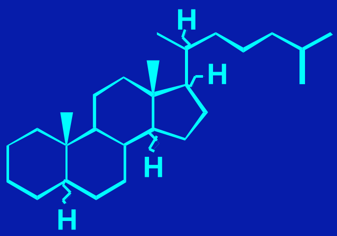
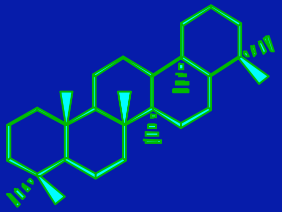
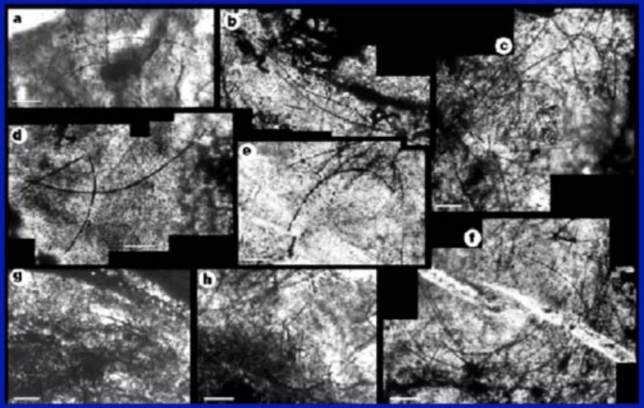
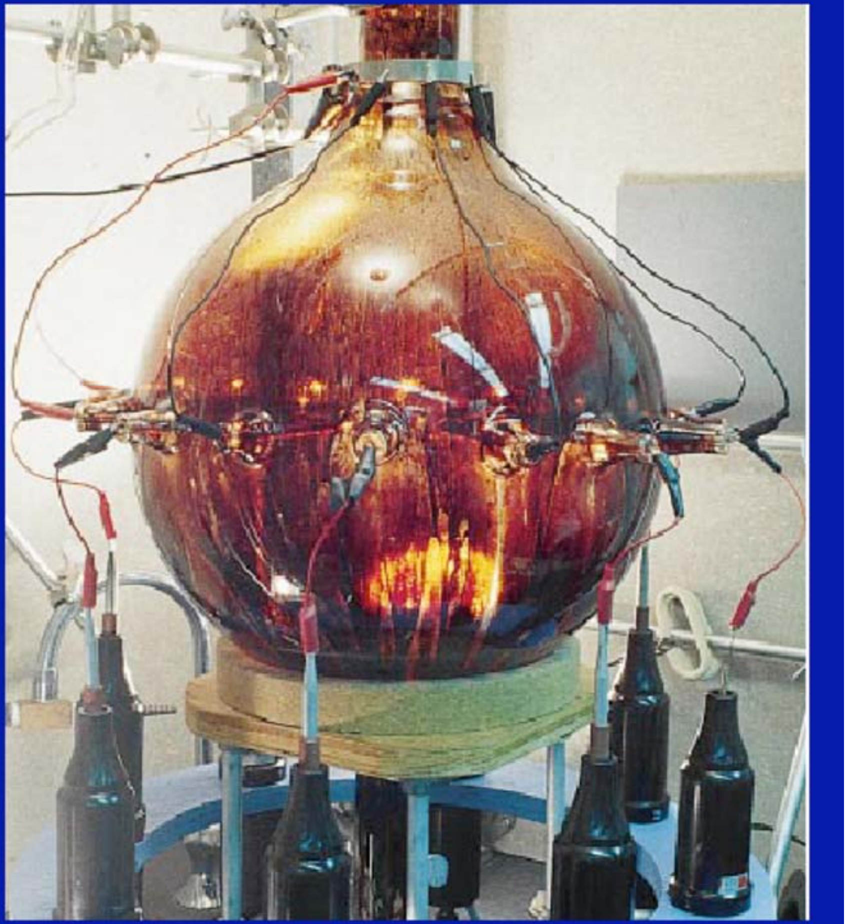
The Origin of Life

OCEAN 355
Lecture Notes #4
Autumn 2008









Theories of the origin of life

"We still have little idea how, when or where life began…. The evidence is circumstantial and can be compared with delving into such records as there are in Massachusetts of the Mayflower, to discern the origins of the English language."

Nisbet & Sleep (2001) "The habitat and nature of early life" *Nature* Vol. 409: 1083-1091.

What is Life?

What Is Life?

The search for extraterrestrial life must begin with the question of what we mean by life. "I'll know it when I see it" is an insufficient answer. Some functional definitions are inadequate: one might identify life as anything that ingests, metabolizes and excretes, but this description applies to my car or to a candle flame. Some more sophisticated definitions—for example, life as recognizable by its departure from thermodynamic equilibrium—fall afoul of the circumstance that much of nature (such as lightning and the ozone layer) is out of equilibrium.

Biochemical definitions—for example, defining life in terms of nucleic acids, proteins and other molecules—are clearly chauvinistic. Would we declare an organism that can do everything a bacterium can dead if it was made of very different molecules? The definition that I like best—life is any system capable of reproduction, mutation and reproduction of its mutations—is impractical to apply when we set down a spacecraft on another world: reproduction may not be done in public, and mutations might be comparatively infrequent.

Carl Sagan (1994) *Sci*. *Am*. Oct. 1994: 92-99.

Some Milestones in Origin-of-Life Science-1

- **~ 5,000 yrs ago**: *The Bible* states God created humans & higher organisms.
- **< mid 1800's**: Creationism + insects, frogs & other small creatures observed to arise spontaneously from mud & rot.
- **mid 1800's**: (1) **Pasteur** demonstrated bacteria & other microorganisms arise from parents resembling themselves. *Spontaneous generation is dead.* (2) **Darwin** proposes natural selection, the theory that environmental pressure results in the perpetuation of certain adaptations. Evolution of complex organisms therefore possible, & all current life forms could have evolved from a single (last) common ancestor.
- ▪ **Darwin** (privately) suggested *life could have arisen from chemistry*: "in some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity, etc., present."

Adapted from Orgel (1994) *Sci. Am.*, Oct. 1994, 77-83.

Some Milestones in Origin-of-Life Science-2

- 1953: *Miller-Urey experiment* (U. chicago) demonstrates that amino acids could be formed with atmospheric gases + lightning.
- Late 1960s: Woese (U. Illinois), Crick (England), Orgel (Salk Inst, San Diego) concurrently proposed RNA may have preceded proteins & catalyzed all reactions for survival & replication of 'last common ancestor'. The *'RNA World' hypothesis* born.
- 1977: Hydrothermal vents on the seafloor discovered teaming with diverse life. Suggests possibility life may not have evolved at the surface.
- 1983: Thomas Cech (U. Colorado) & Sidney Altman (Yale) independently discovered *ribozymes*, enzymes made of RNA. Heritability & reproducibility possible with a single molecule.

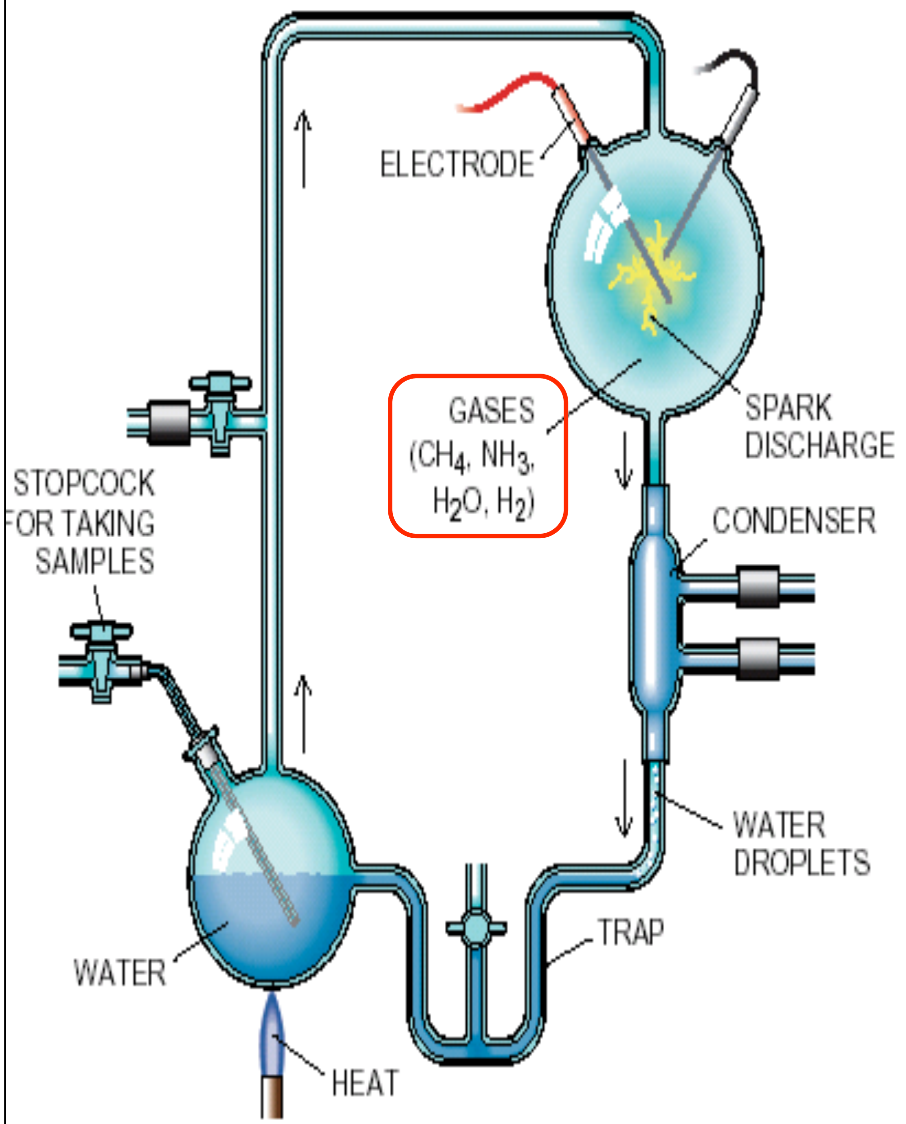
Some Milestones in Origin-of-Life Science-3

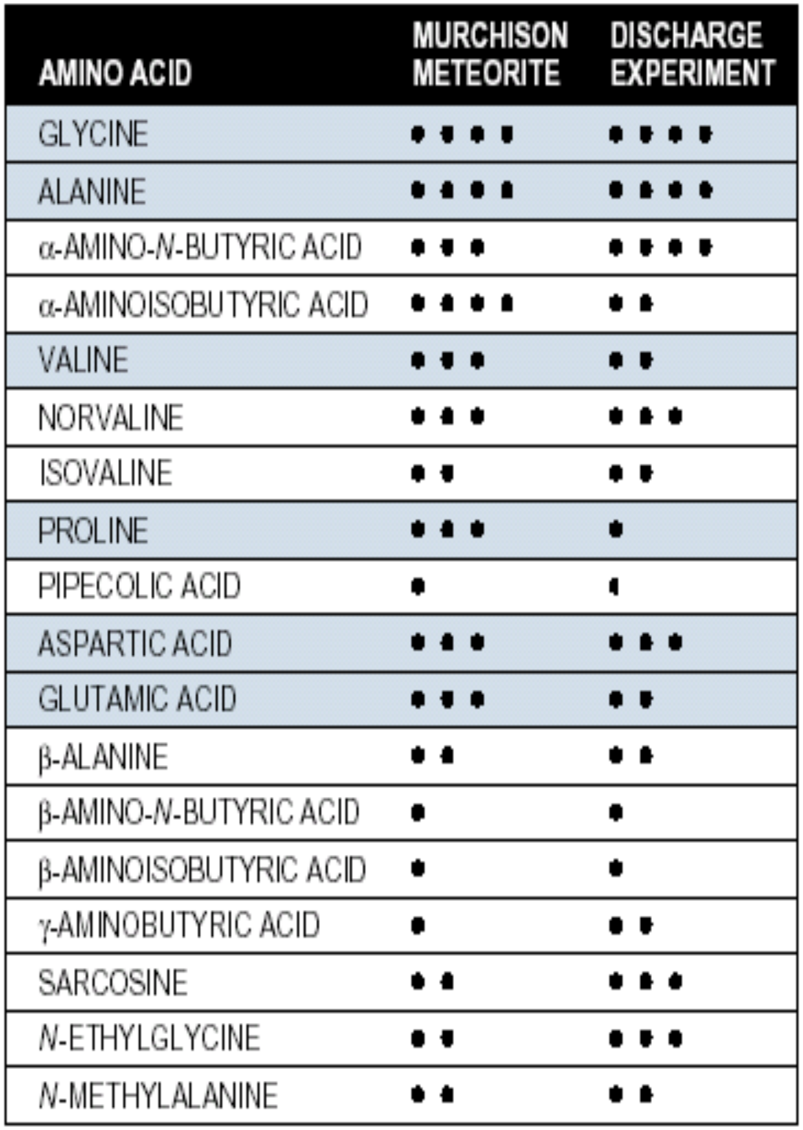
- 1988: Günter Wächtershäuser (German patent lawyer!) theorizes that Fe & Ni sulfide *minerals* at hydrothermal vent systems provided the *template & catalyst* for formation of biological molecules.
- 1997: Jay Brandes (Carnegie Inst.) demonstrates that N_2 is converted to NH_3 in the presence of H_2 & magnetite (Fe_3O_4), at T & P typical of hydrothermal vents. *Mineral surfaces and HT vent environments can produce biologically-useful form of N.*
- 2000: Cody et al. demonstrate synthesis of *pyruvate* using mineral catalysis under hydrothermal conditions. Pyruvate is branch point for many extant biosynthetic pathways.

Building Blocks for Biomolecules

The Building Blocks for Biomolecules: The Miller-Urey Experiment (1953)

Protein aa's





AMINO ACID	MURCHISON METEORITE	DISCHARGE EXPERIMENT
GLYCINE	● ● ● ●	● ● ● ●
ALANINE	● ● ● ●	● ● ● ●
α-AMINO-*N*-BUTYRIC ACID	● ● ●	● ● ● ●
α-AMINOISOBUTYRIC ACID	● ● ● ●	● ●
VALINE	● ● ●	● ●
NORVALINE	● ● ●	● ● ●
ISOVALINE	● ●	● ●
PROLINE	● ● ●	●
PIPECOLIC ACID	●	◖
ASPARTIC ACID	● ● ●	● ● ●
GLUTAMIC ACID	● ● ●	● ●
β-ALANINE	● ●	● ●
β-AMINO-*N*-BUTYRIC ACID	●	●
β-AMINOISOBUTYRIC ACID	●	●
γ-AMINOBUTYRIC ACID	●	● ●
SARCOSINE	● ●	● ● ●
N-ETHYLGLYCINE	● ●	● ● ●
N-METHYLALANINE	● ●	● ●

Orgel (1994) *Sci. Am.*, Oct. 1994, 77-83.

The Building Blocks for Biomolecules: The Miller-Urey Experiment (c.)

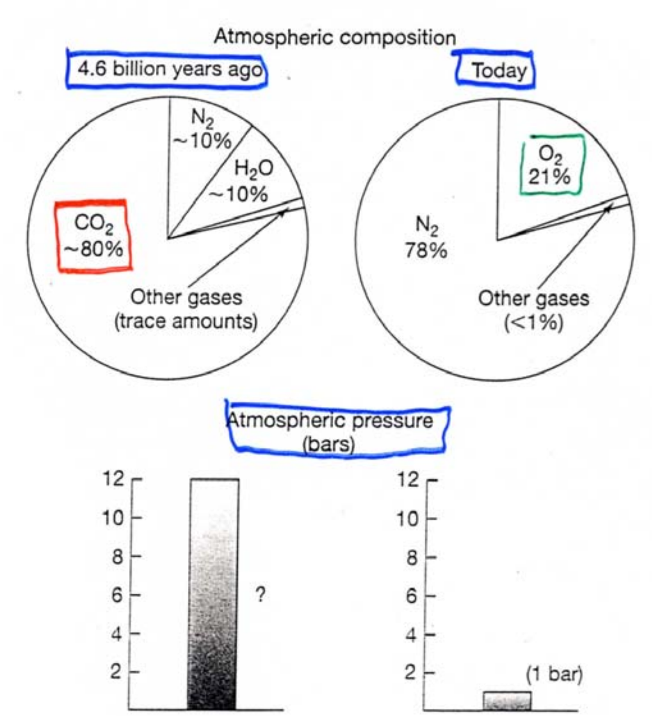
The Original Origin-of-Life Experiment

In the early 1950s Stanley L. Miller, working in the laboratory of Harold C. Urey at the University of Chicago, did the first experiment designed to clarify the chemical reactions that occurred on the primitive earth (*right*). In the flask at the bottom, he created an "ocean" of water, which he heated, forcing water vapor to circulate (*arrows*) through the apparatus. The flask at the top contained an "atmosphere" consisting of methane (CH_4), ammonia (NH_3), hydrogen (H_2) and the circulating water vapor. Next he exposed the gases to a continuous electrical discharge ("lightning"), causing the gases to interact. Water-soluble products of those reactions then passed through a condenser and dissolved in the mock ocean. The experiment yielded many amino acids and enabled Miller to explain how they had formed. For instance, glycine appeared after reactions in the atmosphere produced simple compounds—formaldehyde and hydrogen cyanide—that participated in the set of reactions shown below. Years after this experiment, a meteorite that struck near Murchison, Australia, was shown to contain a number of the same amino acids that Miller identified (*table*) and in roughly the same relative amounts (*dots*); those found in proteins are highlighted in blue. Such coincidences lent credence to the idea that Miller's protocol approximated the chemistry of the prebiotic earth. More recent findings have cast some doubt on that conclusion.

HOW GLYCINE FORMED

$CH_2O + NH_3 + HCN$

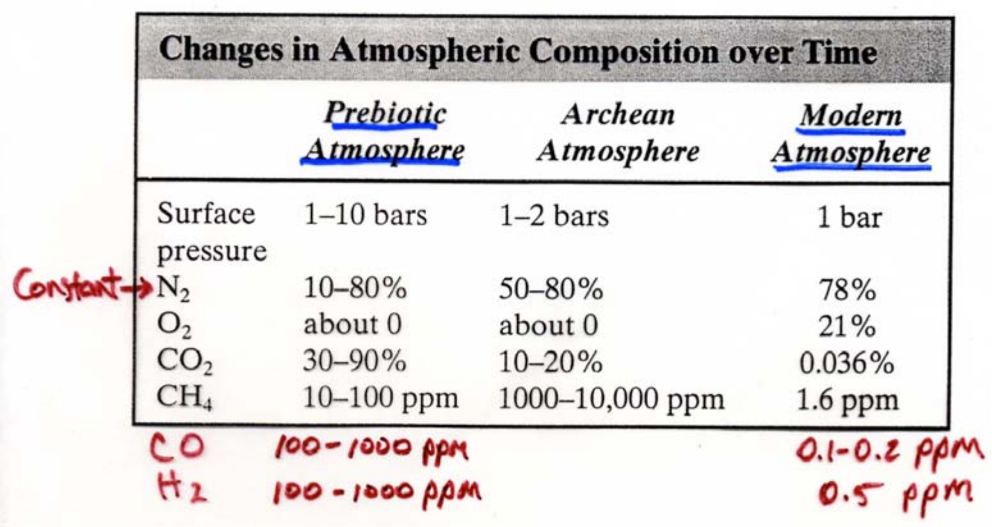
Orgel (1994) *Sci. Am.*, Oct. 1994, 77-83.



Problems with Miller-Urey-type origin for biomolecules

- Hadean atmosphere now thought to have been much less reducing than in Miller-Urey atmosphere (predominance of CO_2 relative to CH_4 & NH_3)

- 50-50 mixture of right- & left-handed molecules is synthesized; natural molecules are 100% left- or right-handed…



Changes in Atmospheric Composition over Time

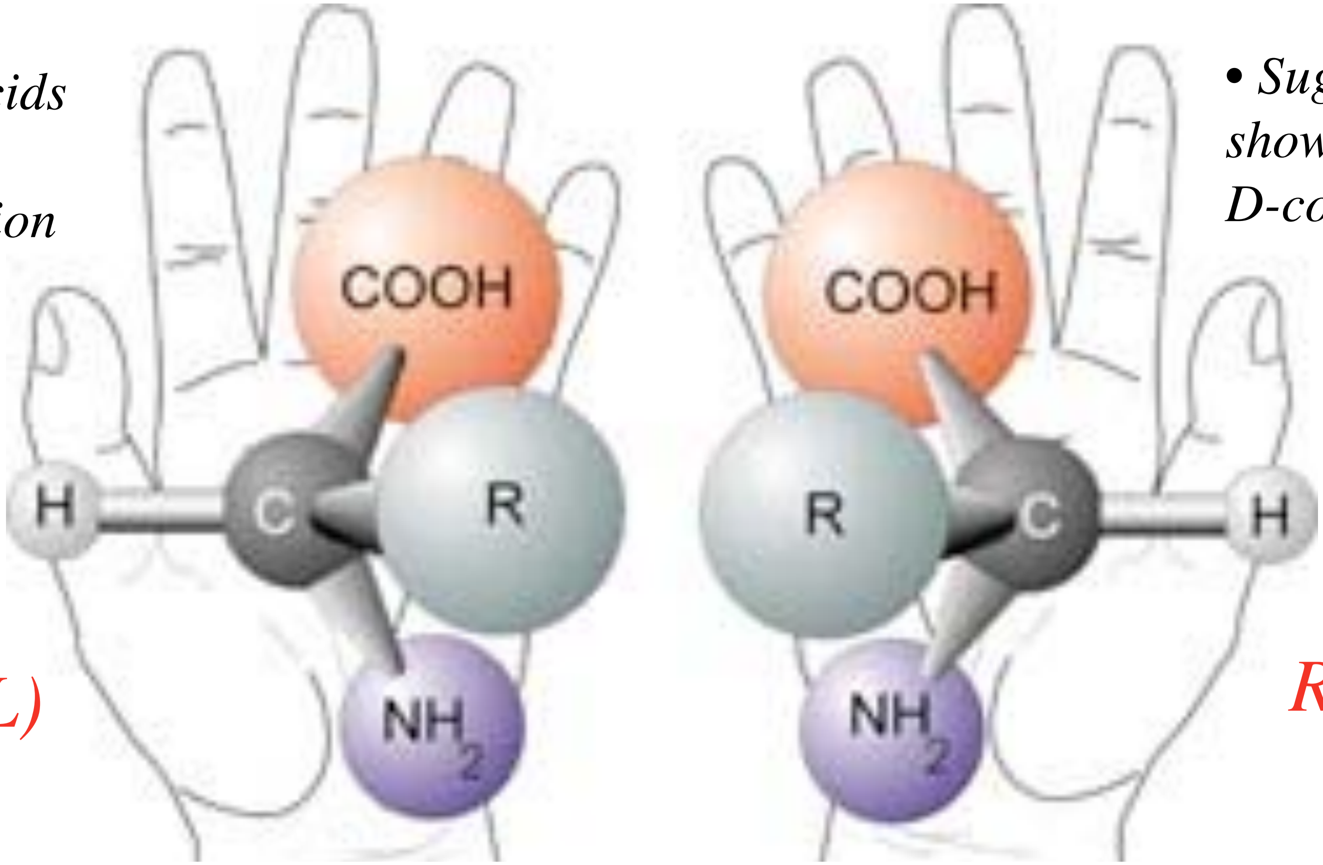
	Prebiotic Atmosphere	*Archean Atmosphere*	*Modern Atmosphere*
Surface pressure	1–10 bars	1–2 bars	1 bar
Constant → N_2	10–80%	50–80%	78%
O_2	about 0	about 0	21%
CO_2	30–90%	10–20%	0.036%
CH_4	10–100 ppm	1000–10,000 ppm	1.6 ppm
CO	100-1000 ppm		0.1-0.2 ppm
H_2	100-1000 ppm		0.5 ppm

Kump et al. (1999) The Earth System, Prentice Hall, New Jersey, 351 p.

Chirality of Biomolecules

- *Amino acids have an L-configuration*

- *Sugars (not shown) have a D-configuration*



Left (L)

Right (D)

- All amino acids in proteins from living organisms are “left-handed” (L-enantiomers), while sugars are “right-handed”. (Chirality was yet another discovery by Louis Pasteur ~150 yr ago!)
- The Miller-Urey experiment, & all similar organic synthetic experiments, produce a 50-50 (racemic) mixture of biomolecules.

http://web99.arc.nasa.gov/~astrochm/aachiral.html

How did chirality of biomolecules arise?

(See Hazen Lecture podcast--link on course Schedule web page: "LEFT & RIGHT: Geochemical origins of life's homochirality", UW Astrobiology Seminar Series, 5/1/07)

- It may have occurred in the solar nebula during the formation of the solar system.
- Amino acids with a slight L-enantiomeric excess are observed in the Murchison & Murray meteorites
- (Although beware of contamination, since all Earthly aa's begin with L configuration. But note: during natural decomposition processes, protein aa's revert to a 50-50 (racemic) mixture over time.)
- Crystal faces have surface structures that are mirror-images. Experiments show that crystal faces can select L or D amino acids quite efficiently (40% excess) (Hazen, 2001). While this mechanism can explain the propagation of the L or D configuration, it cannot explain the *origin* of that preference.

Astrobiology Seminar on Origin of Chirality

Tuesday May 1, 2007
Robert M. Hazen
Geophysical Laboratory, Carnegie Institution of Washington & George Mason University
Title: **LEFT & RIGHT: Geochemical origins of life's homochirality**
Information: http://astrobiology.nasa.gov/nai/seminars/detail/103
Podcast: http://nai.arc.nasa.gov/library/uploads/AB070501-01.mov

Abstract: Life arose on Earth as a geochemical process from the interaction of rocks, water, and gases. Prior to the origin of life, the necessary organic molecules had formed abundantly, but indiscriminately, both in space and on Earth. A major mystery of life's origin is how an idiosyncratic subset of those diverse molecules was selected and concentrated from the prebiotic soup to form more complex structures leading to the development of life. Rocks and minerals are likely to have played several critical roles in this selection, especially as templates for the adsorption and organization of these molecules. Our recent experimental and theoretical studies on interactions between crystals and organic molecules reveal that crystals with chiral surface structures may have facilitated the separation of left- and right-handed biomolecules - the possible origin of life's distinctive homochirality.

Chiral Amino Acids in the Murchison Meteorite

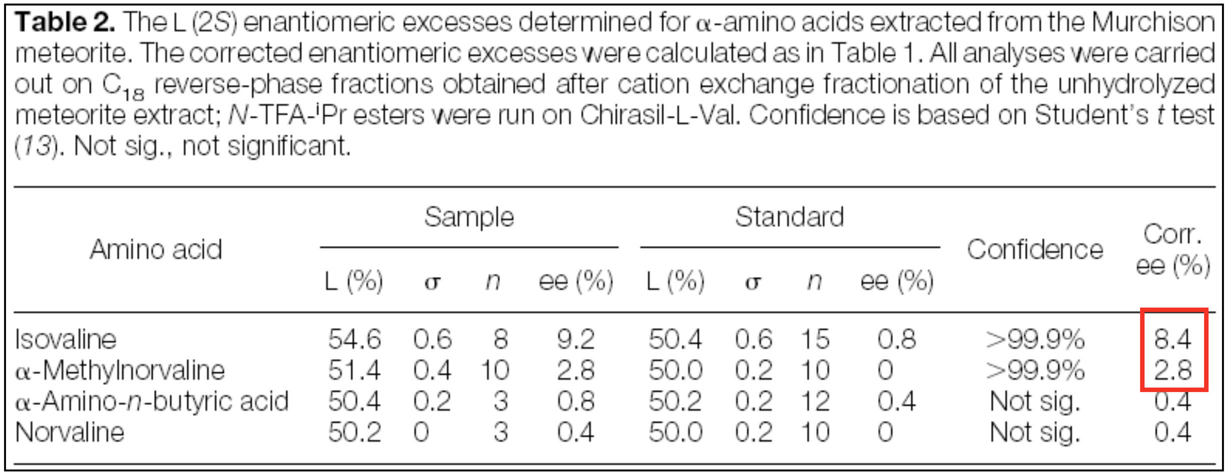


Table 2. The L (2*S*) enantiomeric excesses determined for α-amino acids extracted from the Murchison meteorite. The corrected enantiomeric excesses were calculated as in Table 1. All analyses were carried out on C_{18} reverse-phase fractions obtained after cation exchange fractionation of the unhydrolyzed meteorite extract; *N*-TFA-^{i}Pr esters were run on Chirasil-L-Val. Confidence is based on Student's *t* test (*13*). Not sig., not significant.

Amino acid	Sample				Standard				Confidence	Corr. ee (%)
	L (%)	σ	*n*	ee (%)	L (%)	σ	*n*	ee (%)		
Isovaline	54.6	0.6	8	9.2	50.4	0.6	15	0.8	>99.9%	8.4
α-Methylnorvaline	51.4	0.4	10	2.8	50.0	0.2	10	0	>99.9%	2.8
α-Amino-*n*-butyric acid	50.4	0.2	3	0.8	50.2	0.2	12	0.4	Not sig.	0.4
Norvaline	50.2	0	3	0.4	50.0	0.2	10	0	Not sig.	0.4

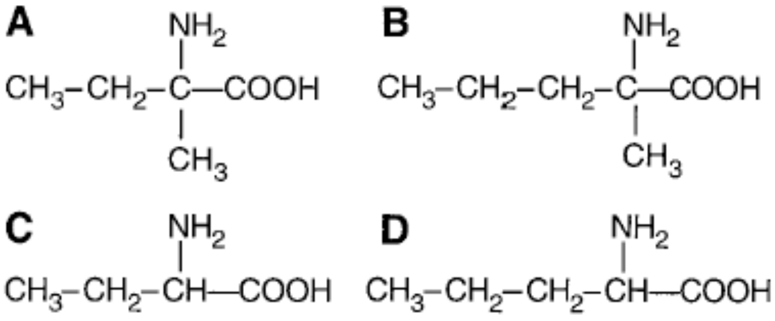


Fig. 4. Four additional amino acids analyzed (Table 2): (**A**) isovaline, (**B**) α-methylnorvaline, (**C**) α-amino-*n*-butyric acid, and (**D**) norvaline. Isovaline and α-methylnorvaline showed enantiometric excesses.

- Murchison fragment (Martin Horejsi)
- Carbonaceous chondrite
- Struck 9/28/69, near Murchison, Australia.

- Non-protein aa's analyzed to avoid contamination (previous L-excesses were shown to be the result of terrestrial contamination)

Cronin & Pizzarello (1997) *Science* Vol. 275: 951-955.

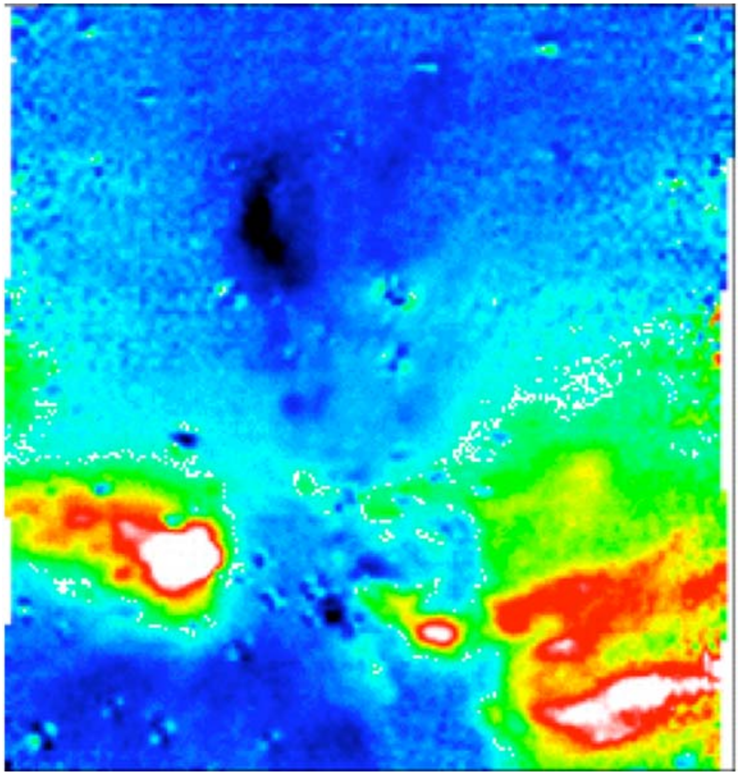
Exogenous delivery of chiral building blocks of biomolecules

Carbonaceous Chondrites: A Window on Organic Chemistry in the Early Solar System
J. R. Cronin
Arizona State University
http://astrobiology.arc.nasa.gov/workshops/1996/astrobiology/speakers/cronin

∝ “Analyses of selected chiral amino acids from the Murchison meteorite suggest L-enantiomer excesses of the order of 5-10%. In general, the finding of enantiomeric excesses in extraterrestrial molecules supports the hypothesis that exogenous delivery made a significant contribution to organic chemical evolution leading to the origin of life. The finding of these enantiomeric excesses specifically in substituted amino acids may have implications for the chemistry of a pre-RNA world insofar as it suggests the possibility that these unusual, but meteoritically abundant, amino acids were early biomonomers. “

[1] Cronin J. R. and Chang S. (1993) in The Chemistry of Life's Origins (J.M. Greenberg et al., eds.) Kluwer, pp. 209-258. [2] Epstein S. et al. (1987) Nature, 326, 477-479. [3] Bonner W. A. and Rubenstein E. (1987) BioSystems, 20, 99-111

Galactic origin for chirality of biomolecules?



- In the model 1st proposed by Rubenstein et al. (1983) (*Nature*, Vol. 306:118) **the action of circular polarized light on interstellar chiral molecules introduced a left handed excess into molecules in the material from which the solar system formed**. Some of this organic material then finds its way onto Earth via impacts of comets, meteorites and dust particles during the heavy bombardment phase in the first few hundred million years of the solar system. These molecules were then part of the prebiotic material available for the origin of life, and tipped the scales for life to develop with L-amino acids and D-sugars.
- Rubenstein et al. originally proposed that synchrotron radiation from neutron stars in supernova remnants would be a suitable source of the required UV circularly polarized light. However, this interpretation is not supported by theory or observation which show that the circular polarization of these sources is very low.
- New observations with the Anglo-Australian Telescope (above) have shown suprisingly high circular polarizations (the red and white regions in the image) in the infrared light from reflection nebulae in the star forming regions Orion OMC1 (a region in the Orion nebula M42) and NGC 6334. Although we can only observe these regions at infrared wavelengths which can penetrate the thick dust clouds in which they are embedded, it is predicted that circular polarization should also be present at the ultraviolet wavelengths needed for asymmetric photolysis of molecules such as amino acids. **If our own solar system formed in such a region of high circular polarization, it could have led to the excess of L-amino acids which we see in meteorites and to the homochirality of biological molecules.** It is possible that without such a process operating it would not be possible for life to start. This may have implications for the frequency of occurrence of life in the universe.

http://www.ast.cam.ac.uk/AAO/local/www/jab/astrobiology/chirality.html

Prebiotic Amino Acids as Asymmetric Catalysts

Sandra Pizzarello[1] and Arthur L. Weber[2]

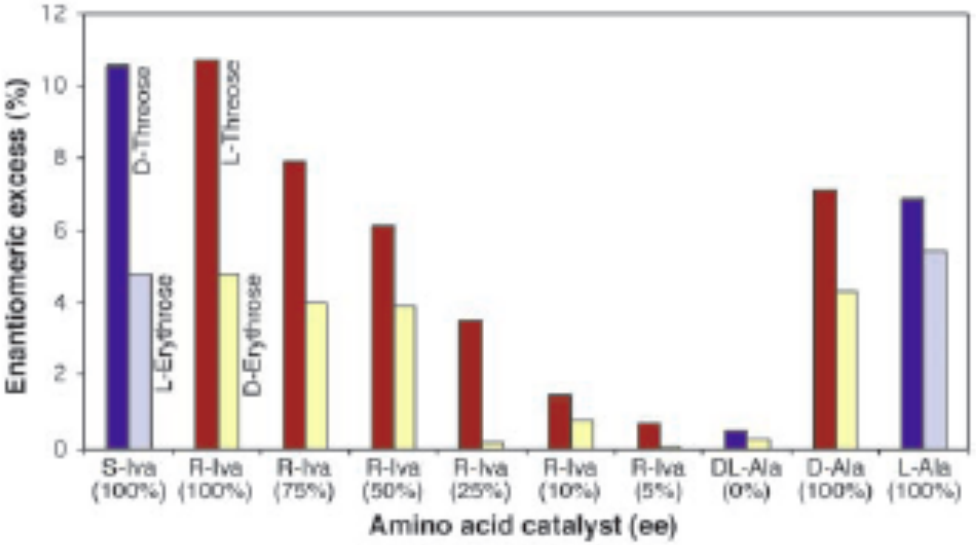


Fig. 1. Effect of amino acid catalyst ee on the asymmetric synthesis of threose and erythrose from glycolaldehyde. S-ivaline is equivalent to L-2-amino 2-methyl butyric acid.

www.sciencemag.org SCIENCE VOL 303 20 FEBRUARY 2004 1151

Enantiomeric excess of D or L amino acid in flask with glycoaldehyde & water results in catalytic production of sugars with enantiomeric excess

- *Once an enantiomeric excess exists in a pool of amino acids it can catalyze the production of sugars with an enantiomeric excess.*

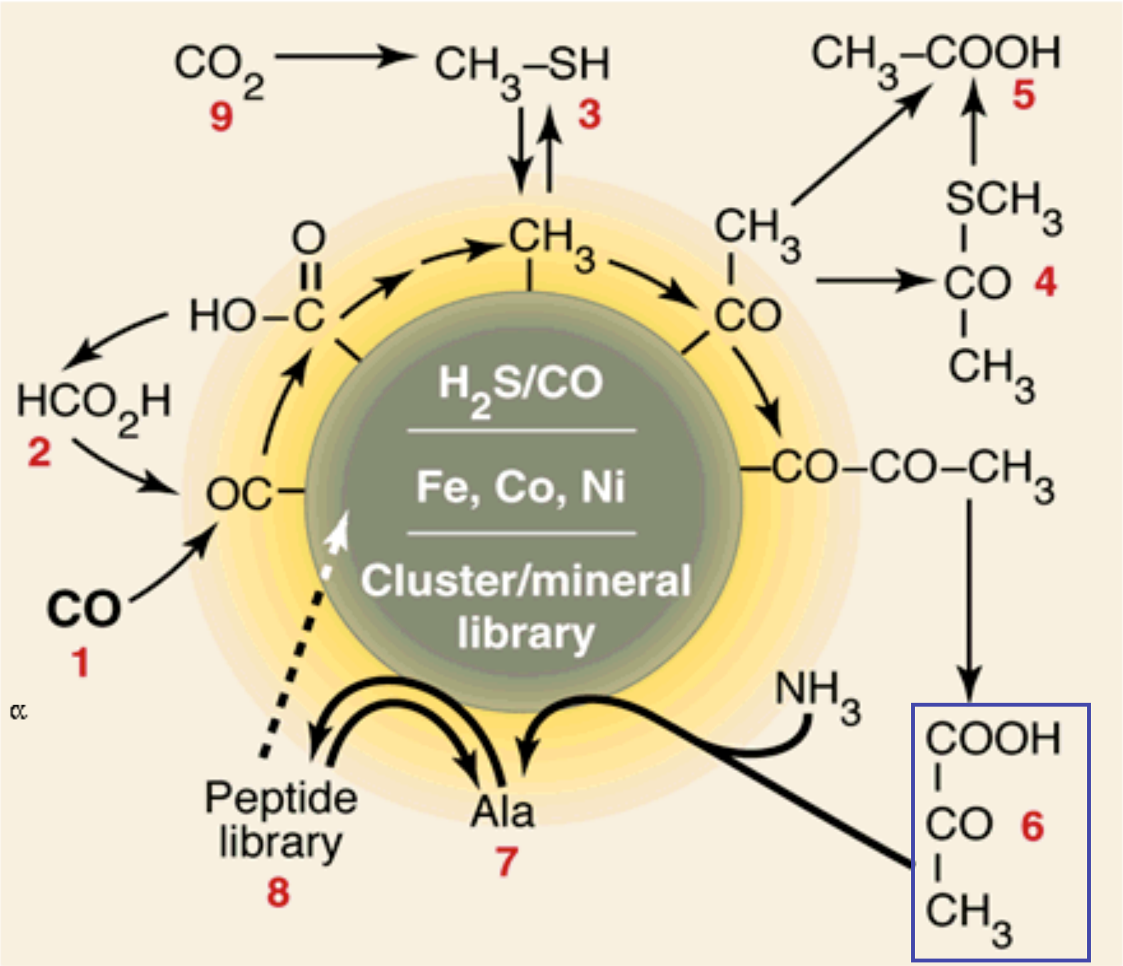
Role of Mineral Mineral Surfaces in Biochemical Evolution

Mineral surfaces can serve as templates for chiral molecules

TEMPLATES—The mineral calcite tends to attract left- and right-handed amino acids to different crystal faces. Such a sorting process could explain why life makes use of only the left-handed variety.

Hazen (2001) *Sci*. *Am*., April 2001: 77-85

Mineral-surfaces can also catalyze organic syntheses under hydrothermal conditions

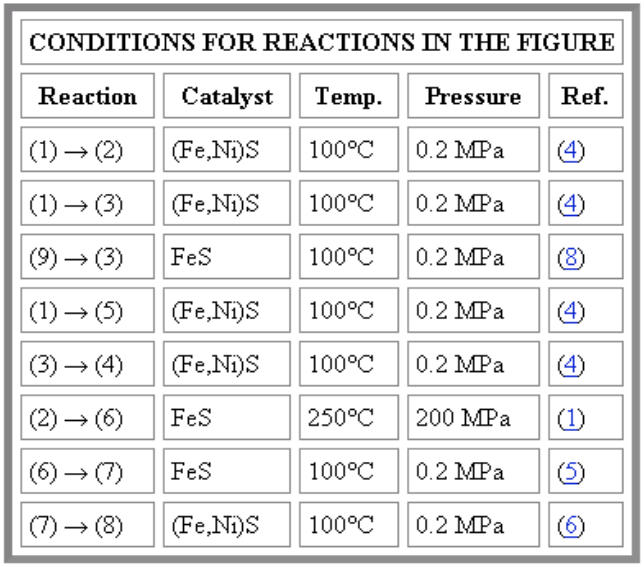


Reactions in the iron-sulfur world. Reaction conditions are given in the table

- Iron-sufide minerals catalyze production of **pyruvate*** & other biomolecules under conditions common in <u>hydrothermal vent systems</u>.

*Pyruvate = branch point for many biosynthetic pathways

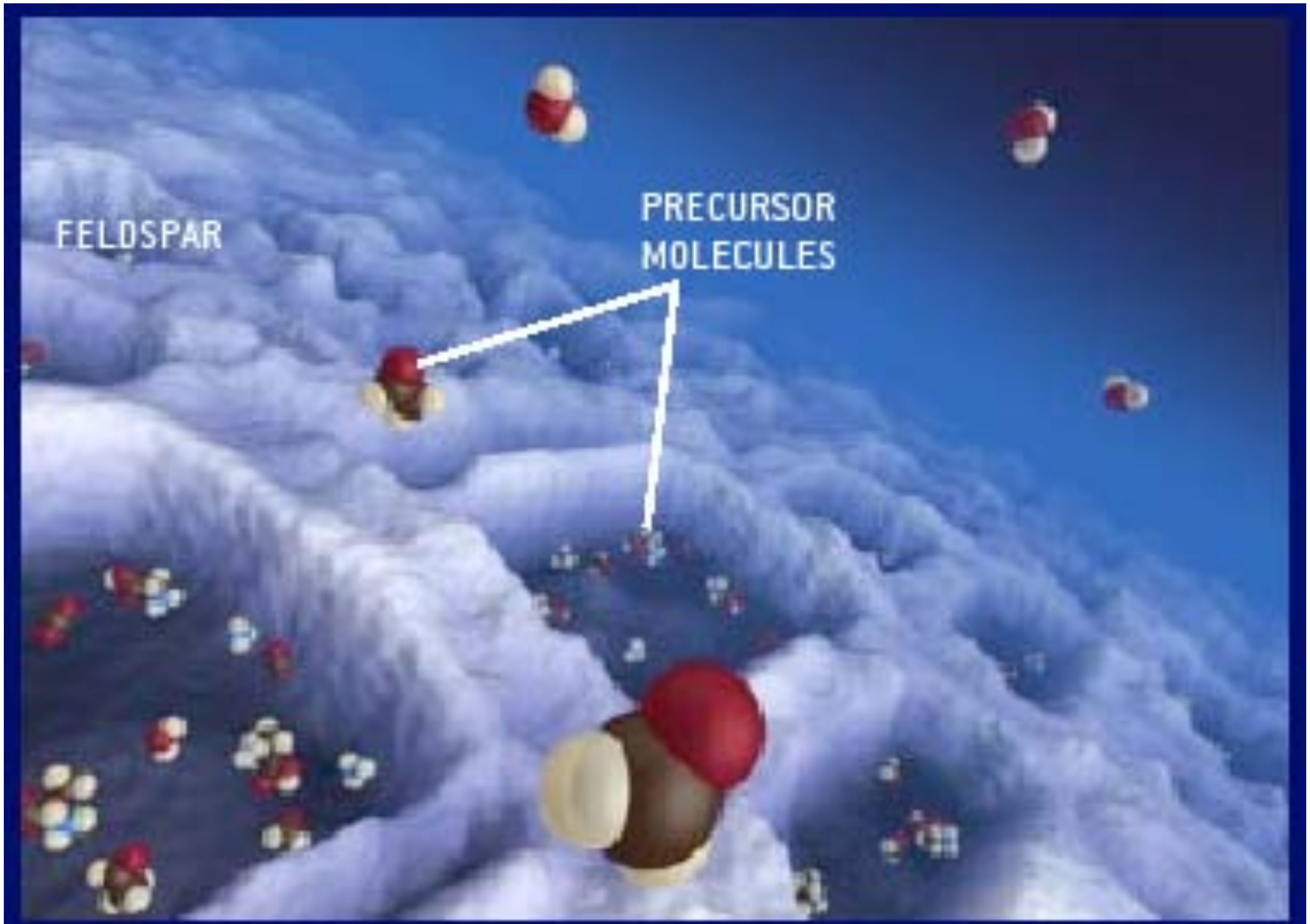
Wächtershäuser (2000) *Science*, Vol. 289:1337.



CONDITIONS FOR REACTIONS IN THE FIGURE

Reaction	Catalyst	Temp.	Pressure	Ref.
(1) → (2)	(Fe,Ni)S	100°C	0.2 MPa	(4)
(1) → (3)	(Fe,Ni)S	100°C	0.2 MPa	(4)
(9) → (3)	FeS	100°C	0.2 MPa	(8)
(1) → (5)	(Fe,Ni)S	100°C	0.2 MPa	(4)
(3) → (4)	(Fe,Ni)S	100°C	0.2 MPa	(4)
(2) → (6)	FeS	250°C	200 MPa	(1)
(6) → (7)	FeS	100°C	0.2 MPa	(5)
(7) → (8)	(Fe,Ni)S	100°C	0.2 MPa	(6)

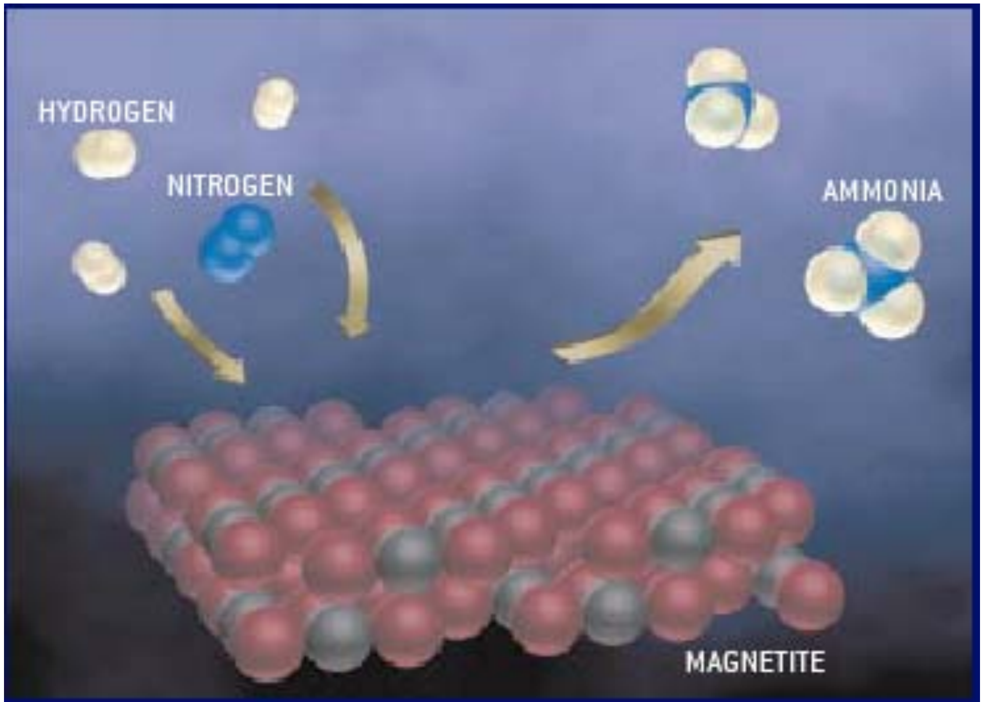
Mineral surfaces can protect fragile molecules



CONTAINERS—Microscopic pits appear in abundance on the weathered surfaces of feldspar and other common minerals. These tiny chambers could have sheltered life's precursor molecules from deadly radiation.

Hazen (2001) *Sci*. *Am*., April 2001: 77-85

Further evidence for mineral catalysis of simple organic molecules



CATALYSTS—Magnetite, an iron oxide mineral, can trigger the recombination of nitrogen and hydrogen gases into ammonia, the essential compound from which living cells acquire nitrogen.

$N_2 + H_2 + Fe_3O_4$(magnetite)

$\rightarrow\rightarrow$ **NH_3**

$FeCO_3$ (siderite) + H_2O →

→ **Hydrocarbons**

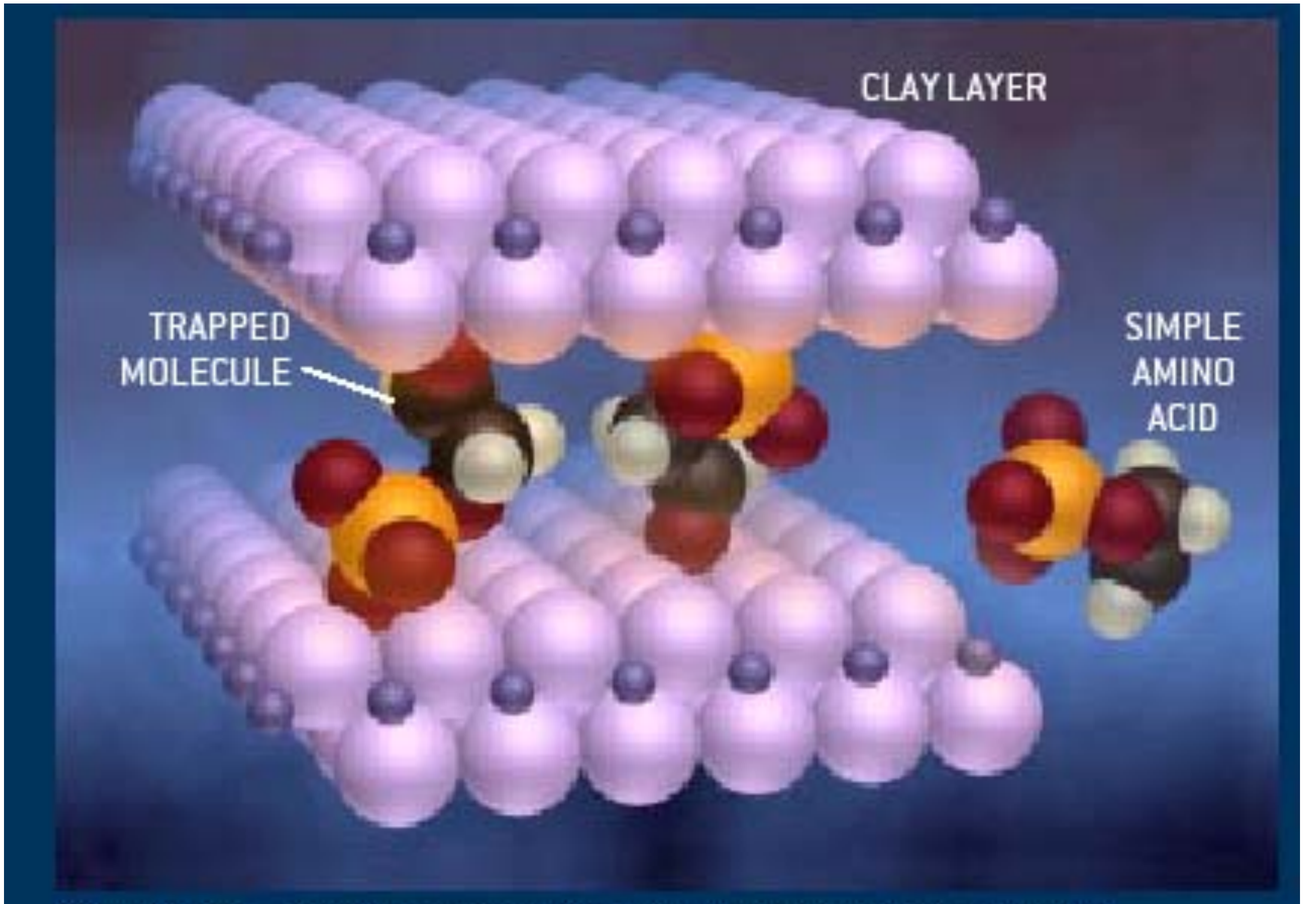
(**PAH + alkanes**)

- Sealed vessel at 300˚C

McCollom (2003) Formation of meteorite hydrocarbons from thermal decomposition of siderite ($FeCO_3$), *Geochimica et Cosmochimica Acta*, Vol. 67(2): 311-317

Hazen (2001) *Sci. Am.*, April 2001: 77-85

Mineral surfaces can act as scaffolds in the synthesis of complex molecules



SCAFFOLDS—Layered minerals such as clays can trap stray organic molecules between their rigid sheets of atoms. Held close to one another, simple molecules can react to form more complex compounds.

Hazen (2001) *Sci*. *Am*., April 2001: 77-85

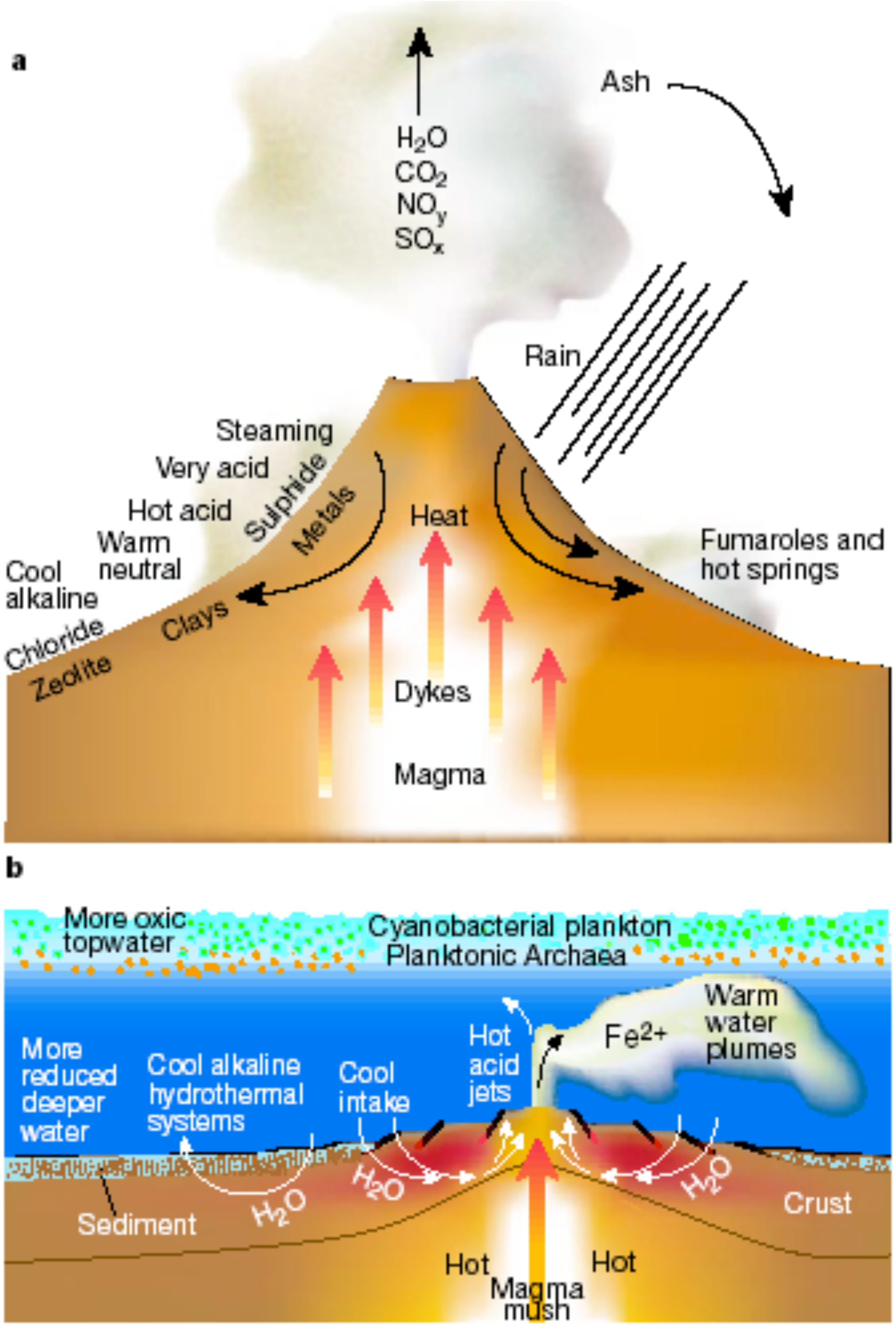
A Hyperthermophilic Beginning for Life?

- Given the inhospitable surface environment on Earth < 3.8 Ga, when the intense bombardment likely melted the crust & vaporized the ocean, perhaps repeatedly, it is frequently proposed that life began in a sub-surface environment, perhaps a hydrothermal system where hot water, CO_2 & a variety of metals are readily available.

- The recognition that many of the essential enzymes for life require metals common in hydrothermal settings (Fe, Ni, Mo, Cu, Co, Zn) supports this supposition.

c.f., Nisbet & Sleep (2001) *Nature*, Vol. 409:1083-1091.

Hydrothermal Habitats for Early Life

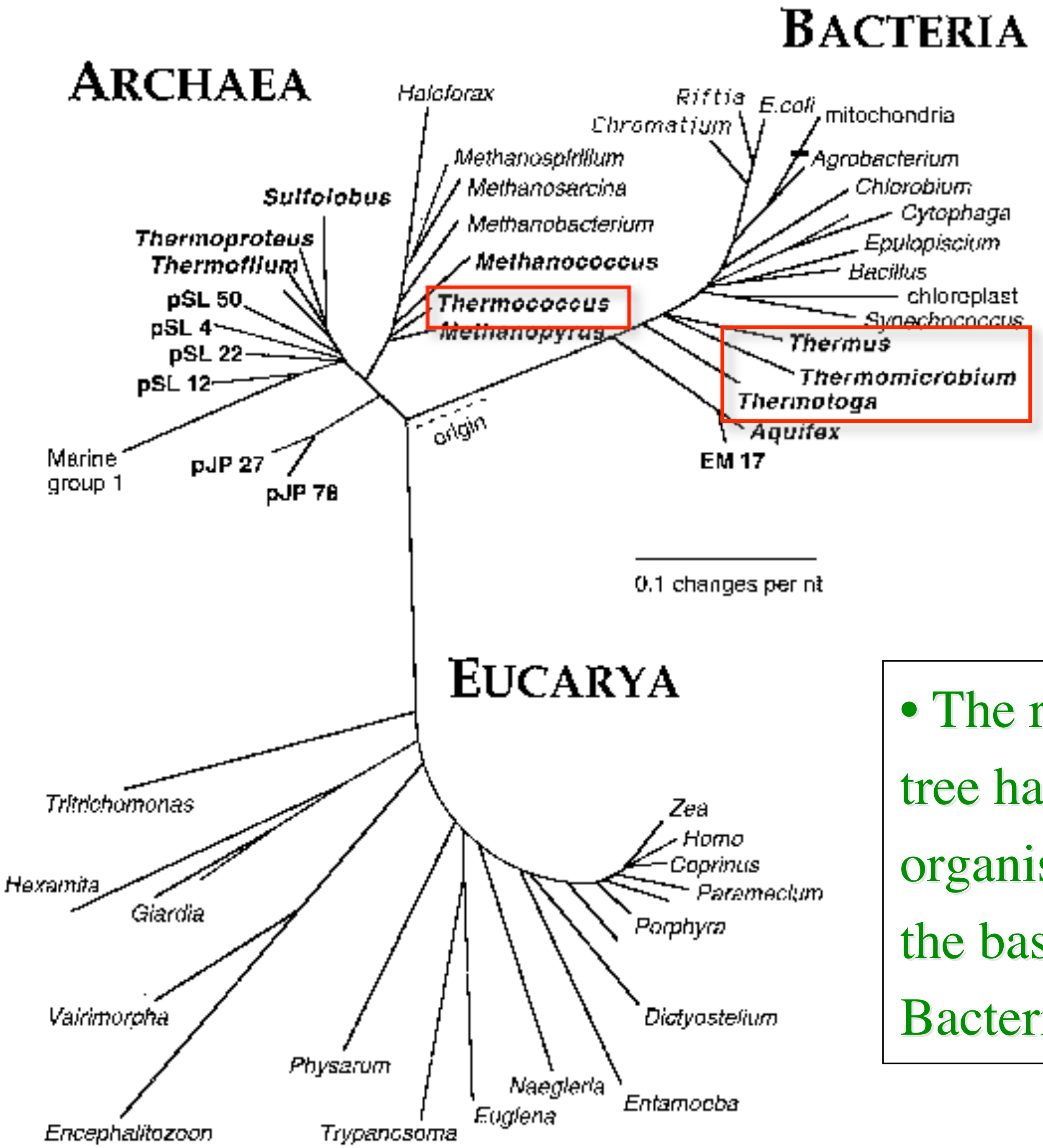


On Land, around a volcano.

On the seafloor, at a mid-ocean ridge.

Nisbet & Sleep (2001) “The habitat and nature of early life” *Nature* Vol. 409: 1083-1091.

rRNA Phylogeny Indicates Hyper-thermophiles are Ancient!



- The rRNA phylogenetic tree has hyperthermophilic organisms clustered near the base of the Archaeal and Bacterial domains

The ‘RNA World’ Hypothesis

Commonality & the Central Problem of Origin-of-Life Research

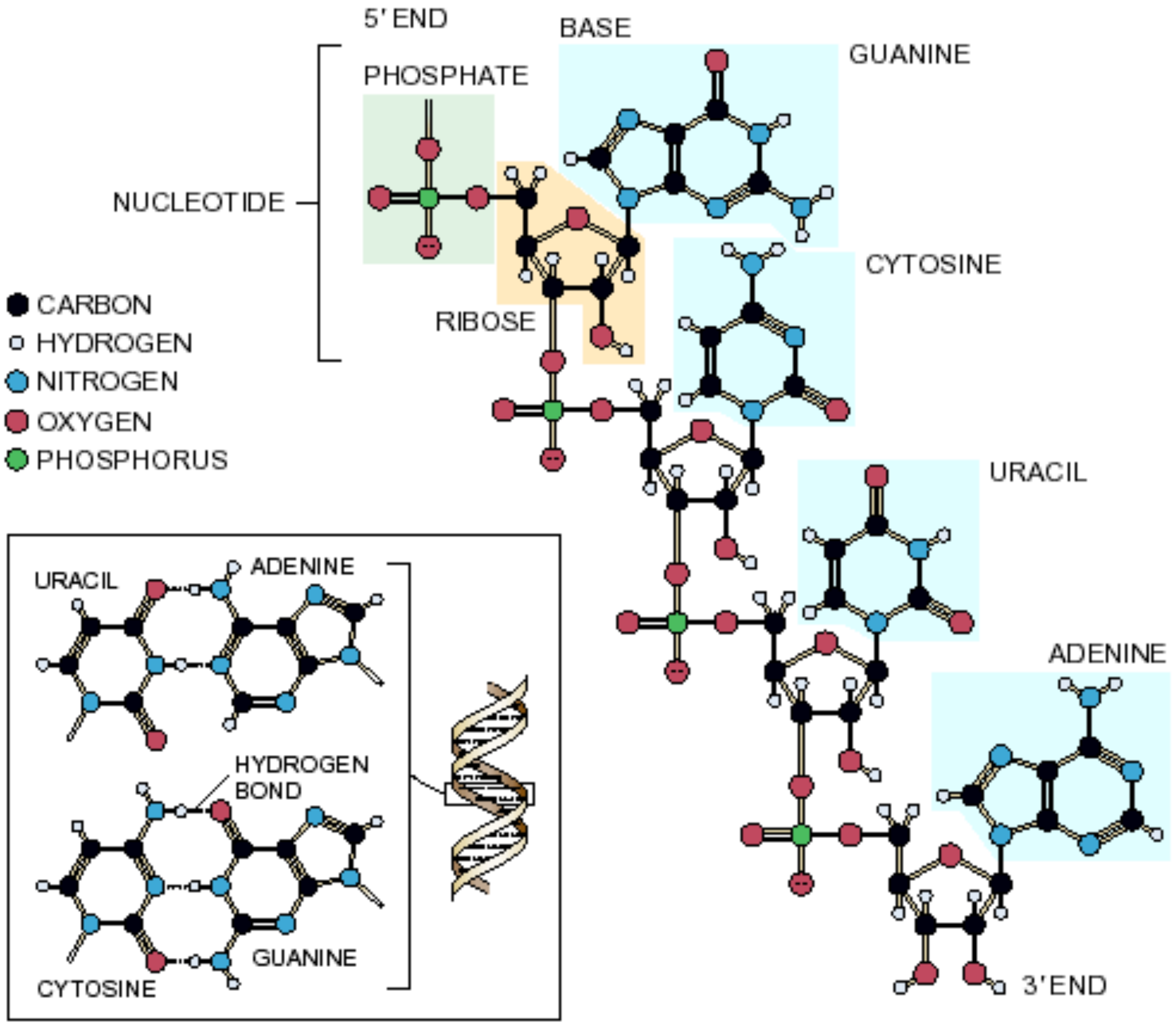
•Insight into the character of the 'last common ancestor' can be gained by identifying *commonalities* in contemporary organisms. I.e., intricate features common to all modern organisms are unlikely to have evolved independently.

•Examples: similar C compounds, same 20 amino acids make all proteins, genetic information in nucleic acids (RNA & DNA).

"our last common ancestor stored genetic information in nucleic acids that specified the composition of all needed proteins. It also relied on proteins to direct many of the reactions required for self-perpetuation. Hence, the central problem of origin-of-life research can be refined to ask, **By what series of chemical reactions did this interdependent system of nucleic acids and proteins come into being**?"

Orgel (1994) *Sci. Am.*, Oct. 1994, 77-83.

The ‘RNA World’ Hypothesis



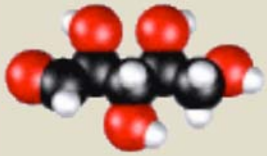
RNA IS COMPOSED OF NUCLEOTIDES, each of which consists of a phosphate group (*green box*) and the sugar ribose (*yellow box*) linked to a nitrogen-containing base (*blue boxes*): guanine (*G*), cytosine (*C*), uracil (*U*) or adenine (*A*). Uracil on one strand of RNA can pair with adenine on another strand, and cytosine can pair with guanine, producing a double helix (*inset*). Such complementary base pairing is thought to have contributed to the ability of early RNA to reproduce itself.

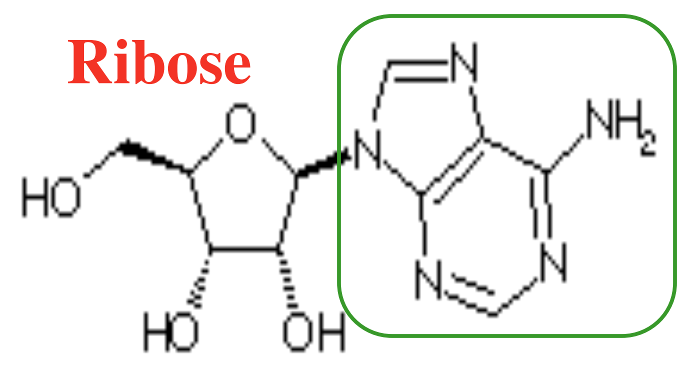
- Late 1960s: Woese (U. Illinois), Crick (England), Orgel (Salk Inst, San Diego) concurrently proposed RNA may have preceded proteins & catalyzed all reactions for survival & replication of ‘last common ancestor’.
- 1983: Thomas Cech (U. Colorado) & Sidney Altman (Yale) independently discovered *ribozymes*, enzymes made of RNA.
- Previously all biomolecules that catalyzed reactions (enzymes) were thought to be proteins (sequences of amino acids).

Orgel (1994) *Sci. Am.*, Oct. 1994, 77-83.

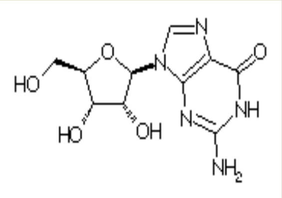
How to make subunits of RNA?

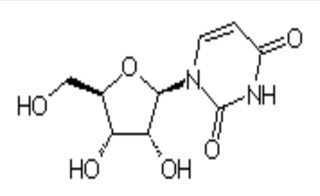
- Phosphate: rock weathering
- Ribose: CO_2 + hν --> 5 COH_2 (formaldehyde) + H_2O --> **Ribose**
- Base: CH_4 + N_2 + hν --> 5 HCN --> **Adenine**

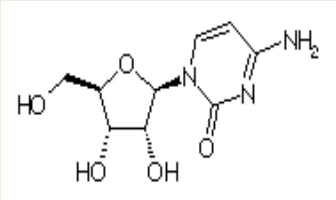




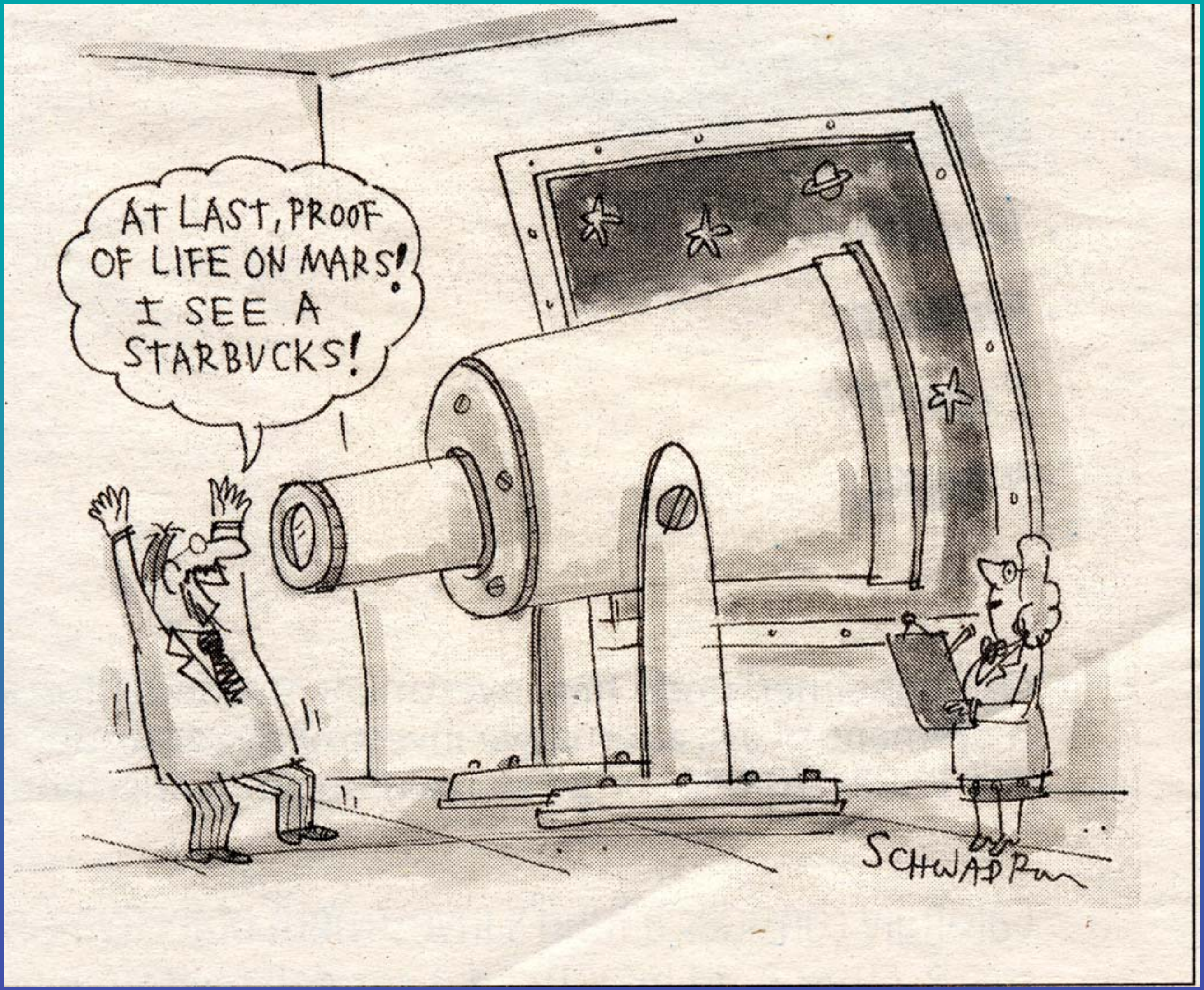
Other 3 RNA Bases: guanine uracil cytosine







Panspermia!



From Barron's (2004)

Panspermia is the hypothesis that "seeds" of life exist already in the Universe, that life on Earth may have originated through these "seeds", and that they may deliver or have delivered life to other habitable bodies.

From Wikipedia

Panspermia 1

Planetary perspective on life on early Mars and the early Earth

by Dr. Norman Sleep

http://astrobiology.arc.nasa.gov/workshops/1996/astrobiology/speakers/sleep/sleep_index.html

Biological evidence
Life may root in thermophile on Earth - one or more almost sterilizing events
Possible Martian fossils come from safe subsurface environment

Space transfer

- Unshocked Mars meteorites fall today on the Earth
- Current transfer rate is 10^7-10^8 rocks per million years
- 10^{-4} of rocks arrive within 10,000 years of impact
- Rate of transfer of fresh rocks is 10^4 per million years
- Early solar system rate 10^3 higher
- Billions of fresh rocks transferred

Conclusions

- Subsurface of Mars was safer than the Earth
- Space transfer of organisms seems feasible
- Indirect biological evidence for partial sterilization of the Earth: Hyperthermophiles at base of Archaeal & Bacterial Domains on rRNA phylogenetic tree
- Space transfer of life to Earth is a viable possibility

Panspermia 2

Planetary perspective on life on early Mars and the early Earth

by Dr. Norman Sleep

http://astrobiology.arc.nasa.gov/workshops/1996/astrobiology/speakers/sleep/sleep_index.html

Large (400 km) projectile

- Ocean completely boiled
- 230 m rock rain
- Return to normal in:

100 yr on Mars
3000 yr on Earth

Refugia from 400-km projectile

- Moderate to deep subsurface (Mars)
- Deep subsurface (Earth)
- Only thermophile survivors on Earth
- Nonthermophiles probably survive on Mars

Small (70 km) projectile

- Dry land surface (Earth & Mars) heated to melting point of rock
- All lakes boiled on Mars
- 25 m of ocean boiled on the Earth
- 1 meter of rock rain
- Planet returns to normal in 25 years
- Sample projectile - Orientale basin on moon

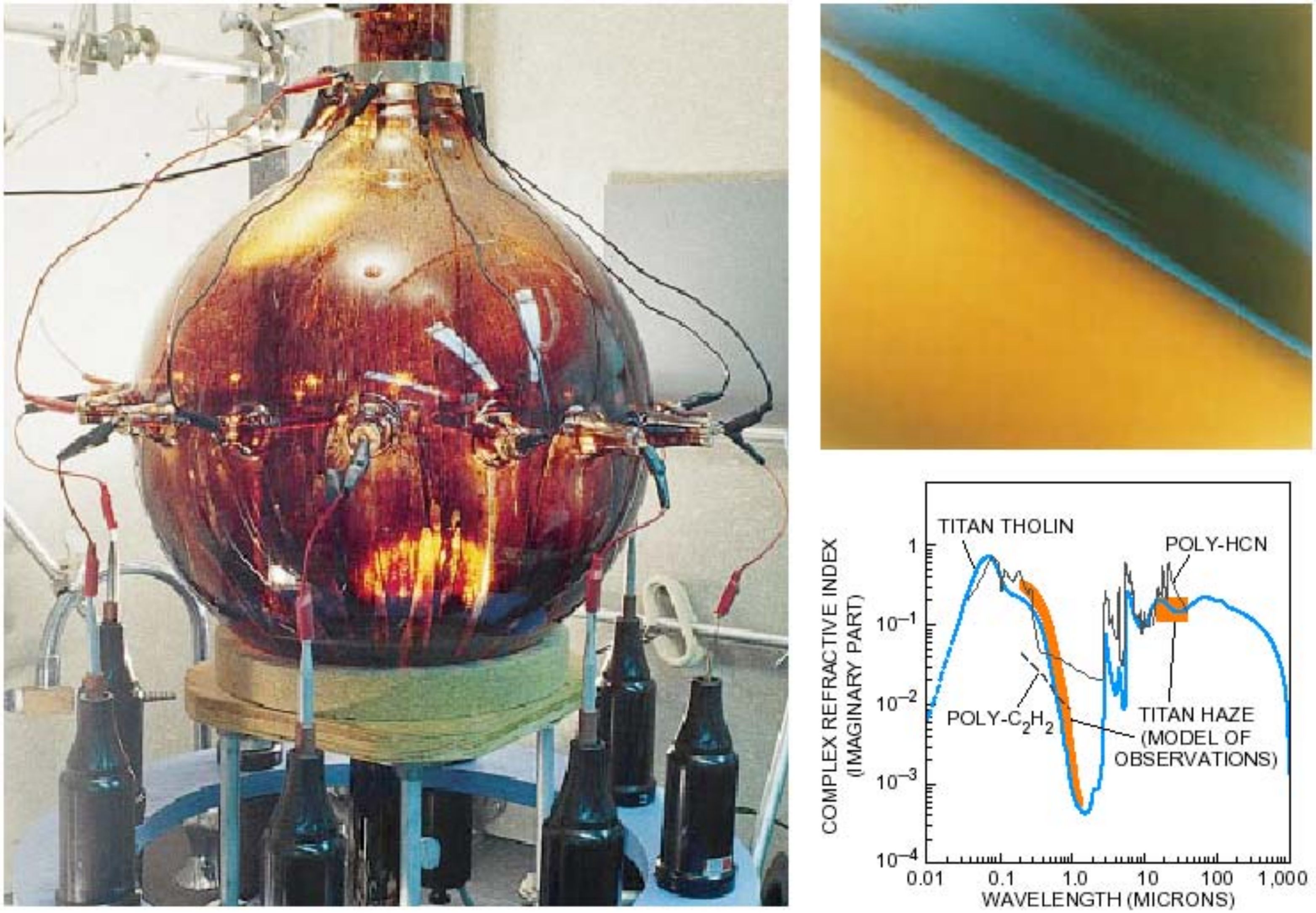
Refugia from 70-km projectile

- Subsurface (Earth & Mars)
- Moderate to deep ocean (Earth)
- Thermophile and nonthermophile survivors on both planets

-60°C too cold *now*, but perhaps not always

Mars Atm.
95% CO_2
2.7% N_2
1.6% Ar

Biomolecules on Saturn’s Moon, Titan?



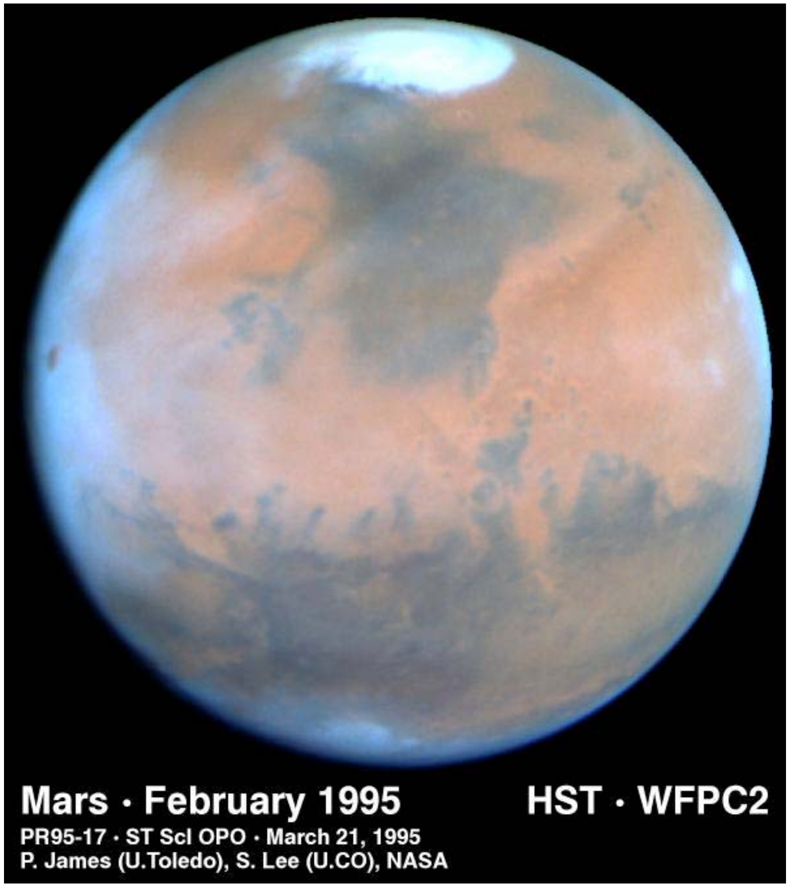
LABORATORY SIMULATION of Titan's nitrogen-methane atmosphere (*left*) yields a tarlike accumulation of complex organic molecules, which the author calls Titan tholin. Analogous chemical reactions may give rise to the haze that obscures Titan's surface (*top right*). The optical characteristics of Titan tholin closely match those of Titan's haze (*bottom right*). When combined with liquid water, Titan tholin produces amino acids, nucleotide bases and other molecules important to terrestrial life. Such molecules might have formed in temporary lakes created by cometary impacts on Titan.

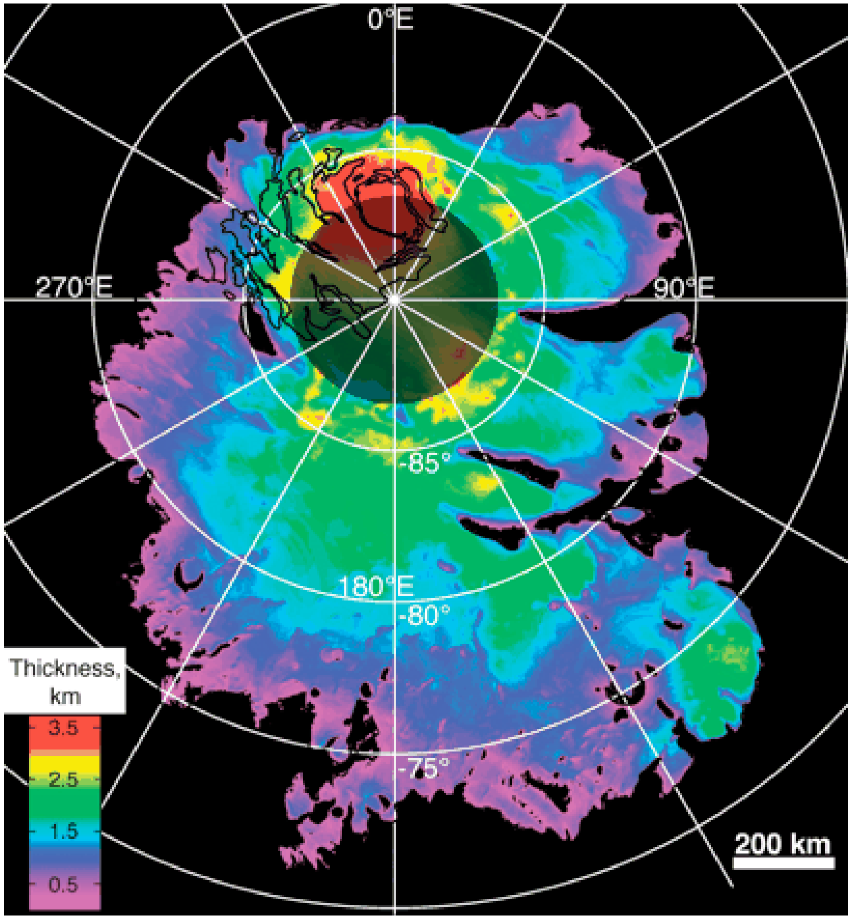
Sagan (1994) *Sci*. *Am*. Oct. 1994: 92-99.

Water Elsewhere in Solar System:

Water Ice on Mars

http://photojournal.jpl.nasa.gov/



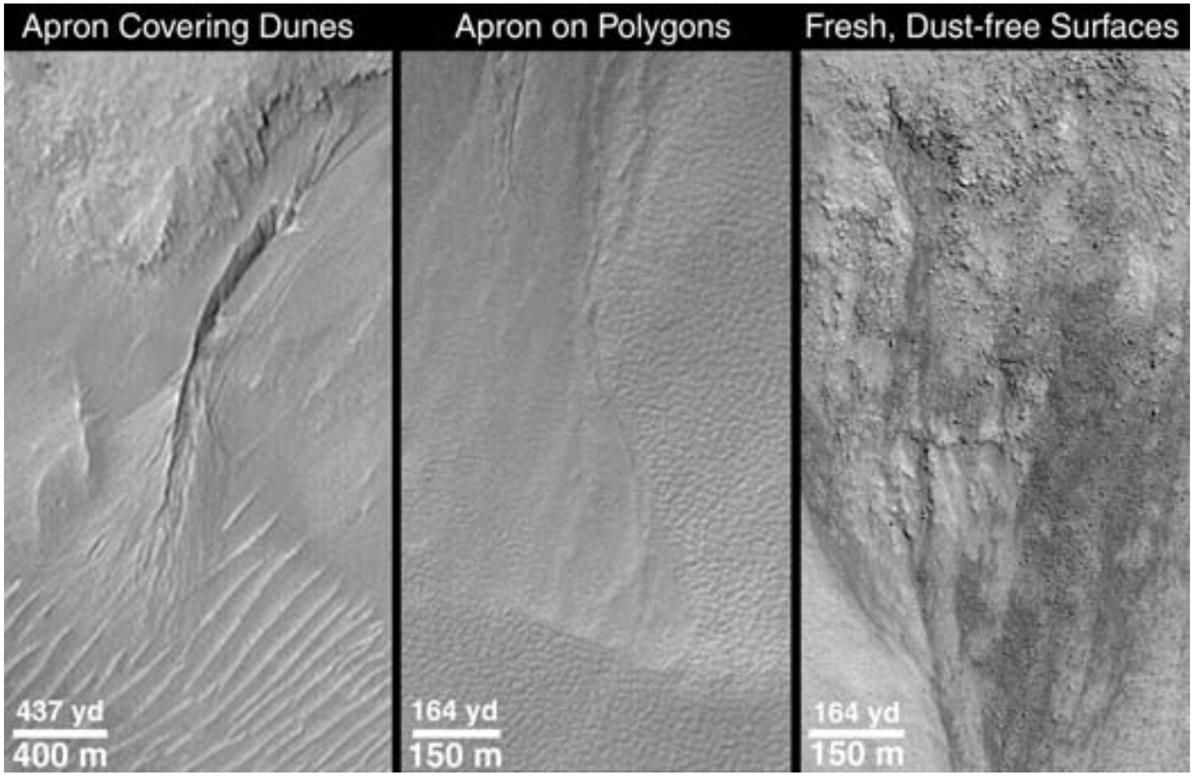


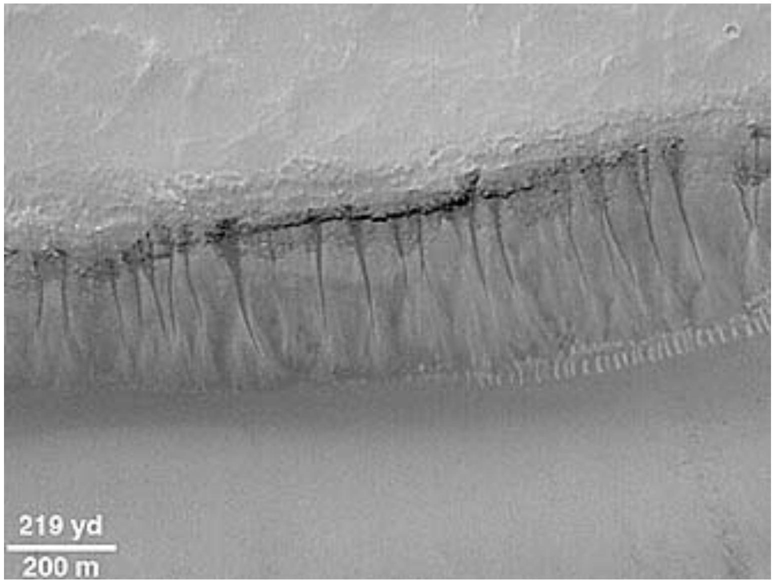
Plaut et al. (2007) *Science*
Vol. 316: 92-95.

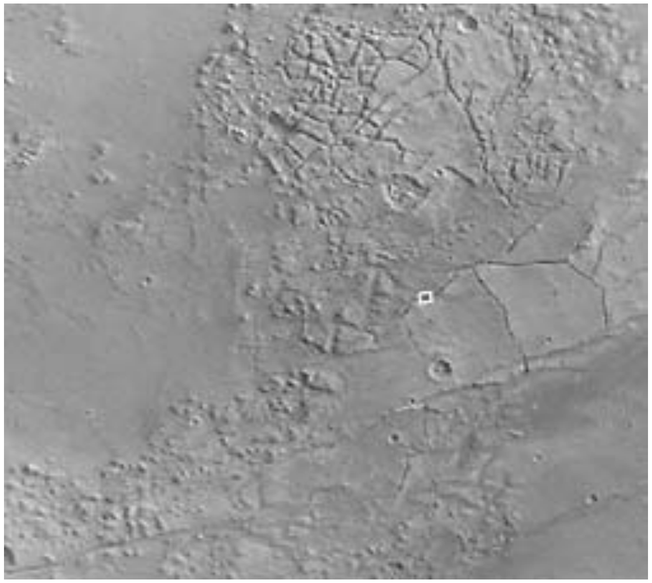
- South Pole water ice thickness: The total volume is estimated to be 1.6 x 10^6 cubic kilometers, which is equivalent to a global water layer approximately 11 meters thick.

Evidence of Recent Water flow on Mars

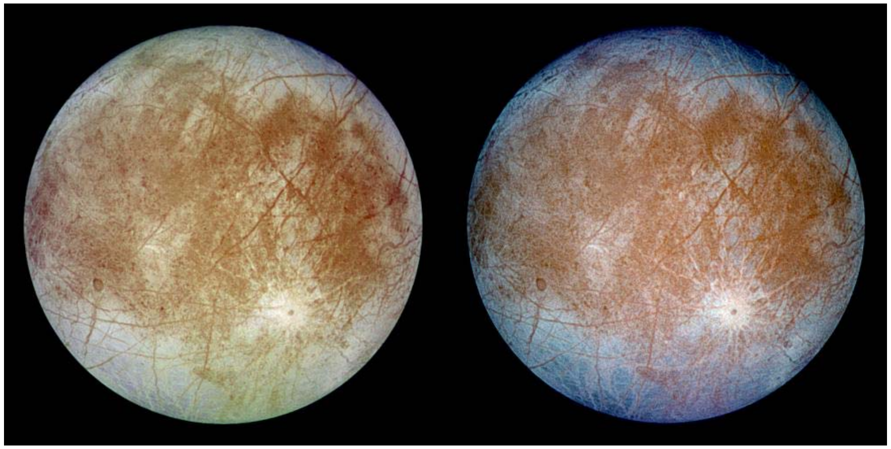
- Martian gullies proposed to have formed by seepage & runoff of liquid water in recent martian times







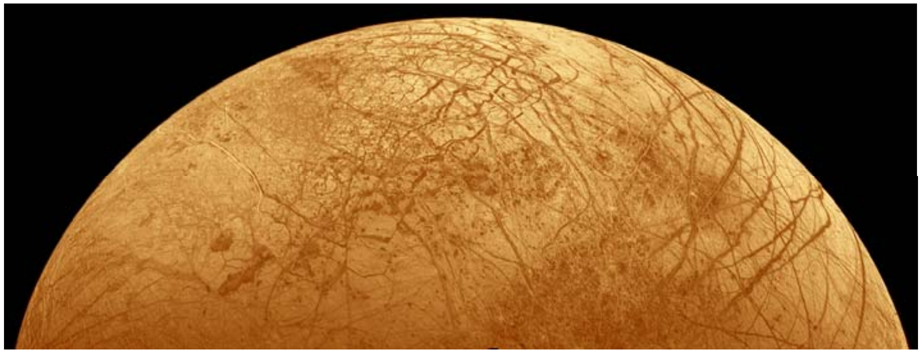
http://www.msss.com/mars_images/moc/june2000/age/index.html



Water on Europa

- One of Jupiter’s 4 large (Galilean) satellites
- 25% of Earth’s radius

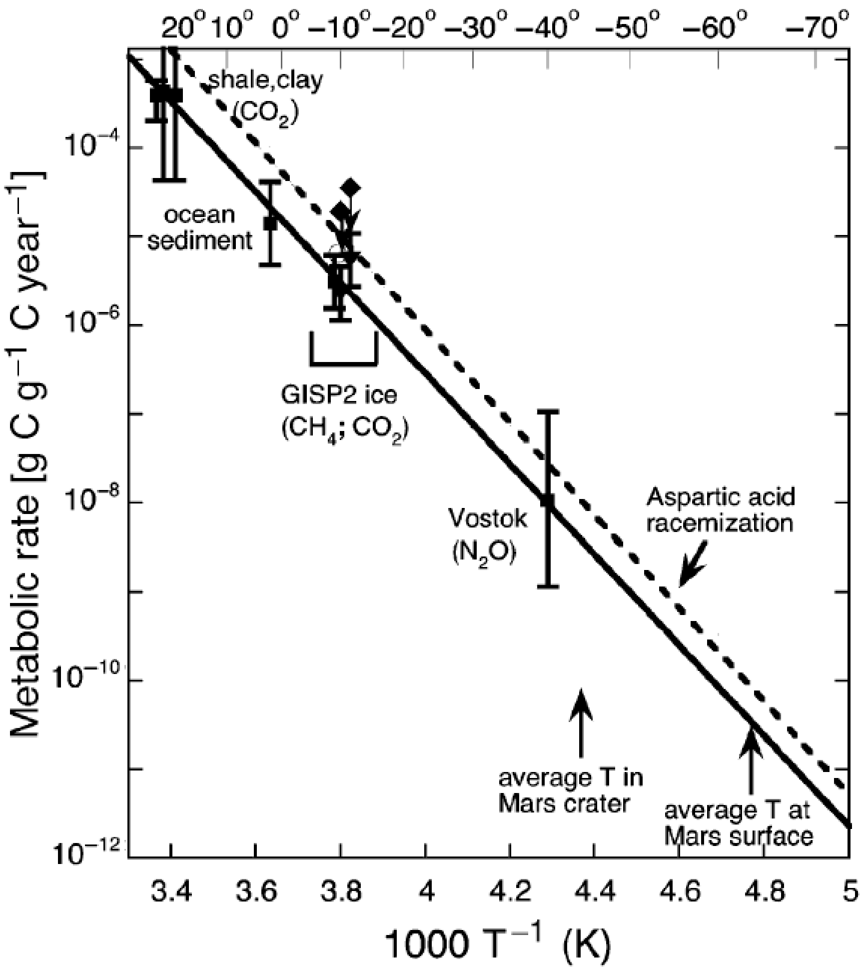
- Crust composed of water & ice



- Fragmented chunks of water ice on Europa’s surface

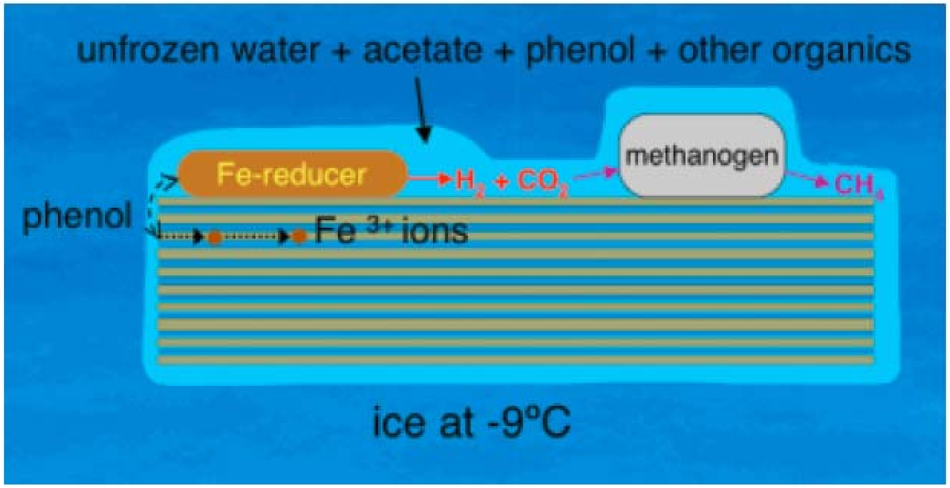
http://science.nasa.gov/newhome/headlines/ast09sep99_1.htm; http://www.solarviews.com/eng/europa.htm

BUT… Life at T below Freezing Point of Water is Possible

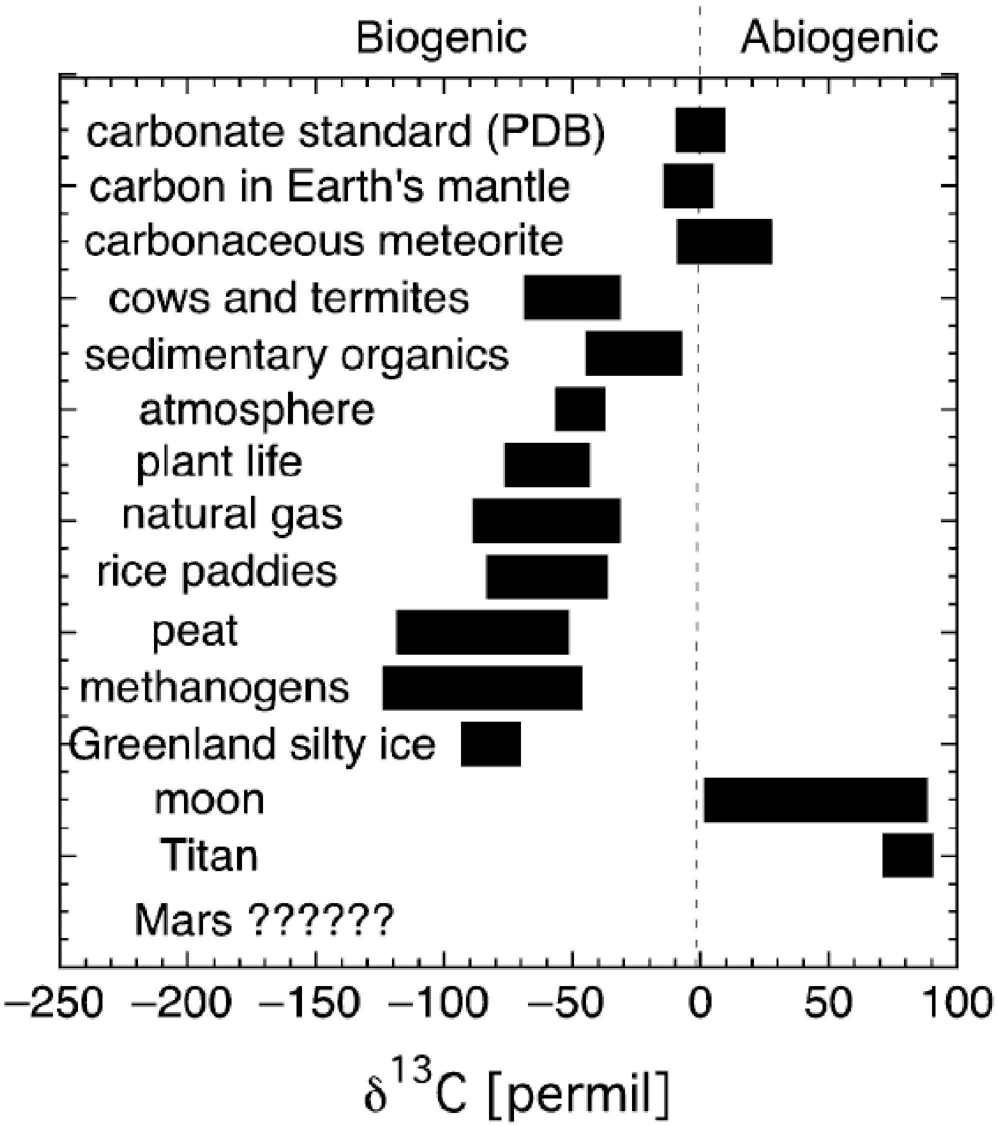


Price (2007) *FEMS Microbiol Ecol* Vol. 59: 217–231

"Application of physical and chemical concepts, complemented by studies of prokaryotes in ice cores and permafrost, has led to the present understanding of how microorganisms can metabolize at subfreezing temperatures on Earth and possibly on Mars and other cold planetary bodies. The habitats for life at subfreezing temperatures benefit from two unusual properties of ice. First, almost all ionic impurities are insoluble in the crystal structure of ice, which leads to a network of micron-diameter veins in which microorganisms may utilize ions for metabolism. Second, ice in contact with mineral surfaces develops a nanometrethick film of unfrozen water that provides a second habitat that may allow microorganisms to extract energy from redox reactions with ions in the water film or ions in the mineral structure. On the early Earth and on icy planets, prebiotic molecules in veins in ice may have polymerized to RNA and polypeptides by virtue of the low water activity and high rate of encounter with each other in nearly one dimensional trajectories in the veins. Prebiotic molecules may also have utilized grain surfaces to increase the rate of encounter and to exploit other physicochemical features of the surfaces."



We Might Infer Life Elsewhere in Solar System the Same Way We Do on Earth--$^{13}C/^{12}C$



Price (2007) *FEMS Microbiol Ecol* Vol. 59: 217–231

Summary of Origin of Life Theories

- Life was probably well-established by ~3.5 Ga
- How it began will seemingly require a lot more work!

- ‘RNA World’
  - -RNA may have preceded proteins
- Hydrothermal Setting / Hyperthermophiles
  - -protection from harsh surf. conditions during heavy bombardment
  - -metals abundant
  - -mineral surfaces for chemical catalysis
- Minerals
  - -catalysis, protection, chirality
- Panspermia
  - -Mars would have been more hospitable for life 4 Ga
  - -Evidence for water & atmospheres conducive to life elsewhere in solar system (e.g., moons of Jupiter & Saturn)

Life Outside the Solar System?

The Drake Equation[*]

Q: What is the possibility that life exists elsewhere in our galaxy?

A: $\boxed{N = N_g f_p n_e f_l f_i f_c f_L \sim \underline{1{,}000}}$

N_g=# of stars in our galaxy ~ 4 x 10^{11} (good)
f_p=fraction of stars with planets ~ 0.1 (v. poor)
n_e=# of Earth-like planets per planetary system ~ 0.1 (poor)
f_l=fraction of habitable planets on which life evolves
f_i=probability that life will evolve to an intelligent state
f_c=probability that life will develop capacity to communicate over long distances $f_l f_i f_c \sim 1/300$ (C. Sagan guess!)
f_L=fraction of a planet's lifetime during which it supports a technological civilization ~ 1 x 10^{-4} (v. poor)

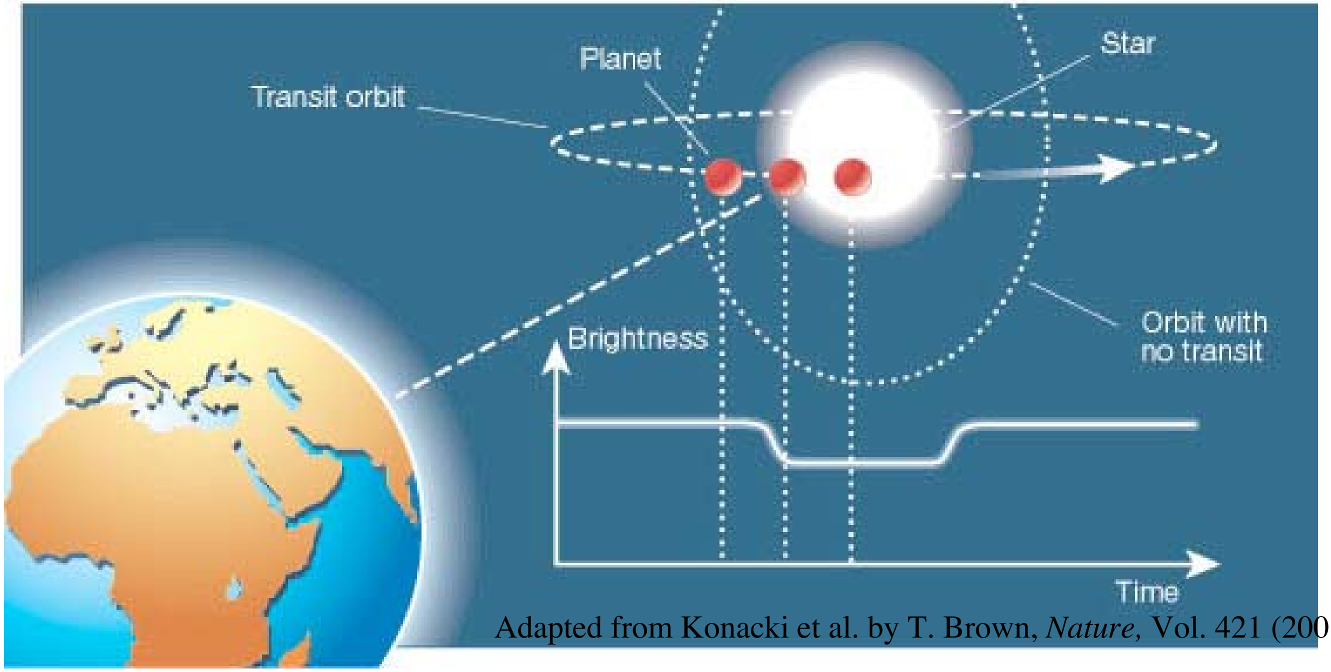
Amended by Siegfried Franck (2008 UW Astrobiology Lecture)

- Fraction of stars with earth-like planets – 0.01
- Fraction in habitable zone – 0.012
- 4x10^{11} (stars in galaxy) * 0.01 * 0.012 =

4.8 x 10^7 habitable planets in Milky Way.

Adapted from Kump et al. (1999) *The Earth System*, Prentice Hall.

Several recent detections of extra-solar planets; one with water!



Adapted from Konacki et al. by T. Brown, *Nature,* Vol. 421 (2003)

- For the first time, water has been identified in the atmosphere of an extrasolar planet. Through a combination of previously published Hubble Space Telescope measurements and new theoretical models, Lowell Observatory astronomer Travis Barman has found strong evidence for water absorption in the atmosphere of transiting planet HD209458b.
- This result was recently accepted for publication in the *Astrophysical Journal.*
- "We now know that water vapor exists in the atmosphere of one extrasolar planet and there is good reason to believe that other extrasolar planets contain water vapor," said Barman.

-April 12, 2007 Astrobiology Magazine

http://www.astrobio.net/news/modules.php?op=modload&name=News&file=article&sid=2298&mode=thread&order=0&thold=0

Earth-like Extrasolar Planet Discovered

"The most enticing property yet found outside our solar system is about 20 light-years away in the constellation Libra, a team of European astronomers said yesterday. The astronomers have discovered a planet five times as massive as the Earth orbiting a dim red star known as Gliese 581. It is the smallest of the 200 or so planets that are known to exist outside of our solar system, the extrasolar or exo-planets. It orbits its home star within the so-called habitable zone where surface water, the staff of life, could exist if other conditions are right, said Stephane Udry of the Geneva Observatory."

-NY Times, 4/25/07