22 October 2019

FROM POLYMERS TO LIFE, LIFE NOT AS WE KNOW IT, & EXTRATERRESTRIAL LIFE IN THE INNER SOLAR SYSTEM

Homework #5 on WeBWorK due Monday at 7pm

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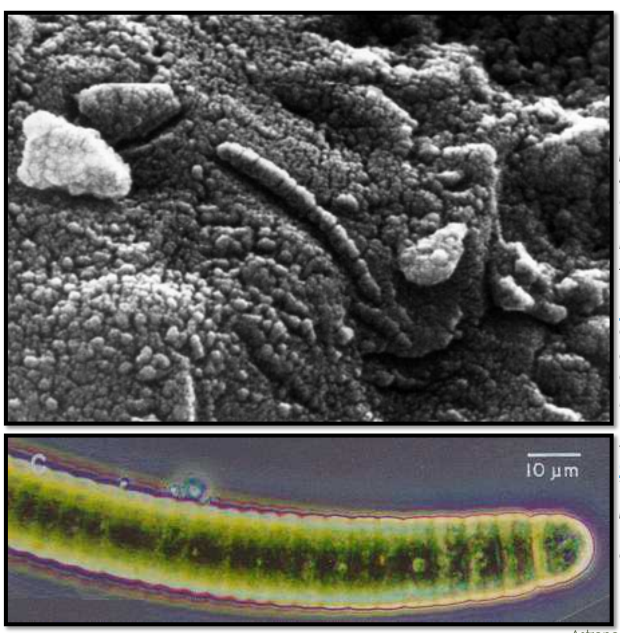


Upper: putative Martian fossil bacteria from the Martian meteorite ALH84001 ([McKay et al. 1996](#)). Lower: a chain of live cyanobacteria (Alejandro Lopez-Cortes & Mark Schneegurt, [Cyanosite](#)). Too bad the lower is 100 times the size of the upper.

From polymers to life, Life not as we know it, & Extraterrestrial life in the inner Solar System

How long does all this take? The importance of baby steps and the heroism of time.

Attempt to shed the Earth bias and consider:

- Clays and crystals as catalysts for the first bio-macro-molecules
- Alternatives to carbon
- Alternatives to water
- Alternatives to atoms

Status of the Drake equation input: f_l, the fraction of habitable planets which give rise to life

The edges of life on Earth; the lack of life on Mercury, the Moon, and Venus

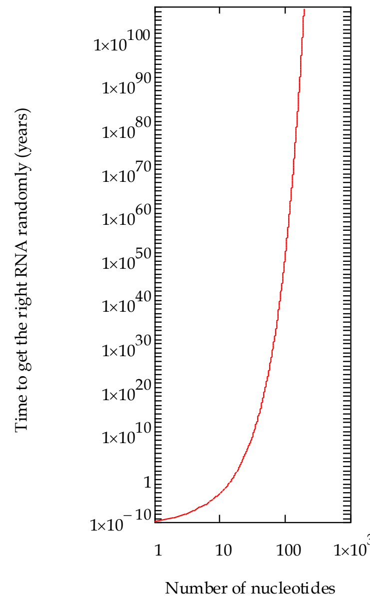
The ongoing search for life, present or past, on Mars

2

Baby steps

If that many attempts were needed to have a reasonable chance of getting the correct molecule, **making them out of single nucleotides one by one**, it would take *much* longer than the age of the Universe.

But it takes much less time to make shorter RNAs. And that, plus natural selection, is the key: **make short RNAs first, then make longer RNAs out of these**.



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Baby steps

For example, consider a two-step process.

Start with water at $T = 300$ K that has the Earth-crust abundance of carbon, 10% of it in nucleotides.

- Then it takes about 0.04 seconds to form an RNA with 24 nucleotides and 0.32 seconds to form one with 192, adding nucleotides one by one.
- To have a good chance to get a *specific* RNA with 24 nucleotides by this means, it takes $4^{24}\times0.04\text{ s} = 3.6\times10^{5}$ years, while it takes $4^{192}\times0.32\text{ s} = 4\times10^{107}$ years to get a specific 192-long RNA.

Clearly, 24-nucleotide RNAs are going to form the slow way much faster than the 192s; also, at least some of them can **self-replicate**, as we have already discussed.

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How many different four-nucleotide-long RNA molecules are there?

Question

A. 4
B. 8
C. 16
D. 32
E. 64
F. 128
G. 256

About how many times would you have to construct length-4 RNAs at random to have a good chance of getting a specific one?

Question

A. 4
B. 8
C. 16
D. 32
E. 64
F. 128
G. 256

In the worst case, you would have to do this serially (one RNA at a time). If it takes 0.05 s to synthesize a length-4 RNA, how long does it take to have a good chance of synthesizing a specific one?

Question

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Baby steps

Suppose that once certain 24-long RNAs formed, **self-replication led quickly ($\ll 10^5$ years) to the incorporation of all the nucleotides around into chains of 24.**

- It gives about 1.6 s to make a chain of 192 out of chains of 24, given the above conditions.

Furthermore, let us assume that there are 24 different length-24 RNAs that have risen to prominence by replication.

Then it will take $24^{\left(\frac{192}{24}\right)}\times 1.6\ \mathrm{s} = 5000$ years to have a good chance of making a *specific* 192-long RNA, like our "RNA replicase" ribozyme. The total time is therefore less than a million years, instead of greater than 10^{107} years.

- And thus much less than the age of the Solar System.
- Goes even faster with more, shorter steps.

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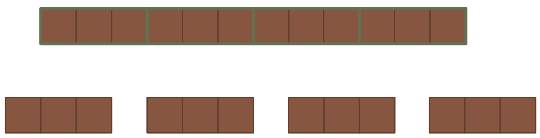
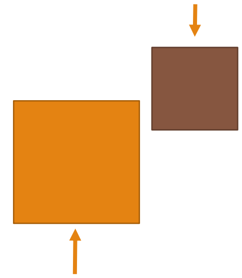
Probability math simplified

Two pieces of information to figure out:

- Length of molecule (number of blanks)
- How many options you have for each blank





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Baby steps

It would be nice to start with primordial soup and see the evolution of ribozymes produced in the lab in this manner, but unfortunately there are few graduate students willing to wait 5000 years to get their PhDs.

- Existing ribozymes have been "intelligently designed" by the likes of Cech and Altman, rather than evolved from a mixture of prebiotic chemicals.

Meanwhile, there are **computer simulations** based on lab data:

- Ma et al. (2007, 2010a): starting with a prebiotic mixture and allowing the basic sequences to be 5-10 nucleotides long (instead of the 24 we used a minute ago), "RNA replicase" is generated in only 52 years.

Scott Lab, *UCSC*

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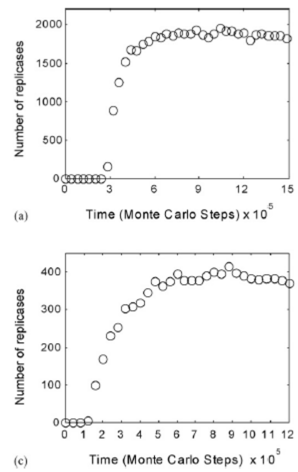
Baby steps

Also in the simulations: once the first kind of RNA replicase is created, more efficient, *mutated* replicases begin to arise.

In similar computer simulations, Ma et al. (2010b) have also shown that ribozymes provided with a protective cell-like membrane soon (within only a few years!) produce ribozymes which can replicate membrane-component molecules.

- Emergence of *cell* self-replication?



Computer simulation of RNA-replicase evolution, using 10-nucleotide (upper) and 6-nucleotide (lower) basic sequences. A "Monte Carlo step" is approximately 0.38 hours (Ma et al. 2007).

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Time is still the hero

A sophisticated biochemical function like the "RNA replicase" ribozyme takes less than one million years to produce from scratch, *via* chemistry and biological **natural selection**.

Of course, there are lots of functions to evolve, but all the functions of the molecules of life did not need to develop serially.

Thousands of millions of years (i.e. Gyr), very roughly, seem reasonable for making many functions of this level of sophistication. Complex simulations bear this out.

Still a long time, but it is much shorter than the time available and is consistent with the fossil record of primitive life on Earth.

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If length-12 RNAs are created and, during this time, 10 length-12 quasispecies develop the ability to self-replicate, how many length-144 RNAs would we need to construct from length-12 RNAs so that we have a good chance of creating one with the desired arrangement?

Question!

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Panspermia

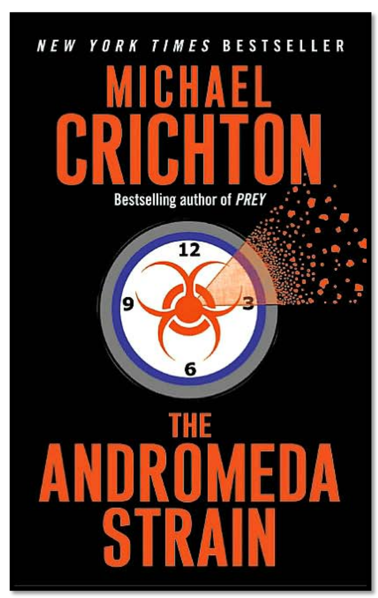
Could life be brought to the Solar System from somewhere else, frozen on the surface of dust grains?

No. There is no evidence of biomacromolecules in meteorites or IDPs, let alone viruses or bacteria.

Hoyle's famous suggestion that the 1918 flu epidemic originated in IDPs from Comet Halley's tail also does not pass medical tests.

Also begs the question of how *that* life began.

Nevertheless, this still a common suggestion.



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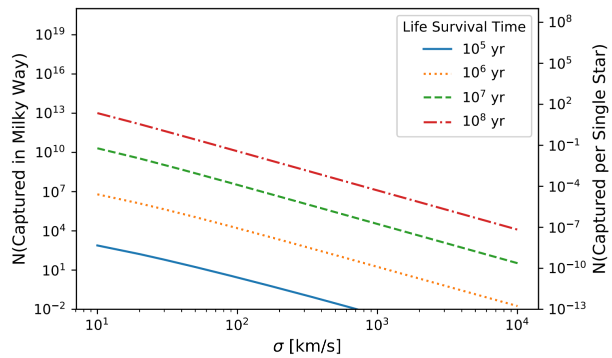
Panspermia

With the discovery of 'Oumuamua being of interstellar origin, the concept of Galactic pansermia has seen a resurgence.

- Benefit – If life evolves on one habitable planet, it can "easily" spread to all habitable planets in the Galaxy.
- If this were the case, then we would expect to find evidence of bacteria, viruses, etc. in meteorites in the Solar System. Which we do not.



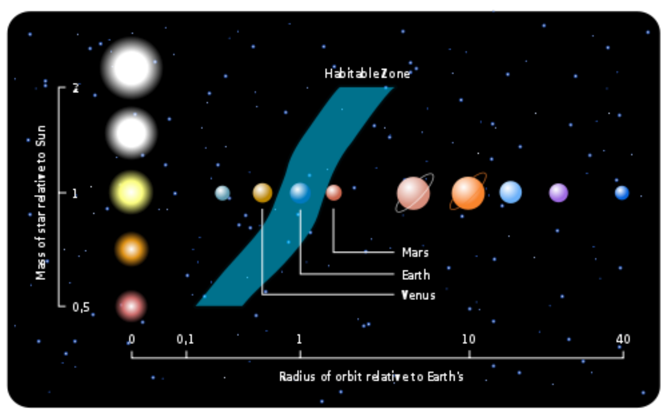
Capture rate of object as a function of velocity dispersion (Ginsburg et al. 2018)

Not quite panspermia…

Lately, it has been even more frequently suggested that primitive life may have come to Earth from Mars because Mars solidified first.

- If early Mars were habitable, and
- If life could form quickly enough, say within 500-600 Myr,
- Then primitive life like the RNA world could have evolved on Mars while Earth was still molten,
- And transferred to Earth by meteorites.

This seems unlikely, though, based on the likely habitable-zone history.



Why molecules? Clay & crystals as catalysts

Certain solid surfaces are good at trapping molecules and therefore have the potential to catalyze the polymerization of amino acids and nucleotides.

Any trapping surface will suffice from this viewpoint with the Dyson (1999) disorder-order-transition model of polymerization, discussed last time.

And some of the available solid surfaces are orderly: even periodic over large dimensions compared to amino acids or nucleotides.

We know that crystalline solids form very early in the life of protoplanetary disks and are present throughout the development of life. Can they serve as templates for the first biopolymers?

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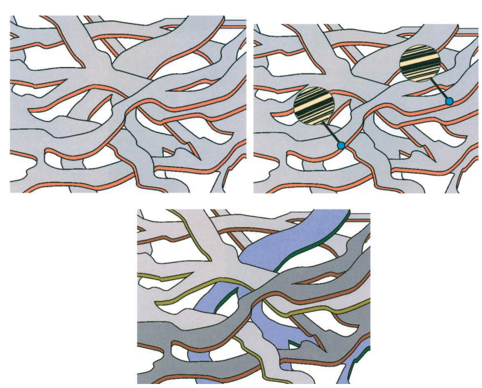
Clay & crystals as catalysts

One interesting setting: **clays**, which consist of very thin layers of crystalline silicate (SiO_x-containing) minerals, with liquids and/or finer grains **intercalated** between the layers.

- Molecules in the interlayer would have many sites in which to be trapped, and there would be patterns of such traps at the spacing of the crystal lattices of the two layers and at the sum and difference of the two spacings.
- It is conceivable that such varieties of spacings will promote the assembly of proteins (Cairns-Smith 1968, 1985).

This is plausible and could be provided rather early…



Schematic diagram of crystal planes in a clay (Cairns-Smith 2008)

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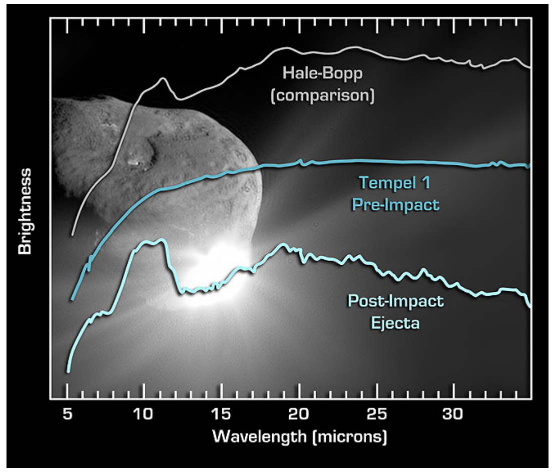
Clay & crystals as catalysts

We normally think of clays as sedimentary deposits caused by chemical weathering of rocks, but they are seen in extraterrestrial objects as well, such as in Comet 9P/Tempel by the Deep Impact experiment and the Spitzer Space Telescope.

Post-impact Temple emission features include some from smectite clay.



Lisse et al. (2006)

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Why carbon? Other tetravalent atoms

To lead to life – especially the intelligent sort – the chemical basis needs to be capable of holding a great deal of information, which means that if it is molecular, it needs to be able to make complex molecules like carbon.

Carbon's complexity is due to its tetravalence, meaning that the atom has four electrons that can make covalent bonds. These elements are all in the same column of the periodic table. Atoms in other columns make fewer bonds.

By far, the most abundant of these elements besides carbon is silicon. Silicon life is a favorite of science-fiction writers when considering alternative forms of life.

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Other tetravalent atoms

Unfortunately, Si-containing molecules do not seem to be very promising as originators of a dominant life form.

- C-C bonds are particularly strong, twice as strong as Si-Si.
- Even Si-H and Si-O bonds are stronger than Si-Si bonds; this makes long chains of Si very unstable.
- Si does not easily make double or triple bonds, which with carbon are very important in chemistry (e.g. the COOH group in amino acids).
- Silicon's oxides, carbides, and nitrides have high melting points and are insoluble, so they are difficult to keep in gas and solutions and thus do not react much under "lifelike" conditions.
- And germanium (Ge), tin (Sn), and lead (Pb) are even worse.

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Other tetravalent atoms

In the case of carbon v. Si, Ge, etc., "Earth chauvinism" is probably not a factor for the *origin* of life.

- In Earth's crust, silicon is hundreds of times more abundant than carbon, yet life on Earth wound up based on carbon.
- If silicon life could not beat carbon life with that much of an edge, how would it do so under cosmically-normal conditions, with carbon a factor of ten more abundant than silicon?

Keep in mind the possibility of non-primitive silicon life, like sentient computers, which are based upon crystalline silicon. Maybe we are just an evolutionary stage on the way to silicon life…

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Vita in silico

Large single crystals of pure silicon do not occur in nature. However, as you know, *intelligent* life forms – like humans, c. 1960 – can create such crystals.

They can also create **transistors** (solid-state switches) in the crystals – far easier in silicon than in any other material.

Transistors can currently be made at a density of about one billion per square centimeter of silicon surface.

Very powerful computers can be made with this many transistors.

Orion Pictures

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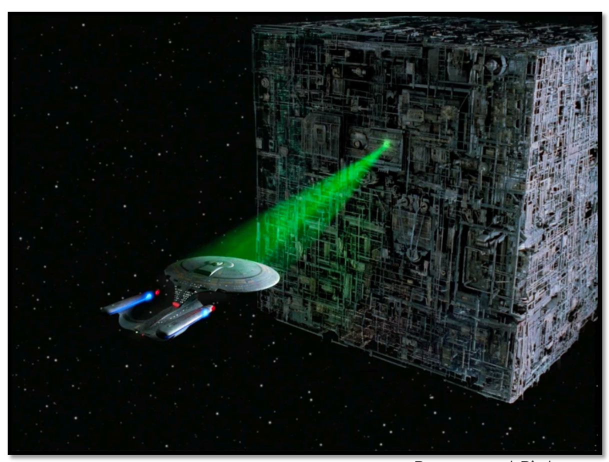
Vita in silico

And, though it cannot be currently proven, many computer scientists think that powerful software on powerful computers could become independent, self-aware intelligences.

Not all life becomes intelligent, but surely intelligence will develop all of the characteristics of life.

So silicon life may be possible in this form, but it would require other intelligent life forms first, with origins in media other than silicon: does not affect Drake's f_l.



Paramount Pictures

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Why water? Other solvents

Lots of other molecules that make good solvents are abundant in the ISM and in protoplanetary disks, and are thus delivered **together** to planets in large quantities. The table includes some samples, along with their freezing and boiling points at Earth-surface atmospheric pressure:

Solvent	Freezing point [K]	Boiling point [K]
Water (H_2O)	273	373
Ammonia (NH_3)	195	240
Formaldehyde (H_2CO)	181	252
Methanol (CH_3OH)	179	338
Ethanol (CH_3CH_2OH)	159	352
Methane (CH_4)	91	109
Ethane (C_2H_6)	90	184

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Other solvents

Cosmically speaking, water is the most abundant of these.

All but methane and ethane are **polar solvents** (like water) – one end of the molecule tends to always have a positive electric charge, and the other negative.

So they tend to dissolve things the same way water does, as well as promote the formation of organic zwitterions.

Water can dissolve significantly more than any other molecule.

Solvent found in meteorites and IDPs	Number per 1000 water molecules
Water (H_2O)	1000
Ammonia (NH_3)	9
Formaldehyde (H_2CO)	10
Methanol (CH_3OH)	20
Ethanol (CH_3CH_2OH)	10
Methane (CH_4)	7
Ethane (C_2H_6)	4

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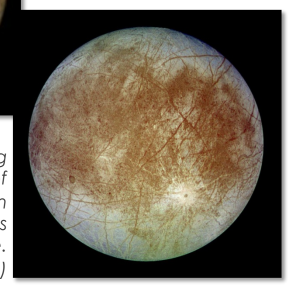
Other solvents

Water also has a larger heat capacity and is a more efficient evaporative cooler than the others, which is valuable in temperature regulation.

So wherever it is liquid, water is probably life's solvent.

On the other hand, the others are liquid at lower temperatures than water: they could support life outside the usual definition of the habitable zone.



Leading (top left) and trailing (bottom right) hemispheres of [Europa](), which has a ~160 km deep water ocean under its ~10 km water-ice surface. (Galileo/JPL/NASA)

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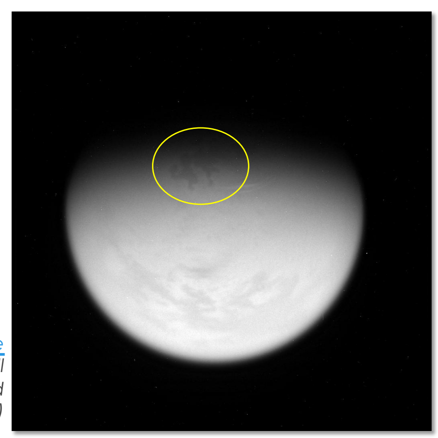
Nonpolar solvents

Methane and ethane are **nonpolar** solvents.

Some molecules (e.g. oils) dissolve more easily in nonpolar solvents than in polar ones.

No zwitterions are made in the nonpolar solvents!

So these solvents would support very different biochemistries, about which we can only speculate.



Titan's North-Pole Great Lake ("Kraken Mare"), which is full of liquid methane and ethane. (Cassini/JPL/NASA)

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Biochemistry in liquid methane

One life-like step demonstrated (theoretically) in liquid methane is the plausibility of **membranes** that would play the role of Oparin's coacervate droplets as possible progenitors of cell membranes.

The mostly-nitrogen atmosphere of Titan is fairly rich in cyanoacetylene (HC_3N), delivered with this moon's original ingredients. This reacts with other molecules to produce acrylonitrile (CH_2CHCN).

Name	Structure	Abundance (ppm)
HCN	$N\equiv C-H$	200
Cyanoacetylene	$N\equiv C-C\equiv CH$	40
Acrylonitrile	$N\equiv C-CH=CH_2$	10

[Stevenson, Lunine, & Clancy (2015)]

We know from NASA *Cassini* observations that these molecules condense into aerosols and rain down onto the surface and into the methane/ethane lakes.

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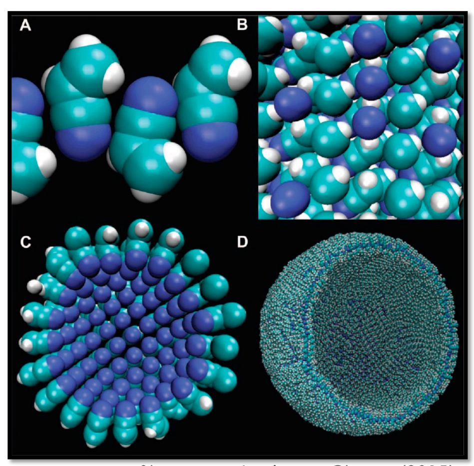
Biochemistry in liquid methane

Acrylonitrile molecules, in turn, have a tendency to hydrogen-bond with each other with the nitrogen on one end matching up with the hydrogens on the other end.

In a methane solution, simulations show that acrylonitrile then self-assembles into spherical shells 9 nm in diameter.

- Called **azotosomes**, in analogy to liposomes.

Mechanical simulations of azotosomes show that they are stretchy, despite the low T.



Stevenson, Lunine, & Clancy (2015)

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Biochemistry of liquid membranes

This structure is backwards from the way lipids form into liposomes in water:

- Liposomes present a polar "face" to the surrounding water, which itself is polar.
- Azotosomes present a nonpolar face which goes with the nonpolar solvent, methane.

Thus at least one of the steps of Life is possible in liquid methane, but the stiffness of long C chains at low temperatures is still a problem.

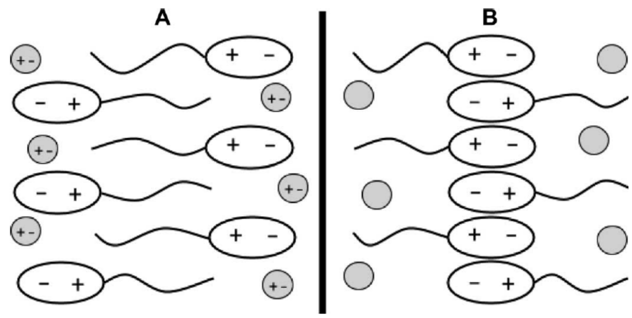

Fig. 1. Liposomes and azotosomes. (**A**) Liposome in polar solvent Polar heads are braced by nonpolar lipid tails. (**B**) Azotosome in non-polar solvent. Nonpolar tails are braced by polar nitrogen–rich heads.

Stevenson, Lunine, & Clancy (2015)

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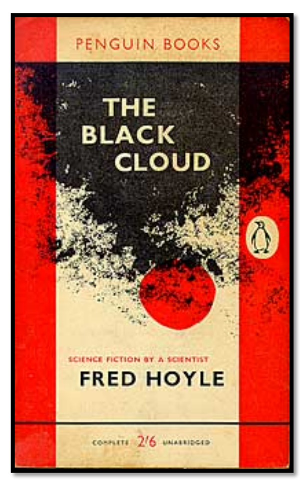
Why atomic matter at all?

It would take too long to discuss all the possible non-matter-based life forms raised by science-fiction writers; here are a few motifs.

"Pure energy." Epitomized by Hoyle's *The Black Cloud*, in which a molecular cloud in the interstellar medium is imagined to come alive, its mind present in electric and magnetic fields and molecules. This particular scheme can be safely ignored: interstellar clouds and all their electromagnetic fields are observed to live for only tens of Myr, and being so low in density, they would need much more time to organize, not less.

- This is not to say that "pure energy" life would never become important; just not in the beginning. But if you have a looooooooong time to evolve…
- If the Universe is open (as indeed it seems to be), then after thousands of Gyr nothing will be left by black holes, photons, and gravity. Believe it or not, it is possible to conceive even intelligent life under these circumstances.



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Why atomic matter at all?

Star life. The remains of dead stars – white dwarfs and neutron stars – become much more orderly as they cool off through eternity; they even crystallize as they do so (atomic crystals in a WD, nuclear crystals in a NS). And they are certainly dense and long lived…

- Hard to evaluate this as it is unsafe to get too close to these objects (even if we could); only objections are that the temperature stays high for many Gyr, and extremely strong gravity may restrict such forms of life to two dimensions. (See *The search for life in the Universe* by Don Goldsmith and Toby Owen, 2002.)

Quantum life. Perhaps reenergized by the new field of quantum computing, some have imagined that subatomic systems, or others that operate quantum mechanically, could be alive and intelligent.

- Upside: huge numbers of internal rearrangements are possible, and time does not really enter the problem.
- Downside: the arrangements do not seem to be deterministic and are instead ruled by probability. As they interact with their surroundings, they would spontaneously switch between alive and dead. Memory would be difficult to imagine.

Summary

It looks as if carbon/water-based life has a few promising ways by which it could have arisen spontaneously, and one – RNA world – that seems as if it could get going very quickly.

If RNA developed first – rather than proteins – a "genetic takeover" would not have had to occur to produce the nucleic-acid version of life we now know.

No other set of molecules seems nearly as promising… and that is not just geocentrism.

In temperature ranges over which water is not liquid, there may be other ways in which life could develop. We do not know, chemically, another "guaranteed" way.

f_l: The fraction of habitable planets on which life develops

As we have seen, at least 25% of the ten billion or so stars in the Galaxy have Earthlike planets, and our existence places a lower limit on f_l. Crudely, and in round numbers,

$$f_l \gtrsim 10^{-9}$$

which does not look particularly useful.

- On the other hand, it appears from the fossil record that life on Earth developed rather quickly.
- It also appears that life can evolve from the RNA world, which in turn can evolve from pre-biotic chemicals.

Can we use the **speed** with which life appears to estimate f_l?

- Analogy: If you buy a winning lottery ticket very soon after they go on sale, the probability of others winning is high.

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Question!

Suppose that you bought the 100th lottery ticket out of 1 million. There are known to be multiple winning tickets, and yours is the first winning ticket. (Congratulations!) How many winners are there likely to be?

A. 10
B. 100
C. 1000
D. 10,000

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What is the corresponding probability that a given ticket is a winner?

Question!

A. 10^{-6} (10^{-4}%)
B. 10^{-5}
C. 10^{-4}
D. 10^{-3}
E. 10^{-2}
F. 0.1
G. 1 (100%)

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If the probability of an event occurring in one interval is p ($\ll 1$), then the probability of it occurring at least once in N intervals is Np ($\ll 1$).

Question!

Suppose the lottery were run again, under the same rules, and one ticket were sold every minute. Crudely speaking, after how many minutes would the probability of having at least one winner be 50%?

A. 20
B. 50
C. 100
D. 200
E. 500
F. 1000

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Can we estimate f_l?

Would it work to reason backward from a time to a probability?

- Leslie Orgel (1998, 2008): **No, we cannot yet estimate f_l.**
  - The fossil record shows that life appeared quickly, but RNA World is a long way from cyanobacteria.
  - It will take several breakthroughs before we understand how some of the other necessary processes – in particular, metabolic cycles – evolved:

  "[S]olutions offered by supporters of geneticist or metabolist scenarios that are dependent on 'if pigs could fly' hypothetical chemistry are unlikely to help."
- Orgel always seemed to have been concerned about the possibility of panspermia being real, and we risk being fooled into thinking that the evolutionary timescale was short.

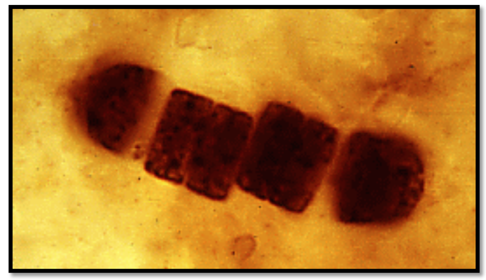
Can we estimate f_l?

- Stanley Miller (with Antionio Lazcano; 1994, 1996): **Yes, we can estimate f_l from the pace of life's appearance.**
  - RNA World itself can evolve in $\ll 1$ Myr; the contents of some meteorites come close to RNA World, and they were only warm enough for $\sim 10^5$ years.
  - The classes of reactions necessary for the establishment of protein enzymes and metabolism are short in this context; the *slowest* have ~40 yr half-lives.
  - Even if RNA World were delivered intact, the rest would have to be developed within 5 Myr, the half-life for ocean circulation through sub-marine vents.
- Miller ignores the *interstellar* origin of prebiotic meteorite contents but has a good point against panspermia.

Estimating f_l with the speed of life on Earth

We will choose to side with Miller on this one. So, how fast did life appear on Earth?

- The oldest fossil lifeforms yet found are fossil cyanobacteria (shown on right; Schopf 1993).
- The sedimentary rocks in which the fossils are found are encased in (igneous) basalt. The U-Pb radiometric ages of the basalt pin the age of the fossils at 3.465 ± 0.005 Gyr.
- The oldest igneous rocks on Earth are 3.8 ± 0.2 Gyr old, consistent with the Earth's surface solidifying after the bombardment suffered in the Uranus-Neptune switch.



Therefore, primitive life had something like 100-600 Myr to develop from prebiotic, meteoritic contents.

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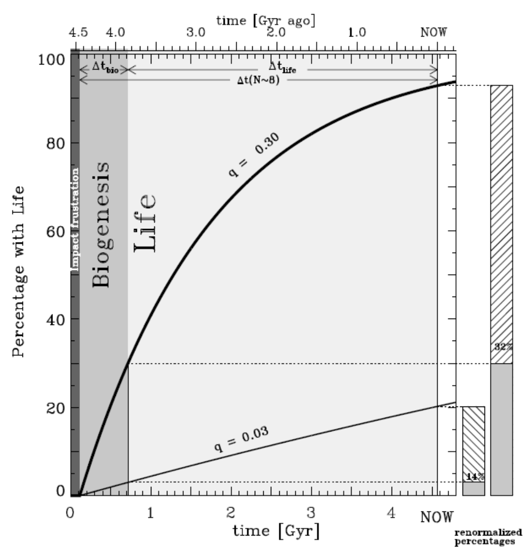
Estimating f_l

Using 600 Myr and a lottery-winning-like probabilistic model, Lineweaver & Davis (2002, 2004) estimate that 36% of terrestrial planets that are at least 1 Gyr old have life, at 95% confidence: $f_l = 0.36$

If we turn out to have been lucky, this could be less; accounting for different mechanisms or taking a biogenesis time shorter than 600 Myr, f_l is larger.



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Testing our estimate of f_l

These are probabilities; if we got lucky on that first ticket, we would be wildly overestimating the chances. Is there a way to test this? Brandon Carter has suggested a test that would apply in the pessimistic limit.

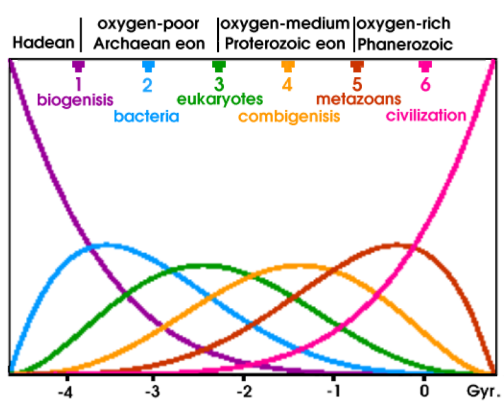
- Suppose life is actually *rare* in the universe because there are **hard steps**: necessary "accomplishments," such as the development of a genetic code, that actually take much longer than the lifetime of a habitable zone.
- If so: it is possible to show, statistically, that the steps would be **evenly spaced in time** during the habitable-zone lifetime (Carter 2008).
- If we can identify evenly-spaced events in the fossil record that correspond to the hard steps, then we can find their number and work backwards to find the (very small) probability, from which we could infer f_l.

Testing our estimate of f_l

Carter is more interested in the product of the next three Drake factors (f_l, f_i, f_c), and he takes the lifetime of the Sun's habitable zone to be 6 Gyr and identifies five or six candidate hard steps.

…driven by our own appearance less than 1.5 Gyr from what he takes to be the End.

In this scheme, "biogenesis" (creation of RNA World) would only be a hard step if it developed on Mars first and was delivered to Earth.



Carter (2008)

Our estimate of f_l

We will need to discuss this further when we get to the Drake L factor, the lifetime of civilizations.

For now, it looks like the "Carter test" **either** leaves the development of RNA World as an easy step, **or** posits the earlier development of RNA World on Mars (hard step), and the delivery to Earth in large enough quantities.

The second of these currently looks like a wilder speculation, so we will take the first: that RNA World is an easy step, and that we can estimate the probabilities based on a lottery model.

In which case the Lineweaver and Davis estimate holds:

$$\boxed{f_l = 0.36}$$

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Prospects for life elsewhere in the Solar System

While RNA World and alternative chemistries are fresh in our mind, we should consider life elsewhere in the Solar System, where chances are it would be primitive if it exists.

Conditions are quite different in the inner and outer Solar System: that is, between the classical habitable zone and places with sources of heating other than sunlight, or life based upon solvents other than water.

We will consider the liquid-water and liquid-methane ranges, as already discussed.

Phases of Venus (Wah!)

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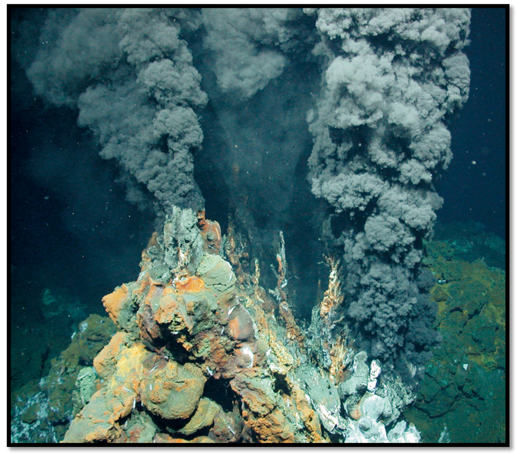
Prospects for life elsewhere in the Solar System – temperature restrictions

Why not hotter? So far, we have taken the upper temperature edge to be that of boiling water. This still looks good:

- Higher temperature solvents (e.g. ethylene glycol) are much rarer in nature than any we have yet considered.
- Temperatures only slightly higher than boiling tend to denature long molecules such as starches, proteins, and nucleic acids. On Earth, this process is best known as **cooking**.
- Hotter liquid-water conditions can be found on Earth, especially under high pressure (e.g. seafloor volcanic vents such as **black smokers**).



A black smoker (World Ocean Review)

Life in the hot zone

Sure enough, life is found in some of these hotter-than-boiling places. These are a subset of extremophiles, known as **(hyper)thermophiles**.

- > 80 different kinds have been found (Canganella & Wiegel 2014): 2/3 bacteria, 1/3 archaea

Even though (hyper)thermophiles live in surprisingly hot (and acidic) conditions, they are not stretching the boundaries much. Current record holders:

- *G. barossii* $T \leq 121 - 130°\mathrm{C}$ (403 K)
- *M. kandleri* $T = 80 - 122°\mathrm{C}$ (395 K)

Cistern Spring, Yellowstone National Park. The blue and yellow colors come from thermophiles representing six different kinds of archaea.

The non-starters: Mercury, Venus, & the Moon

None of these bodies are habitable by the Rules, as they are always too hot or too cold.

Mercury and the Moon have no surface organics. Each has a little bit of ice in permanently-shadowed polar craters, but the ice on the Moon is polluted with as much mercury as water.

Venus, the poster child for the greenhouse effect, has a nearly uniform-temperature 735 K (864°F) surface, a nearly pure CO_2 atmosphere with sulfuric-acid clouds, and virtually no water or organic material.

Body	From Sun [AU]	Albedo	$T = 279\ K \times \left(\frac{1-A}{(r[\mathrm{AU}])^2}\right)^{\frac{1}{4}}$	Average surface temperature [K]
Mercury	0.387	0.12	420	100-720
Venus	0.723	0.59	254	735
Earth	1	0.39	239	287
Moon	1	0.11	262	100-390
Mars	1.52	0.15	210	227

Mars & its similarity to Earth

For the past century, ever since it was first appreciated that Mars has an atmosphere, this planet has been the focus for the search for life outside Earth. Though it is chilly, Mars has:

- An atmosphere – pressure 0.56% of Earth's, and mostly CO_2 – and reasonable surface gravity, 0.38 Earth gs.
- A day length and seasons almost the same as Earth
- Terrestrial composition, even terrestrial appearance
- Not much in the way of surface impact cratering; evidence of past volcanism, though no plate tectonics
- Atmospheric **methane**, which somehow gets replenished
- Surface color variegation that, for a time, was though to possibly reveal vegetated areas, fancifully connected by "canali" in the view of early observers
- **Water**, though not (presently) much on the surface

Mars & Earth – which is which?

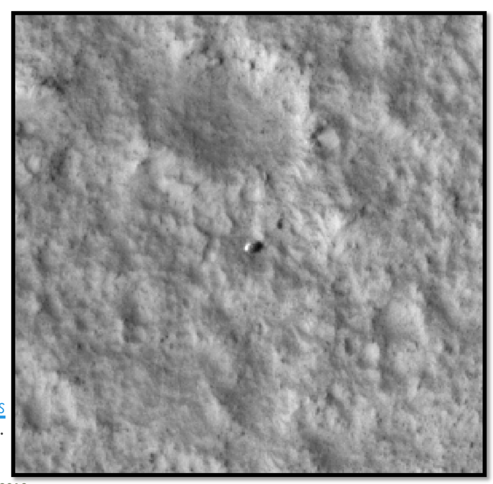
One is southern Morocco, the other Mars. (Morocco by Filipe Alves, Mars by the *Spirit* rover (MER/JPL/NASA))

Tests for Martian life by the NASA Viking probes

NASA landed two probes on Mars is 1976 to join in the US Bicentennial celebration: Vikings 1 and 2.

- Viking 1 went to Chryse Planitia (22° N)
- Viking 2 went further north, to Utopia Planitia (48° N)

Both had several experiments on board: cameras, organic-matter analysis, life detection, and a ditch digger.



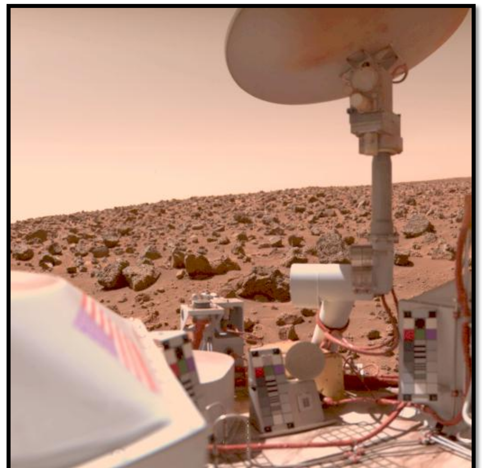
Viking 1, as seen in 2006 from the Mars Reconnaissance Observer in orbit.

Viking's organic matter analysis (GCMS)

Both Vikings had mass spectrometers and gas chromatographs to infer the presence of carbon-bearing molecules.

Found: concentrations below a few parts per billion for organic molecules with more than two carbon atoms in them.

This is **100-1000 times lower than terrestrial deserts**. Pretty dead.



Viking 1 selfie (JPL/NASA)

Viking's life searches

All were designed to detect organic/water microorganisms.

Fairly close to the surface: within the few-cm range of their ditch diggers.

Either **heterotrophs**… (which would presumably produce metabolic products if they were fed: the probe could detect common metabolytes)

…or **autotrophs**. (The probes could also detect photosynthetic products.)

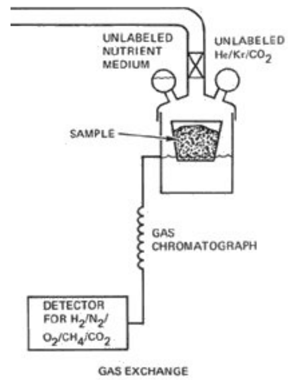
If signs of life were found, a control experiment would follow. (Obtain another sample, sterilize it, and then feed or water it and look again for metabolytes, etc.)

Life search #1: the Gas Exchange Experiment (GEX)

Also known as the Chicken Soup experiment.

1. A sample was dug up, sealed, pressurized, and warmed to $T = 10°\mathrm{C}$.
2. First mode: humidify. Gases were immediately released: N_2, Ar, CO_2, O_2. The O_2 required a chemical reaction between the sample and the water, which was very encouraging.
3. Second mode, one week later: Add nutrients (very generic ones). Monitor for six months thereafter.

No sign of metabolizing, earth-like life activity.



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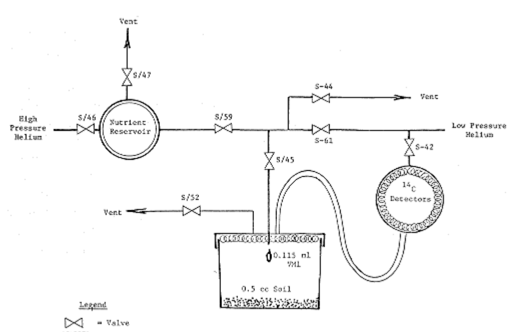
Life search #2: the Labeled Release (LR) experiment

Less Earth bias in this one…

1. Prepare a soil sample as before, and treat it with a mix of nutrients that is simpler than before, but in which some of the carbon is the radioactive version, ^{14}C.
2. A metabolizing organism would produce $^{14}CO_2$; this could be detected in very small amounts.



Results: immediate release of $^{14}CO_2$ from the sample, but it did not produce proportionally larger amounts of $^{14}CO_2$ when larger amounts of nutrients were added.

Thus, a chemical and **not biological** reaction was suspected.

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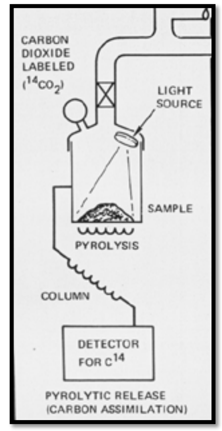
Life search #3: the Pyrolitic Release (PR) experiment

1. Prepare a sample and supply light and Martian atmosphere, but label some of the gases radioactively: $^{14}CO_2$ and ^{14}CO.
2. Incubate for a few months as before, and then remove the gases and burn (pyrolize) the sample. If anything is produced in the burning, it would have to have been taken out of the gases autotrophically (photosynthesis-like).

And so it was: $^{14}CO_2$ was seen in the pyrolytic products.

So they tried again with a sterilized sample: the activity was reduced but not eliminated. **Most likely a non-biological chemical reaction again.**



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Results expected for terrestrial life

	Response for sample	Response for heat-sterilized control
GEX	Oxygen or CO_2 emitted	None
LR	Labeled gas emitted	None
PR	Carbon detected	None

Results expected for no life

	Response for sample	Response for heat-sterilized control
GEX	None	None
LR	None	None
PR	None	None

Actual results

	Response for sample	Response for heat-sterilized control
GEX	Oxygen emitted	Oxygen emitted
LR	Labeled gas emitted	None
PR	Carbon detected	Carbon detected

Viking life search summary

Non-biological processes were operating and producing the "life-like" results seen in GEX and PR.

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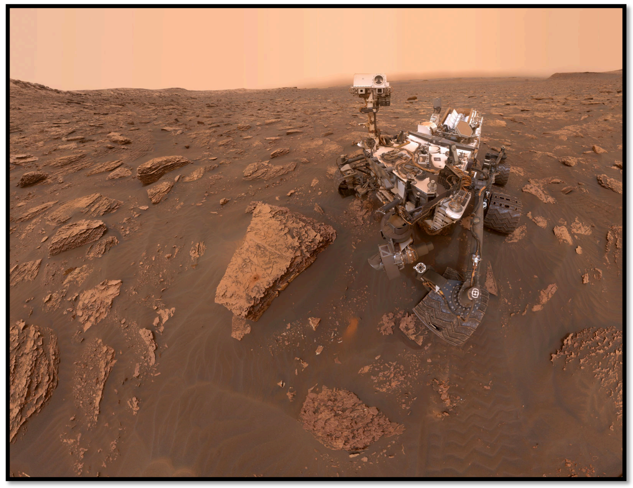
Curiosity

Of course, much fancier experiments could be performed on Martian rocks and soils either by transporting laboratories to Mars or by transporting Martian samples here.

Selection and analysis of such samples is the mission of NASA's Mars Science Laboratory, a.k.a. the *Curiosity* rover, which arrived at Mars in August 2012 and has been busy looking for water and habitats.



NASA/JPL-Caltech/MSSS

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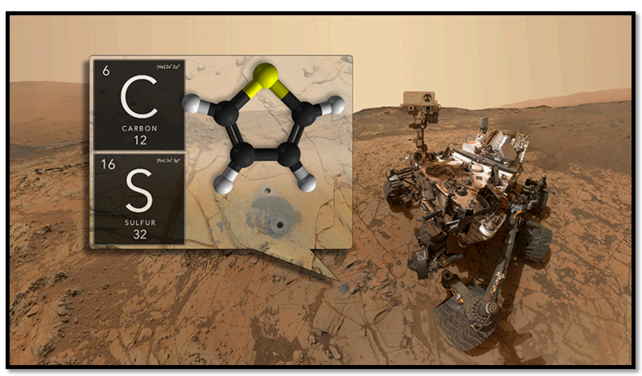
Mudstones on Mars

Curiosity drilled into sedimentary rock in four different locations within the Gale Crater. Using SAM (Sample Analysis at Mars), the samples were heated to about 850°C, releasing organic matter preserved in the rock for 3.5 billion years.

Results: Organic molecules released at high temperatures, indicative of complex organic molecules. Some contained sulfur, helping in preservation. Carbon in a concentration of 10 ppm, including small carbon chains.



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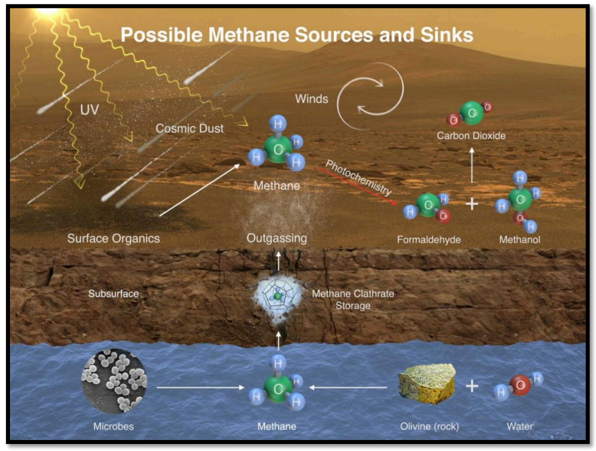
Methane on Mars

Methane is a popular "signature" for life, as most methane on Earth is produced by living things.

Traces of methane have been detected on Mars over the past 16 years, though without any discernable pattern.

A transient gas plume of methane was detected by *Curiosity* in the Gale Crater in June. Even though this was the highest level of methane seen so far on Mars, we are still unsure of its source.



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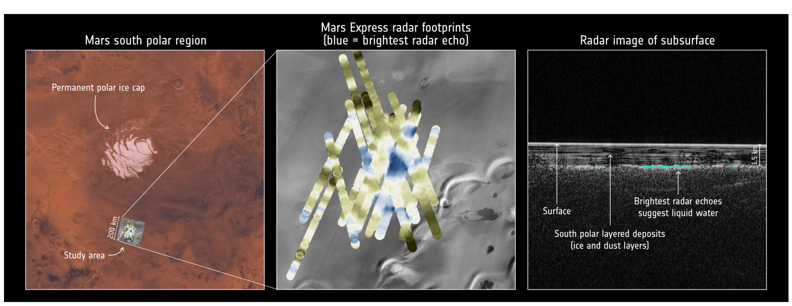
Water on Mars

Using radar, the *Mars Express Orbiter* (ESA) is mapping the surface of Mars to search for signs of subsurface liquid water, concentrating on the area beneath the ice caps. They discovered a subsurface lake about 20 km (12 mi) wide, 1.5 km (~1 mi) below the surface in 2018.

And in 2019, the NASA InSight lander also detected magnetic oscillations that are consistent with a planet-wide reservoir of liquid water beneath the surface.



Orosei et al. (2018)
NASA/Viking

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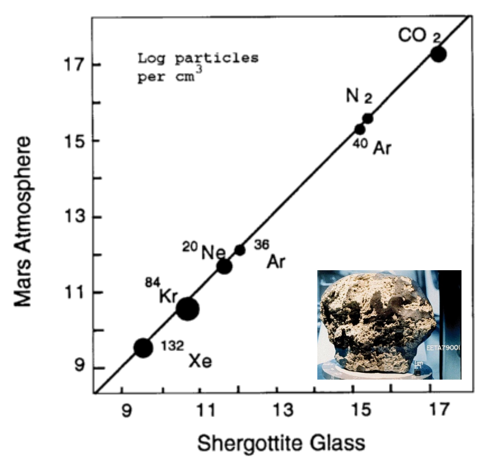
Acquiring Martian meteorites

Some samples have been delivered to us already, free of charge, and still look at least as interesting.

Studying Martian meteorites

241 meteorites have been recovered, mostly from various deserts, that share the distinctive mineral content of parts of the Martian surface and have trapped-rare-gas abundances different from Earth but the same as the atmosphere of Mars.

They are thought to have been ejected from Mars in extremely oblique, grazing impacts, such as the one previously shown.

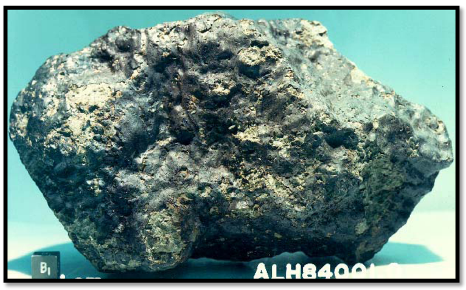


Composition of trapped gases in EETA79001 compared to that of the Martian atmosphere (Pepin 1985)

Oldest Martian meteorite – ALH84001

By far the oldest one is ALH84001:

- Solidified 4.09 ± 0.03 Gyr ago (Lapen et al. 2010)
- Ejected from Mars about 15 Myr ago, probably from Eos Chasma (Hamilton 2005)
- Came to Earth about 15,000 years ago and was found in 1984 during a search of the ice fields near Allan Hills, Antarctica



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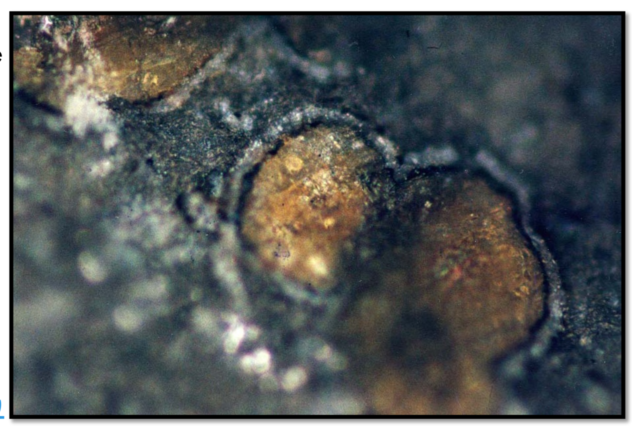
Life in ALH84001?

ALH84001 has been cracked, perhaps by meteoritic impact, a few times since 3.6-3.9 Gyr ago, during the time in which there could have been a good deal of liquid water on the Martian surface. Water gets into cracks…

And, indeed, the cracks are full of carbonate inclusions (right), which seem to have formed in water at $T = 18 \pm 4$℃ (Halevy et al. 2011).



Romanek et al. (1994)

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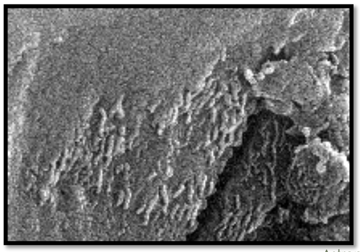
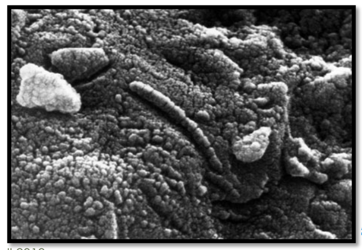
Life in ALH84001?

Electron-microscope images of thin sections of the "cracked" parts reveal mineral deposits in shapes that resemble bacteria.

They are too small, though: 30x130 nm and smaller. (Recall that a nucleobase pair is about 2 nm long.)

Similar structures in rocks on Earth have often been considered to be fossil cyanobacteria, though these are all 10,000-nm size.





McKay et al. (1996)

Life in ALH84001?

In particular, there is no structure seen in the ALH84001 "bacteria" to compare with evidence for cell walls in Earth's fossil cyanobacteria (e.g. below; Schopf 1992).

Along with the "fossil bacteria" and carbonate inclusions are compounds that can be associated with microbial systems.

- Magnetite crystals, like those made by magnetotactic bacteria on Earth.
- PAH molecules (i.e. organics)

Unfortunately, all of these features also have ready explanations by non-biotic processes, so ALH84001 is not generally considered to present compelling evidence for primitive life on Mars. But neither has it been disproven.