Searching for Life in the Solar System... and Beyond!

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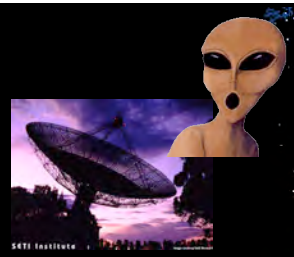
Cornell University

Outline

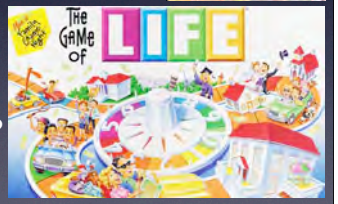


- What is Life?
- Life in Extreme Environments
- The Searches for Extrasolar Planets and Extraterrestrial Intelligence (SETI)

Astrobiology

- *Astrobiology* (sometimes called *Exobiology*) is the study of life in the Universe
  - *Origin of Life*
  - *Distribution of Life*
  - *Ultimate Fate of Life*
- Astrobiology today is an *extrapolation* from the one known example (Earth life), using the basic principles of chemistry & physics and observing the Universe around us...

But first...What is Life?



- The question is philosophical, poetic, spiritual, intangible... but also scientific!
- To find life we must define what we seek...
- "Intuitive" definition:
  - *"I know it when I see it"*
    - Not very rigorous
    - Applies only to Earth life?

What is Life?

- A more rigorous definition:
  - Something is alive if it has the ability to ingest nutrients, give off waste products, & reproduce
  - But what are nutrients?
  - What are waste products?
  - Is *growth* important? (mountains "grow"...)
- Clearly the definition must acknowledge that life is hard to define and that there are likely to be exceptions to any rules proposed...

Attributes of Living Systems...

- Rather than *defining* life, can we *describe* it in terms of specific attributes?
- Life has at least two unique attributes:

(1) A living system must be able to reproduce, to mutate, and to reproduce its mutations

(2) A living system must be able to convert external energy sources into useable internal energy sources

But even this gets dicey...

- There are systems with one attribute but not both
  - Chemical Reactions
    - CO_2 "reproduces"
    - But it's not alive!

CO_2 + sunlight --> CO + O
H_2O + sunlight --> H + OH
CO_2 + OH --> CO_2 + H

  - Crystals
    - "reproduce" in regular patterns, get distorted (mutated)
  - Fire
    - Uses "nutrients", converts energy, "grows", "reproduces", ...
  - Many other "fuzzy" cases...
    - Mules? A virus? Computer programs? Robots?

The Essential Requirements

- *Liquid Water*
  - "Medium" for the chemistry of life (mobility, nutrients)
  - Stable over wide range of temperatures
  - Unique freezing properties help maintain stability
  - Complex organic compounds don't dissolve in water!
- *Source of Excess Energy*
  - Sunlight (photosynthesis)
  - Chemical (oxidation)
  - Thermal or geothermal...
- *Source of Organic Molecules*
  - C, H, N, O, P, S combined in both simple and complex ways
  - "Simple" organic molecules appear to be abundant out there…

Origin of Life on Earth?

- Key Questions:

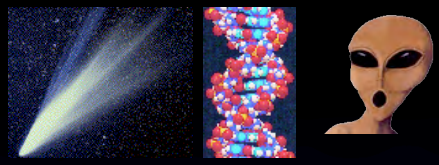
(1) Did life originate on Earth or in space?

(2) If life originated on Earth:

(a) What were the conditions like on early Earth that made possible the origin of life?

(b) Did life originate on or near the surface, below the surface, or in the oceans?

"Panspermia"

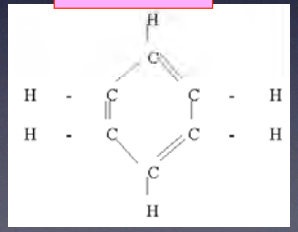


- Swedish chemist Svante Arrhenius proposed in 1908 that life is ubiquitous in the Cosmos and that "spores" or the seeds of life were delivered to Earth essentially by accident
  - No attempt to explain how life originated, only how it got to Earth
  - How did the "spores" get off other planets? (impacts?)
  - How did the "spores" survive harsh interstellar radiation?
- More recent variation: "intentional" panspermia
  - Life was planted on Earth by space travelers
  - Popular among science fiction fans and conspiracy groupies
  - Still doesn't explain how life originated though...

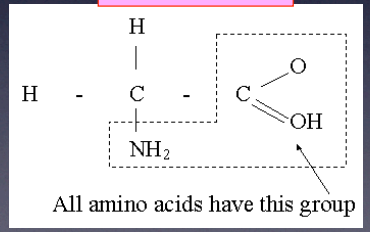
Organic Molecules in Meteorites

- Some complex organic molecules (molecules containing carbon) have been found in some of the most primitive carbonaceous chondrite meteorites
  - Alkanes, benzene, paraffins, amino acids, …

Benzene: C_6H_6



Glycine: $C_2NH_5O_2$



Organic Molecules in Exotic Places

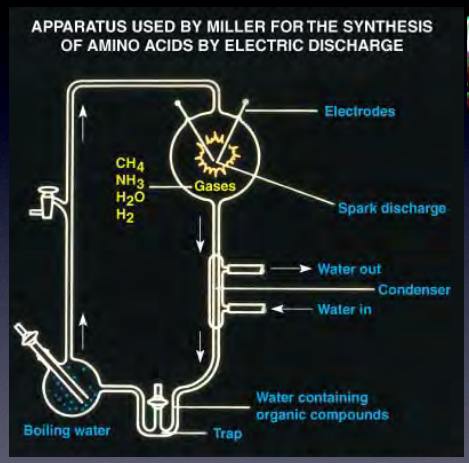
✓Complex organic molecules have also been found or inferred to exist in:
- –Interstellar molecular clouds
- –Comets
- –Interplanetary dust particles
- –Some dark asteroids, rings, & planetary satellites
- –Some other "anomalous" meteorites (*e.g.*, ALH84001)

✓Did life on Earth originate from raw materials brought in by the early "rain" of debris from asteroid, comet, and cosmic dust impacts?

Could Life Have Originated on Earth?

- Hypothesized environment of the early Earth:
  - Heating of interior, release of volatiles
    - H_2, H_2O, CH_4, and NH_3
  - H_2O forms liquid ocean at Earth's P,T
    - NH_3 dissolves in water
  - Result is a highly-reducing atmosphere
    - H_2, CH_4 abundant
    - Little if any free O_2
- Can *simulate* this environment in the lab...

The Miller-Urey Experiments
(early 1950s, U. Chicago)



- Water = primitive ocean
- CH_4, NH_3, H_2 = primitive atmosphere
- electrical discharge = lightning
- cycling through ocean...

- RESULTS:
  - complex organic molecules
  - simple amino acids!
  - life's building blocks!

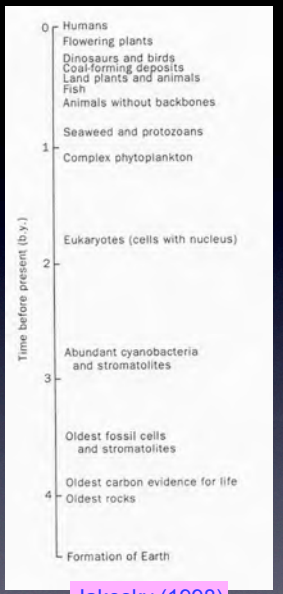
Making Primordial Soup

Life on Earth

- The Miller-Urey experiments were perhaps too simplistic, but they demonstrated that the interactions of liquid water, natural energy sources, and organic molecules leads to the production of complex organic molecules
- Even if the Urey/Miller process was not efficient enough to produce large quantities of organics, remember that organics formed elsewhere were still being delivered to the early Earth by impacts...
- The building blocks of life are abundant in the Cosmos!
- But how did the building blocks become *alive* ???

Life on Earth

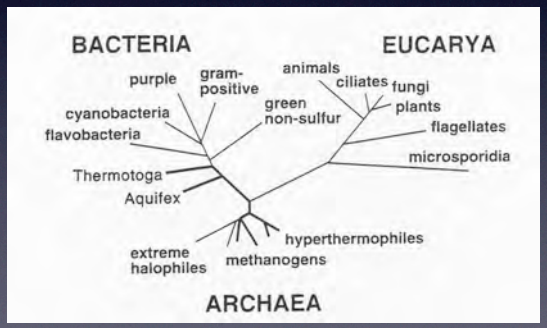
- Very soon after the early Earth cooled and the impact rate slowed, life appeared
- How? No one knows...
- Miller-Urey and more than 50 years of subsequent experiments have not been able to reproduce the result
- Life has slowly increased the amount of free O_2 in Earth's atmosphere over time
- Atmosphere is in *disequilibrium*



Jakosky (1998)

Starting Simple...

- Life on Earth started simple
- Most life on Earth *remains* simple
- All life on Earth is similar at a basic level

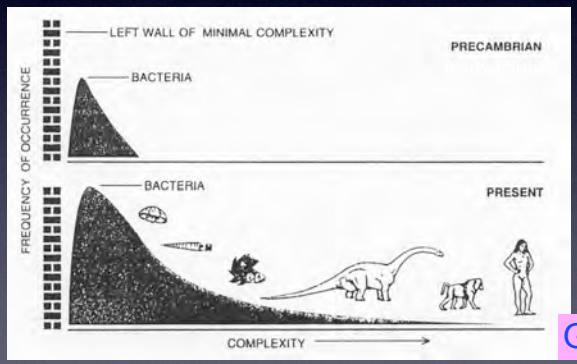


"Tree of Life" for Earth, based on similarity in RNA sequences among all life forms (past and present) on this planet

(Woese, 1987)

Complexity is rare...

- A census of life on Earth today or 3 billion years ago would reach the same conclusion: life on Earth is dominated by simple bacteria!



Gould (1994)

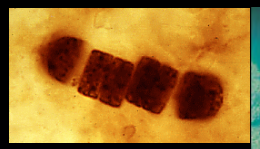
...and Accidents Happen!

- Evolution towards more complex life forms is not necessarily inevitable
  - bacteria are very efficient life forms...
- External, even random forces play a role
  - *e.g.*, Gould's theory of "punctuated equilibrium"
- Starting over again with the same initial conditions, could the experiment be repeated?
  - Would life form at all? (hmm...)
  - Would evolution follow the same path? (probably not)

Some Big Questions

- Has this happened elsewhere?
  - in the solar system?
  - in the Galaxy?
  - in the Universe?
- Can we use our knowledge of the formation and evolution of life on Earth to make predictions about the nature, distribution, and abundance of life "out there" ?
- Should we seek simple life, or complex life?

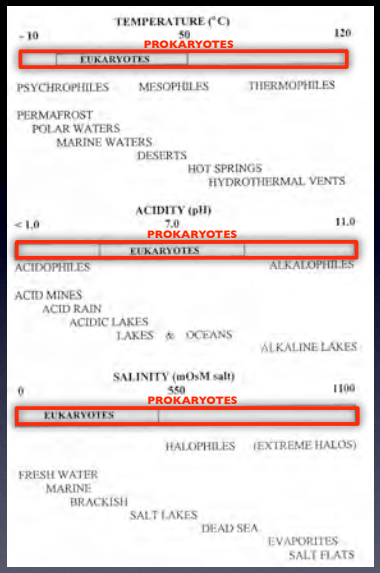
Life on Earth



- Life developed *early* on the Earth
- Conditions have not always been ideal...
  - Changing atmospheric chemistry
  - Large-scale variations in climate
  - Active geology
  - Impacts
- The result of life's adaptability to these variations is a dizzying array of *diversity*

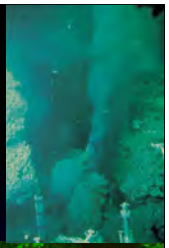
Extremophiles

- Evidence of the diversity of life is provided by groups of micro-organisms knows as *extremophiles* (lovers of extreme conditions)
- These life forms occupy niches of:
  - Extreme temperature
  - Extreme acidity
  - Extreme salinity
- Greatest range: prokaryotes
  - Simple, single-celled organisms
- Substantial range: eukaryotes
  - More complex, nucleated, and/or multicellular organisms

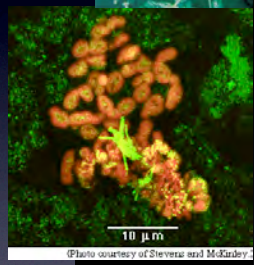


Nealson (1997)

Life in Extreme Environments!



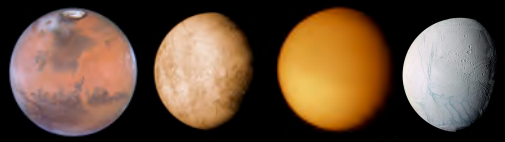
- From permafrost to hot springs
- From battery acid to salty lakes
- Deep under the ocean
  - Life relies on geothermal energy
- Deep under the ground
  - Life using geochemical energy
- Some organisms have even survived long-duration exposure to the vacuum and radiation of space



(Photo courtesy of Stevens and McKinley)

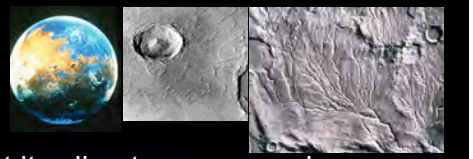
Life Elsewhere in Our Solar System?

- The enormous range of diversity and ruggedness of life on Earth has only recently been recognized
- The idea of simple life beyond Earth is not as crazy as it used to be!
- We can make a "short list" of places to look:
  - *Mars*
  - *Europa*
  - *Titan*
  - *Enceladus*

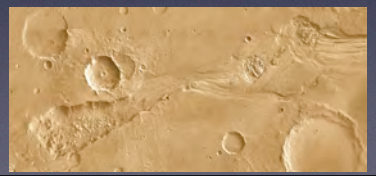


- And there may be more that we could add...

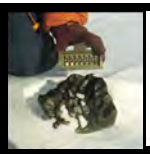
Life on Mars?

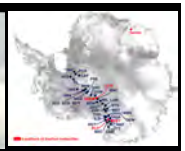


- Mars preserves clues that its climate may once have been very different...
- And that there is still a substantial (?) inventory of water at or near the surface...
- And that there were abundant volcanic, impact, and/or geothermal heat sources...
- Liquid water, heat sources, organic molecules... the requirements for life as we know it!



Evidence of Life on Mars from a Meteorite?

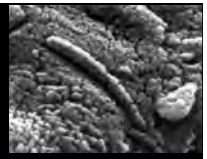




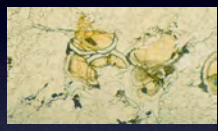
- A small number (~50) of meteorites are thought to have come from Mars

- Special one: ALH84001
- Found in Antarctica in 1984
- Thought to be a sample of *ancient* Martian crust: radiometric age around 3.5 billion years
- Cosmic ray exposure indicates ejection from Mars around 15 million to 20 million years ago
- Outer chemical evidence indicates that it fell to Earth about 13,000 years ago

Evidence of Life on Mars from a Meteorite?

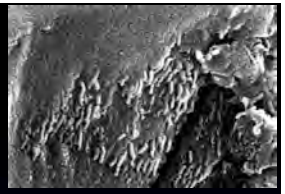


- Four pieces of evidence presented by scientists that ALH84001 preserves signs of past life on Mars:
  - *Carbonate* minerals: precipitated from a once thicker, warmer, atmosphere?
  - *Magnetite* grains: similar in shape to magnetite formed bacterially
  - Complex organic molecules: specifically *PAH* molecules
  - Segmented, "bacterial" shapes



Landmark paper published by McKay *et al.* (1996) *Science, 273,* p. 924

But Much Skepticism!



- Is the rock from Mars?
- Was it contaminated by Earth life while sitting in Antarctica for 13,000+ years?
- There have been abiologic explanations proposed for each piece of "biologic" evidence
- No "controls" on some new methods used
- *"Extraordinary claims require extraordinary evidence" --Carl Sagan*
- Proponents remain steadfast, despite more than a decade of skepticism and criticism...

The Real Message of ALH84001...

- Whether or not ancient fossil microbes actually exist in this Mars meteorite may be secondary
- ALH84001 and data from telescopes and space missions appear to show that:
  - **liquid water** existed in the Martian subsurface
  - **complex organic molecules** were there too
  - **energy** was provided by volcanoes, impacts, geothermal
- The *ingredients* for life all appear to have existed at one time on Mars. Do they still exist today??

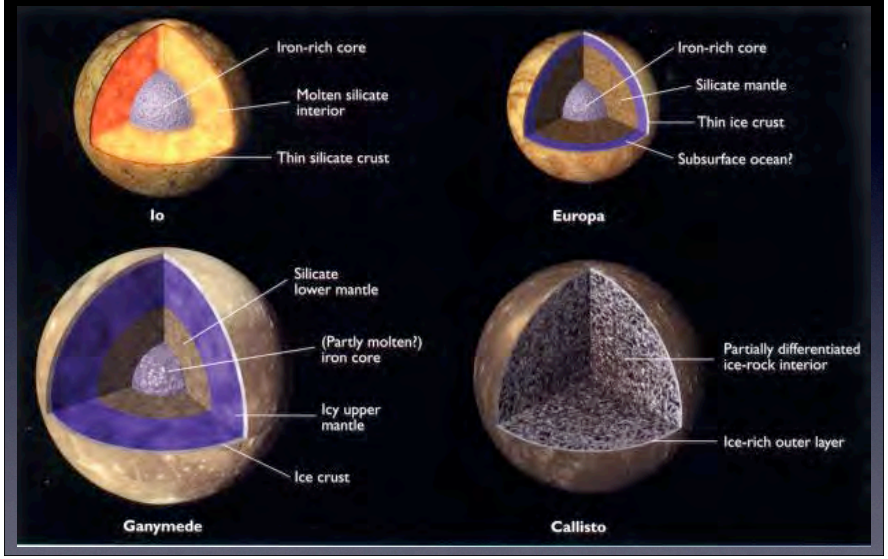
Possible abodes for life discovered in the Jupiter system by the *Voyager* and *Galileo* missions...

Europa

Ganymede

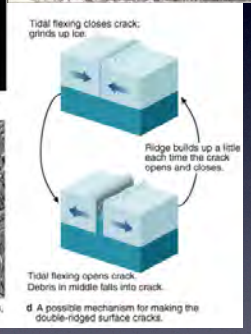
Callisto

Galilean Satellite Interiors



Europa

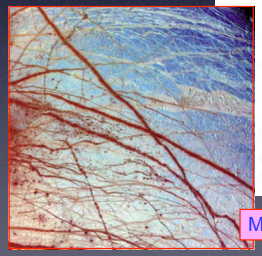
- Ice-covered Moon
- flat flat flat!
- Crust broken up into moving plates!
- "salty" deposits well up between plates
- Subsurface ocean??



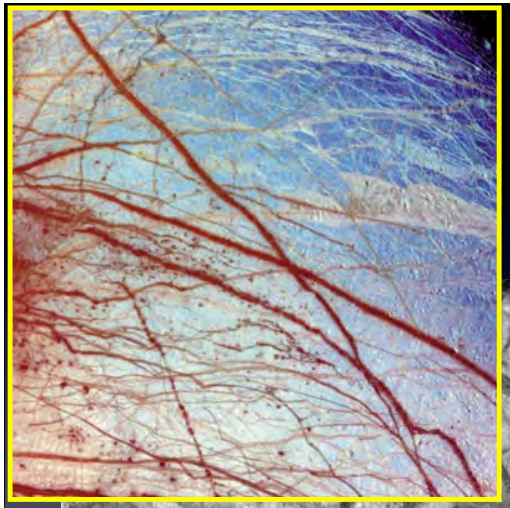
a Europa's icy crust is criss-crossed with cracks.

b Some regions show jumbled crust with icebergs, apparently frozen in slush.

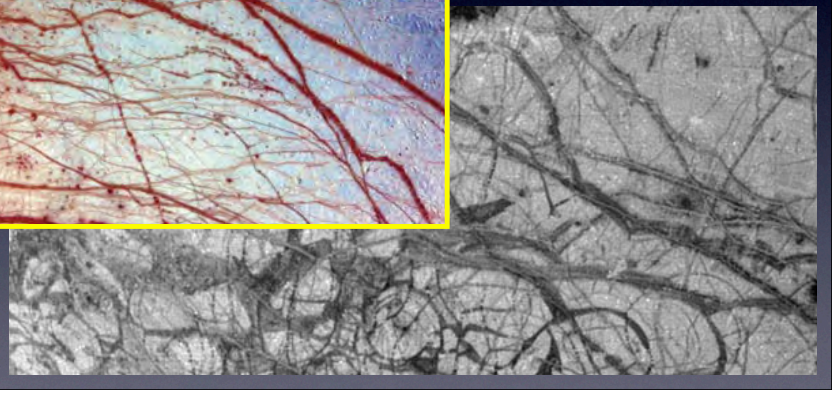
d A possible mechanism for making the double-ridged surface cracks.



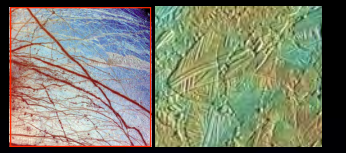
Map of salt-rich "contaminants" in Europa's crust



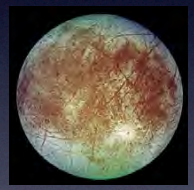
- Ridges show different compositions: hydrated sulfate salts that appear to have "erupted" from the interior (ocean?)...



Life on Europa?



- Europa may have a subsurface **liquid water** ocean
- The ocean may be warmed by **tidal energy**
- **Organic molecules** delivered by comets over time?
- Could there be life down there?
- Finding out will not be easy
  - First, we must prove that there's an ocean
  - Then, we must figure out how to access it
- And there are *ethical* issues to face as well, especially if we find evidence for life there



Saturn's Satellites and Ring Structure

Tiny Enceladus

Organic-rich Titan

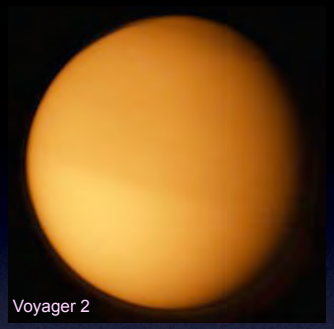
Two potential abodes for life discovered in the Saturn system by the *Voyager* and *Cassini* missions...

Titan

Composition of the Titan's Atmosphere

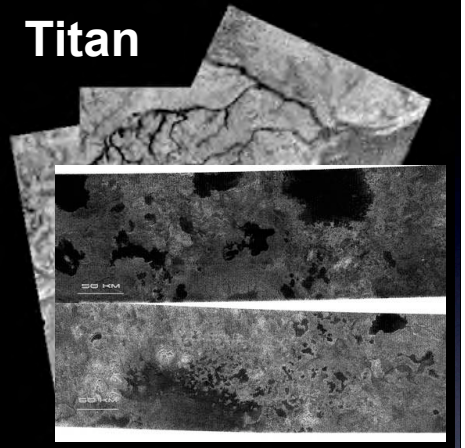
Gas	Formula	Amount
Main Constituents (in percent)		
Nitrogen	N_2	82 – 99
Argon	Ar	0 – 6#
Methane	CH_4	0 – 6#
Trace Constituents (parts per million)		
Hydrogen	H_2	2000
Hydrocarbons		
Ethane	C_2H_6	20
Propane	C_3H_8	20
Ethylene	C_2H_4	0.4
Diacetylene	C_4H_2	0.1-0.01
Methylacetylene	C_3H_4	0.03
Nitrogen Compounds		
Hydrogen Cyanide	HCN	0.2
Cyanogen	C_2N_2	0.1-0.01
Cyanoacetylene	HC_3N	0.1-0.01
Oxygen Compounds		
Carbon Monoxide	CO	50–150
Carbon Dioxide	CO_2	0.015

Argon can only be inferred indirectly. There may be none at all. Hence the abundance of nitrogen would increase. Methane varies with altitude and still poorly determined.


Voyager 2

- Mercury-sized “planet”!
- Thick, hazy atmosphere, with lots of hydrocarbons
  - formed by sunlight breaking up CH_4 molecules
  - similar to early Earth?
- Surface pressure: 1.5 bars!
- Surface temp.: 95K (-290°F)

Titan



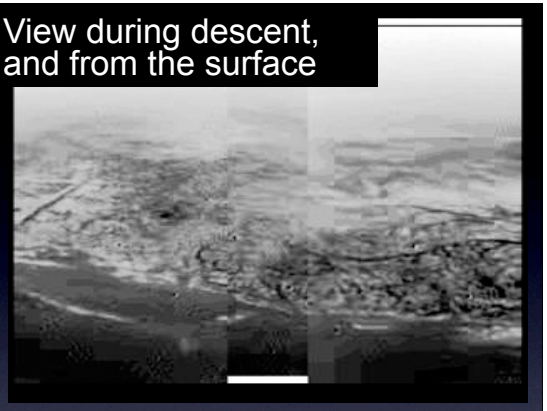
- Infrared, Radar Mapping
- Huygens descent imaging and lander

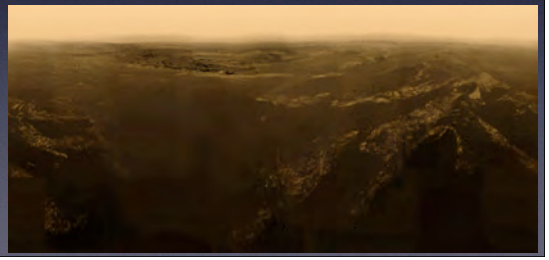
Life on Titan?

- Complex organic chemistry in the clouds
- Molecules should sink and accumulate on surface
- Could be seas/lakes of liquid ethane (C_2H_6)?
- What happens to the organics on the surface?
  - Simple accumulation?
  - Geologic "recycling"?
  - "Evolution"?

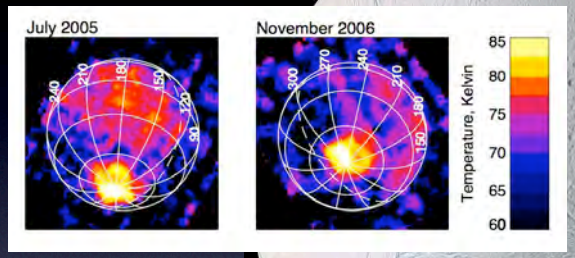
- At T=90K, chemistry likely to be sluggish...
- The Huygens Probe studied Titan up close!

View during descent, and from the surface

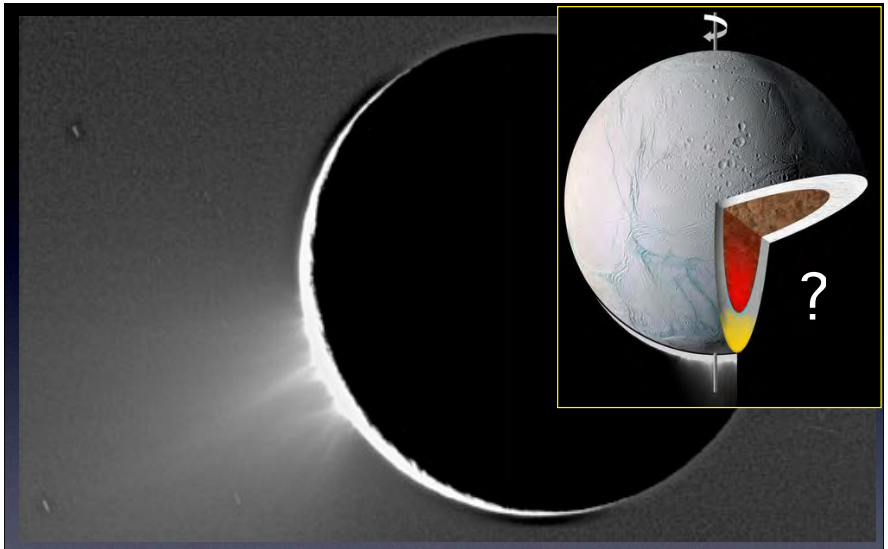




Enceladus



A tiny moon (only 500 km), but surprisingly active!



Enceladus

- Only 500 km diameter, yet internally active!
- Subsurface liquid water? Newest astrobiology "hotspot" in the solar system...

Other Possible Places for Clues

- "Hospitable" planetary atmosphere levels
  - High up on Venus?
  - Near the 1 bar level on Jupiter, Saturn?
- Subsurfaces of small bodies
  - Comets
  - Asteroids
  - Other planetary satellites
- What surprises await?

Simple Life vs. Complex Life...

- Simple organic molecules are abundant in the solar system and beyond
- Simple, bacteria-like life forms dominate life on Earth
- Focus of Mars and Europa exploration is on uncovering evidence for simple life forms
- So why, then, should we even consider extending the search towards more complex life forms, and ultimately ones that are *intelligent*?

The Search for Extraterrestrial Intelligence (SETI)

- Is anyone else out there?
- How can we find out?
- What would it mean?

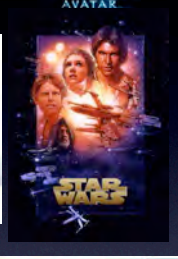
Why Care About E.T.s?

- Pros:
  - Increased awareness of our place in the Cosmos
  - Answers the question "Are We Alone?"
  - Maybe they will teach us new things
- Cons:
  - "Common wisdom" that complex life is rare
  - Two-way communication takes too long
  - We have enough trouble dealing with each other and other species on *this* planet...
  - Searching for them costs money
  - Maybe they will kill/eat/enslave us!

But We Already Care!

- Science (fiction) sells!
  - Books
  - Games
  - Movies
  - TV
  - Magazines
  - Web
  - NASA
  - ...

Billions of $$$$ industries



THE X FILES

The Science of SETI...

SETI@home
The Search for Extraterrestrial Intelligence

- SETI can be done scientifically
- But the search takes resources like money, people, time, equipment, ...
- How much should we devote to this search??
- Fundamentally, the answer depends on society's and individual people's balance between looking *inward* and looking *outward*

Is SETI Practical?

- Do we have valid reasons to believe that anyone else is out there?
- Perhaps...
  - The Sun is a common type of star, and there are probably > 100 billion Sun-like stars in the Galaxy
  - Planetary formation appears to be a common process around single Sun-like stars (theory and observations)
  - So: do the math:
    - 100 billion stars • 30% in single-star systems • 10 planets/star
    - = 300 billion planets!

Some SETI Math...

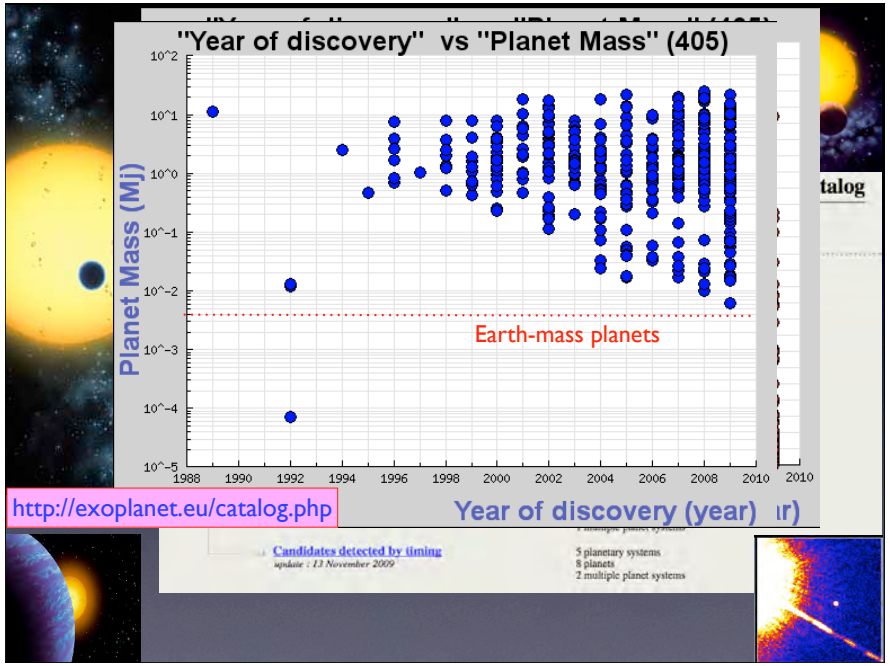
- But how many of these putative planets contain life?
- Is our solar system typical? If yes: 10%
- Is life on Earth a freak accident? If yes: ~ 0%
- So out of ~300 billion planets:
  - could be from just 1 to >30 billion in our Galaxy with life
- But how many planets have *intelligent* life?
- Is that intelligent life *technological*?
- And just how good are these kinds of estimates???

The Drake Equation

- Astronomer Frank Drake's attempt to quantitatively estimate SETI's potential success

$$N = R_* \times f_s \times N_p \times f_e \times f_L \times f_i \times L$$

- Where:
  - N = # of civilizations in the Galaxy capable of communicating with us
  - R_* = The rate of star formation in the Galaxy (stars/year)
  - f_s = fraction of stars that are Sun-like
  - N_p = number of planets per star
  - f_e = fraction of "environmentally correct" planets
  - f_L = fraction of planets where life develops
  - f_i = fraction where intelligent & technological life develops
  - L = lifetime of an intelligent & technological civilization (years)



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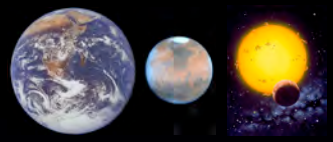
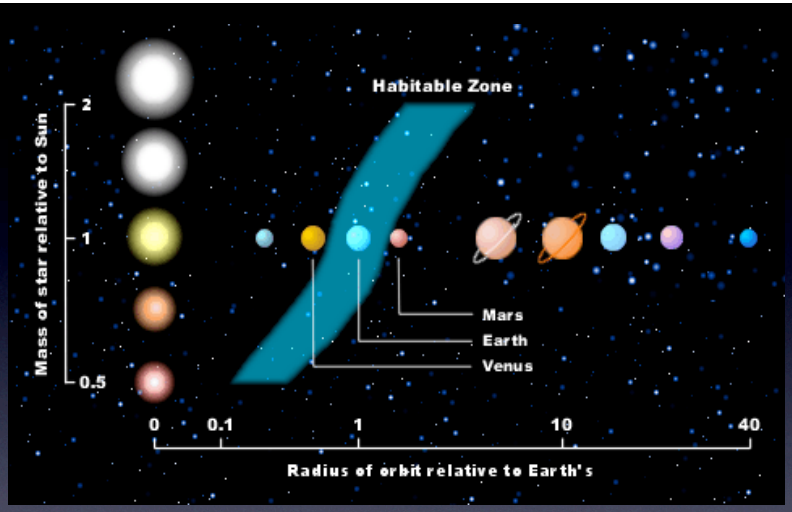
Habitable Zones



- To estimate the number of planets that have the potential for life to form/exist, we need to know how many have the right environment
- The *Habitable Zone* is the distance from a star in which liquid water could be stable
- Depends on the size & temperature of the star and the atmospheric pressure of the planet



Example: Our solar system's habitable zone (the "Goldilocks" scenario...)

Estimating N

Factor	Optimistic	Pessimistic	Best Estimate
R_*: Star formation rate	50	20	30
f_s: Fraction of Sun-like stars	1	1/15	0.3
N_p: Number of planets per star	20	5	10
f_e: Fraction of habitable planets	1	1/1,000,000	1/40
f_L: Fraction of those with life	1	1/1,000,000	0.5*
f_i: Fraction with intelligent life	1	1/1,000	0.75*
L: Lifetime of that civilization	?	?	?
			= 0.85L

From Goldsmith & Owen (1992)
*Wild Guess

$$N = R_* \times f_s \times N_p \times f_e \times f_L \times f_i \times L$$

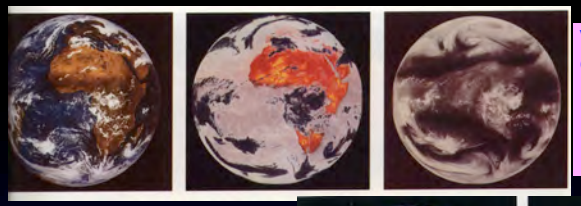
For reasonable (?) estimates, N ≈ L

Caveats...

- The Drake Equation is an *estimate* and not a true scientific derivation
  - Call it "back of the envelope" or "handwaving"
- There is much incertainty in the various factors in the equation!
  - (N = 1 to 1,000,000 !)
- The general relationship that N~ L implies that:
  - Optimism about L implies optimism about N
  - Optimism about L implies optimism about SETI
- For us, L ~ 100 years (so far) as a transmitting & receiving species
- The number of civilizations in the galaxy is closely related to:
  - (a) how long a technological species survives
  - (b) how long any single technological phase lasts
  - (c) the duration of technological phases that are compatible with our current search methods

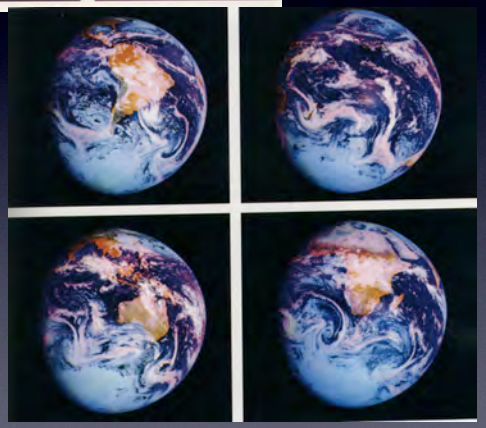
Intelligent Life on Earth

- We know (assume) there is intelligent life here...
- So could *we* be detected by extraterrestrials?
  - Directly?
    - Images
    - Electromagnetic "leakage" (radio, TV, military, ...)
  - Indirectly?
    - O_2 detected in Earth's atmosphere
    - Pollution/smog in the atmosphere?



Views of Earth as it could be seen from an extra-terrestrial telescope (hundreds of km resolution)

(Top): Global view of Earth in visible light (left), infrared light (middle), and within a water vapor absorption band (right)

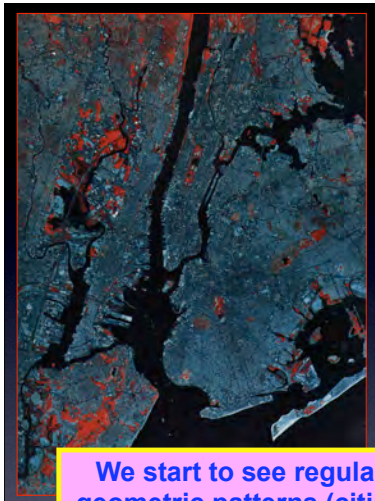


(Right): Global infrared view of Earth from the Galileo spacecraft during an Earth gravity assist flyby

Views of Earth as seen from a low-resolution orbiting satellite platform (tens of km resolution)

Views of Earth as seen from a higher-resolution orbiting satellite platform (a few km resolution)

No unambiguous signs of intelligent life at these scales...



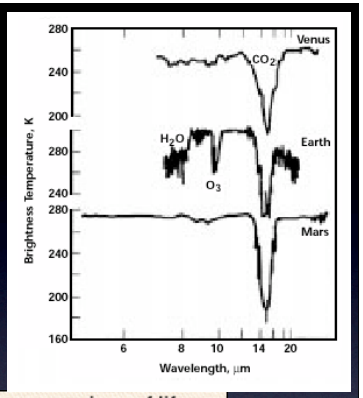
Views of Earth as seen from a very high resolution orbiting satellite platform (a few tens of meters resolution)

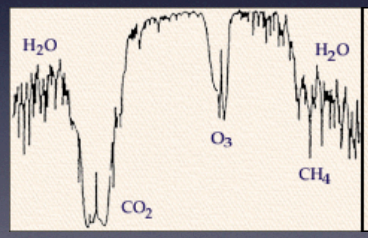
We start to see regular, geometric patterns (cities, farms, other structures) at these scales

Views of Earth as seen from an ultra high resolution orbiting satellite or an airborne platform (a few meters resolution)

Spectra of Earthlike Planets

- Greater sensitivity to Earth-like "disequilibrium" atmospheres can be obtained by measuring the spectra of extrasolar planets
- Hard! Requires advanced technology





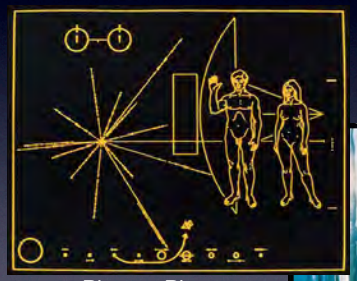
Spectrum - some signs of life:

- The spectral shape shows the temperature of the planet and it is right for water to be liquid
- The strong carbon dioxide band shows we have a planet with an atmosphere
- The ozone band shows plentiful oxygen, probably produced by life
- The spectral features of water show abundant water, indicating a planet with an ocean

Message in a Bottle...

- A few directed radio messages sent
- Pioneer, Voyager plaques and records

1974 Arecibo radio signal directed at M13, 21,000 l.y. away



Pioneer Plaque

Voyager Record

Summary

- Life is a difficult thing to define
- But all life on Earth shares similar attributes:
  - (1) A living system must be able to reproduce, to mutate, and to reproduce its mutations
  - (2) A living system must be able to convert external energy sources into useable internal energy sources
- The raw materials for life are common in the Cosmos
- Simple life forms dominate life here; complexity is rare...
- Life exists in *extreme environments* on Earth
- Enhances prospects for finding life on Mars, Europa, Titan, Enceladus, and other places in our solar system...
- SETI and the search for exoplanets are pushing us farther!

Searching for Life in the Solar System... and Beyond!

Find out more online!

http://astrobiology.nasa.gov
http://www.astrobiology.com
http://exoplanet.eu
http://www.seti.org
http://setiathome.ssl.berkeley.edu

We must not cease from exploration.
And the end of all our exploring will
be to arrive where we began and to
know the place for the first time.
-T.S. Eliot