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.

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 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.

Characteristics of the Habitable Zone: known requirements of life?

- Liquid water

- Sources of carbon and energy
  - CO_2, organic matter
  - energy from chemistry of rocks + water
  - energy from the sun

- Mechanisms of renewal and recycling
  - Nutrients limited
  - Space = habitat limited

  - **Mechanism = Tectonism. Is it that simple?**

The Hadean Eon, an inhospitable place

It is more useful to define the Hadean Eon as the time when impacts ruled the Earth than to define it as the time before the rock record. For decades now it has been obvious that the coincidence between the timing of the end of the lunar late bombardment and the appearance of a rock record on Earth is probably not just a coincidence. I doubt I am pointing out something that the reader hasn't long ago given thought to. While the Moon was struck by tens of basin-forming impactors (100 km objects making 1000 km craters), the Earth was struck by hundreds of similar objects, and by tens of objects much larger still. The largest would have been big enough to evaporate the oceans, and the ejecta massive enough to envelope the Earth in 100 m of rock rain. Smaller impacts were also more frequent. On average, a Chicxulub fell every 10^5 years. **When one imagines the Hadean one imagines it with craters and volcanos: crater oceans and crater lakes, a scene of mountain rings and island arcs and red lava falling into a steaming sea under an ash-laden sky.** I don't know about the volcanos, but the picture of abundant impact craters makes good sense --the big ones, at least, which feature several kilometers of relief, are not likely to have eroded away on timescales of less than ten million years, and so there were always several of these to be seen at any time in various states of decay. The oceans would have been filled with typically hundreds of meters of weathered ejecta, most of which was ultimately subducted but taking with them whatever they reacted with at the time --CO_2 was especially vulnerable to this sort of scouring. The climate, under a faint sun and with little $CO_2$to warm it, may have been in the median extremely cold, barring the intervention of biogenic greenhouse gases (such as methane), with on occasion the cold broken by brief (10s to 1000s of years) episodes of extreme heat and steam following the larger impacts. In sum, the age of impacts seems sufficiently unlike the more familiar Archaean that came after that it seems useful to give this time its own name, a name we already have, and that, if applied to the Hadean that I have described, actually has some geological value.

http://www.agu.org/cgi-bin/Sfgate,U51A-10 The Hadean Atmosphere Zahnle, K

Building Blocks for Biomolecules

Problems with a 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 and NH_3)
- 50-50 mixture of right- & left-handed molecules is synthesized; natural molecules are 100% left- or right-handed…

Chirality of Biomolecules

- 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 BP!)
- The Miller-Urey experiment, and 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?

- It may have occurred in the solar nebula during the formation of the solar system.
- Amino acids with a slight L-enantiomeric excess is 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 selct 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.

Chiral Amino Acids in the Murchison Meteorite

See the images and table by Cronin & Pizzarello. *Science* Vol. 275(1997): 951-955.

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

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

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
α 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

Role of Mineral Mineral Surfaces in Biochemical Evolution

Mineral-surfaces can also catalyze organic syntheses under hydrothermal conditions

α See the image and table by Wächtershäuser comment on, Cody et al. *Science* 289 (2000): 1337.

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

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.

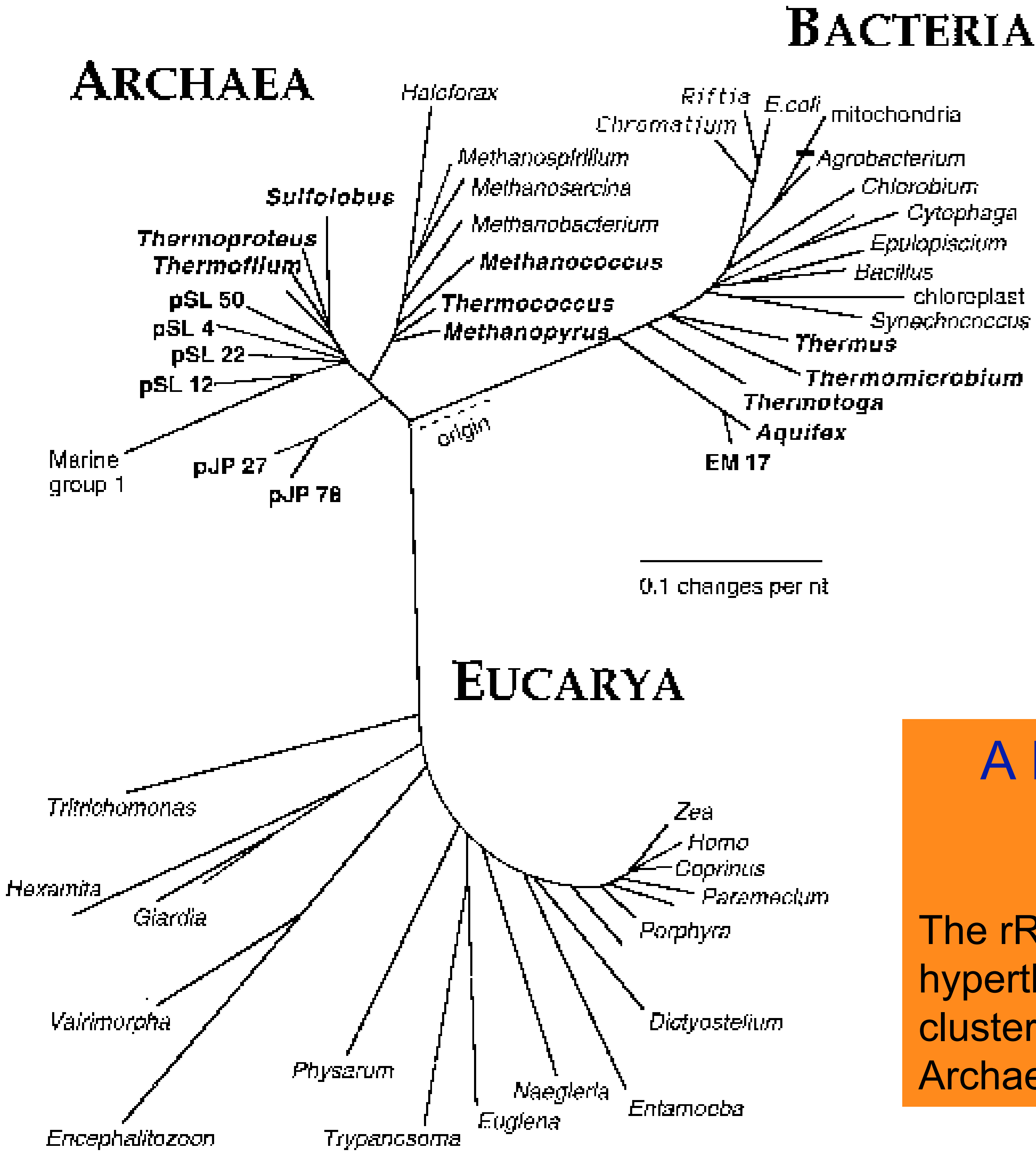
•The recognition that many of the essential enzymes for life require metals common in hydrothermal settings (Fe, Ni, Mo, Cu, Co, Zn) supports this supposition.

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

Shock, E.L. (2001) Geochemical habitats in hydrothermal systems. In: First Steps in the Origin of Life in The Universe, Proceedings of the Sixth Trieste Conference on Chemical Evolution, ed. J. Chela-Flores, Kluwer (in press).

http://zonvark.wustl.edu/geopig/

- Organic synthesis from dissolved inorganic carbon (DIC) is favored by the chemical disequilibria that exists between hot hydrothermal fluids and seawater



rRNA Phylogeny indicates hyper-thermophiles are ancient!

A hyperthermophilic Origin?

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

See the image by Orgel *Sci*. *Am*., Oct. (1994), 77-83.

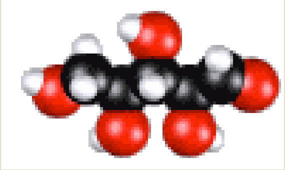
•Late 1960s: Woese (U. Illinois), Crick (England), Orgel (Salk Inst, San Diego) concurrently proposed RNA may have preceded proteins & catalyzed all reactions for survival & replication of 'last common ancestor'.

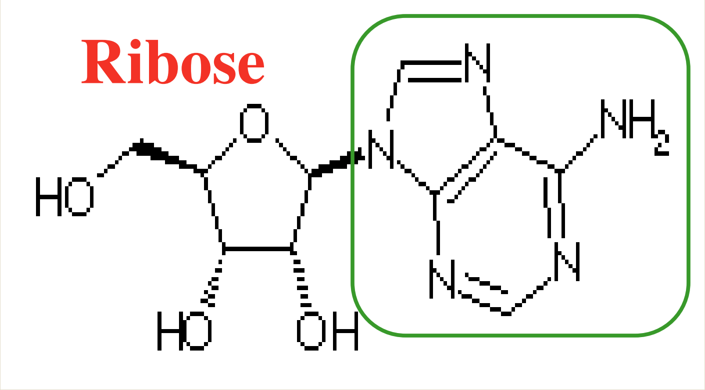
•1983: Thomas Cech (U. Colorado) & Sidney Altman (Yale) independently discovered *ribozymes*, enzymes made of RNA.

• Previously all biomolecules that catalyzed reactions (enzymes) were thought to be proteins (sequences of amino acids).

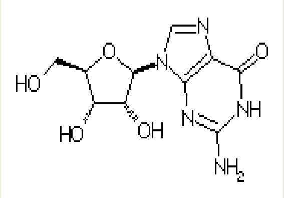
How to make subunits of RNA?

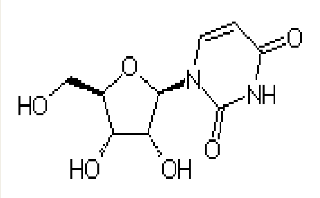
- Phosphate: rock weathering
- Ribose: CO_2 + hν --> 5 COH_2 (formaldehyde) + H_2O --> **Ribose**
- Base: CH_4 + N_2 + hν --> 5 HCN --> **Adenine**

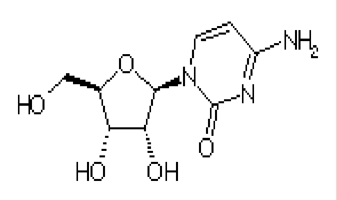




Other 3 RNA Bases: guanine uracil cytosine

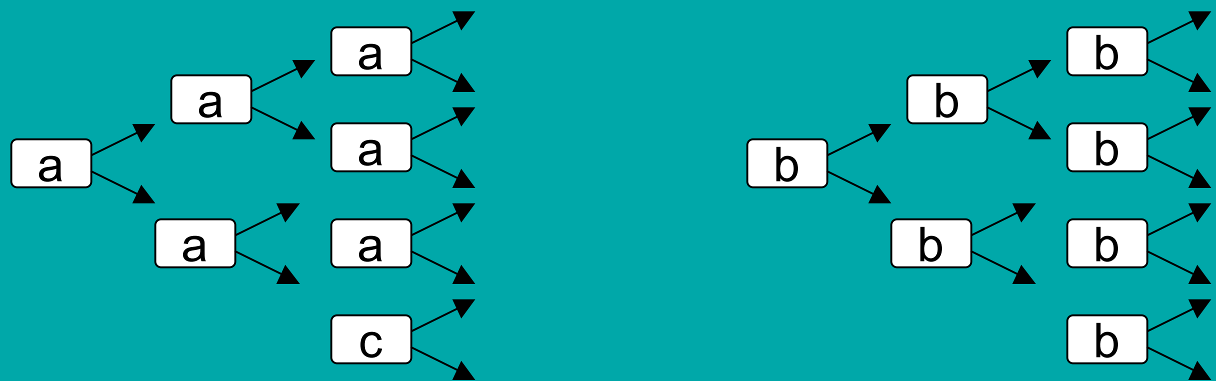






Characteristics of Life-1

- Nobody has a perfect definition
  - Life is disequilibrium! (eg Nisbet & Sleep, 2001)
  - Life defined by characteristics of multiplication, heredity & variation which imply natural selection & metabolism (Maynard-Smith & Szathmary, 1999)

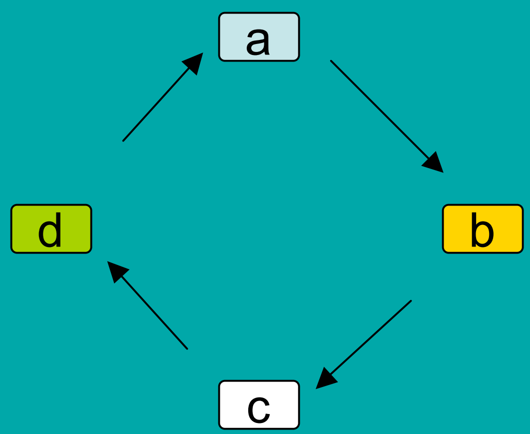


- Multiplication implies one can make two, can make four, etc. Inheritance is not perfect and environmental pressure selects adaptive traits. Thus diversity increases.

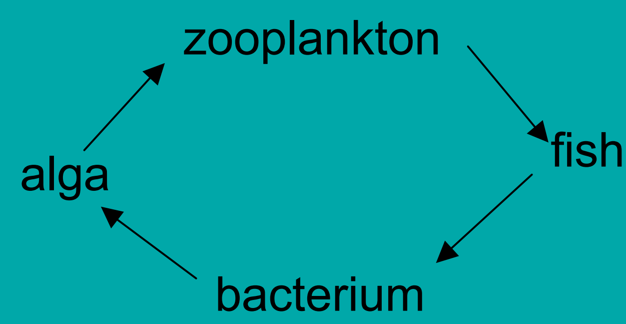
Characteristics of Life-2

<u>Synergy in metabolism</u>

Rates of replication of ‘independent’ replicators become ‘dependent’ if one can utilise another (Maynard-Smith & Szathmary, 1999)

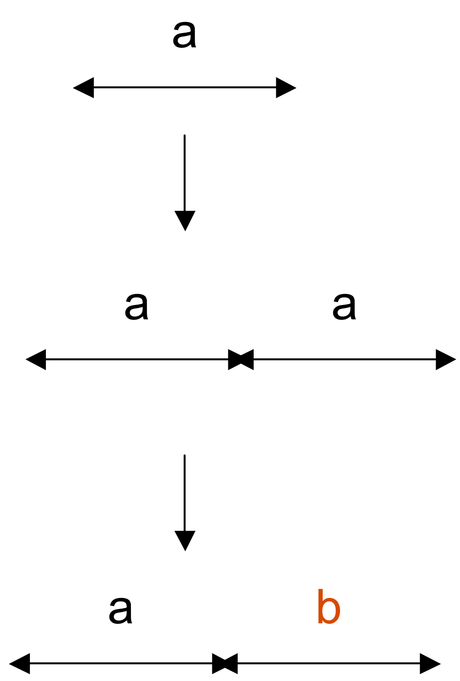


The hypercycle

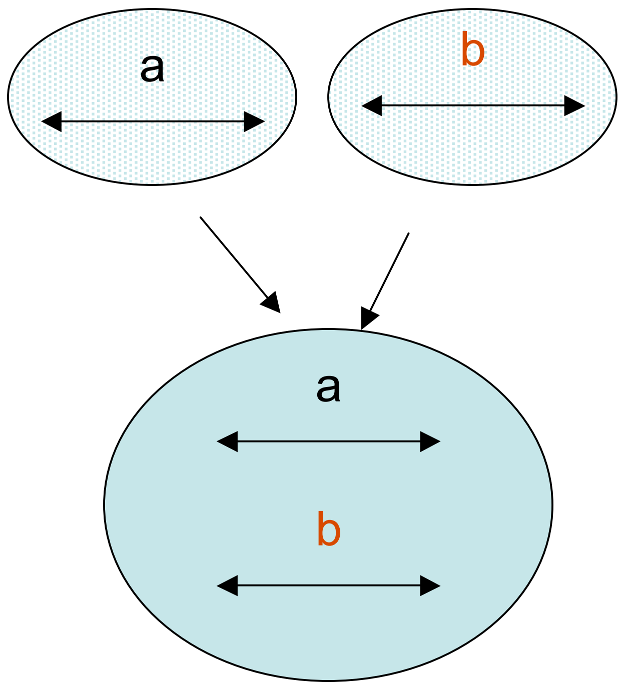


An ecological hypercycle

Two Ways of Increasing Genetic Information



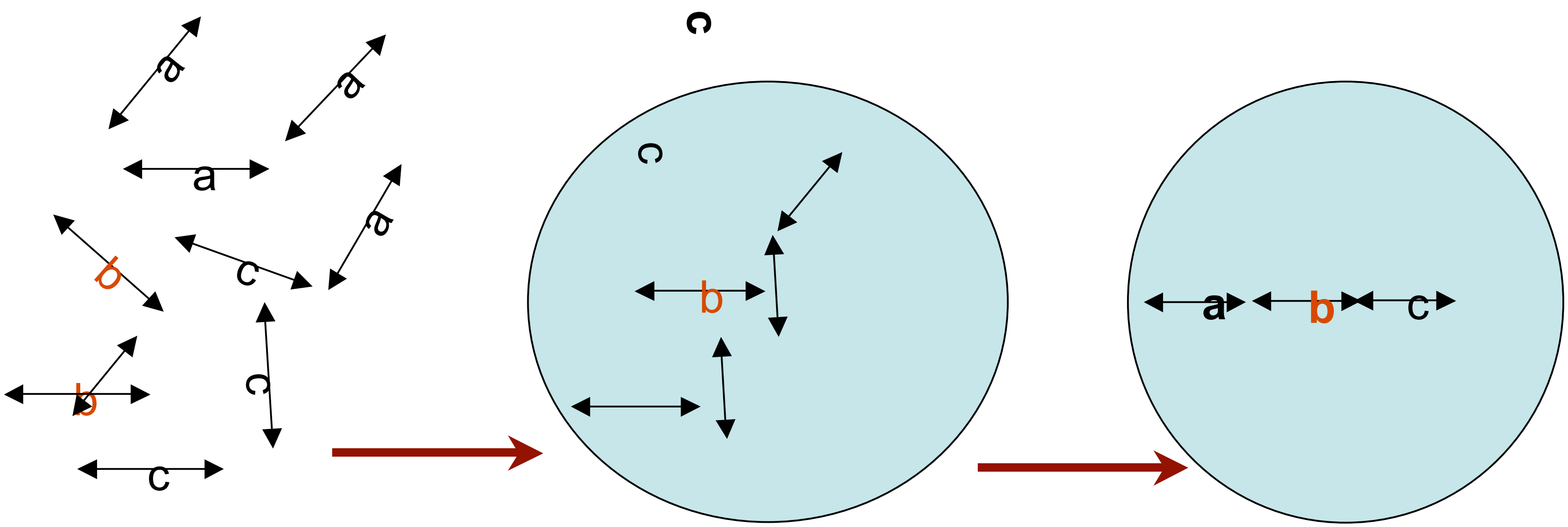
duplication and divergence



symbiosis

After Maynard-Smith and Szathmary, 1999

Other Ways of Increasing Genetic Information



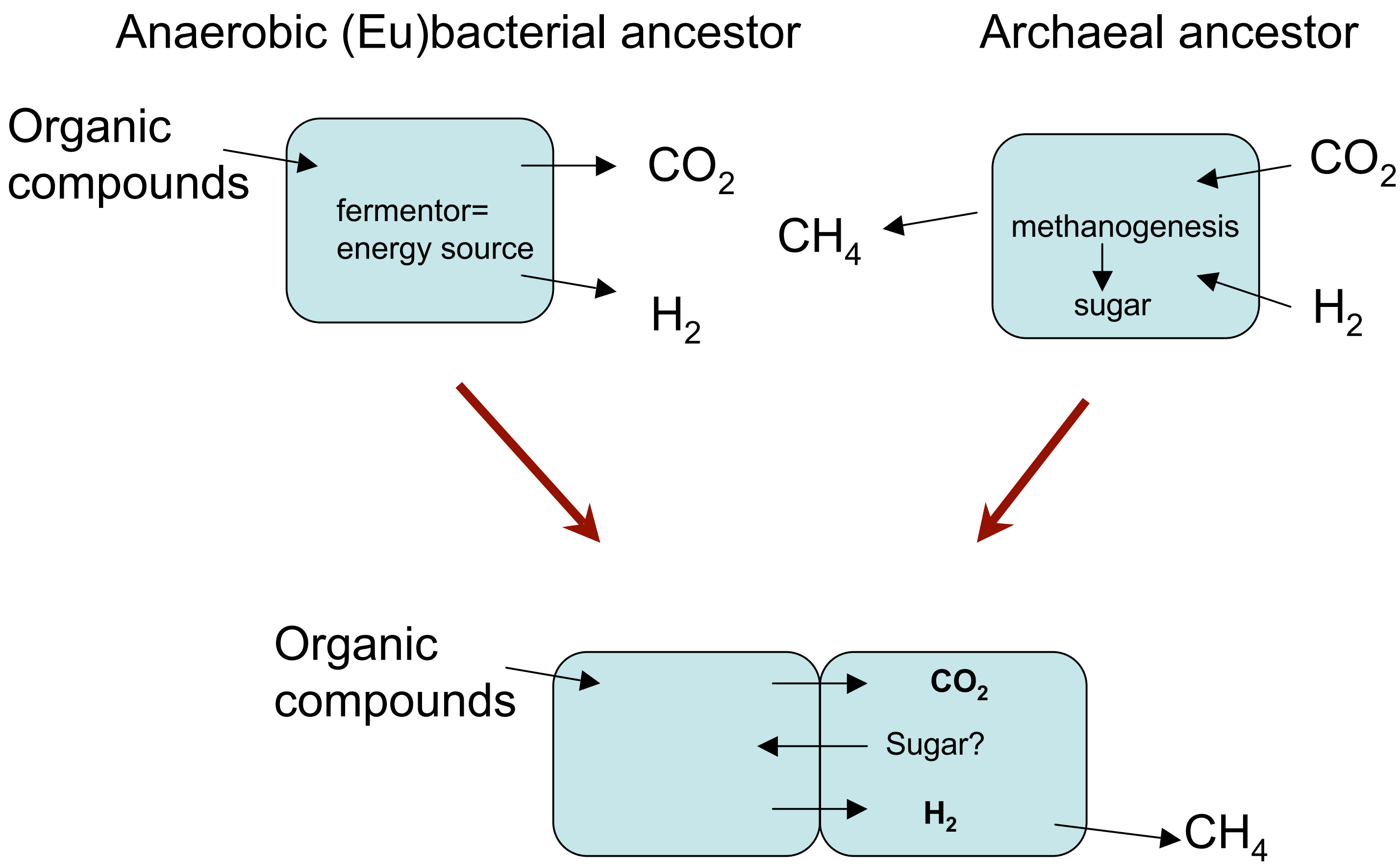
Population of independent replicators in solution

Replicators contained in protocell

'symbiosis' = replication of one requires replication of all ie cooperation

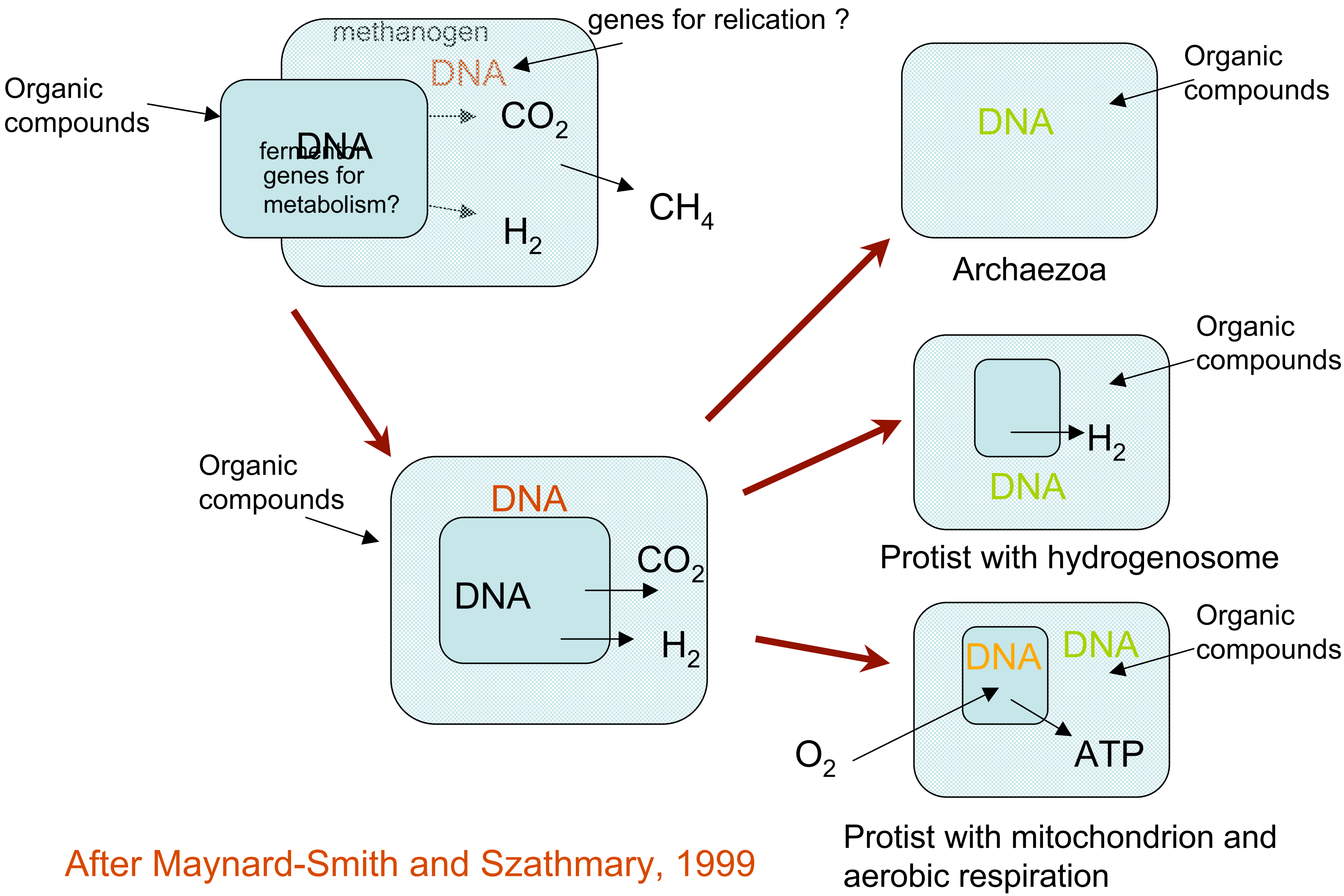
After Maynard-Smith and Szathmary, 1999

Symbiosis leading to proto-eukaryote



After Maynard-Smith and Szathmary, 1999

Symbioses leading to Eukaryotes



After Maynard-Smith and Szathmary, 1999

Complexity of Extant Life

Species	**Type**	**Approx. Gene Number**
Prokaryotes		
E. Coli	typical bacterium	4,000
Protists		
O. Similis	protozoan	12,000-15,000
S. Cerevisiae	yeast	7,000
Distyostelium discoideum	slime mould	12,500
Metazoan		
C. Elegans	Nematode	17,800
D. melanogaster	Insect	12,000-16,000
S. Purpuratas	Echinoderm	<25,000
Fugu rubripes	Fish	50,000-10,0000
Mus musculus	Mammal	80,000
Homo sapiens	mammal	60,000-80,000

After Maynard-Smith and Szathmary, 1999

Major Transitions in Origin/Evolution of Life

replicating molecules	populations of molecules in protocells
independent replicators	chromosomes
RNA as a gene and enzyme	DNA genes, protein enzymes
prokaryotic cells	Cells with nuclei & organelles ie eukaryotes
asexual clones	sexual populations
single bodied organisms	fungi, metazoans and metaphytes
solitary individuals	colonies with non-reproductive castes
primate societies	human societies with language

After Maynard-Smith & Szathmary (1999)

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

Large (400 km) projectile
Ocean completely boiled
230 m rock rain
Return to normal
(100 years Mars)
(3000 years Earth)

Small (70 km) projectile
Dry land surface (Earth and 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 400-km projectile
Moderate to deep subsurface (Mars)
Deep subsurface (Earth)
Only thermophile survivors on Earth
Nonthermophiles probably survive on Mars

Refugia from 70-km projectile
Subsurface (Earth and Mars)
Moderate to deep ocean (Earth)
Thermophile and nonthermophile survivors on both planets

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

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 107-108 rocks per million years

10-4 of rocks arrive within 10,000 years of impact

Rate of transfer of fresh rocks is 104 per million years

Early solar system rate 103 higher

Billions of fresh rocks transferred

Conclusions

Subsurface of Mars was safer than the Earth

Space transfer of organisms seems feasible

There is biological evidence for partial sterilization of the Earth

Space transfer of life to Earth is a viable possibility

Water Elsewhere in Solar System CO_2 +

Water Ice on Mars

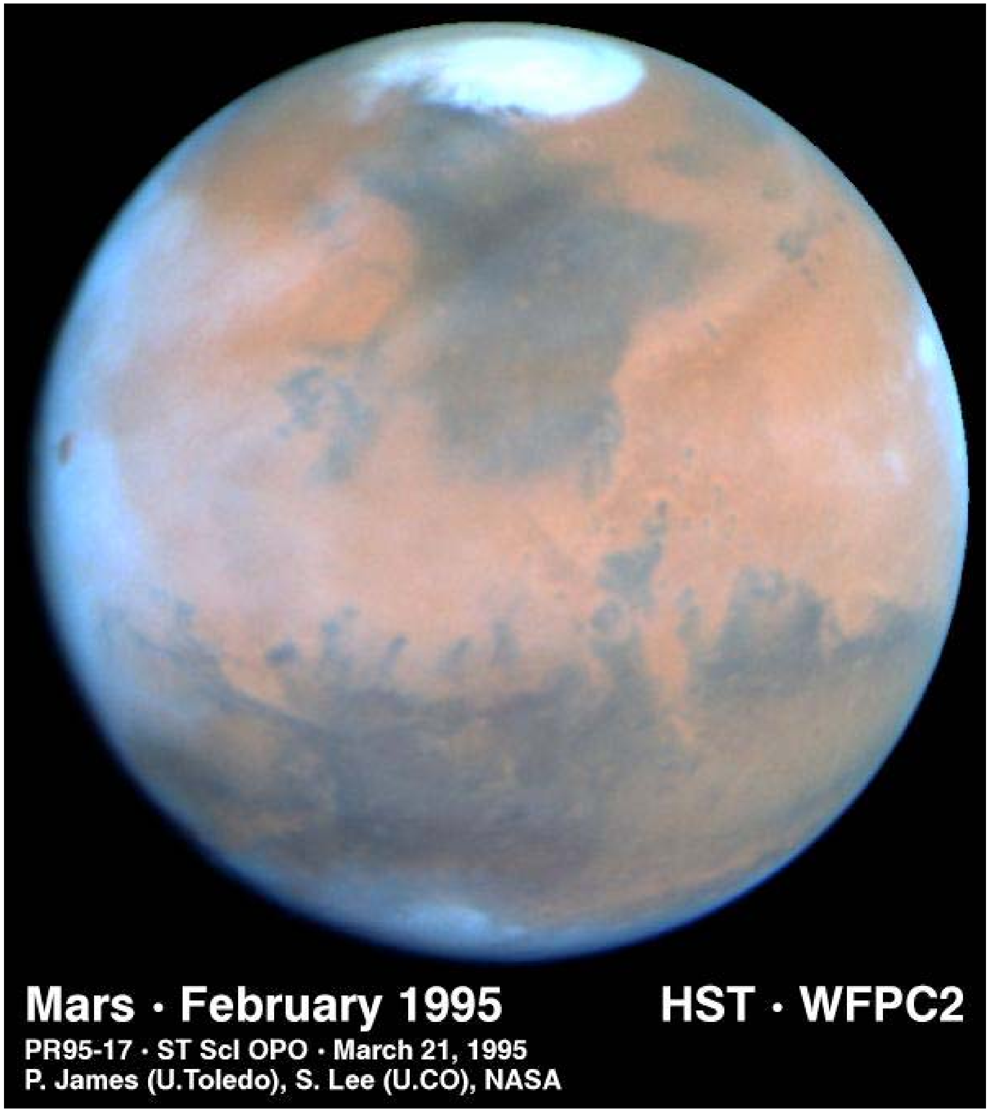


Image courtesy of Hubble Space Telescope.

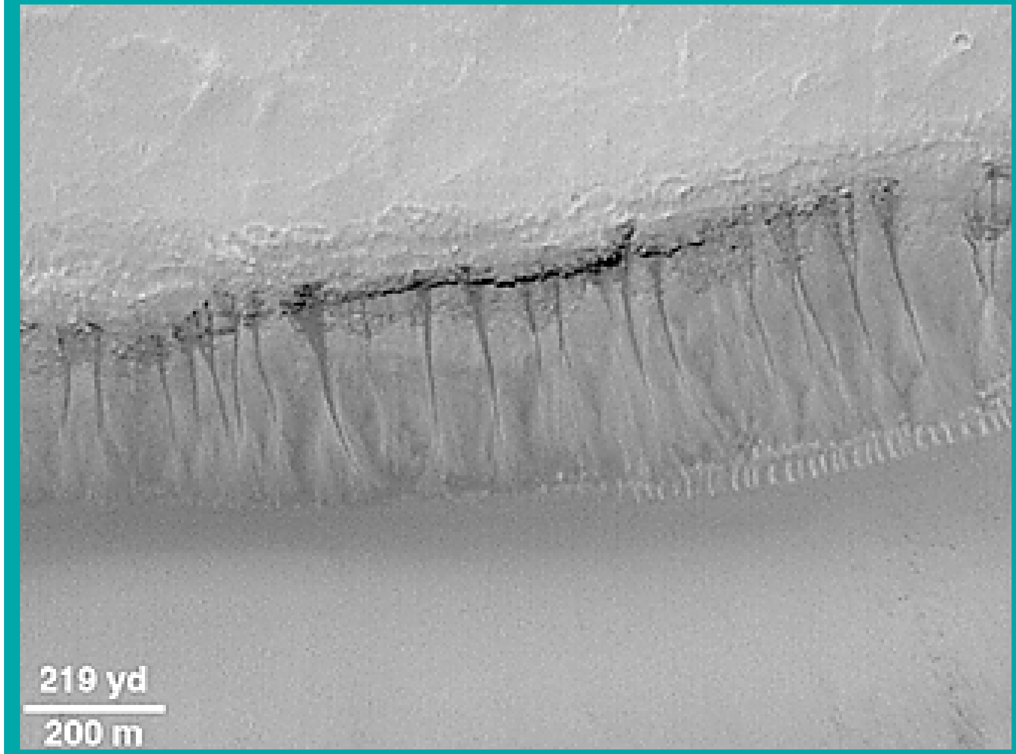
Water Elsewhere in Solar System Evidence of recent water flow on Mars

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

Gullies seen on martian cliffs and crater walls in a small number of high-resolution images from the Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) suggest that liquid water has seeped onto the surface in the geologically recent past. The gully landforms are usually found on slopes facing away from mid-day sunlight, and most occur between latitudes 30° and 70° in both martian hemispheres. The relationship to sunlight and latitude may indicate that ice plays a role in protecting the liquid water from evaporation until enough pressure builds for it to be released catastrophically down a slope. The relative freshness of these features might indicate that some of them are still active today--meaning that liquid water may presently exist in some areas at depths of less than 500 meters (1640 feet) beneath the surface of Mars. The evidence for recent water activity is described in a paper by MGS MOC scientists being published in the June 30, 2000, issue of Science. The gullies are rare landforms that are too small to have been detected by the cameras of the Mariner and Viking spacecraft that examined the planet prior to MGS.

Martian Gullies

This picture (left), acquired by the Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) in May 2000 shows numerous examples of martian gullies that all start—or head--in a specific layer roughly a hundred meters beneath the surface of Mars. These features are located on the south-facing wall of a trough in the Gorgonum Chaos region, an area found to have many examples of gullies proposed to have formed by seepage and runoff of liquid water in recent martian times.



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!

<u>Some promising theories:</u>

•'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 and atmospheres conducive to life elsewhere in solar system (e.g., moons of Jupiter and Saturn)

Life Outside the Solar System?

The Drake Equation*

Q: What is the possibility that life exists elsewhere?

A: $\boldsymbol{N = N_g f_p n_e f_l f_i f_c f_L}$ **~ 1,000**

N_g=# of stars in our galaxy ~ 4×10^{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 $f_l f_i f_c$ ~ 1/300 (C. Sagan guess!)

f_L=fraction of a planet's lifetime during which it supports a technological civilization ~ 1×10^{-4} (v. poor)

*An estimate of the # of intelligent civilizations in our galaxy with which we might one day establish radio communication.