Short Course: Methane on Mars

Biology: Potential Life in the Martian Context

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The problem with Life: It’s hard to define!!

Does life have to be like earthly life? Why?

Could we detect it if it was different? How?

Can one devise a non-EC strategy?

Which properties of life are universal?

Which properties of life can be quantified?
Characteristics of Living Systems

1. Complexity of structure
   (elemental composition; monomer compositions; chirality, etc.)
   
   A. Cellular structure separating inside from outside: (membranes)
   B. Complex machines (enzymes)
   C. Elemental composition (non-mineral)
   D. Proteins, Nucleic acids, Lipids, etc.

2. Complexity of function
   Uptake, metabolism, excretion
   
   A. Enzyme Catalysts speed up reactions
   B. Transport systems take up “food”
   C. Complex metabolism converts energy
   D. Transport systems dispose of waste

3. Observable environmental effects
   establishment of chemical gradients and layers
   
   A. Consumption or production at fast rates – gradient formation/LMC’s
   B. Kinetic isotope effects
   C. Food disappears; waste appears

4. Non-random movement
   
   A. All life is capable of movement of some kind!
Fundamental Features of Life

ENERGY CONSUMPTION

Many Different Shapes
Metabolic Diversity

LIFE
SHAPE
COMPOSITION
-- Complexity --

PRODUCTS:
WASTE
BIOMINERALS
CELLS

ACTIVITIES:
MOVEMENT
(molecules, cells, etc.)

Many Copies (never see one!)

EVOLUTION

REPLICATION
What is general about life?

**Structure and Chemistry**
- Find the structures
- Determine their chemistry
  - Elemental composition
  - Chiral composition
  - Isotope fractionation
  - Complex molecules

**Thermodynamics and Kinetics**
- Define the system
  - Energy sources
  - Electron donors
  - Electron acceptors
- Identify temporal and spatial extents of energy disequilibria
  - Layer formation
  - Temporal disruptions

**Non-Random Movement**
- Observe Movement
  - Spatial scales
  - Temporal scales
  - Data treatment

*Geobiology*  *USC*  *Astrobiology*
So: what does life require?

1. Solvent: Very hard to catalyze organic reactions without water (hydration and dehydration are the essence of biochemistry)

2. Source of nutrients (food) = electron donors and electron acceptors

3. Structural nutrients: Carbon, hydrogen, oxygen, nitrogen, phosphorous, sulfur

4. Functional nutrients: Carbon, nitrogen, phosphorous, sulfur, plus metals
electrons

Respiration = electron flow!

- RED = Animal Respiration
- RED & BLUE = Bacterial Respiration
- Green = solids

ENZYMES

CELL MEMBRANE

\[ e^- + O_2 \rightarrow H_2O \]

Voltage For Biological Work (making ATP!)

- CO₂
- SO₄²⁻
- Fe(OH)₃
- MnO₂
- NO₃⁻
Relative Voltage ($P\varepsilon^o(W)$)

-10
-8
-6
-4
-2
0
+2
+4
+6
+8
+10
+12
+14

Organic Carbon via photosynthesis

- $H_2$
- $H_2S$
- $SO$
- $Fe(II)$

Inorganic Fuels -- from hydrothermal reactions or via anaerobic respiration

- $NH_4^+$
- $Mn(II)$

These inorganic fuels used only by prokaryotes (bacteria & archaea)

(From Stumm & Morgan, Aquatic Chemistry)
Oxidants of Life: (electron acceptors)

Oxygen is best oxidant
(most energy)
Used by “all” eukaryotes

Inorganic compounds are used only by prokaryotes (Bacteria and Archaea)

Now Add things like chlorinated hydrocarbons (man-made oxidants)

\[ \text{CO}_2, \text{SO}_4^{2-}, \text{AsO}_4^{3-}, \text{FeOOH}, \text{SeO}_3^{2-}, \text{NO}_2^-, \text{NO}_3^- \]

\[ \text{MnO}_2, \text{NO}_3^-/\text{N}_2, \text{O}_2 \]
The Geological Environment Supplies Many Oxidants And Reductants That Life has Learned to Utilize!!

Let's put This Together NOW!!

Voltage Available For Charging Biological Capacitor!
HOW LIFE WORKS (on Earth!)

Mitchell “Hypothesis”

1. Impermeable membrane to charged molecules
2. Membrane bound electron and H carriers
3. Alternation of these carriers
4. Spatial arrangement

5. Electrons flow from high to low energy state
6. Ultimately oxidized by some electron acceptor

7. During this process, protons transported to exterior

8. Reactions are (should be) reversible
Energy from electron flow used to drive reactions of life -- Same idea for virtually all of life on Earth!

Electron Donor → Electron Flow (absolutely necessary!) → Electron Acceptor

Charge Separation !!
How Life Works** (part II)

Electron Donor = NADH

Electron flow pumps protons to exterior – proton and pH gradient used to make biological energy “charging the biological capacitor” !! = PMF !!
How Life Works: (ATP synthesis)

Electron Donor

$3 \text{H}^+ + 3e^- = \text{Proton motive force (PMF)}$

Membrane with e- carriers

ATPase

ADP + Pi $\rightarrow$ ATP

ATP made as protons flow back into cell

PMF used directly for transport, motility, and other functions.
How Life Works: (motility)

Electron Donor

\[ 3H^+ + 3e^- \]

Proton motive force (PMF)

\[ H^+ H^+ H^+ \]

Membrane with e- carriers

Flagellum Motor !!

PMF used directly for motility --
Flagellum doesn’t use ATP, powered by proton flow!

Electrons flow, PMF generated, flagella rotate !!
How Life Works: (transport)

Electron Donor

\[ 3 \text{H}^+ + 3e^- \]

Proton motive force (PMF)

Membrane with e- carriers

Transport Proteins

H+

As protons flow back into cell
PMF used directly for transport
Transport good things IN, or
Bad things OUT !!

Electron Acceptor
Light -- Photons

Organics – e⁻

Inorganics – e⁻

Phototrophy

Organotrophy

Lithotrophy

NAD → NADH

Life – electron flow

Mitchell Mechanism

Proton Motive Force (PMF)

ATP (energy)

Active Transport

(good things in; bad things out)

Motility
Bacterial respiration

Chemical Energy (ATP)

Metal Oxide

Glucose → H_2O + CO_2
The molecular machines
Of Extracellular
Electron Transport (EET)

Shewanella oneidensis

ELECTRODE
(ANODE)

ΔΨ+

ΔΨ-

MtrC

MtrB

MtrA

CymA

Heme

Q/QH₂ pool

QH₂

Q

Q/H₂ pool

Outer membrane

Periplasm

Inner membrane
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Water as a solvent: we need more information, but with recent reports of flowing water on Mars, the stage is at least partially set.

Energy (electron flow) -- Electron donors

Photons: light can power electron flow, but still need reductants for photosynthesis:
  On Earth, life uses H₂S, S⁰, H₂, Fe²⁺, and H₂O – can’t do electron flow without electrons

Inorganics: a wide array of inorganics can be used, including H₂, produced geologically can be used, with resulting reduction of CO₂ to organic carbon, and/or methane.

Organics: methane is a high-energy substrate used by a number of prokaryotes both aerobically and anaerobically (the experts will be at the workshop!).
What will sustain life on Earth?

Energy (electron flow) -- Electron acceptors also needed

Inorganics:
  - gases – oxygen & CO₂
  - dissolved salts – NO₃⁻, SO₄²⁻, etc.
  - solids – Mn oxides; Fe oxides (Extracellular Electron Transport)

EET: Well-documented for iron and manganese oxides
EET: Well-documented for soluble metals that become insoluble on reduction (U,Cr,Se, etc.)
EET: Well-documented for microbes that grow on reduced solids (S⁰, FeSₓ, etc.)
EET: Well-documented for microbes that grow on electrodes
  - anodes: electron acceptors
  - cathodes: electron donors
What can we learn by studying the Earth, that will help us in the search for life on Mars?

1. Life is tough – extremophiles!
2. Life is tenacious (long survival times)
3. Life is metabolically diverse (it eats anything, it breathes anything!!)
4. Life is intimately connected with the geosphere – minerals and rocks are the product of life’s interaction with geosphere!
What do we need to learn about Mars in order to ascertain whether life is (or was) present on the red planet?

1. The presence over time of a suitable solvent (water)
2. The types and abundances of electron donors over time.
3. The types and abundances of electron acceptors over time.
4. Detailed analyses of Martian minerals and structural materials: a) Elemental analyses; b) organic analyses; c) stable isotopes.
LET’S THINK ABOUT THIS TOGETHER !!

THANKS FOR YOUR ATTENTION
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