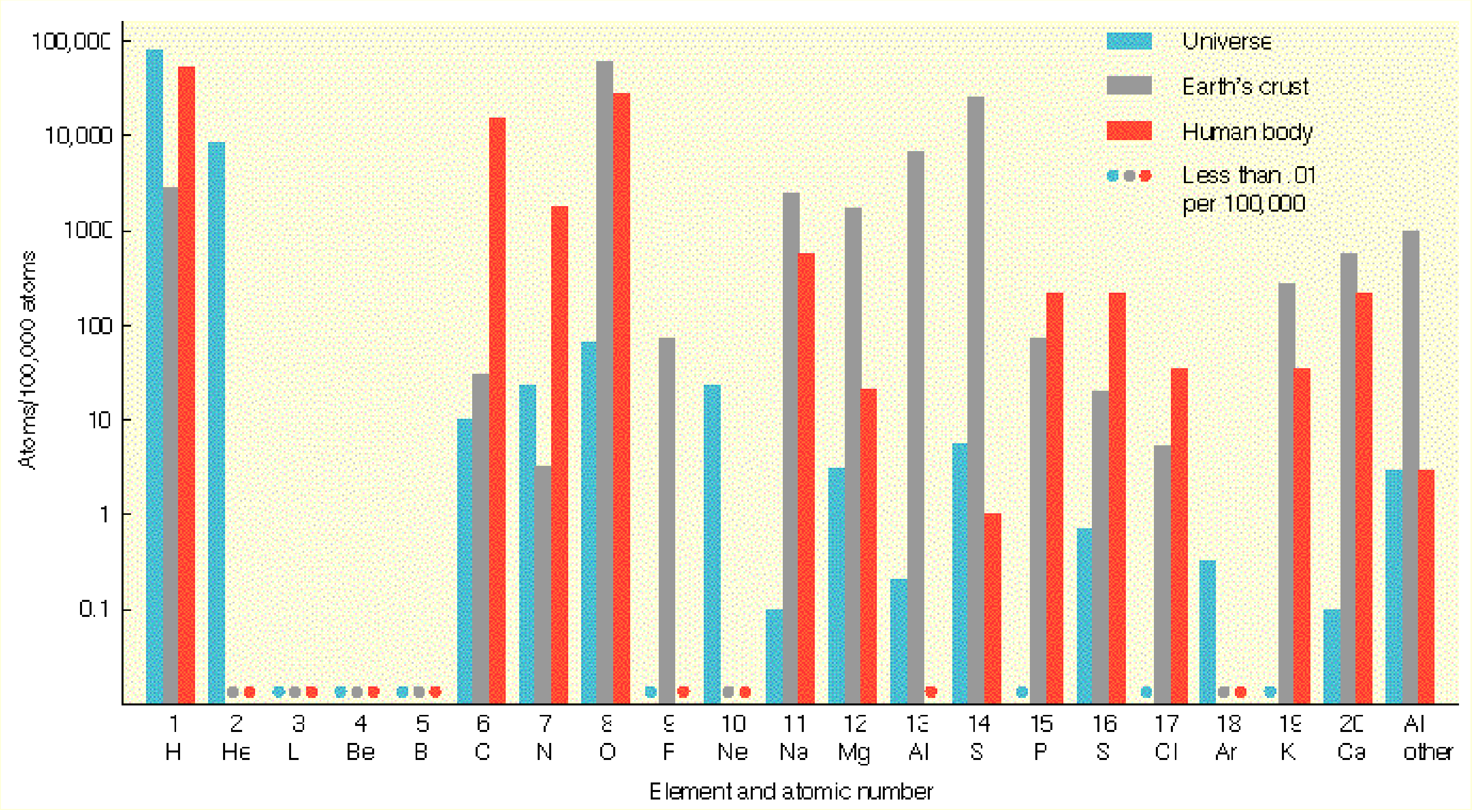
John Robert Brucato

INAF - Osservatorio Astrofisico di Arcetri, Firenze, Italy

jbrucato@arcetri.astro.it

Life is a phenomenon of 2nd generation of stars

Composition of Universe, Earth's crust and Human body



Amounts are expressed as number of atoms of each element per 100,000 atoms
(Courtesy Addiso-Wesley Pub. Comp.)

Elements found in organisms

The abundance of oxygen and hydrogen in organisms is explained partly by the major role of water in life on Earth.

We live in highly aqueous world.

The elements C,H,O, and N are important to life because of their strong tendency to form covalent bounds. In particular, the stability of carbon-carbon bonds and the possibility of forming single, double, or triple bonds give carbon the versatility to be part of an enormous diversity of chemical compounds.

Many other elements are necessary for terrestrial organism. A "second tier" of essential elements includes sulphur and phosphorus, which form covalent bonds, and the ions Na+, K+, Mg2+, Ca2+, and Cl-.

Elements that play quantitatively minor (third and second tier), but often indispensable, role are metals.

(Courtesy Addiso-Wesley Pub. Comp.)

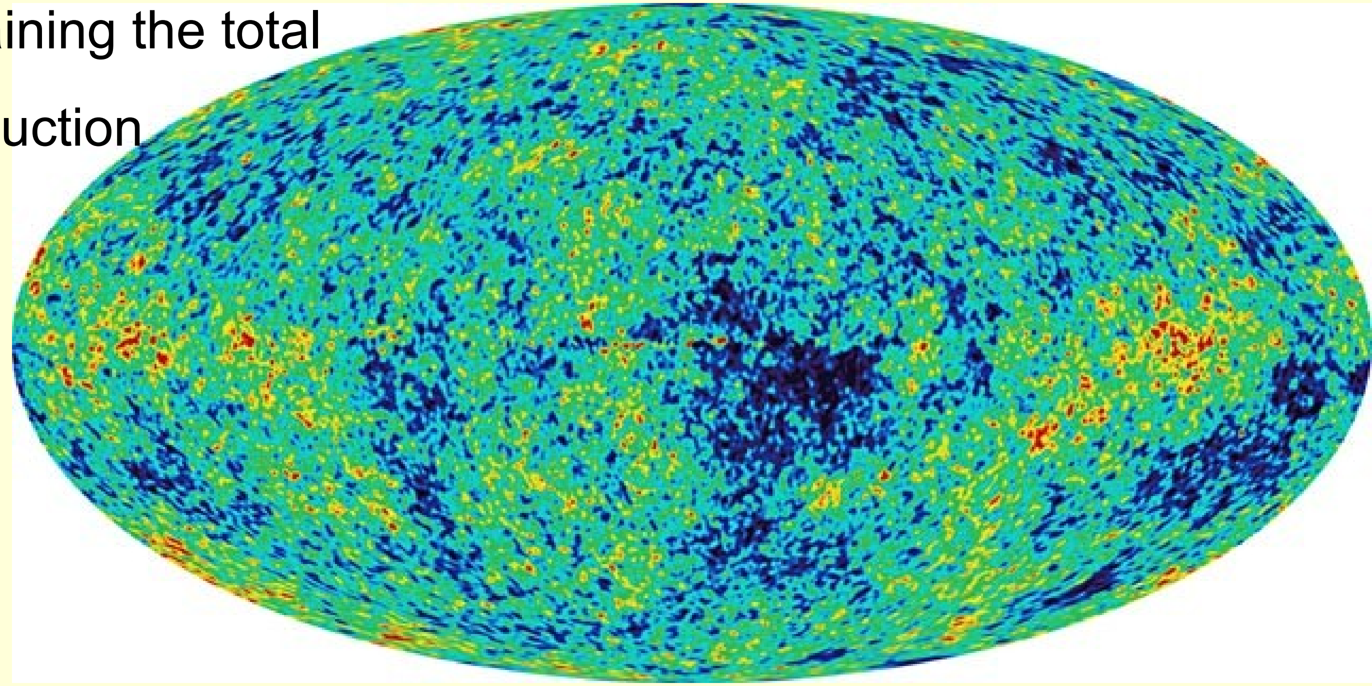
Element	Comment
First Tier	
Carbon (C)	Most abundant in *all* organisms
Hydrogen (H)	
Nitrogen (N)	
Oxygen (O)	
Second Tier	
Calcium (Ca)	Much less abundant but found in *all* organisms
Chlorine (Cl)	
Magnesium (Mg)	
Phosphorus (P)	
Potassium (K)	
Sodium (Na)	
Sulfur (S)	
Third Tier	
Cobalt (Co)	Metals present in small amounts in *all organisms* and essential to life
Copper (Cu)	
Iron (Fe)	
Manganese (Mn)	
Zinc (Zn)	
Fourth Tier	
Aluminum (Al)	Found in or required by *some organisms* in trace amounts
Arsenic (As)	
Boron (B)	
Bromine (Br)	
Chromium (Cr)	
Fluorine (F)	
Gallium (Ga)	
Iodine (I)	
Molybdenum (Mo)	
Nickel (Ni)	
Selenium (Se)	
Silicon (Si)	
Tungsten (W)	
Vanadium (V)	

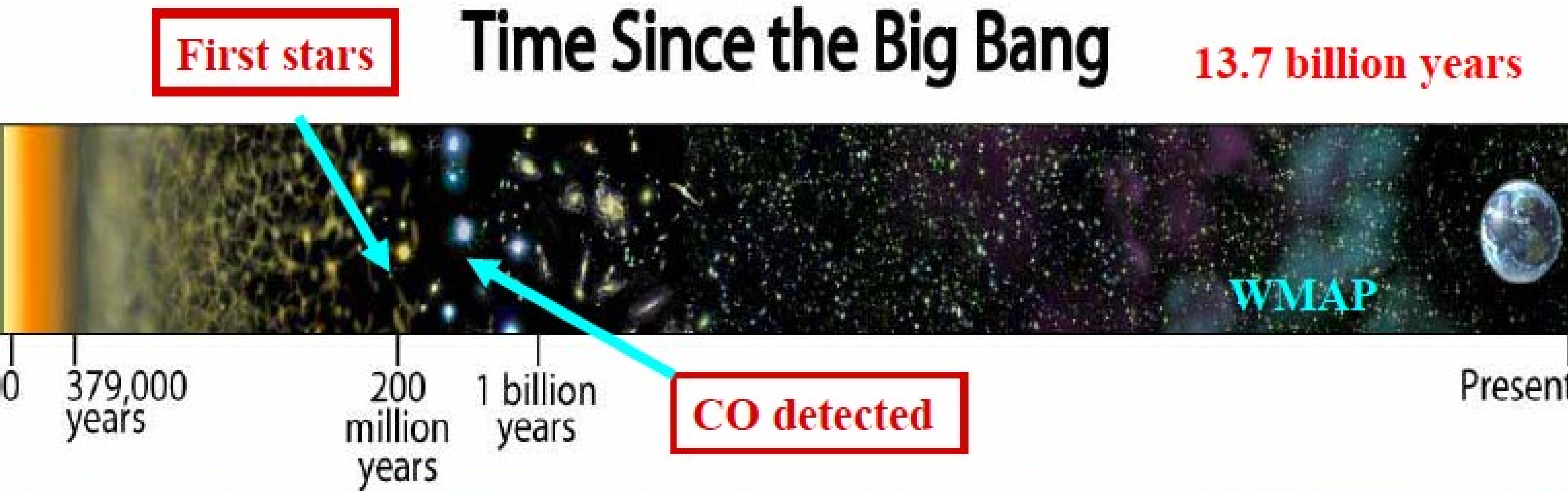
The First Stars (Pop III)

From an homogeneous simple universe to a highly structured complex one.

The chemistry in the very early universe, the so-called Big-Bang nucleosynthesis, only produce very light elements: *hydrogen, helium and traces of deuterium, tritium, lithium and beryllium*. All other chemical elements occurring in living being were formed by nucleosynthesis during the course of stellar evolution.

WMAP observed the large polarization anisotropy of the cosmic microwave background constraining the total ionizing photon production from the first stars (e.g. Cen et al. 2003).





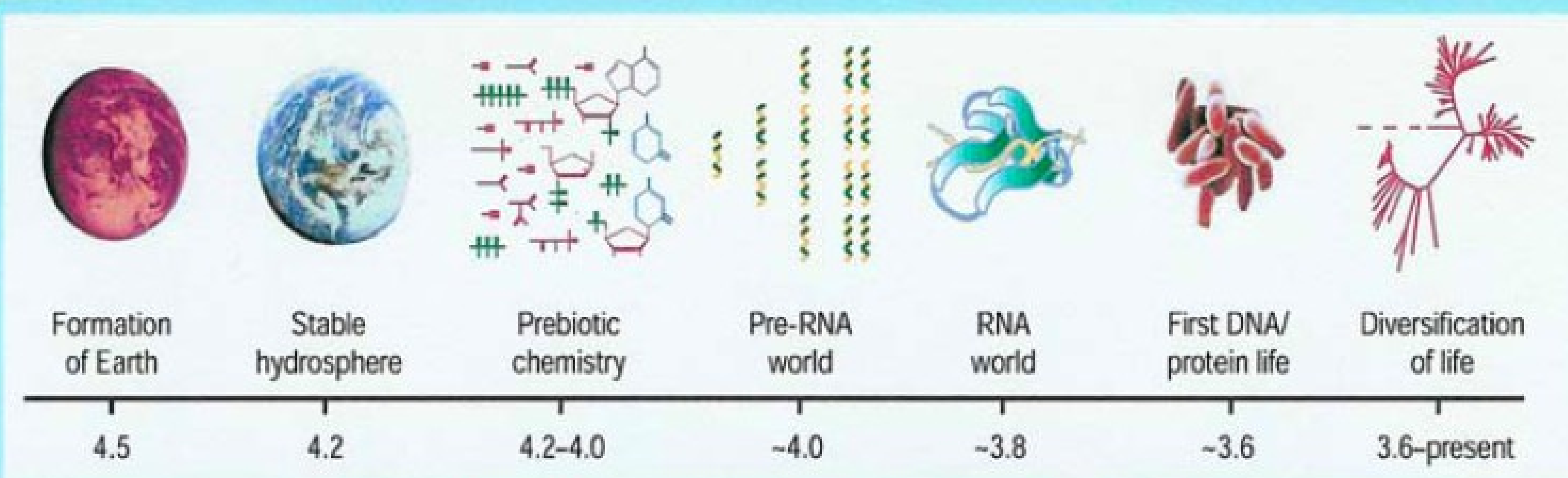


Figure 1 Timeline of events pertaining to the early history of life on Earth, with approximate dates in billions of years before the present.

The Early metal enrichment

The crucial transition from a smooth homogeneous universe to an increasingly complex and structured one is made by the death of the first stars.

How did the first stars died?

$140\ M_\odot < M_* < 260\ M_\odot$ $\longrightarrow$ PISN pair-instability supernova

metal yields $M_Z/M_* \sim 0.5$

$M_* < 140\ M_\odot$ $\longrightarrow$ Black holes *no metal enrichment*

$M_* > 260\ M_\odot$

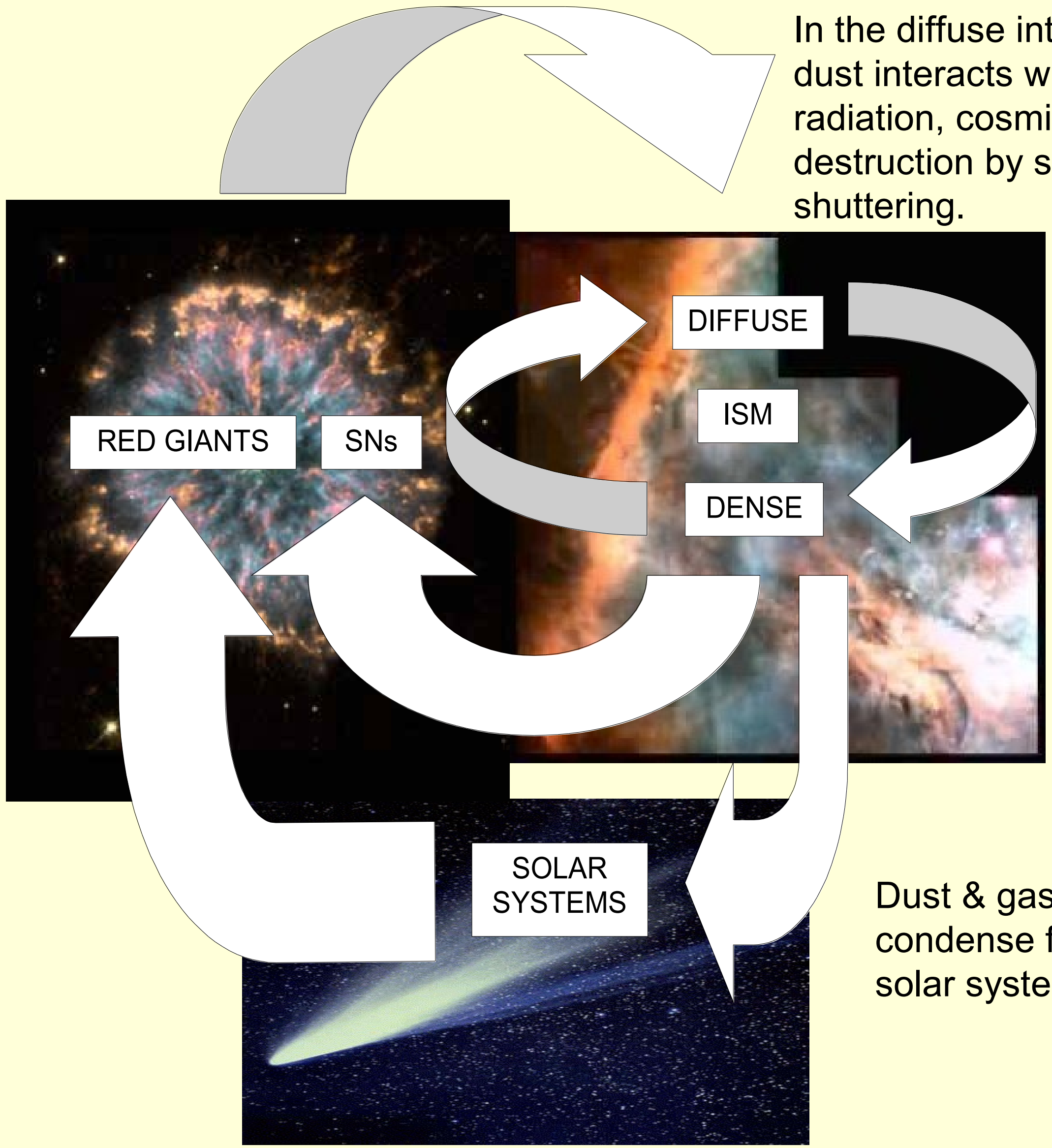
Part of the produced heavy elements (Si & C) are embodied into small dust grains in a time scale of 50-100 Myr (Spitzer 1978)

Pop I & II stars and their co-evolution with ISM

Dust is ubiquitous in Space

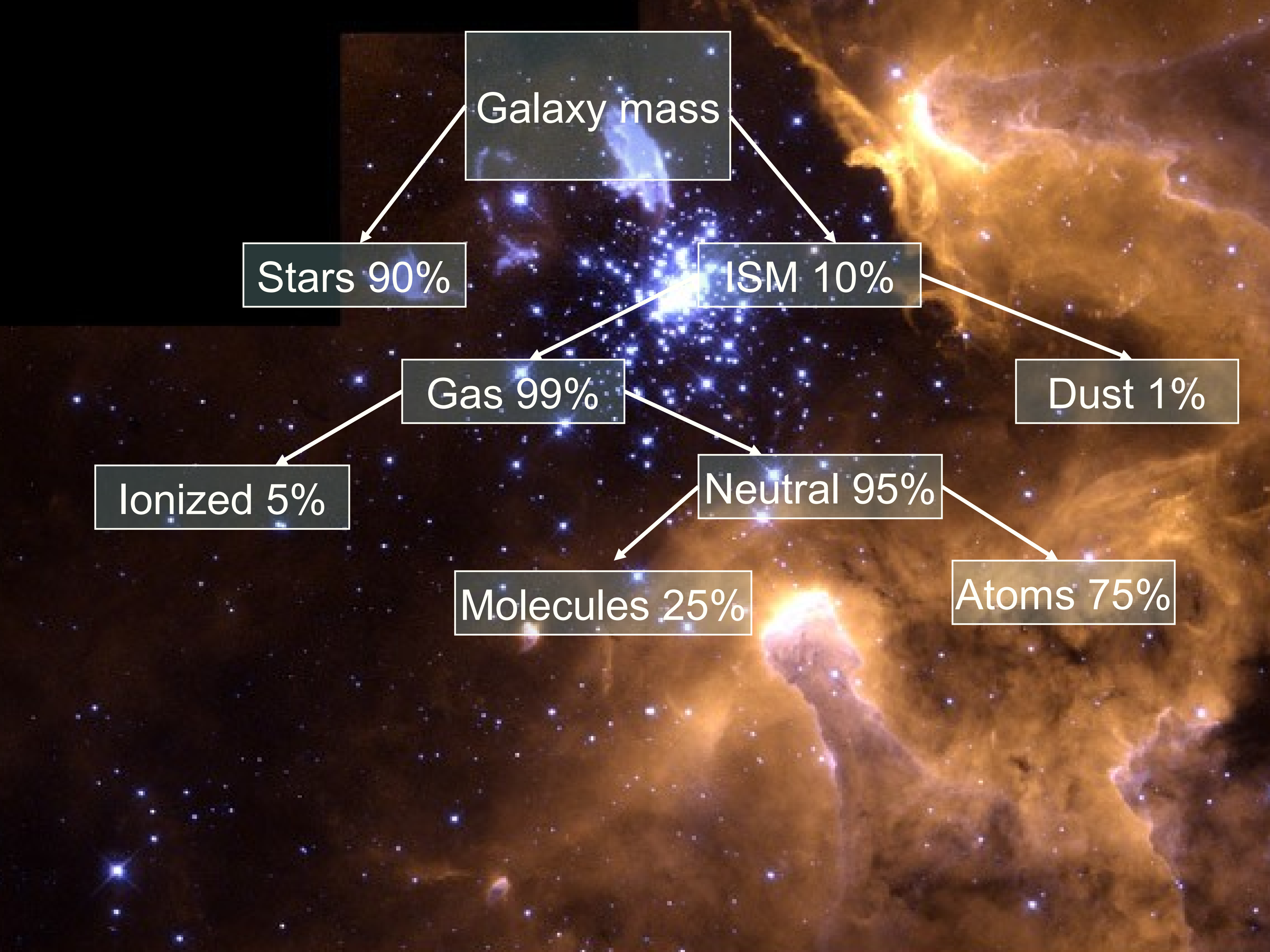
In the diffuse interstellar medium dust interacts with hot gas, UV radiation, cosmic rays, undergo destruction by sputtering and shuttering.

Dust condense in cool atmosphere of evolved stars



In dense interstellar medium dust growths through ice accretion and coagulation and undergo chemical evolution.

Dust & gas condense forming solar system objects



Galaxy mass
Stars 90%
ISM 10%
Gas 99%
Dust 1%
Ionized 5%
Neutral 95%
Molecules 25%
Atoms 75%

Multi-Phase ISM

	Phase	T (K)	cm^{-3}	Volume fract.
Molecular	$H2$	15	$>10^3$	<0.01
Atomic	HI	80	$3\ 10^2$	0.03
Hot	HI, HII	8000	3	0.2-0.3
Ionized	HII	$5\ 10^5$	$5\ 10^{-2}$	0.7-0.8

$C/O>1$ or $C/O<1$

The ISM is enriched primarily by matter ejected from old evolved stars. The outflows from these stars foster gas-phase chemistry. The chemical complexity in circumstellar envelopes was thought to be dominated by the elemental C to oxygen ration. Observations have suggested that envelopes with more carbon than oxygen (C/O>1) have a significantly greater abundance of molecules than their oxygen-rich analogues (C/O<1).

Formation of dust in the stellar envelopes

Dust condense in the stellar envelopes when temperature is lower than T_c ~ 1000K

For a star with radius R_s it occurs at $r \sim 10R_s$ where density is $n \sim 10^{19}$ m^{-3}

Condensation of some species occurs when its partial pressure exceeds the vapor pressure in the condensated phase.

Random encounter of atoms or molecules produces clusters

$$n_i = n_1 exp(-\Delta\ E_i/kT)$$

Clusters number density

Free energy

monomers number density

Dust formation is a **two steps** processes:

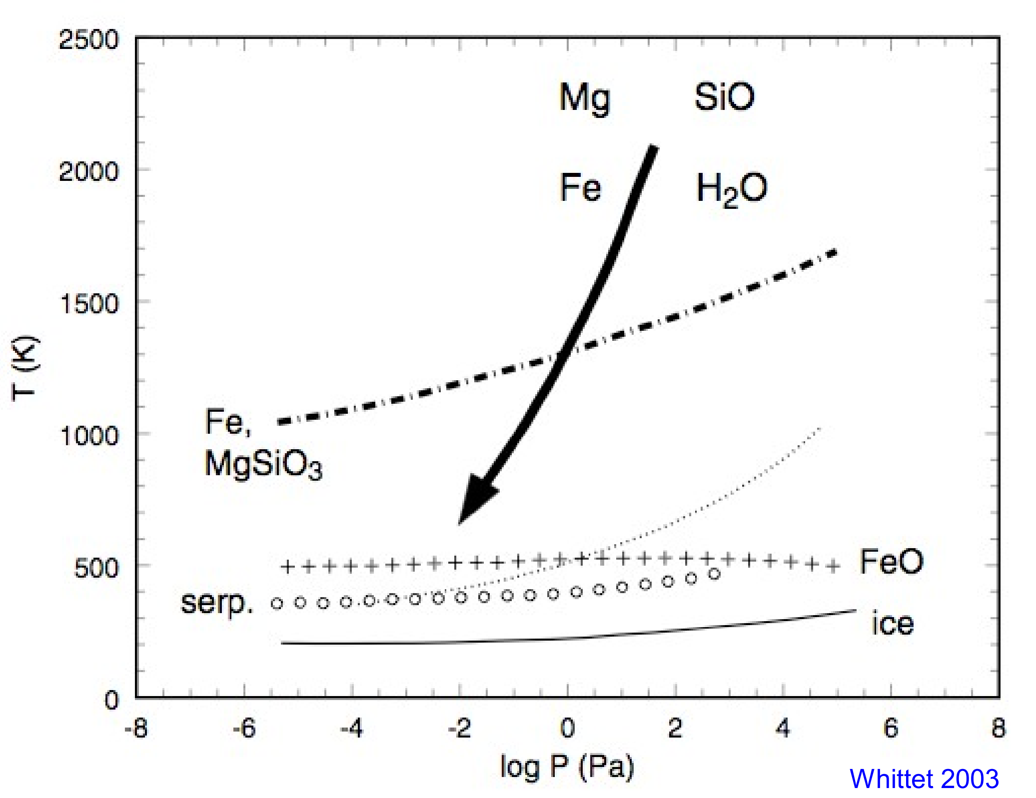
a) formation of clusters of critical sizes

b) growth of clusters in macroscopic grains

CO is the most abundant molecule containing heavy elements.
It forms first and it is stable at temperature below 3000K.
CO binding energy (11.2 eV) is sufficiently high to prevent it is broken.

CO influences tremendously the chemistry of dust condensation

O-rich stars (C/O<1)



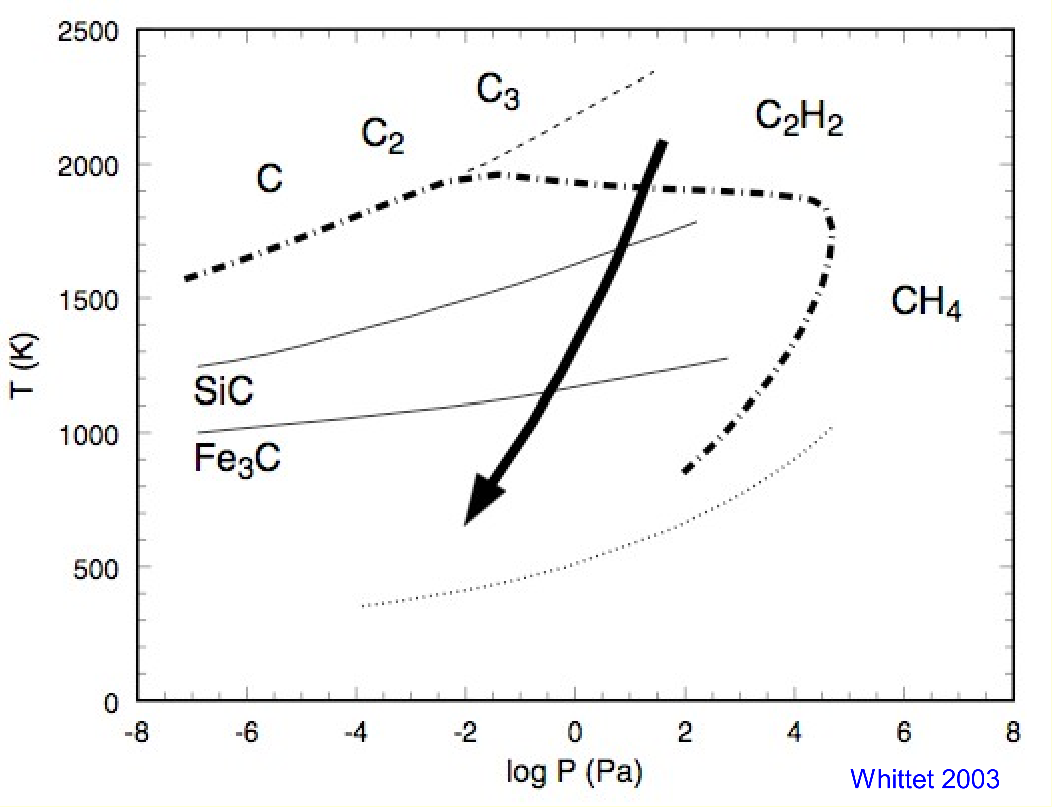
CO is stable everywhere

All the Carbon is locked

Temperature-Pressure phase diagram illustrating stability zones for major solids in O-rich star.

Condensation occurs at T=1200-800 K starting with nucleation and growth of SiO clusters

C-rich stars (C/O>1)

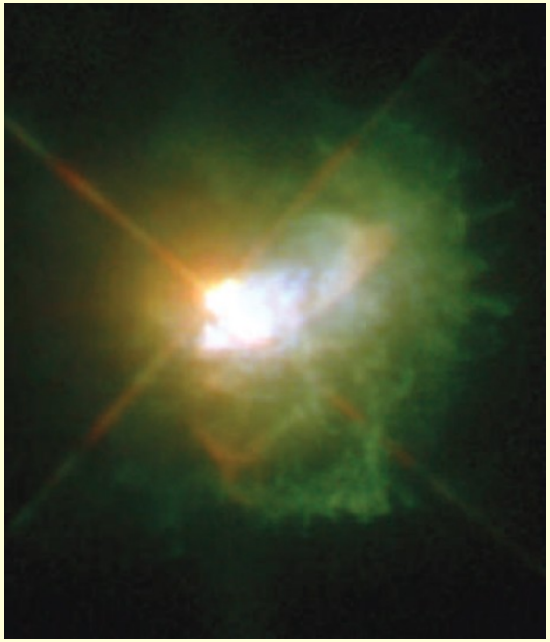


CO is stable everywhere

All the Oxygen is locked

Temperature-Pressure phase diagram illustrating stability zones for major solids in C-rich star.

News on stellar chemistry



VY Canis Majoris Supergiant 25 $M_{\odot}$
3,000K; masso loss rate 2 10^{-4} $M_{\odot}$/yr
(Ziurys *et al. Nature* 2007)

Colour composite picture VY CMa O-rich evolved star with unexpected richness in molecular complexes.

Table 1 | Molecular abundances in VY Canis Majoris

Molecule*	Source radius (arcsec)		Abundance relative to H_2		
	Spherical wind	Red/blue flow	Spherical wind	Red-shifted flow	Blue-shifted flow
CN	6	8.5	2×10^{-8}	3×10^{-8}	1×10^{-8}
CO	6	8.5	5×10^{-5}	6×10^{-5}	8×10^{-5}
CS	0.5	0.7	1×10^{-7}	4×10^{-8}	1×10^{-7}
H_2O	0.1		4×10^{-4} †		
H_2S	6	8.5	7×10^{-8}	2×10^{-7}	1×10^{-7}
HCN	3	3.5	8×10^{-5}	4×10^{-5}	4×10^{-5}
HCO^+	6	8.5	2×10^{-8}	2×10^{-8}	2×10^{-8}
HNC		0.7		2×10^{-8}	2×10^{-8}
NaCl	0.25		8×10^{-9}		
NH_3				4×10^{-6} ‡	4×10^{-6} ‡
NS		8.5		1×10^{-8}	6×10^{-9}
OH				maser	maser
PN	0.5		4×10^{-8}		
SiO	6		$\sim 1 \times 10^{-5}$		
SiS	0.5	0.7	7×10^{-6}	2×10^{-6}	7×10^{-7}
SO		8.5		5×10^{-8}	4×10^{-8}
SO_2		8.5		4×10^{-7}	3×10^{-7}

Abundances are relative to H_2. Abundances and source sizes were derived by modelling the line profiles, assuming an appropriate geometry and mass loss rate. In almost all cases, at least two transitions were simultaneously fitted to establish abundances. Collisional excitation was assumed. See Supplementary Information for details.
* Bold denotes first time observed towards VY CMa.
† Ref. 28.
‡ Ref. 29.

[1]NASA Astrobiology Institute, [2]Department of Astronomy/Steward Observatory, [3]Arizona Radio Observatory, University of Arizona, 933 North Cherry Avenue, [4]Department of Chemistry, University of Arizona, 1306 East University Boulevard, Tucson, Arizona 85721, USA.

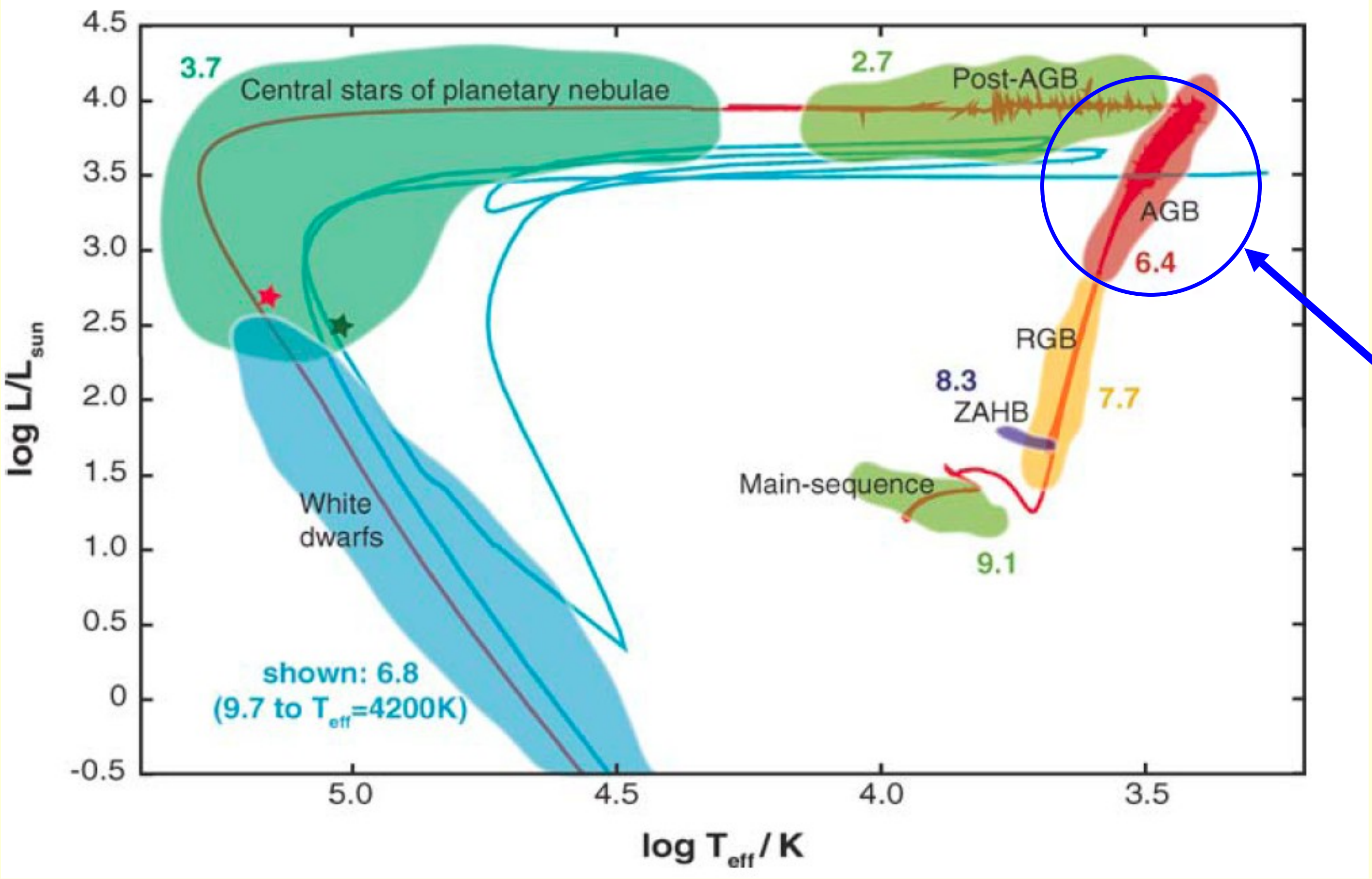
There is much more to be learnt about the use of old stars as laboratories for studying interstellar chemistry.
How do these stars manage to make complex molecules in the extreme low-density environment?
Do physical shocks,radiation or even grain-surface chemistry contribute to the molecular-formation process?
What chemical pathways lead from the simple gas-phase molecules to complex organic solids?
And what roles do these molecules have in the enrichment of the Galaxy and maybe even the early Solar System?

Estimates of mass-loss rates in the Galaxy

in M□ yr-1

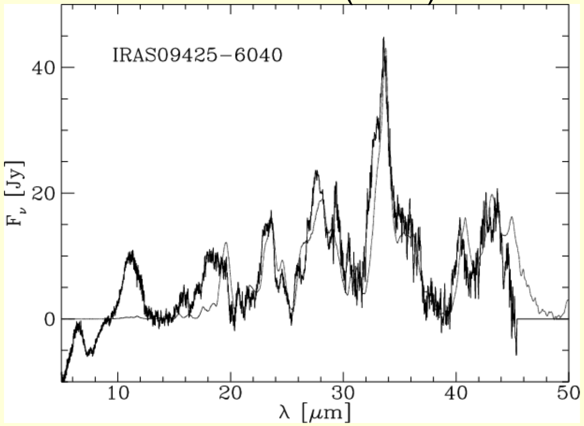
Stellar type	C or O	$[\dot{M}_G]$	$10^3\ [\dot{M}_G]_d$
O-rich AGB	O	0.5	3
C-rich AGB	C	0.5	3
Supernovae	both?	0.2	1 (?)
M giants	O	0.04	0.2
M supergiants	O	0.02	0.1
WC stars	C	0.01	0.06
Novae	both	0.003	0.02

Hertzsprung-Russel diagram of a 2 $M_{\odot}$ evolution track of solar metallicity star (Herwig 2005)



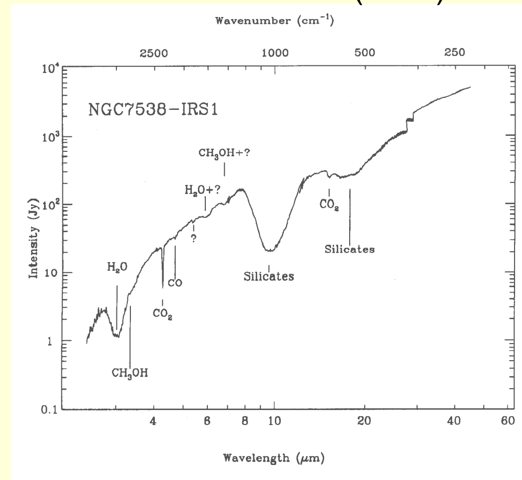
Cristalline silicates in evolved stars

Molster et al. (2002)



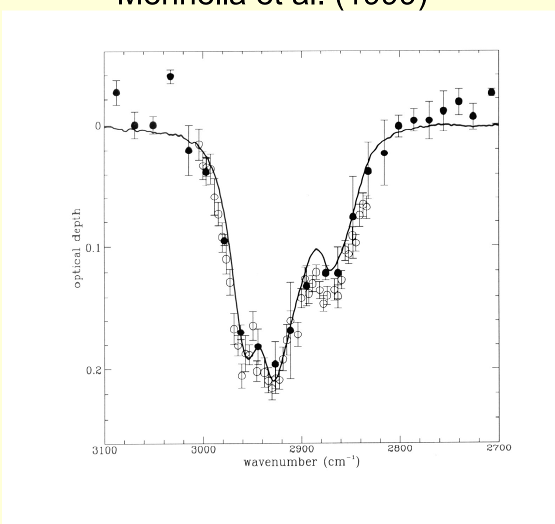
Amorphous silicates in ISM

Strazzulla et al. (1998)



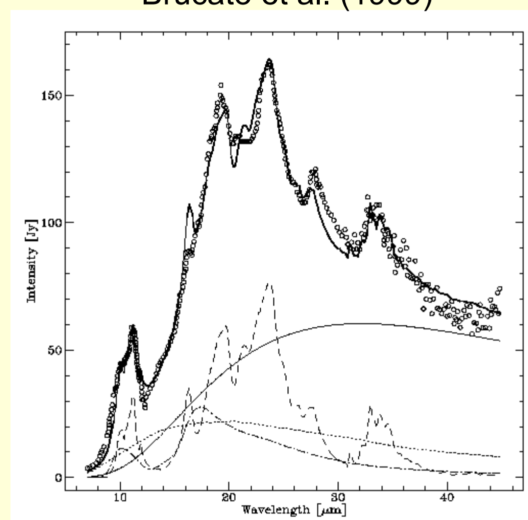
Hydrogenated a-Carbon in ISM

Mennella et al. (1999)



Silicate & a-carbon in comets

Brucato et al. (1999)



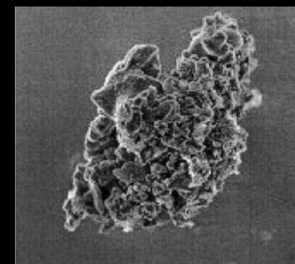
Dust composition *(incomplete)* inventory

Oxides:	SiO_2, MgO, FeO, Fe_2O_3, TiO_2, ZrO_2, Al_xO_y
Carbide:	SiC, Fe_3C
C-based	a-carbon, diamond, graphite
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: $CaMg(CO_3)_2$

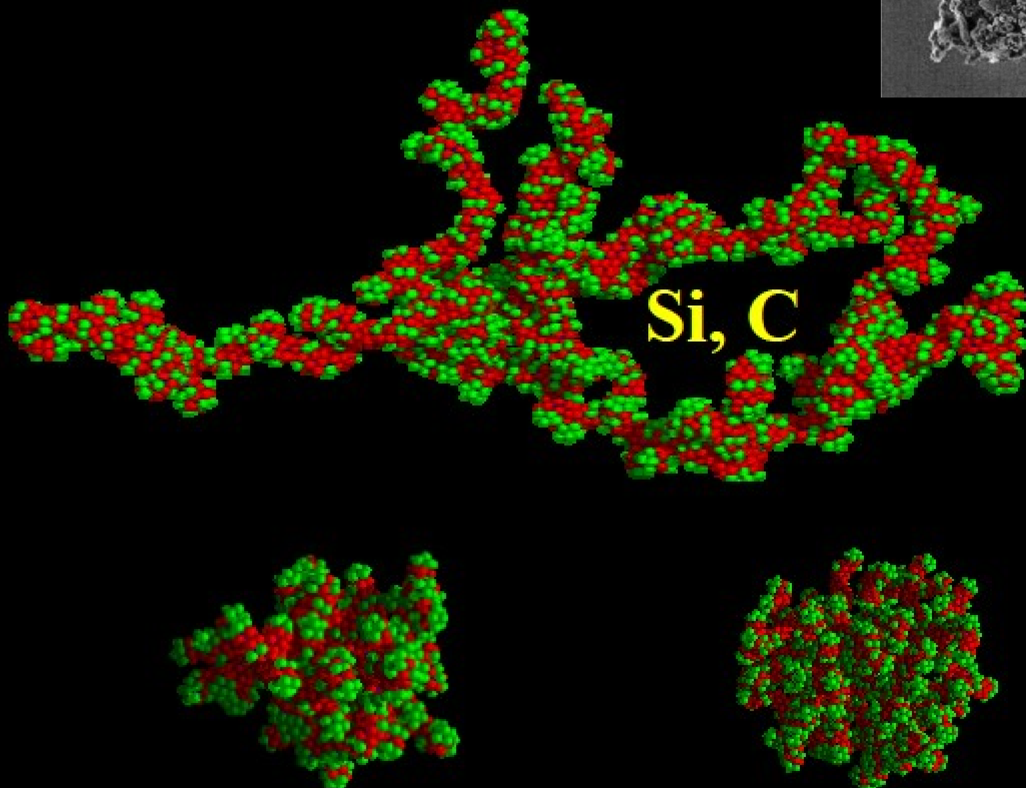
Dust surface reactions and the origin of molecules

Dust particles: the seeds of planets

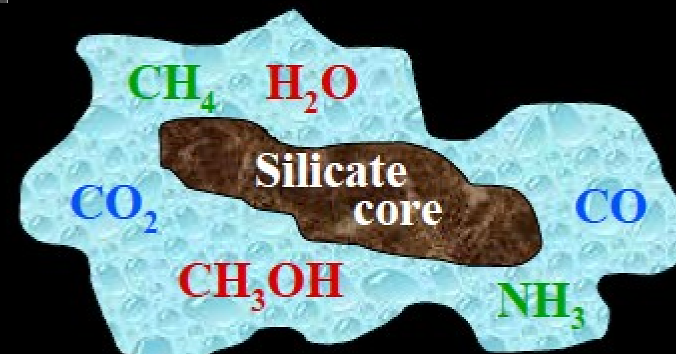
T > 100 K



T < 100 K



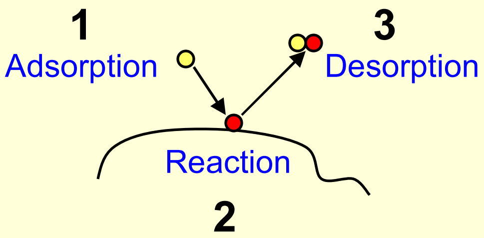
Ice coating ....



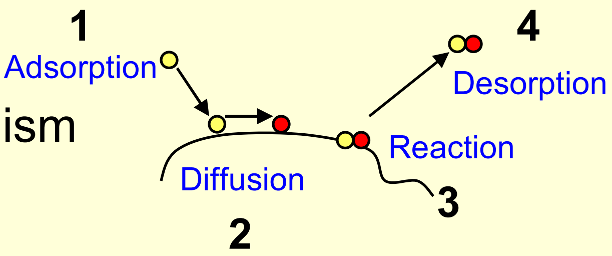
Surface catalysis

The exchange of matter between gas and dust regulate the chemical evolution of the interstellar medium. Surface catalysis allow molecules formation that are not possible in the gas phase. It open new pathways for the chemical evolution of the Galaxy.

Eley-Rideal mechanism



Langmuir-Hinshelwood mechanism



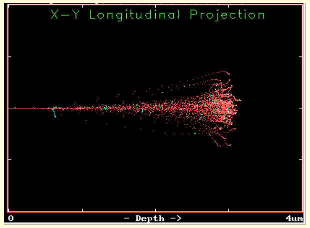
H_2 is the most abundant molecule in ISM. It plays a crucial role in the initial cooling of clouds during gravitational collapse and is involved in most reaction schemes that produce other complex molecules.

$$H + H + \text{grain} \longrightarrow H_2 + \text{grain}$$

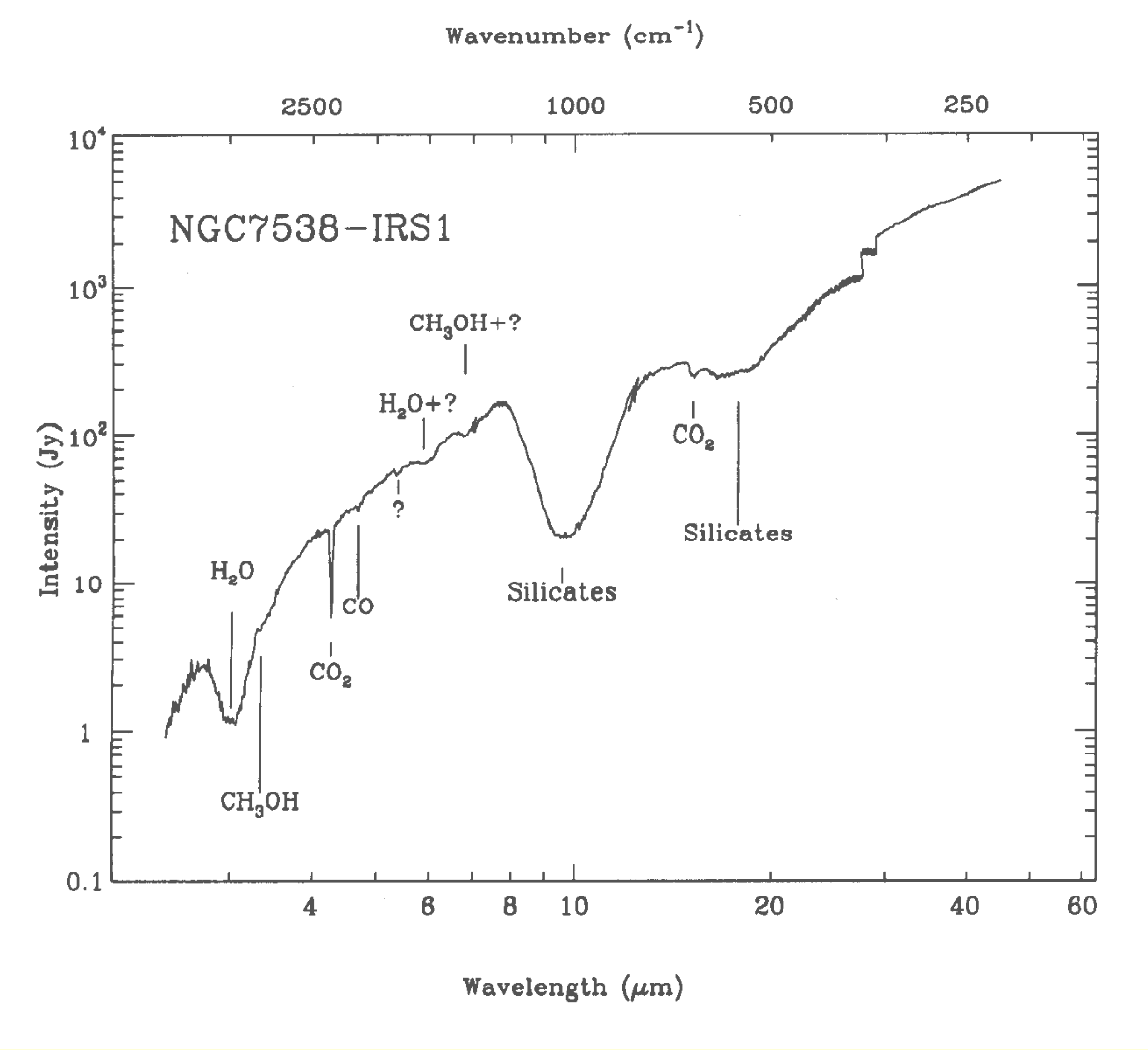
It is widely accepted that H_2 formation takes place on dust grains: Heterogeneous catalysis

Photochemistry

Radiochemistry



ISM chemistry of ices on dust at low temperature

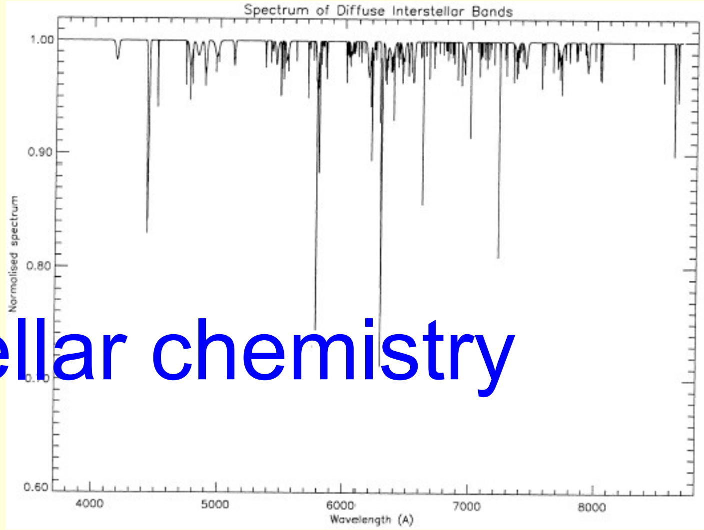


Interstellar & circumstellar chemistry

Molecules

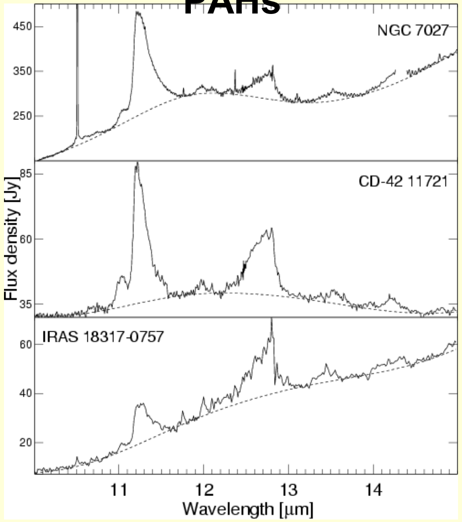
Number of atoms							
2	3	4	5	6	7	8	≥ 9
Interstellar inorganic molecules (22)							
H_2	H_2O	NH_3					
OH	H_2S	H_3O^+					
SO	SO_2						
SiO	HNO						
SiS	NH_2						
NH	N_2H^+						
NO	N_2O						
NS	H_3^+						
PN							
HCl							
SO^+							
HF							
Interstellar organic molecules (79)							
CH^+	HCN	H_2CO	HC_3N	CH_3OH	HC_5N	$HCOOCH_3$	HC_7N
CH	HNC	H_2CS	C_4H	CH_3CN	CH_3CCH	CH_3C_3N	CH_3OCH_3
CN	HCO	HNCO	CH_2NH	CH_3NC	CH_3NH_2	CH_3COOH	CH_3CH_2OH
CO	OCS	HNCS	CH_2CO	CH_3SH	CH_3CHO	H_2C_6	CH_3CH_2CN
CS	HCO^+	c-C_3H	NH_2CN	NH_2CHO	CH_2CHCN	CH_2OHCHO	CH_3C_4H
C_2	HOC^+	l-C_3H	HOCHO	HC_2CHO	C_6H		CH_3C_5N
CO^+	HCS^+	C_3N	c-C_3H_2	C_5h	c-C_2H_4O		CH_3COCH_3
	C_2H	C_3O	CH_2CN	H_2CCCC	CH_2CHOH		HC_9N
	C_2O	C_3S	H_2CCC	HC_3NH^+			$HC_{11}N$
	C_2S	H_2CN	HCCNC				$OHCH_2CH_2OH$
	CH_2	CH_3	HNCCC				NH_2CH_2COOH
	CO_2	C_2H_2	CH_4				
	C_3	$HOCO^+$	H_2COH^+				
		$HCNH^+$					
Circumstellar molecules (23)							
CP	SiCN	HCCN	C_5	C_2H_4		C_7H	C_8H
SiC	c-SiC_2	c-SiC_3	SiH_4	C_5N			
SiN	NaCN		SiC_4				
NaCl	MgCN						
AlCl	MgNC						
KCl	AlNC						
AlF							
SH							

Diffuse Intertellar Bands



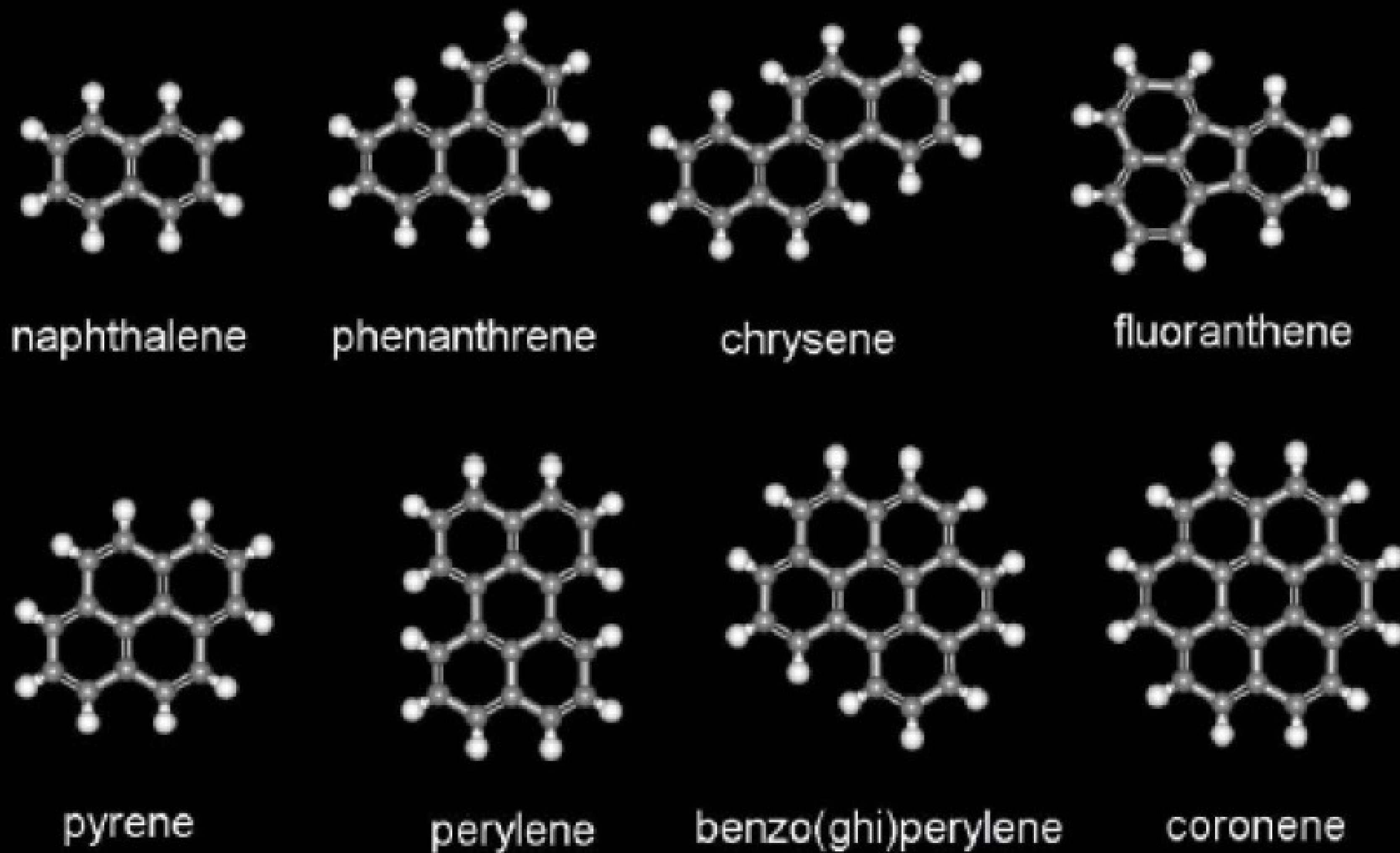
(Jenniskens & Desert1994)

PAHs

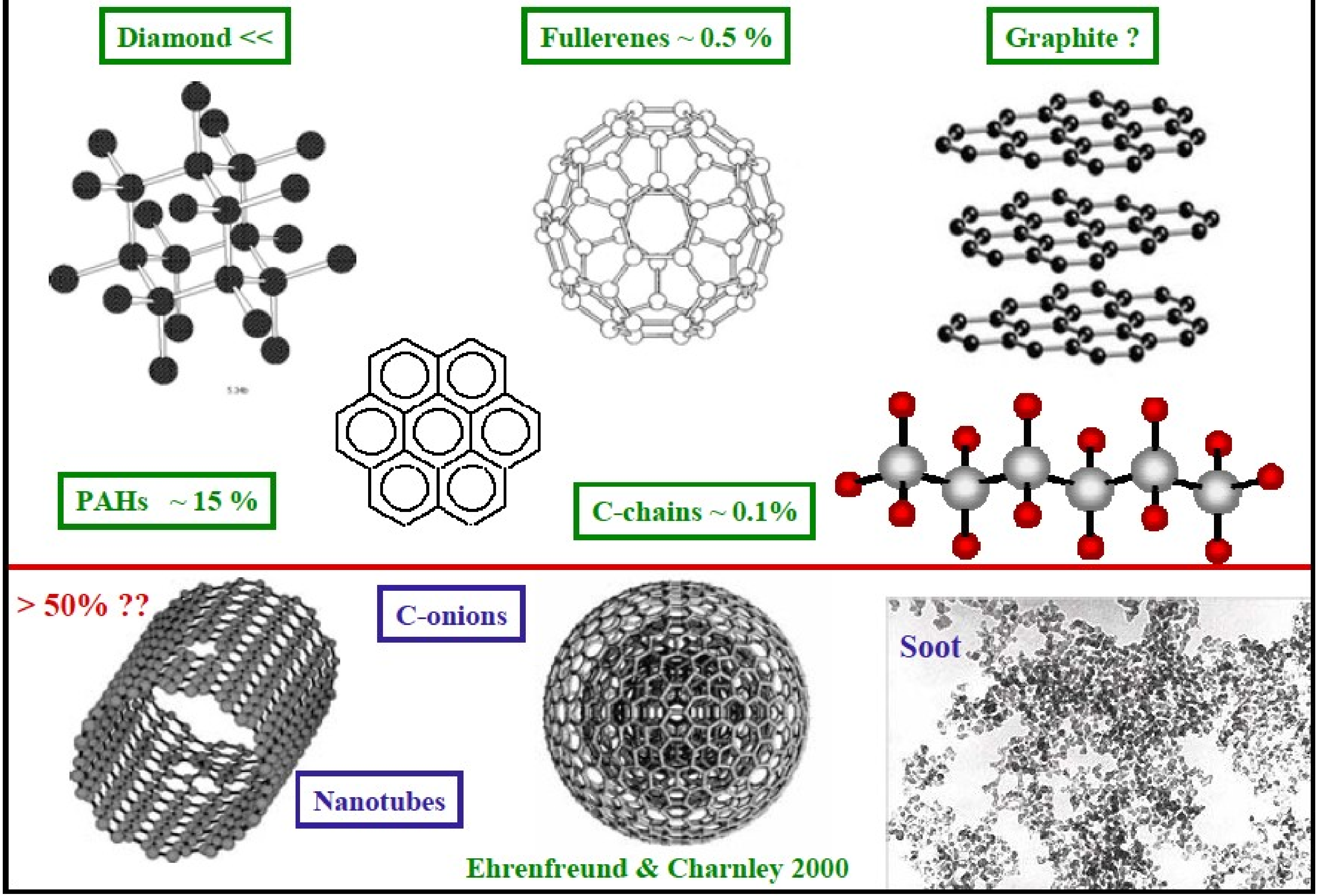


(Hony et al. 2001)

PAHs – Polycyclic Aromatic Hydrocarbons



Large carbonaceous molecules in space



Environment (ice residence time in years)	Ion Processing: Flux, 1 MeV p^+ (eV cm^{-2} s^{-1})	Ion Processing: Energy absorbed (eV cm^{-2} s^{-1})[a]	Ion Processing: Dose (eV $molec^{-1}$)	Photon Processing: Flux (eV cm^{-2} s^{-1})	Photon Processing: Energy absorbed (eV cm^{-2} s^{-1})	Photon Processing: Dose (eV $molec^{-1}$)
Diffuse ISM (10^5 - 10^7)[b]	1 x 10^7	1.2 x 10^4	<1 - 30	9.6 x 10^8 at 10 eV[b]	5 x 10^8 0.02 □m ice	10^4 - 10^6
Dense cloud (10^5 - 10^7)[b]	1 x 10^6	1.2 x 10^3 0.02 ▪m ice	<< 1 - 3	1.4 x 10^4 at 10 eV	1.7 x 10^3 0.02 ▪m ice	< 1 - 4
Protoplanetary nebula (10^5 - 10^7)[c]	1 x 10^6	1.2 x 10^3 0.02 □m ice	<< 1 - 3	2 x 10^5 at 1-10 keV[d]	5 x10^4 0.02 ▪m ice[e]	2 ‘ 240
Oort cloud (4.6 x 10^9)	φ(E)[φ]	φ	~150 (0.1 μ) ~55–5 (1–5 μ) <10 (5–15 μ)	9.6 ξ 10^8 ατ 10 ες	9.6 ξ 10^8 0.1 □μ ιχε	2.7 ξ 10^8
Λαβορατορψ (4.6 ξ 10^{-4})[γ]	8 ξ 10^{16}	2 ξ 10^{15} 1 □μ ιχε	10	2.2 ξ 10^{15} ατ 7.4 ες	2.2 ξ 10^{15} 1 □μ ιχε	10

a The absorbed energy dose from 1 MeV cosmic-ray protons assumes a 300 MeV cm2 g-1 stopping power and an H2O-ice density of 1 g cm-3. Protons deposit energy in both the entrance and exit ice layer of an ice-coated grain.

b 10eV photons = 1200 Å, vacuum UV (UV-C). Jenniskens et al., (1993).

c Typical disk longevities. (Lawson et al., 1996).

d Typical flux at 0.1 pc, 1 keV photons = 12 Å, soft X-rays (Feigelson & Montmerle, 1999).

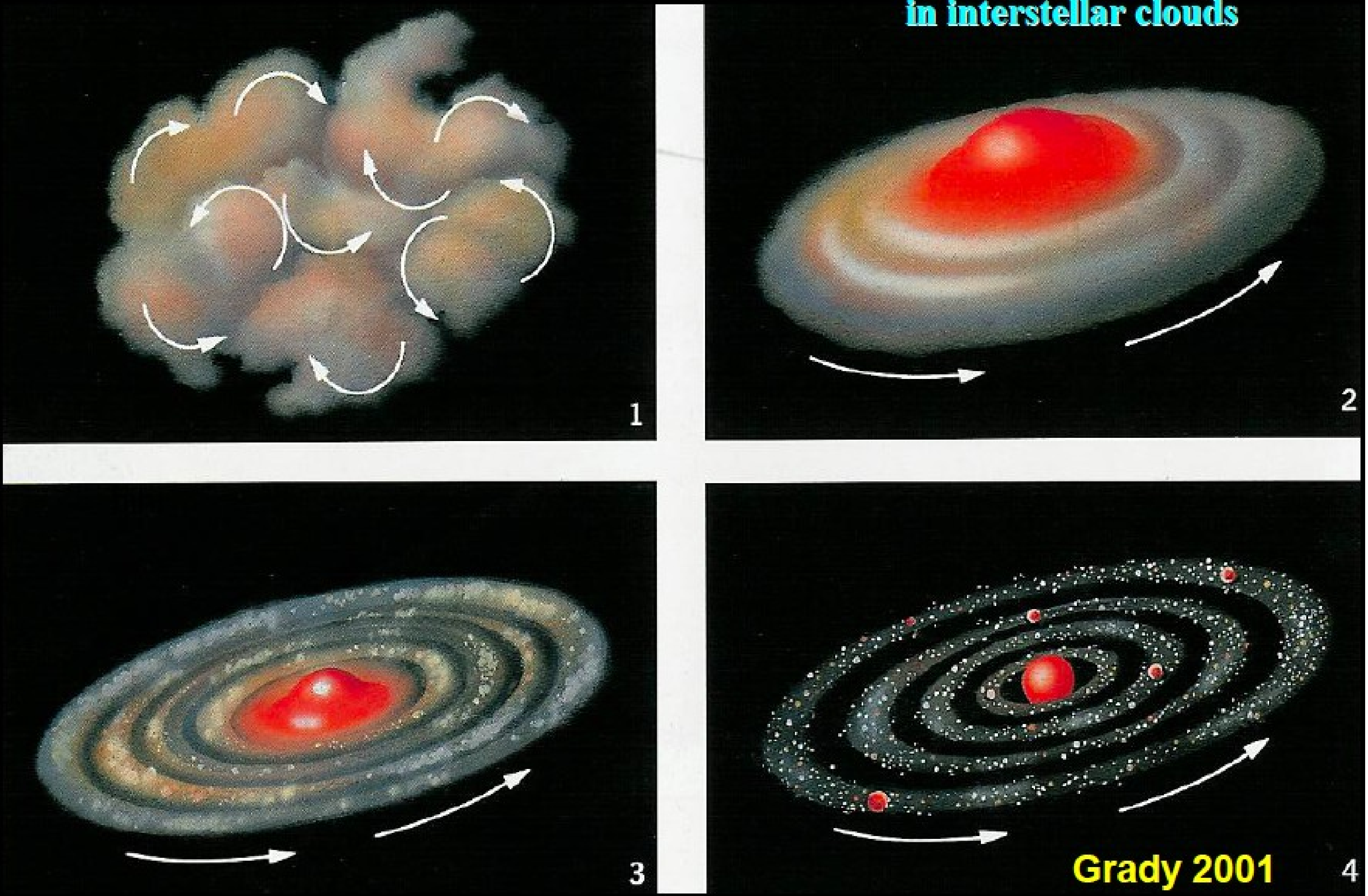
e Absorbed energy dose from 1 keV x-rays assumes a 1 keV electron production in 1 g cm-3 H2O-ice with a 127 MeV cm2 g-1 stopping power.

f An energy dependent flux, j(E), was used to calculate the resulting energy dose at different depths in a comet nucleus for an H2O-ice density of 1 g cm-3. For details see Strazzulla and Johnson (1993) and references therein.

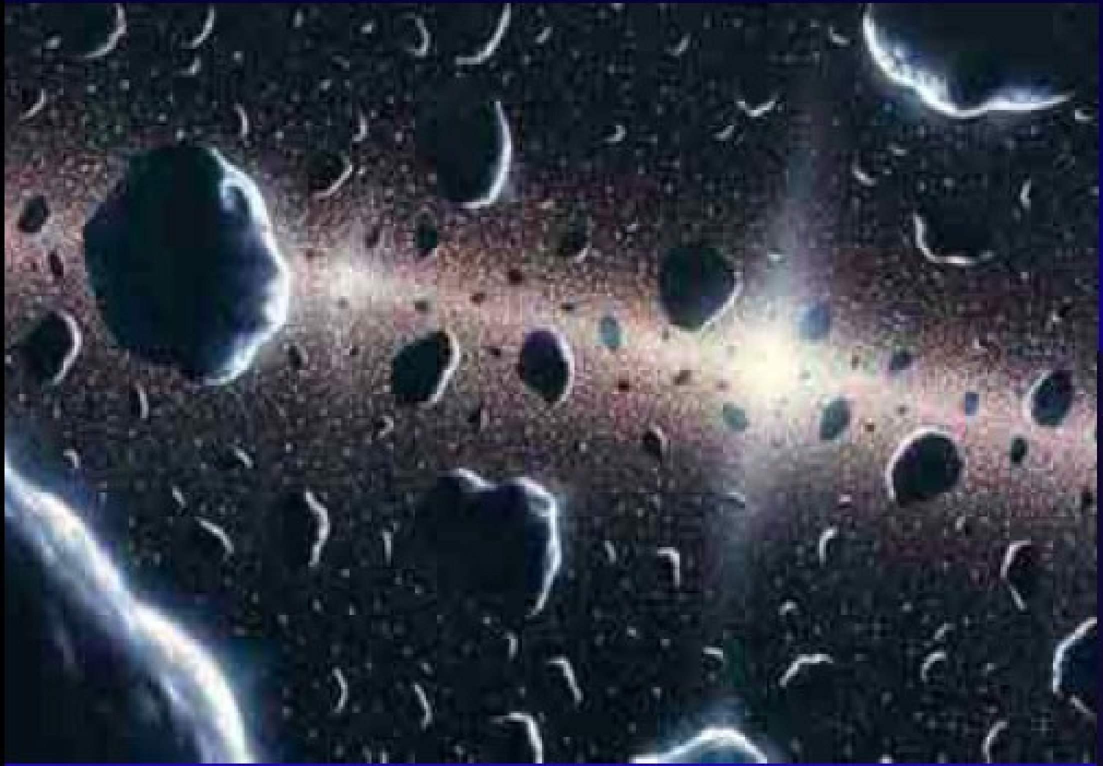
g Typical proton and UV data from the Cosmic Ice Laboratory at NASA Goddard.

❖ Star and planetary formation

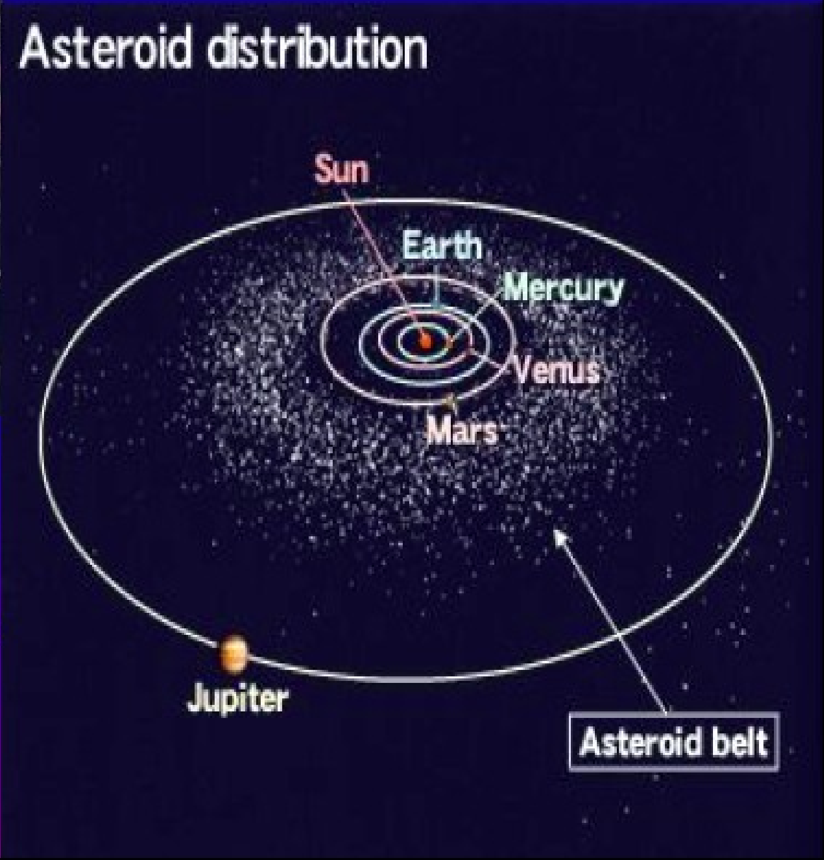
New generations of stars and planets arise from dust and gas in interstellar clouds



Small bodies in our Solar System



Their destiny…..



- ➢ **Impact on planets**
- ➢ **Trapped by gravitational interaction**
- ➢ **Ejected out of the Solar System**

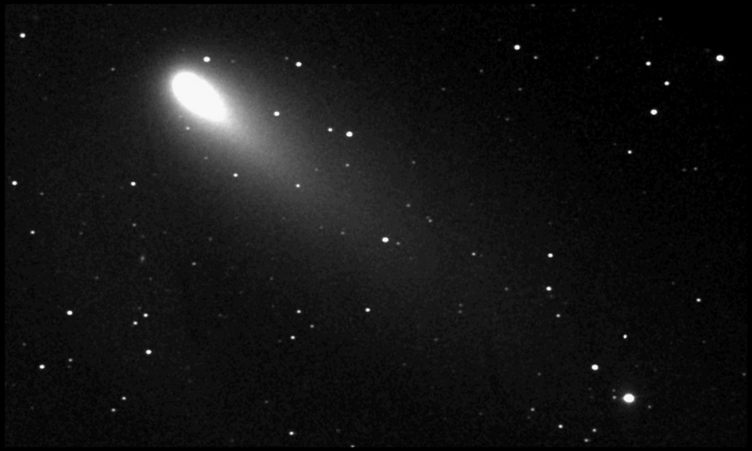
Delivery of ET materials on Earth

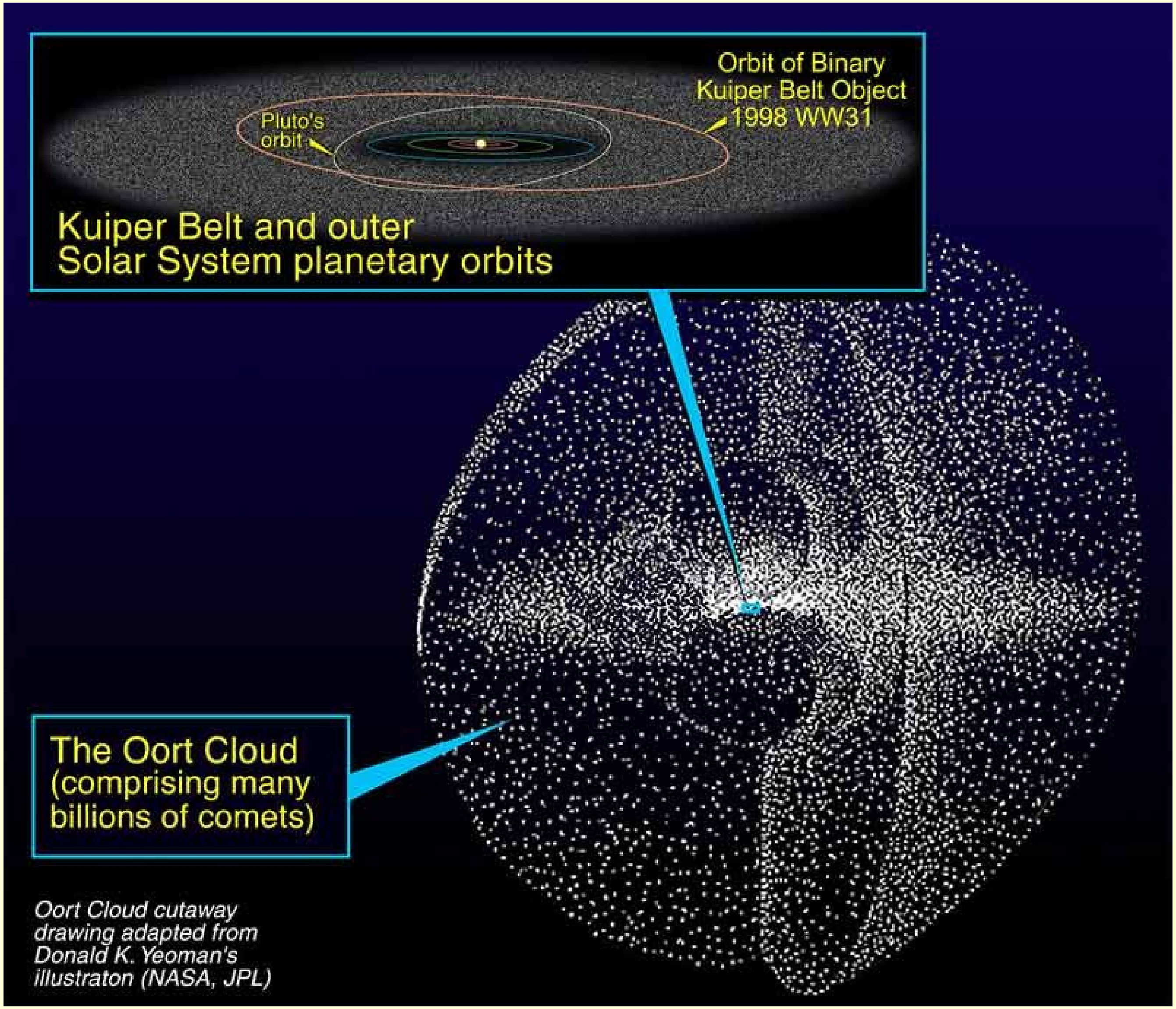
Thickness Covering the Earth

Origin of terrestrial bombardment	Chondritic silicates	Water	Carbon compounds	Atmosphere
Chondrites from asteroids	2.0 km	0.02 km	0.01 km	—
Comets from Jupiter's zone	9.6 km	35 km	13.0 km	1900 bars
Comets from Saturn's zone	1.6 km	5.2 km	2.0 km	140 bars
Comets from Uranus' zone	0.15 km	0.5 km	0.2 km	23 bars
Comets from Neptune's zone	0.06 km	0.2 km	0.08 km	10 bars
Totals	13 km	41 km	15 km	2100 bars
Mass in 10^{25} g	1.9	2.0	1.5	0.2

Delsemme 1997

COMETS



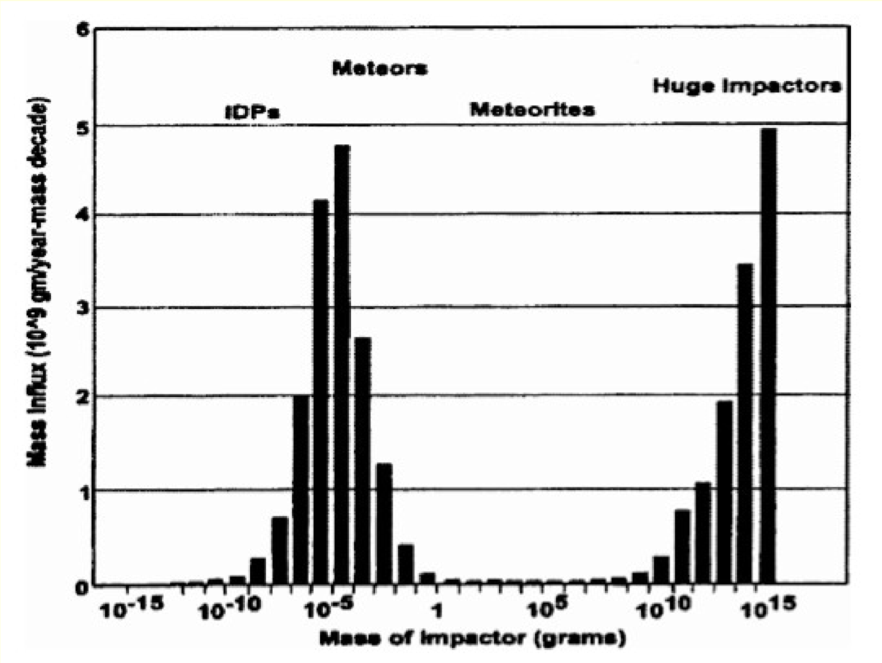

Orbit of Binary
Kuiper Belt Object
1998 WW31
Pluto's
orbit
Kuiper Belt and outer
Solar System planetary orbits
The Oort Cloud
(comprising many
billions of comets)
Oort Cloud cutaway
drawing adapted from
Donald K. Yeoman's
illustraton (NASA, JPL)

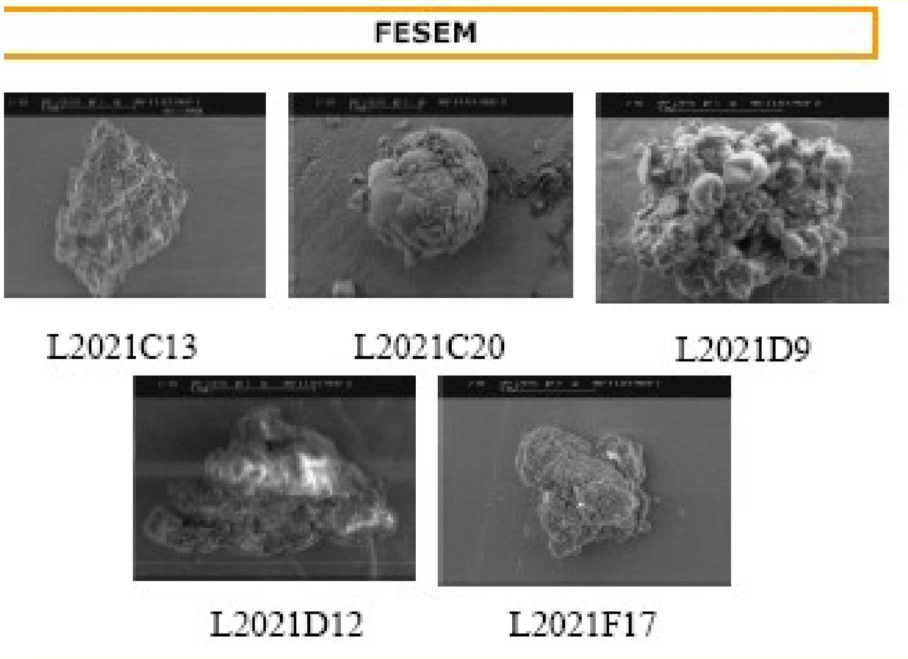
Cometary molecules

Molecule	*$[X]/[H_2O]$*
H_2O	100
HDO	0.06
CO	23
CO_2	20
CH_4	0.6
C_2H_2	0.2
CH_3OH	2.4
H_2CO	1.1
HCOOH	0.08
NH_3	0.7
HCN	0.25
DCN	0.25
HNCO	0.10
HNC	0.25
CH_3CN	0.02
HC_3N	0.02
NH_2CHO	0.015
H_2S	1.5
OCS	0.4
SO	0.3
CS	0.2
SO_2	0.2
H_2CS	0.02
NS	0.02
H_2O_2	<0.03
CH_2CO	<0.032
C_2H_5OH	<0.05
HC_5N	<0.032
Glycine I	<0.5

Source: Bockelee-Morvan and Crovisier (2002).

ET matter, ranging from sub-micron size dust up to objects tens of meters in size, accretes onto the Earth each year.





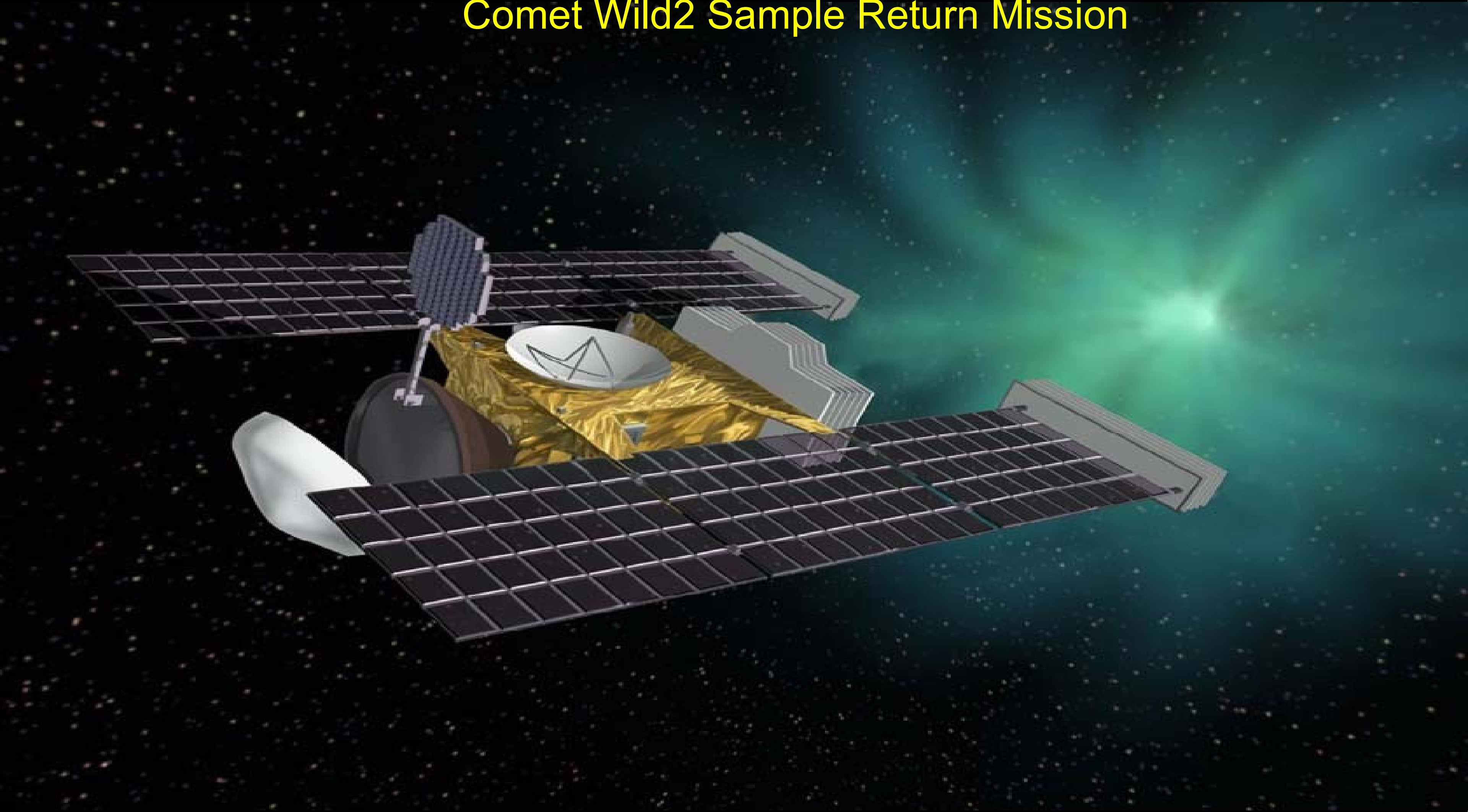
10 μ m size IDPs

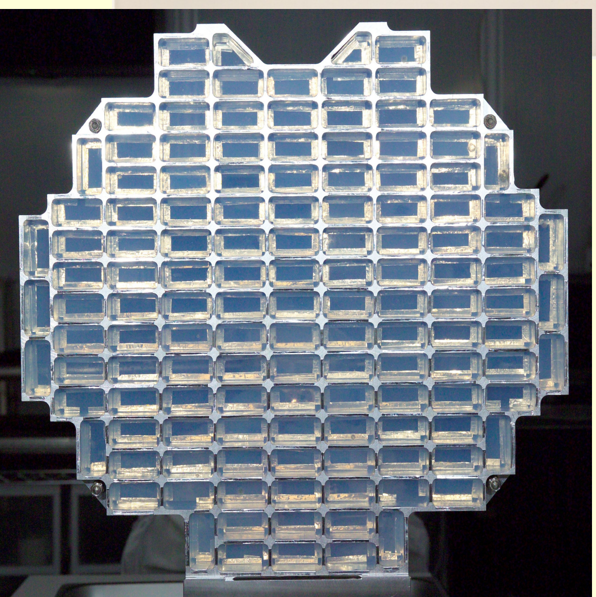
In the present era, **about 30,000 tons/year** of dust accretes onto the Earth.

This dust decelerates by interacting with the Earth atmosphere. Most of the larger dust particles (>100 μ m) vaporize, producing meteor trails in the atmosphere. The smaller particles (5–35 μ m) have a large enough surface area to mass ratio that they radiate away heat rapidly. Many of them survive atmospheric deceleration without being severely heated. These particles, called interplanetary dust particles (IDPs), decelerate at an altitude of 90 km then settle gently on the Earth's surface.

NASA STARDUST MISSION

Comet Wild2 Sample Return Mission



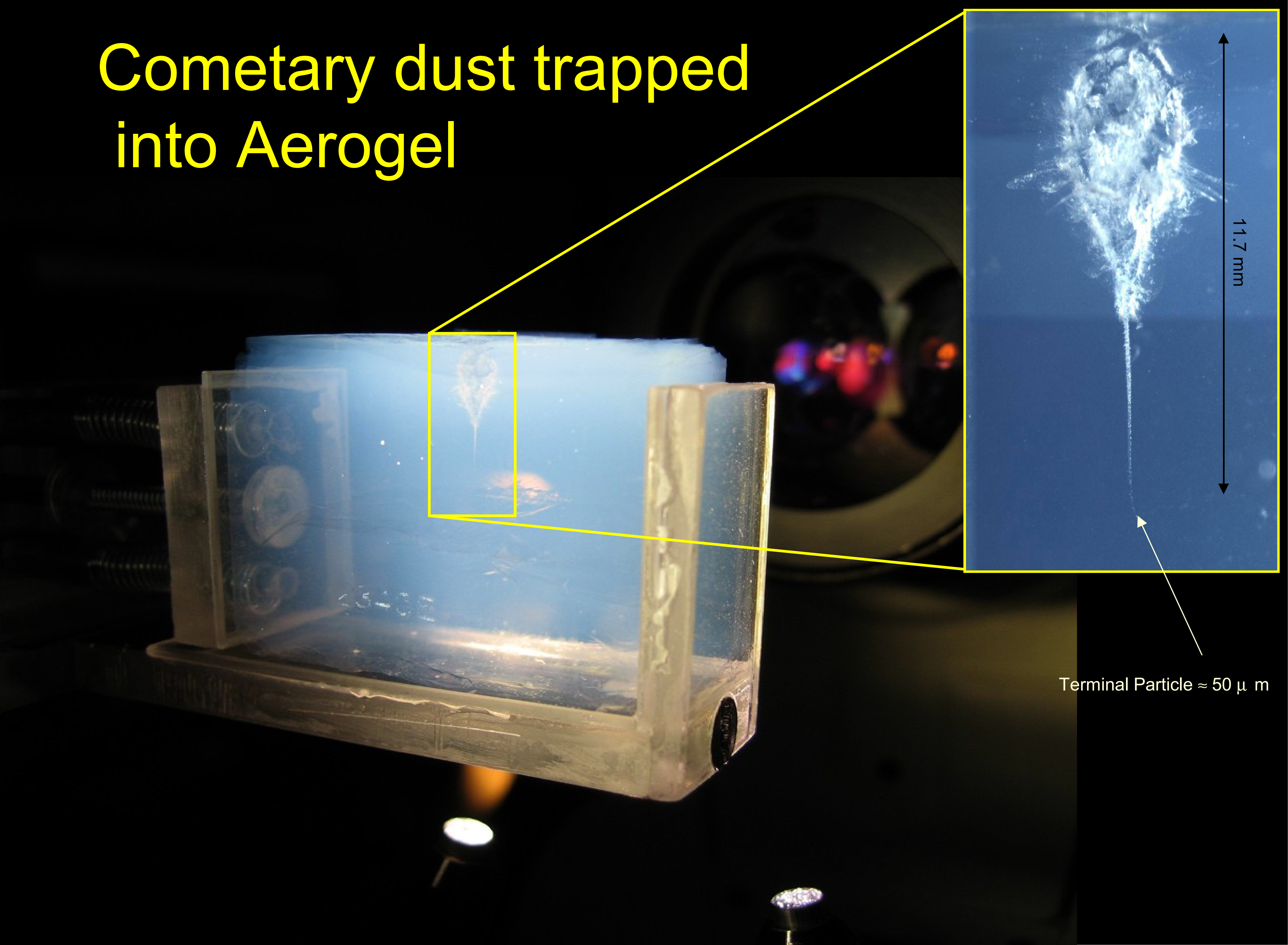


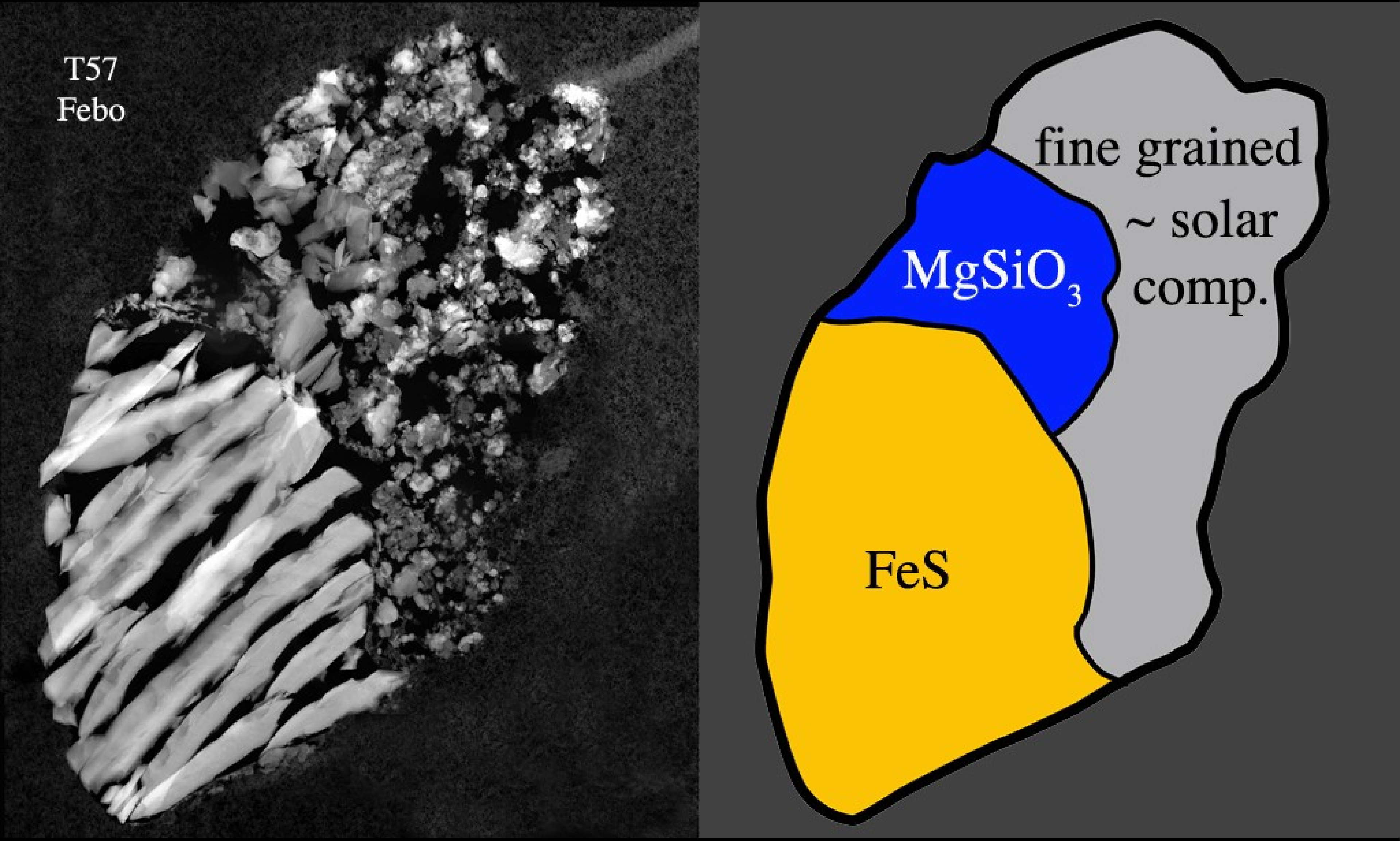
Super-Fantastic Aerogel

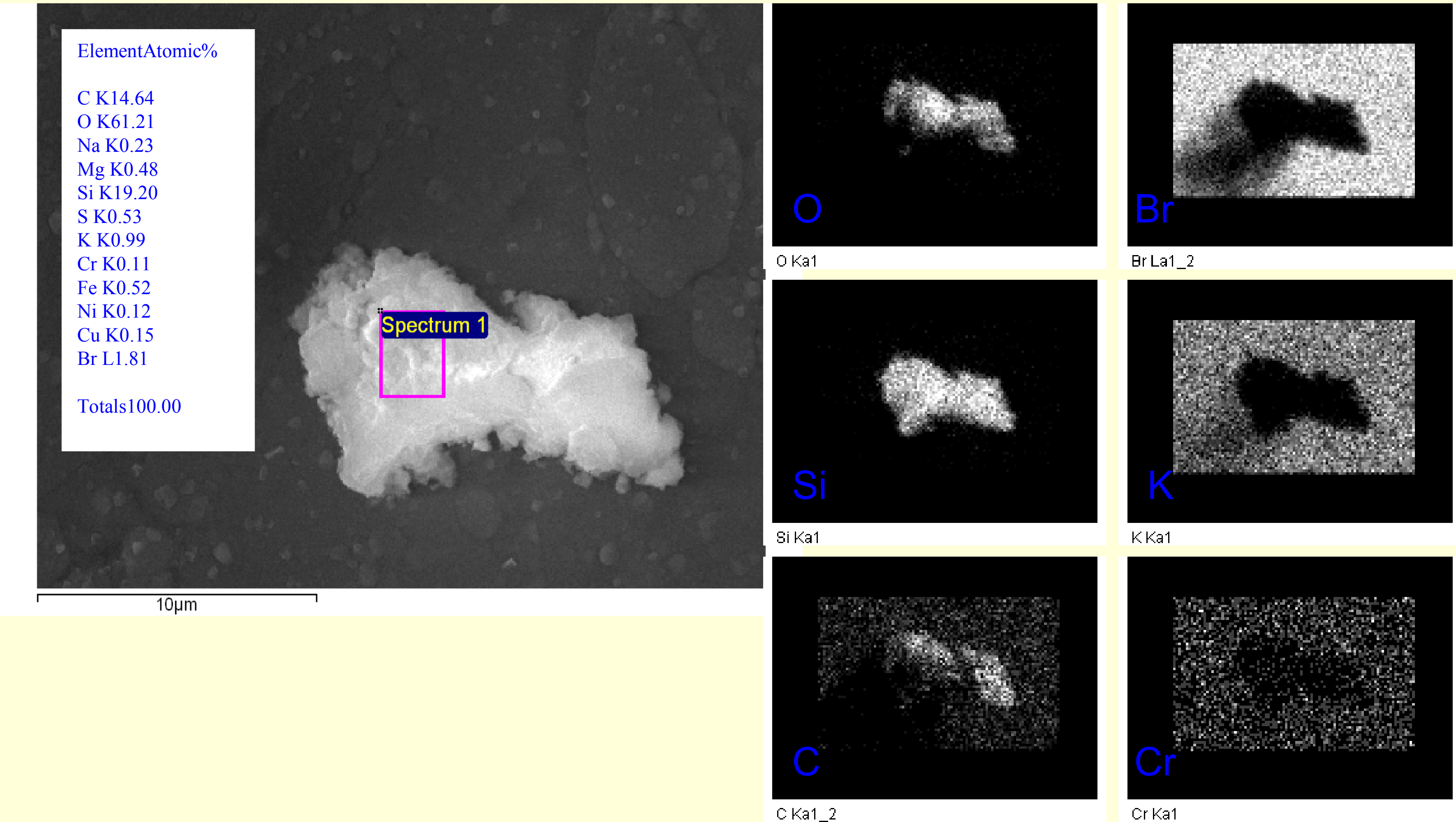
SiO_2 - PURE QUARTZ FOAM

1. The lowest density solid, <1.5 mg/ml
2. The widest density range, $>7x10^2$
3. The smallest pore size, ~ 50nm
4. The highest porosity, >99.9%
5. The lowest thermal conductivity, <16mW/mK
6. The lowest sound speed, <70 m/s
7. The lowest dielectric constant, <1.003
8. The lowest refractive index, <1.0003
9. Lowest loss tangents, $<10^{-4}$
11. The widest compressive modules, $> 7 \times 10^6$
12. Highest acoustic impedance, 10^6 kg/m^{2}s
13. Highest refractive index range, 116%
14. The lowest Young's modules $<10^6$ N/m^2

Cometary dust trapped into Aerogel



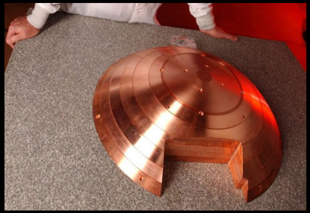

T57
Febo
fine grained
~ solar
comp.
$MgSiO_3$
FeS



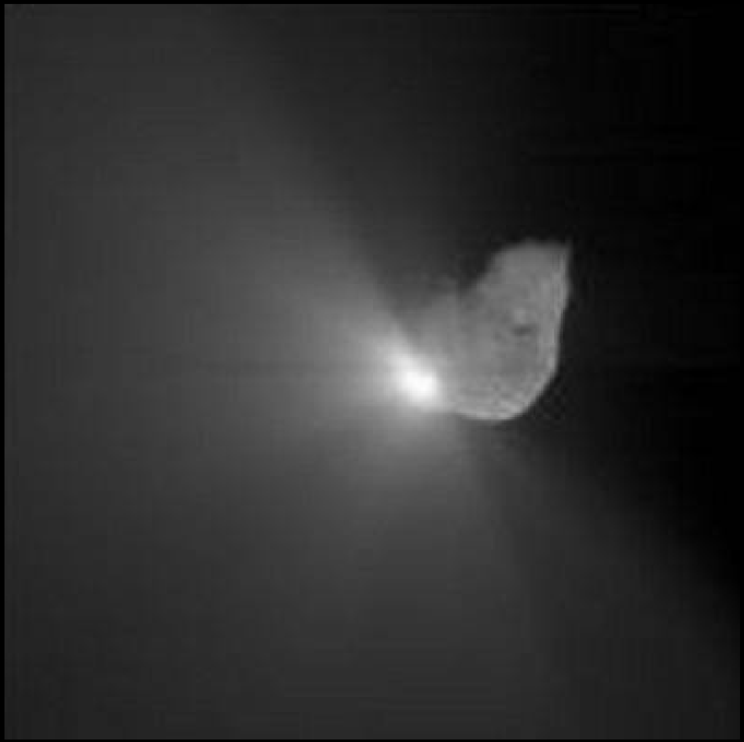
The distributions of Si and O suggest that the particle it is possibly completely covered by aerogel. O seems not present in the lower part of the particle but this could be actually a bias introduced by the fact that the detector (up right) is shadowed by the particle. Same effect in K and Br maps (bottom left). Cr, with which the substrate is coated, is present also within the particle. Carbon is distributed on the whole particle but particularly concentrated in the two areas bottom right and up left.

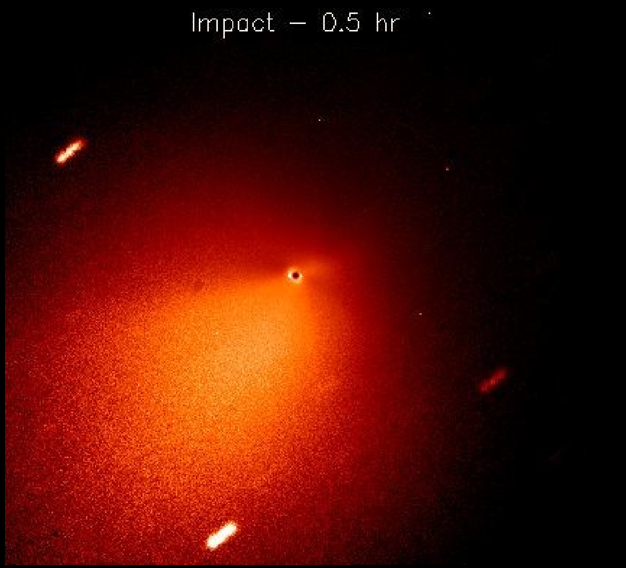
NASA DEEP IMPACT

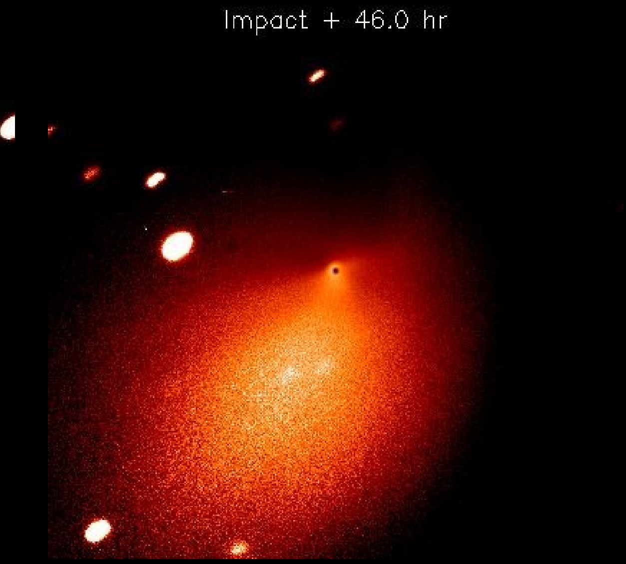
Comet 9P/Tempel 1



350 kg Cupper projectile

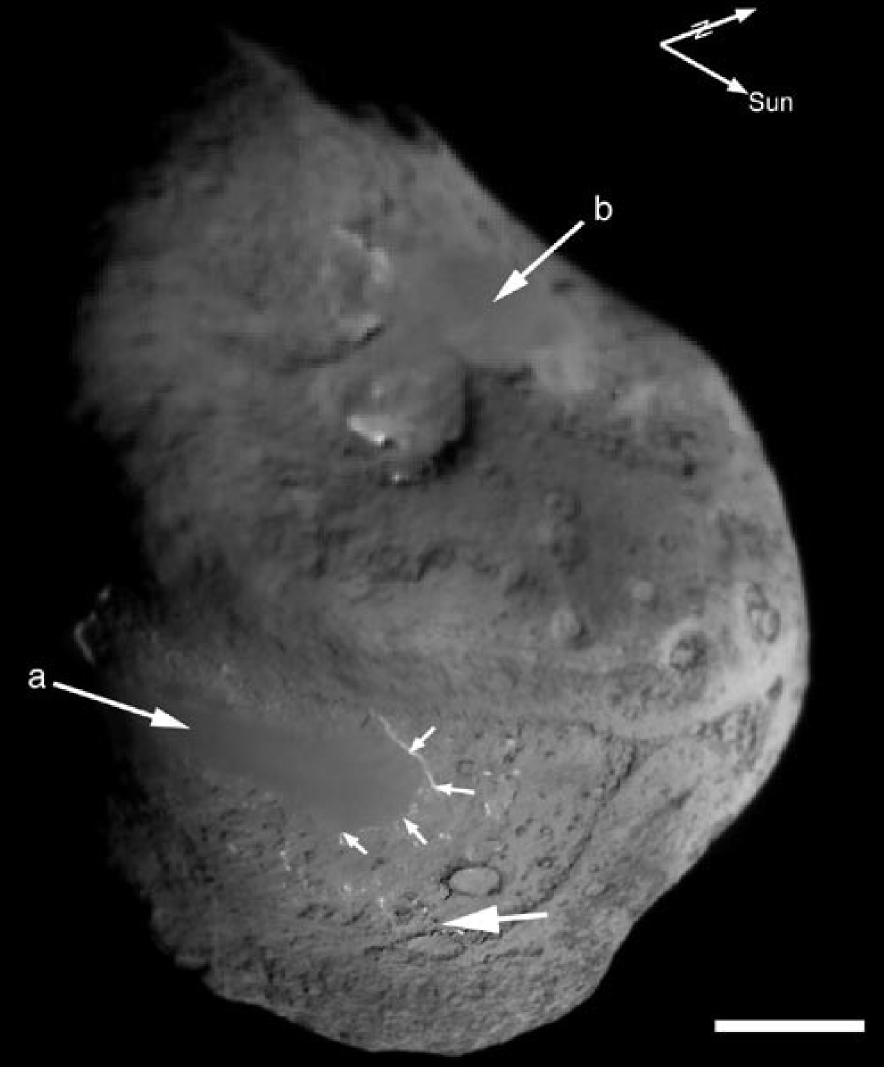






Wild 2

Tempel 1



Tempel 1 (Deep Impact/Spitzer) compared with Wild 2 (Stardust)

Mineral	Tempel 1* Weighted surface area (%)	Wild 2 (>1%?)
1 Ferrosilite [$FeSiO_3$]	33	no
2 Forsterite [Mg_2SiO_4]	31	yes
3 Amorphous Olivine [$(Mg,Fe)_2SiO_4$]	17	no
4 Niningerite [Mg,Fe)S	15	no
5 Smectite nontronite (hydrated silicate)	14	no
6 Diopside [$CaMgSi_20_6$]	12	no
7 Orthoenstatite [$MgSiO_3$]	10	no
8 Fayalite [Fe_2SiO_4]	9	no
9 Siderite [$FeCO_3$]	5	no
10 Amorphous pyroxene [$(Mg,Fe)SiO_3$]	4	no
11 Magnesite [$MgCO_3$]	3	no

Lisse et al 2006

Wild 2 mineralogy ≠ Tempel 1

- ***Wild 2 - Sample analysis***

  Abundant high temperature minerals that condense at or above 1400K.

  Presolar & nebular materials.

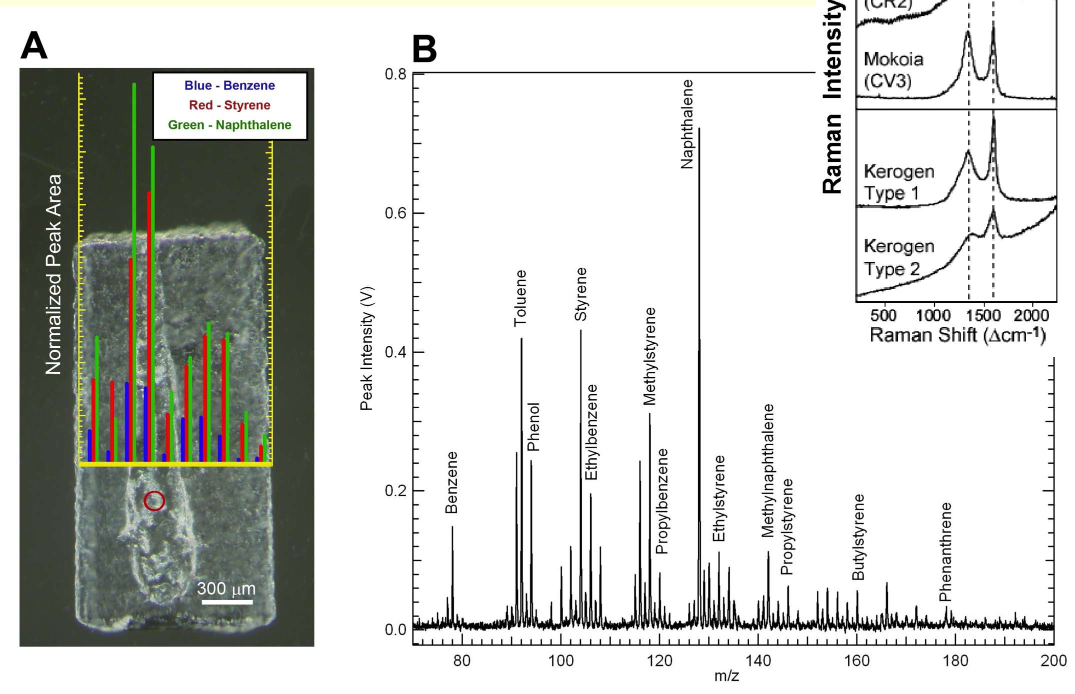
  No hydrothermal alteration products.

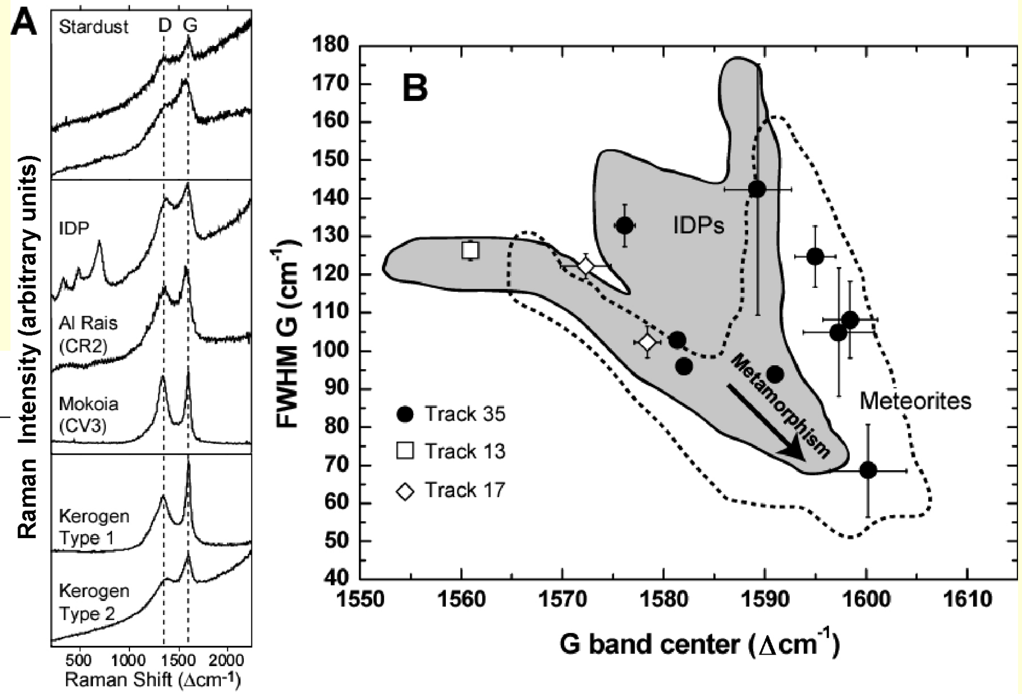
- ***Tempel 1- IR spectra***

  Hydrothermal alteration products (hydrated silicates, carbonates).

  Unusual minerals that rarely occur in primitive SS materials.

Organics in Stardust





Many particles tracks show simpler distributions of light PAHs. Similar distributions can be made by high laser intensity shots on aerogel alone, so some of these molecules in these simpler distributions may have been produced during the impact process.

Raman D and G band parameters span the range observed in meteorites and IDPs.

It is not clear how much this range reflects ‘metamorphic’ changes and how much reflects impact alteration.

The presence of Stardust points in the upper left indicates that at least some of the cometary organics are very primitive and were captured with relatively little alteration

STARDUST Mission tells us:

10% or possibly more of the comet’s mass was transported outward from the inner regions of the solar nebula as particles larger than a micron.

The solar nebula may not have been well mixed, but the Stardust mission results show that there was abundant transport of solids on the largest spatial scales.

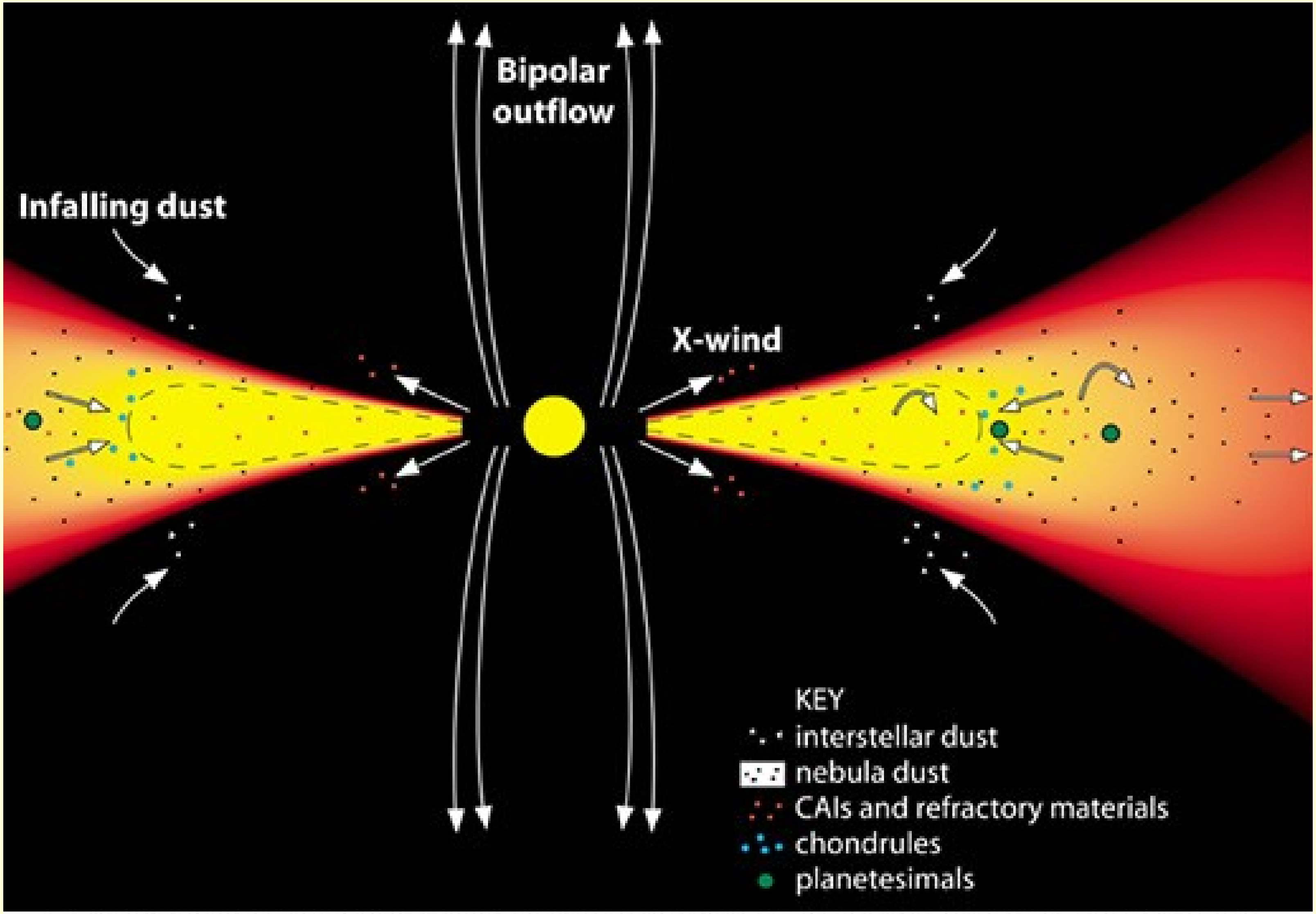
The presence of high O and N contents and the high ratios of CH_2/CH_3 seen in the infrared data indicate that the Stardust organics are not similar to the organic materials seen in the diffuse ISM

The organic populations detected are distinct from those seen in primitive carbonaceous chondrites and IDPs, but some show similarities to both.

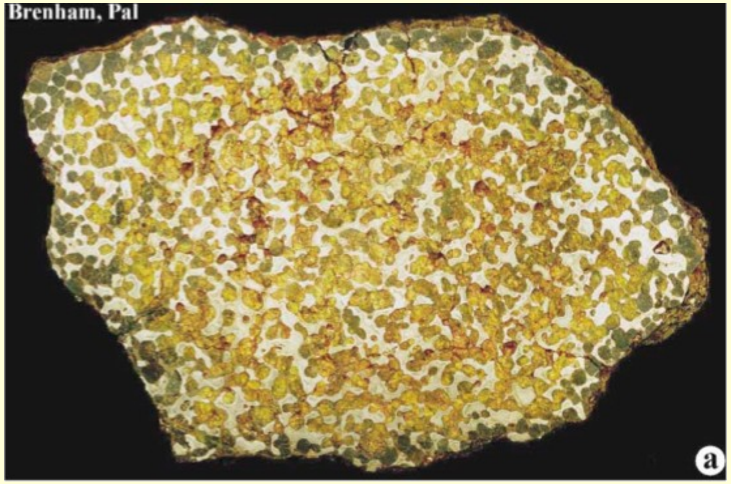
At least some of the organics appear to be relatively labile, as evidenced by their presence beyond the edges of the physical impact tracks in the aerogel.

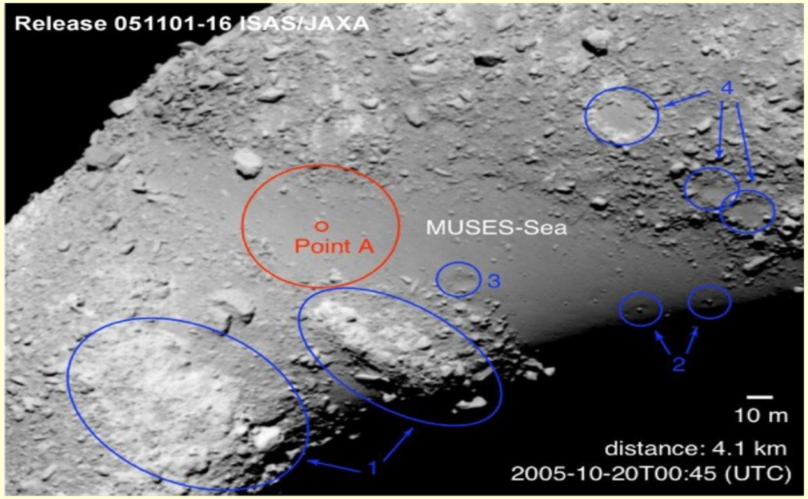
On the whole, the organics appear to be more “primitive” than the bulk of organics in primitive meteorites and richer in non-aromatic materials.

This suggests that the Stardust organics are not the direct result of stellar ejecta or diffuse ISM processes but rather result from dense cloud and/or protosolar nebular processes.



(PSRD graphic by Nancy Hulbirt, based on a conceptual drawing by Edward Scott, Univ. of Hawaii.)



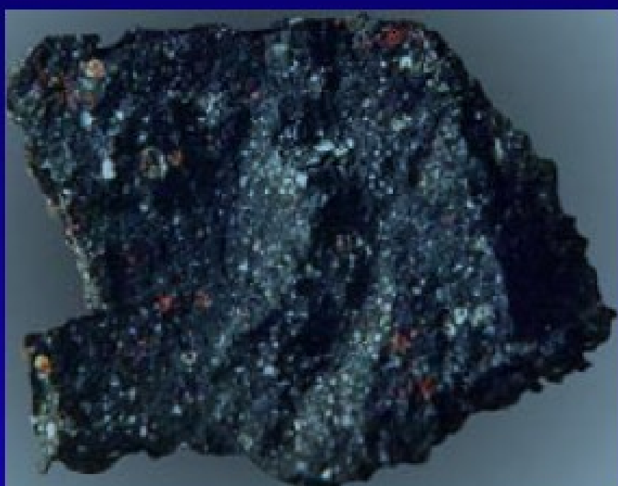


ASTEROIDS & METEORITES

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

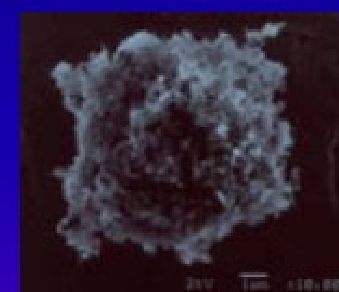
Carbonaceous chondrites – most pristine!



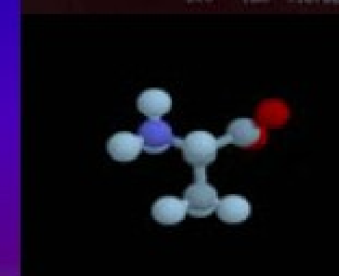
Murchison

Insoluble Carbon-fraction:

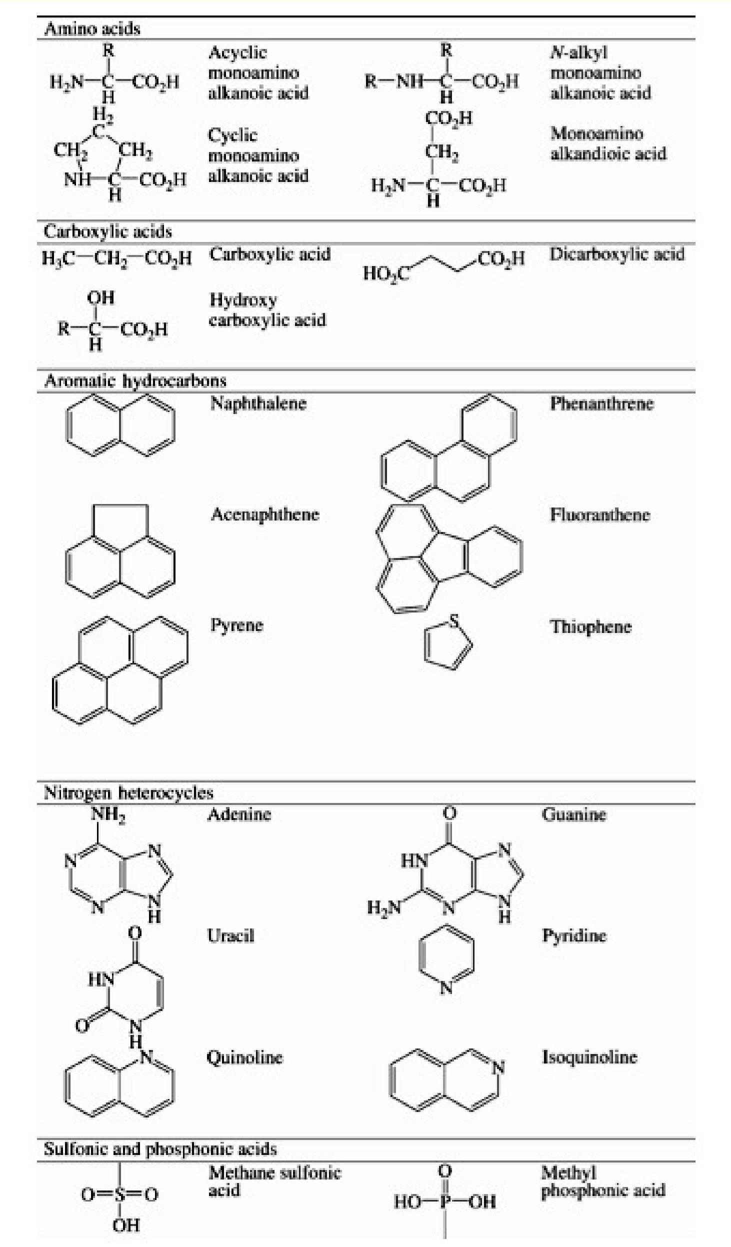
60-80 % aromatic carbon
highly substituted small aromatic moieties branched by aliphatic chains



Volatile fraction:



Extractable classes of organic matter found in carbonaceous chondrite



Carbonaceous chondrites, the most primitive objects of the Solar System, may contain up to 3% of organic matter. They are considered as one of the possible sources of organic material on Earth.

A minor part (10-30%) of the organic matter in the carbonaceous chondrites is made of a complex mixture of soluble molecules, some of which are similar to those found in biochemical systems.

However the major fraction (70-90%) is made of an insoluble macromolecular carbonaceous material, the structure of which is complex and still not fully elucidated.

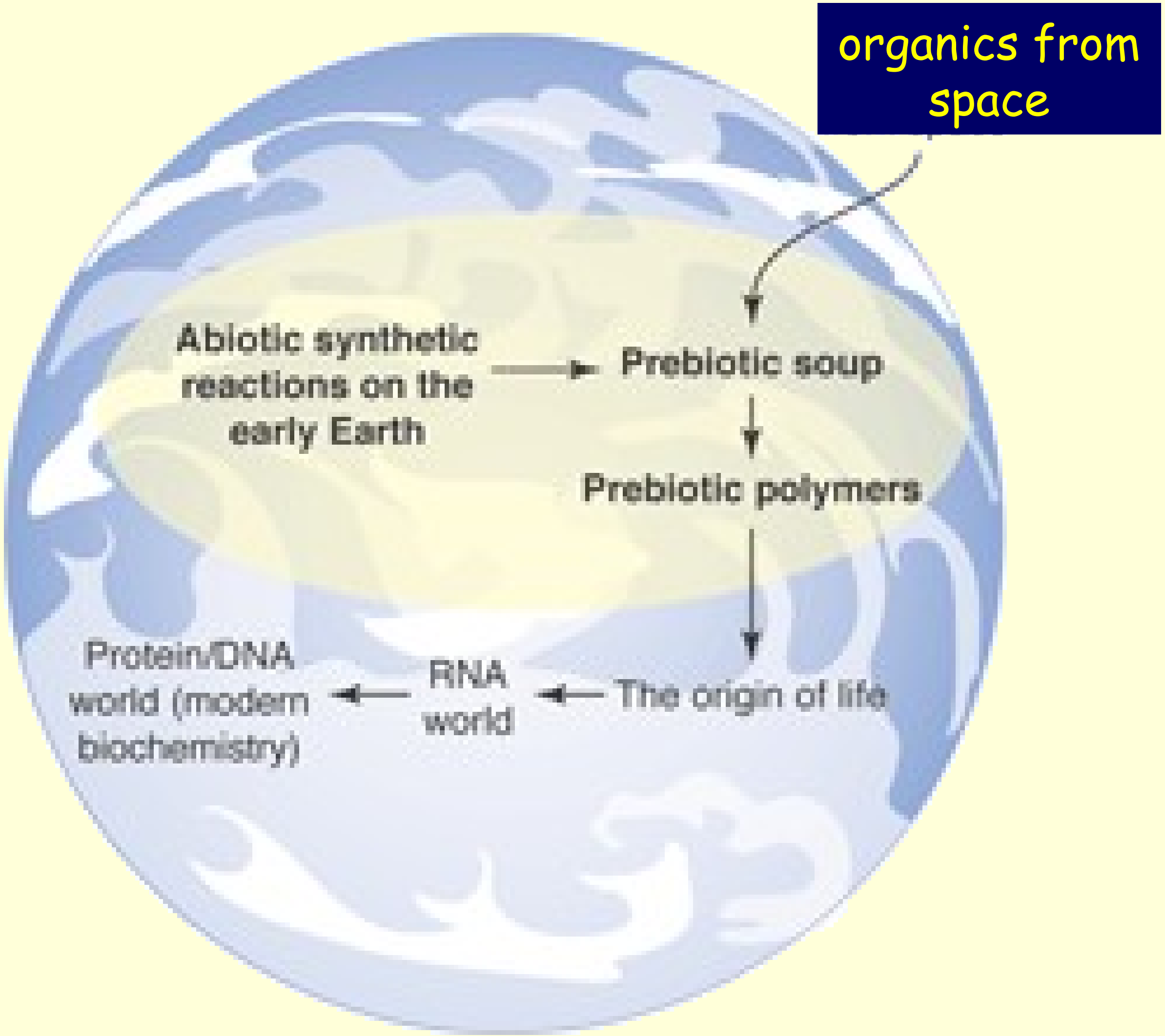
Compounds	*Abundance* (ppm)	*References*
Carbon dioxide	106	1
Carbon monoxide	0.06	1
Methane	0.14	1
Hydrocarbons		
Aliphatic	12–35	2
Aromatic	15–29	3
Carboxylic acids		
Monocarboxylic	332	4,1
Dicarboxylic	25.7	5
α-Hydroxycarboxylic	14.6	6
Amino acids	60	7
Alcohols	11	8
Aldehydes	11	8
Ketones	16	8
Sugars and related compounds	~60	9
Ammonia	19	10
Amines	8	11
Urea	25	12
Basic *N*-heterocycles	0.05–0.5	13
Pyridinecarboxylic acids	>7	14
Dicarboximides	>50	14
Pyrimidines	0.06	15
Purines	1.2	16
Benzothiophenes	0.3	17
Sulfonic acids	67	18
Phosphonic acids	1.5	19

References: 1. Yuen *et al.* (1984), 2. Kvenvolden *et al.* (1970), 3. Pering and Ponnamperuma (1971), 4. Lawless and Yuen (1979), 5. Lawless *et al.* (1974), 6. Peltzer *et al.* (1984), 7. Cronin *et al.* (1988), 8. Jungclaus *et al.* (1976b), 9. Cooper *et al.* (2001), 10. Pizzarello *et al.* (1994), 11. Jungclaus *et al.* (1976a), 12. Hayatsu *et al.* (1975), 13. Stoks and Schwartz (1982), 14. Pizzarello *et al.* (2001), 15. Stoks and Schwartz (1979), 16. Stoks and Schwartz (1981), 17. Shimoyama and Katsumata (2001), 18. Cooper *et al.* (1997), and 19. Cooper *et al.* (1992).

The current accretion rate of unablated carbonaceous matter is estimated to be $\sim 3 \times 10^5$ kg/yr (Anders 1989). If this rate were to remain constant, the timescale to accrete a biomass (i.e. the total mass of organic carbon in the current biosphere, estimated by Chyba et al 1990 to be $\sim 6 \times 10^{14}$ kg) would be ~ 2 Gyr.

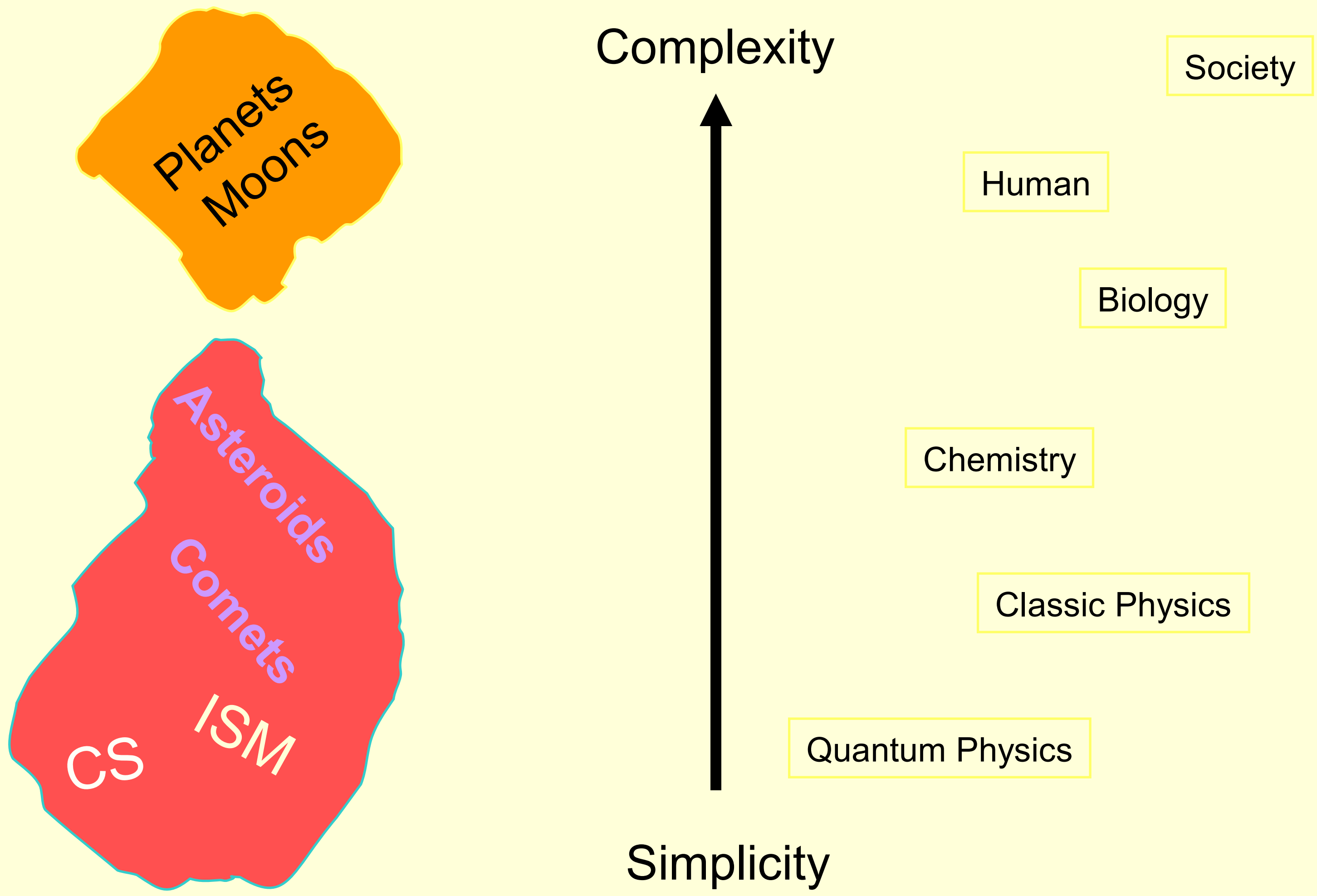
However, it seems reasonable to suppose that the accretion rate would have been much higher at earlier times, during the final stages of planetary formation. Adopting an accretion model based on the lunar cratering record (Chyba and Sagan 1992), the rate 4 Gyr ago could have been $\sim 5 \times 10^7$ kg/yr, or a biomass in only ~ 10 Myr.

Although subject to considerable uncertainty, these simple calculations illustrate that the contribution of exogenous organic matter to the early Earth could well have been substantial.

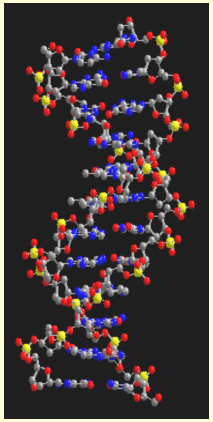


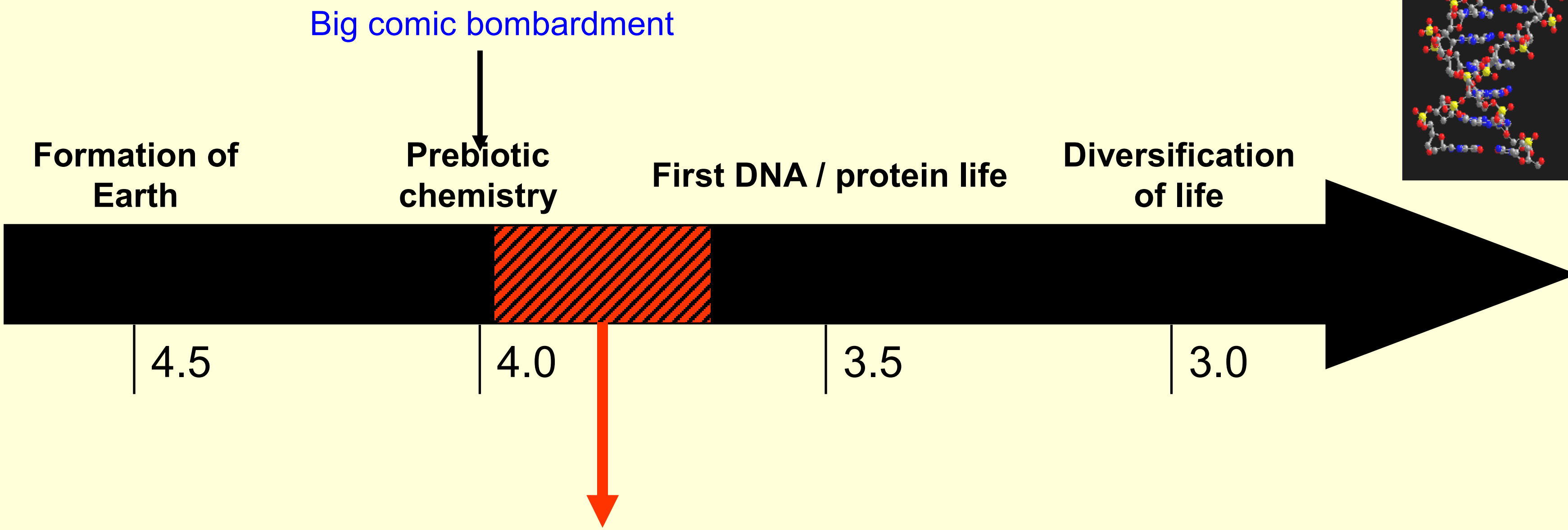
Bada & Lazcano (2002) *Science*

Planets as complex macrosystem

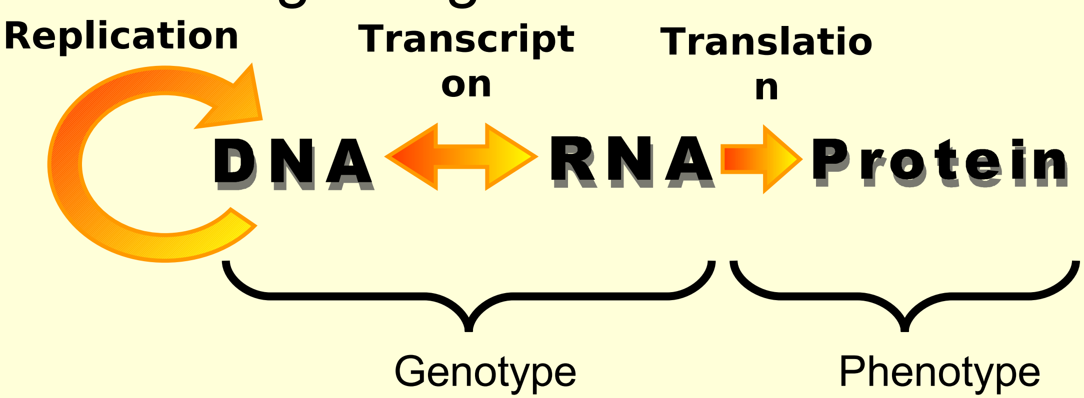


Molecular Evolution





The “appearance” of a nucleic acid-like polymer able to evolve marks the beginning of life



CONCLUSION

The origin of life on Earth is best understood in terms of a sequence of emergent chemical events, each of which added a degree of structure and complexity to the prebiotic world.

While we don’t yet know all the details, there is no compelling evidence to suggest that life’s origin was other than a natural process.