24 October 2019

LIFE NOT AS WE KNOW IT & POSSIBILITIES FOR EXTRATERRESTRIAL LIFE IN THE SOLAR SYSTEM

Homework #5 on WeBWorK due Monday at 7pm

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View of the surface of Saturn's largest moon Titan, from the Huygens landing craft (ESA/ISA/NASA). The bigger rocks in the foreground are about six inches across. (Why do they look like river rocks?). The haze is real and resembles ordinary smog.

Life not as we know it & Possibilities for extraterrestrial life in the Solar System

- Attempt to shed the Earth bias and consider 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
- Tidal heating, Europa and Enceladus, Ganymede and Dione, and their global subsurface liquid-water oceans
- Titan, its surface liquid-hydrocarbon lakes *and* possible global subsurface liquid-water ocean

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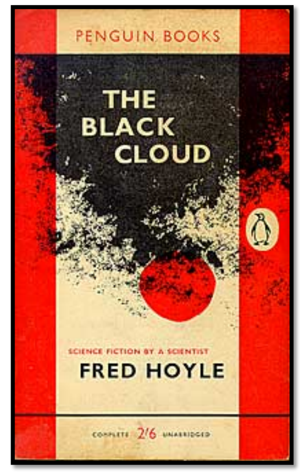
Why atomic matter at all?

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.

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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 potentially habitable 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.

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?

Question!

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

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%)

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

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, with which 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 the 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.

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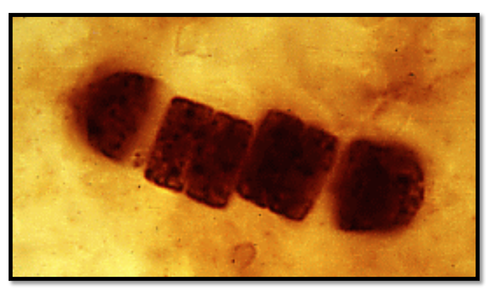
Estimating f_l with the speed of life on Earth

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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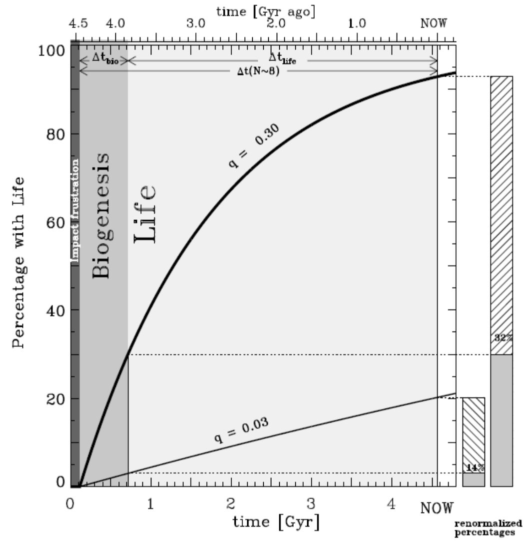
Estimating f_l

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.

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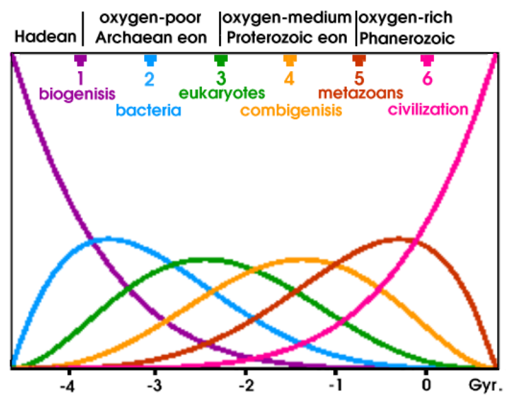
Testing our estimate of f_l

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)

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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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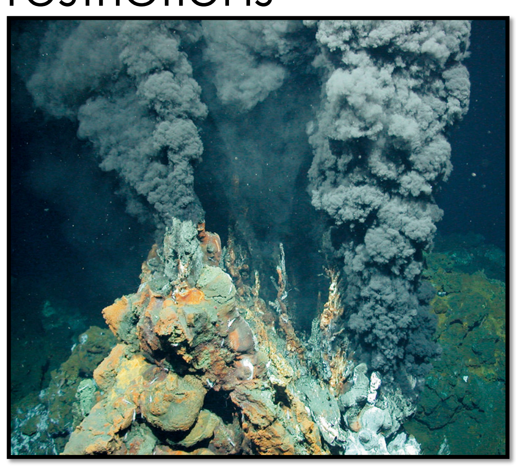
Prospects for life elsewhere in the Solar System – temperature restrictions

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)

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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* $T \leq 121 - 130℃$ (403 K)
- *M. kandleri* $T = 80 - 122℃$ (395 K)

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

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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

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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?

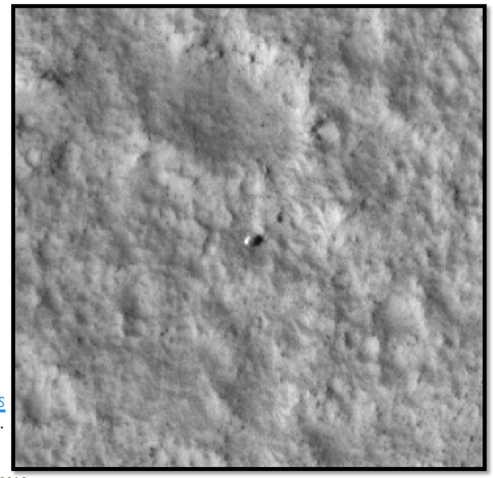
One is southern Morocco, the other Mars. (Morocco by Filipe Alves, Mars by the *Spirit* rover (MER/JPL/NASA))

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.

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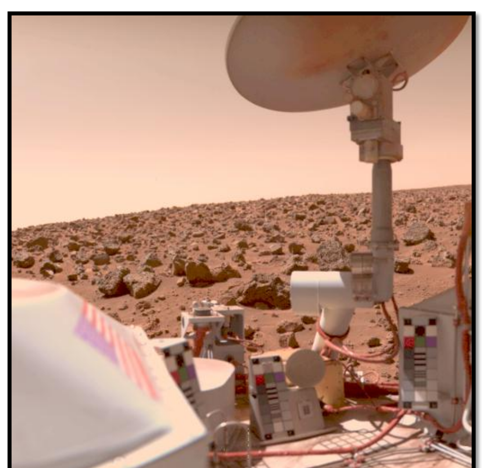
Viking's organic matter analysis (GCMS)

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)

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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.)

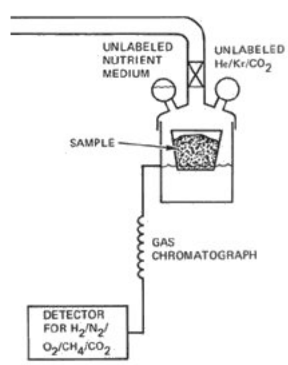
If signs of life were found, a control experiment would follow. (Obtain another sample, sterilize it, and then feed or water it and look again for metabolytes, etc.)

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.



GAS EXCHANGE

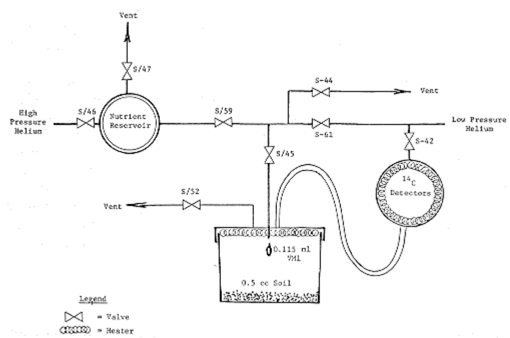
Life search #2: the Labeled Release (LR) experiment

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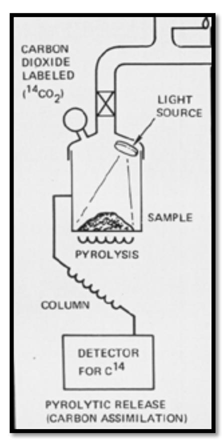
Life search #3: the Pyrolitic Release (PR) experiment

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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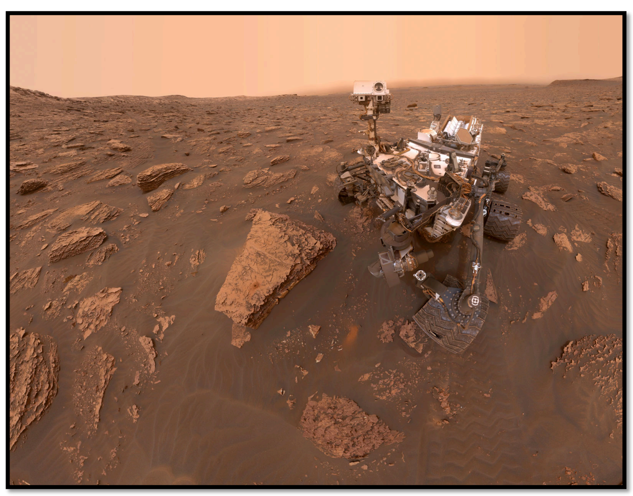
Curiosity

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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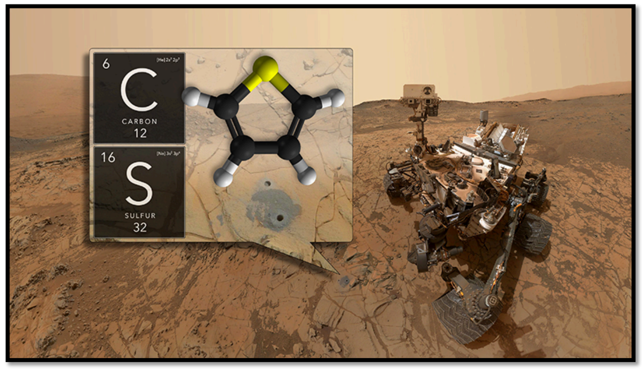
Mudstones on Mars

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℃, 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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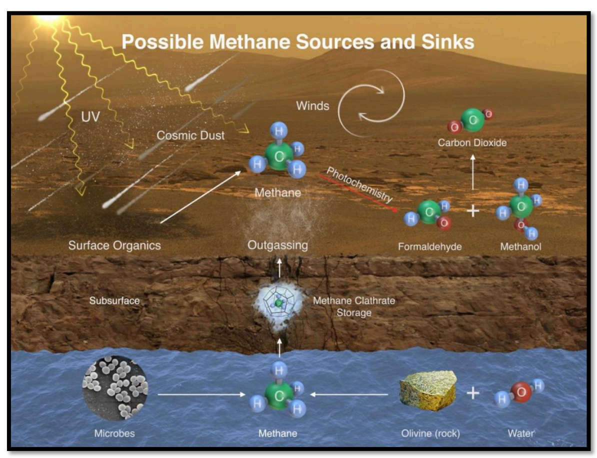
Methane on Mars

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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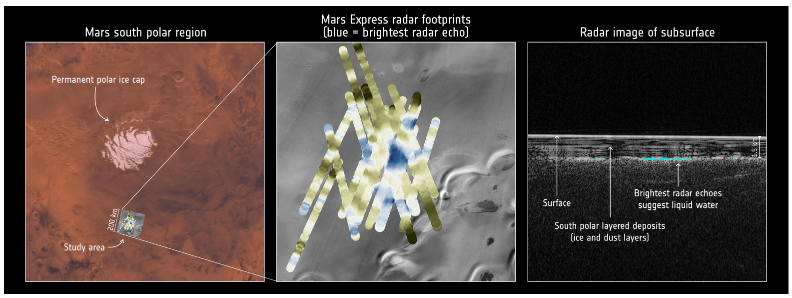
Water on Mars

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

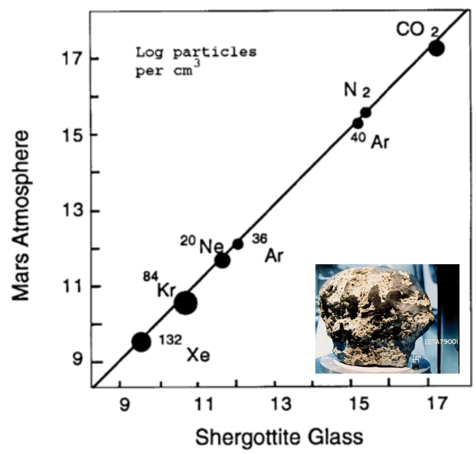
Acquiring Martian meteorites

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)

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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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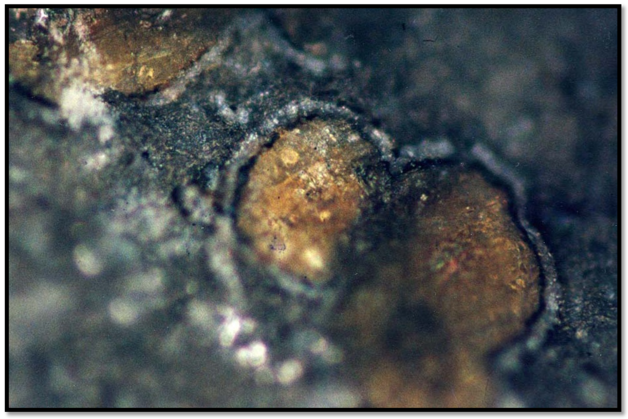
Life in ALH84001?

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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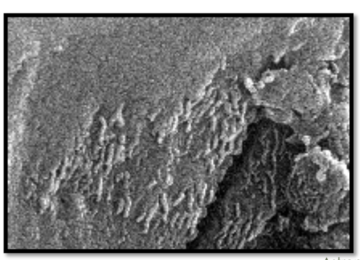
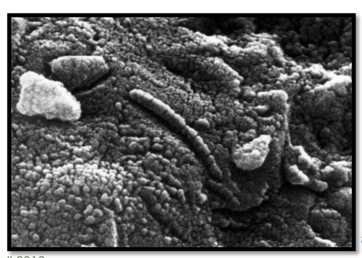
Life in ALH84001?

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)

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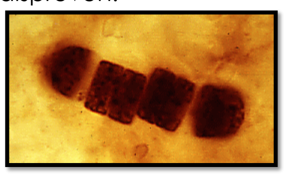
Life in ALH84001?

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.



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Question!

What is the best evidence that Mars might have harbored or currently has life?

A. Lots of long-chain and aromatic carbon molecules on the surface
B. Lots of water, presently cm-m deep under the surface
C. Lots of atmospheric methane
D. Lots of chemical evidence of metabolism in its CO_2 atmosphere
E. Fossil record of primitive organisms on the surface
F. Organic matter in sedimentary rock

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Orbital resonances & tidal heating

When Jupiter and Saturn formed, their moons formed as rapidly rotating objects from the leftovers in orbits smaller than they have now.

Energy losses from tidal heating soon slowed their rotation; all are now tidally locked and rotating synchronously.

As the spin associated with their *rotation* decreased, they drifted away from their planets as the spin associated with their *revolution* increased (orbital motion).

As they drifted outward, they captured one another in **orbital resonances**: orbits with integer ratios of orbital periods.

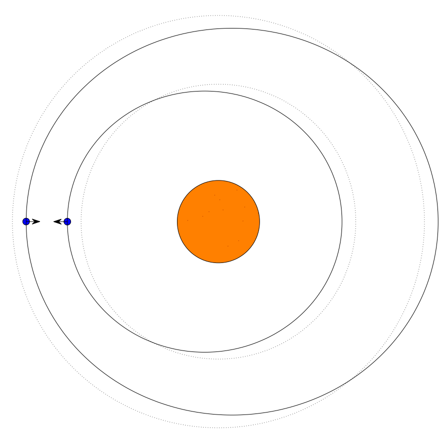
- For example, Io orbits Jupiter precisely twice for every orbit Europa makes, and precisely four times for every orbit Ganymede makes.

Orbital resonances & tidal heating

In resonant orbits, the attraction of the moons for each other keep their orbits slightly **eccentric** (elliptical) rather than circular.

- …because their point of closest approach always occurs at the same point in the orbit. If this took place at random locations, the long-term shapes would be close to circular.

So the stretch and squish from the planet's tidal forces **vary** around the orbit, resulting in a never-ending cycle of stretching and relaxing. This causes the moons to be tidally heated.



The large moons of Jupiter

	Io	Europa	Ganymede	Callisto
Orbital radius [10^{10} cm]	4.22	6.71	10.7	18.8
Orbital eccentricity	0.004	0.010	0.002	0.007
Orbital period [days]	1.77	3.55	7.15	16.69
Orbital period [Io orbits]	1	2.01	4.04	9.43
Mass [10^{26} g]	0.893	0.480	1.48	1.08
Albedo	0.62	0.68	0.44	0.19
Average density [g cm^{-3}]	3.53	3.01	1.94	1.83

Strong low-order orbital resonances

Icy surfaces

Rocky interiors

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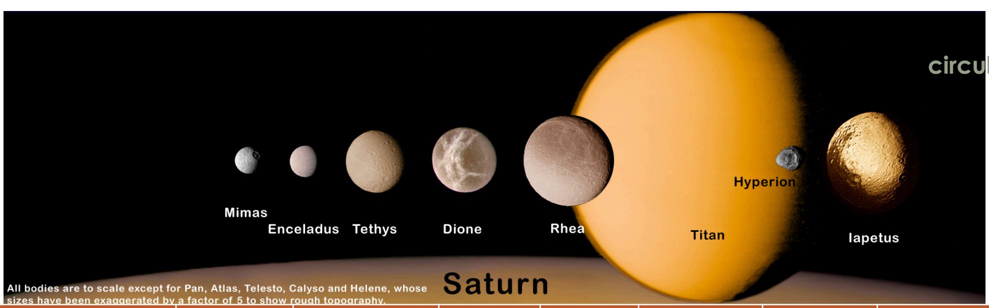
The large moons of Saturn

Strong low-order orbital resonances

Icy surfaces

Practically circular orbit (!?)



Orbital...	Mimas	Enceladus	Tethys	Dione	Rhea	Titan	Hyperion	Iapetus
Radius [10^{10} cm]	1.86	2.38	2.95	3.77	5.27	12.2	14.8	35.6
Eccentricity	0.020	0.005	0.000	0.002	0.001	0.029	0.104	0.028
Period [days]	0.942	1.37	1.89	2.74	4.52	15.9	21.3	79.3
Period [half-Mimas orbits]	2	2.91	4.01	5.81	9.59	33.8	45.2	168
Mass [10^{23} g]	0.375	1.08	6.27	11	23.1	1345.5	0.2	15.9
Albedo	0.5	1.0	0.9	0.7	0.7	0.22	0.3	0.05/0.5
Density [g cm^{-3}]	1.14	1.61	1.0	1.5	1.24	1.88	0.5	1.02

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Orbital resonances important for tidal heating

Tidal stretch is larger when:

- **the mass of the planet is larger**
- **the orbit is smaller**
- **the eccentricity (noncircularity) of the orbit is larger**

Jupiter's inner-moon orbits are extremely likely to have been solidly locked since shortly after formation, but those of Saturn probably change their eccentricity over time.

- 1:2:4 **Laplace resonance** is particularly stable: **eccentricities are "permanent"**
- The table on the right ignores the 4:3 resonance of Titan and Hyperion.

Planet	Moon	Tidal stretch (relative)	Orbital resonances
Jupiter	Io	18	4:1, 2:1
Jupiter	Europa	10	2:1, 1:2
Jupiter	Ganymede	0.61	1:2, 1:4
Saturn	Mimas	36	*3:2*, 2:1, *3:1*
Saturn	Enceladus	4.8	2:3, *4:3*, 2:1
Saturn	Tethys	0.0	1:2, *3:4*, *3:2*
Saturn	Dione	1.3	*1:3*, 1:2, *2:3*

Weaker resonances indicated in italics

The extremes: Io

Io suffers the most tidal heating of the Jovian moons.

Unlike other moons, Io has hardly any craters. There is no reason why it would be hit less often than the other moons, so it must have some way of filling in the craters.

Io has hundreds of active volcanoes capable of filling in these craters – it is the most volcanic body in the Solar System. Its mantle may be completely molten.

The surface is smooth, covered with lava flows topped with frozen vapors composed mostly of water (white) and sulfur dioxide (SO_2, yellow) ice.

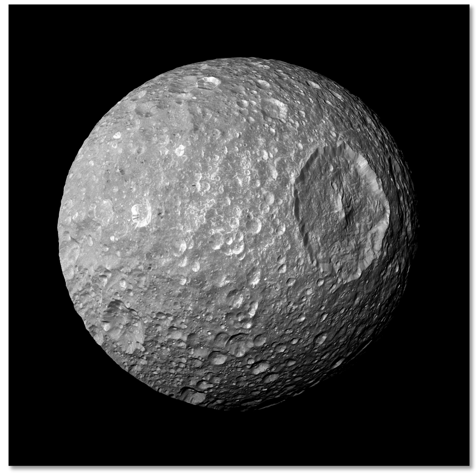
The extremes: Mimas

Mimas should be even worse than Io, but instead, it has an ancient, bombarded surface with craters of all sizes.

This includes the giant crater Herschel, which features a central peak like the larger craters on the Moon.

And it has absolutely no volcanoes.

Planetary scientists call this odd situation the **Mimas paradox**.



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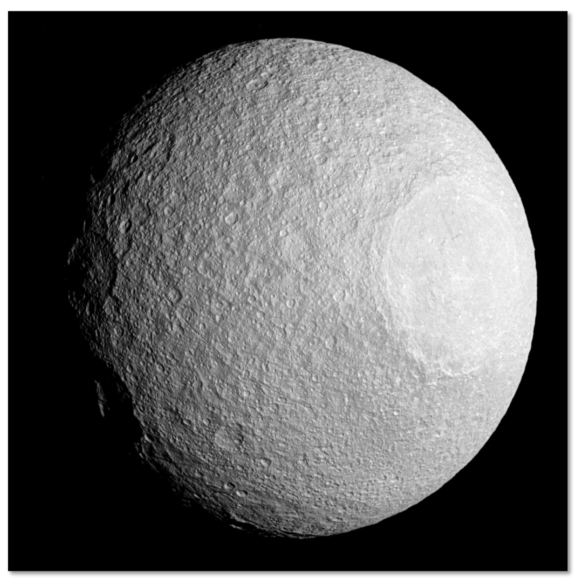
Mimas paradox

There is no good explanation yet for why Mimas is not a flaming lump of magma like Io. Possibilities include

- A fairly recent large orbit-eccentricity increase due to perturbations by the other moons, recently enough that it has not yet melted.
  - Mimas is locked in a 2:1 orbital resonance with Tethys, but it has no other near-locks.
  - Tethys also has a heavily cratered surface (including a giant crater larger than the one on Mimas), and (currently) a peculiarly circular orbit.
- Tidal heat is somehow dissipating within Saturn instead of in the moons.



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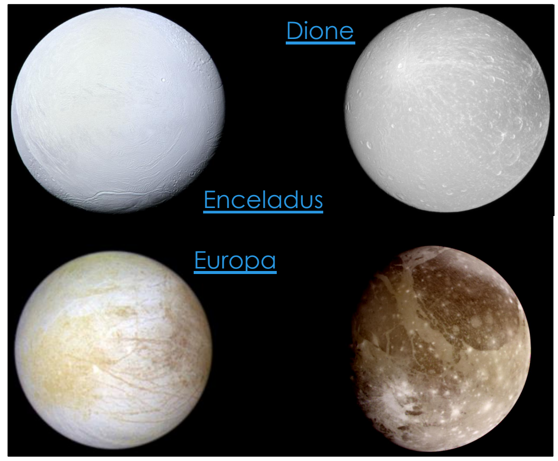
Which explanation is more likely?

Since the latter of these two options has a few "if pigs could fly" parts to the explanation, we will presume that the former is more likely.

- The more complex perturbations among the Saturnian moons may make their tidal heating **episodic**.
- The robust 1:2:4 resonance among the inner Jovian moons (with only Callisto as a significant non-resonant perturber) has made their heating stable over the past ~4.5 Gyr.



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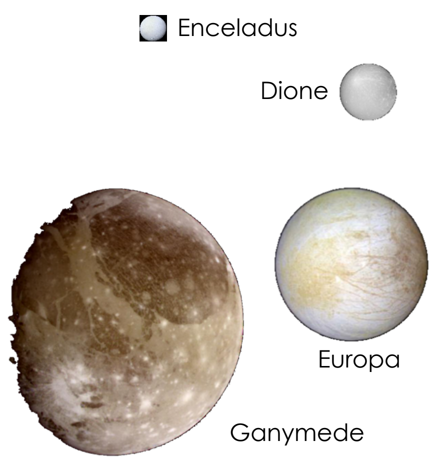
Potentially tidally-heated habitats

The airless moons – all but Titan – would have the best chance of supporting life in subsurface oceans kept liquid by tidal heat.

For tidal heating, then, we will reject both Mimas (no heating apparent yet) and Io (too hot) and focus instead on the orbitally-locked pairs

- Europa and Ganymede
- Enceladus and Dione

Only Ganymede is larger than our Moon.



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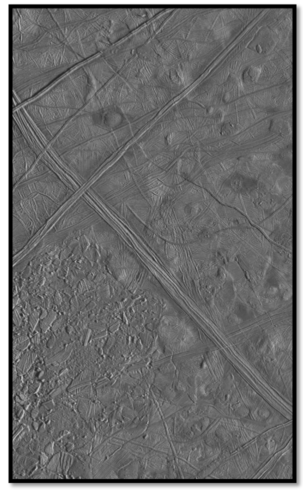
Europa's global subsurface ocean

Europa is 100% covered in water ice, with prominent salty patches and traces of minerals and organic molecules.

Like Io, Europa has far fewer craters per acre than Ganymede and Callisto.

Since there is no reason why it would not experience the same rate of bombardment as the other two, Europa must have some way to fill in the craters.

A clue to how: Europa's surface looks like Earth's oceanic pack ice, complete with places that look like the ice sheet **repeatedly cracked and refilled with liquid water**, which then froze.



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Europa's global subsurface ocean

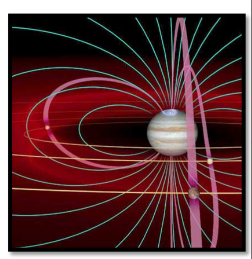
Can we sense liquid under the ice? **Yes**

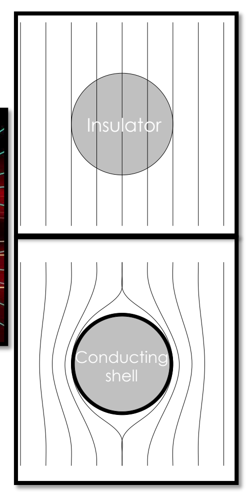
Jupiter has a strong bar-magnet-like magnetic field, within which its moons orbit.

Rocks and ice are electrical insulators, and they do not affect externally-applied magnetic fields. Most moons (like our own) behave this way in their planet's field.

But magnetic measurements in close satellite flybys, especially by NASA's *Galileo*, have shown Europa to repel Jupiter's magnetic field in a way an electrically-conducting surface would do.

A **global saltwater ocean** under the ice (about 160 km deep) would repel the field as observed.





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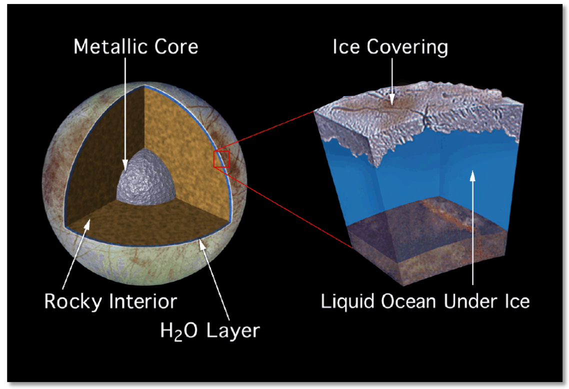
Europa's global subsurface ocean

Judging from the few craters, the ice is probably 20-110 km thick.

- **Europa has 2-3 times as much water as Earth!**
- Since organics go with water in primitive Solar System bodies, **Europa has 2-3 times as much organic carbon as Earth!**

Europa's average density is large, especially for a moon – about that of basaltic rock – so the global ice-covered ocean probably sits directly on the warm, tidally-heated rocky crust.

Europa has precisely the situation of the Arctic Ocean and has been that way for about 4.5 Gyr!



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Which life-promoting feature(s) of Earth's oceans is (are) likely to be absent from Europa's oceans?

Question!

A. Hydrothermal vents (smokers) providing local heating and material from deeper within Europa
B. Dissolved organic prebiotic molecules such as those made in the Miller-Urey experiment's "atmosphere"
C. Dissolved inorganic substances
D. Circulation of the ocean water
E. Sunlight

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Enceladus’ global subsurface ocean

Enceladus has the highest albedo in the Solar System, very close to 1. So, it must be covered in clean (water) ice with a smooth surface.

Indeed, the surface is smooth: not many impact craters, just lots of thin cracks and fissures. At close range, it displays a Europa-like or pack-like appearance.

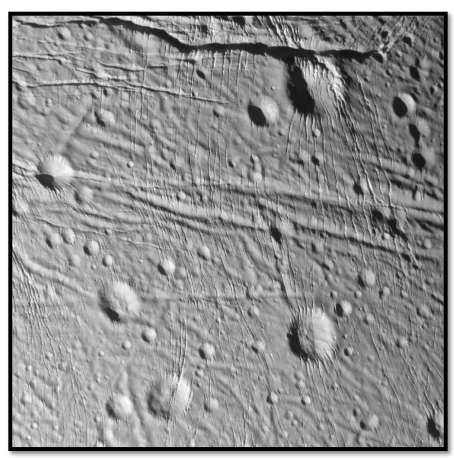
55

Enceladus’ global subsurface ocean

So the surface also gets frequently recoated. This requires heat sufficient to melt water ice, and a means to distribute it over the surface.

Because of its position within one of Saturn’s outer, icy rings – the one called the E-ring – it has long been thought that Enceladus was responsible for the formation of this ring.

Precisely how this happens was obscure until the flybys by *Cassini*, which revealed water geysers at Enceladus’s south pole.



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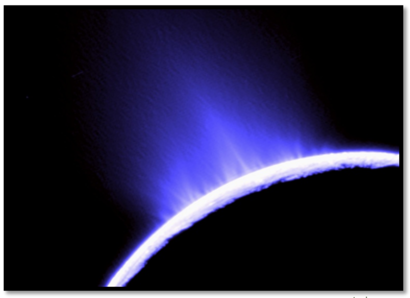
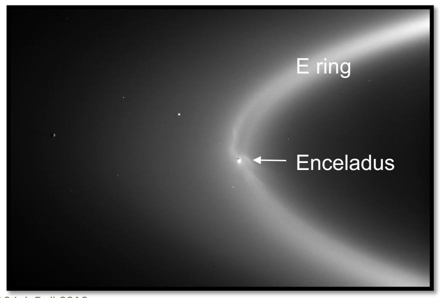
Enceladus’ global subsurface ocean

Thus Enceladus, too, has bodies of liquid water underneath the ice in at least some places.

Along with water, minerals and organic molecules are detected in the geyser plumes.

The plumes produce enough ice particles to explain the E-ring and to refresh the moon’s ice coating.

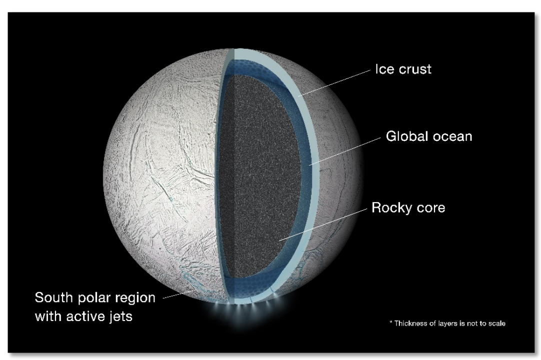




Enceladus’ global subsurface ocean

It has not yet been possible to determine the extent of the ocean magnetically, but there is another clever way:

- Elliptically-orbiting bodies undergo oscillations in their orientation, an effect known as **libration**. Theory and observations of libration agree for essentially all Solar System bodies.
- For Enceladus, the observed libration is ten times as large as expected, if one assumes that the moon is solid (Thomas et al. 2016).
- So far, the only way to account theoretically for the observations is to disconnect the surface and core with a **global ocean**. The ocean might be **preferentially tidally heated** from this stirring.
- The ocean probably sits on top of the rock/ice core.



Ganymede & Dione

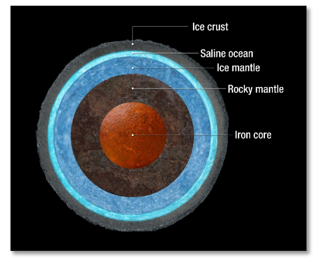
Ganymede and Dione mostly create the eccentricities that provide Europa and Enceladus with tidal heating. In turn, their orbits are also eccentric, but they are far enough from their planets that the tidal heating is much less.

For Ganymede, we observe magnetic "repulsion," though it is not as perfect as on Europa. In part, this is due to the moon having its own magnetic field in addition to Jupiter's.

Ganymede also has its own auroras. The positions of the auroras are in agreement with theory only if Ganymede has a saltwater-like shell like Europa's, 150-330 km beneath the surface (Saur et al. 2015).

So Ganymede, too, is likely to have a global ocean, though it probably sits on top of an ice mantle rather than directly on the rocky mantle.

Unfortunately, Dione has not yet been frisked for oceanic contents.



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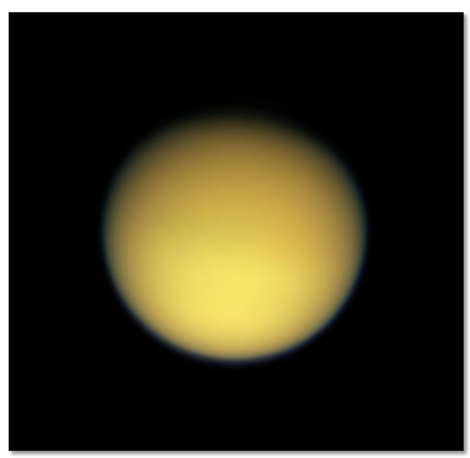
Titan's hydrocarbon lakes

Titan is the second-largest satellite in the Solar System (slightly smaller than Ganymede) and was the first one discovered after the Galilean satellites (by Huygens in 1665).

It is not locked in an orbital resonance, but it has a relatively large orbital eccentricity: four times the tidal stretch of Ganymede.

It is the only moon in the Solar System with a dense atmosphere: pressure of about 1.6 Earth atmospheres at the surface, 95% nitrogen (most of the rest is methane and ammonia), and is so heavily laden with photochemical smog that the surface cannot be seen at visible wavelengths. So *Cassini* packed infrared cameras and radars.



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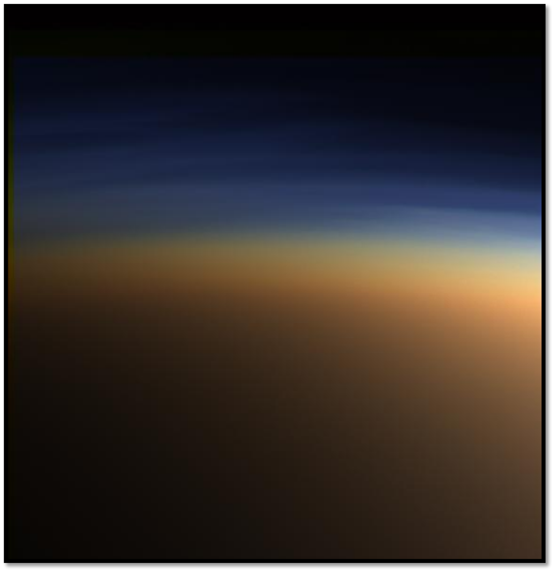


Titan's hydrocarbon lakes

Haze in Titan's upper atmosphere

Photochemical smog below

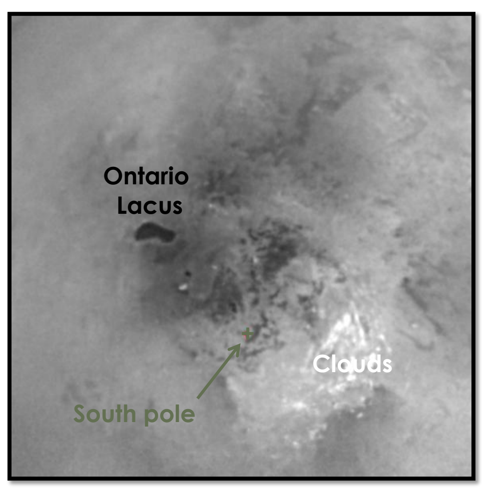
Titan's hydrocarbon lakes

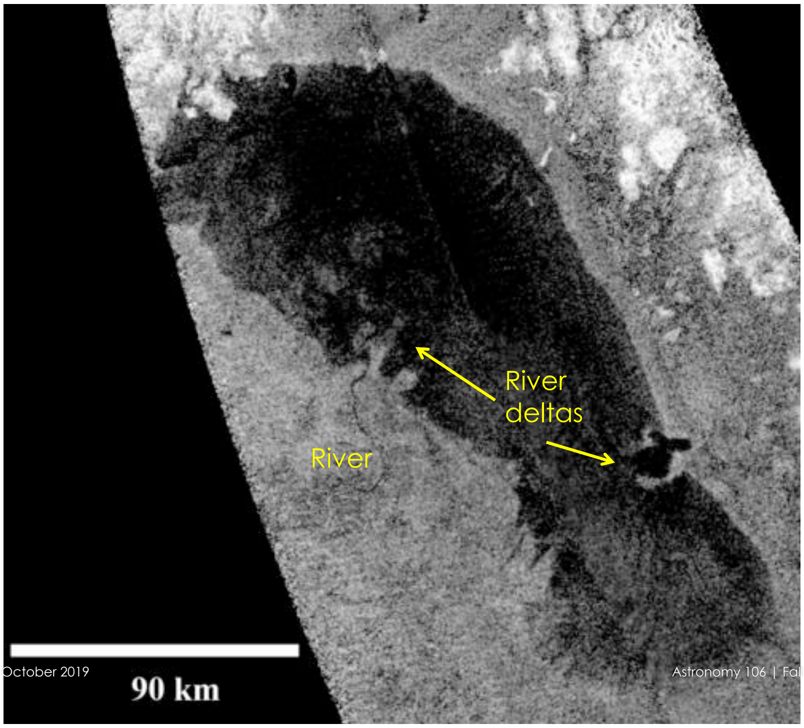
Besides Earth, Titan is the only Solar System body to have liquids permanently resident on its surface.

Hundreds of lakes are seen, especially near the poles: they change in depth over time and are fed by rivers with deltas.

In Ontario Lacus, liquid ethane (70%) and methane (10%) dominate the contents.

Ligeia Mare is nearly pure liquid methane and ethane and is 170 m deep.





Titan's hydrocarbon lakes

Radar image of Ontario Lacus, taken in 2010 by *Cassini*.

Note the rivers – rivers imply rain!

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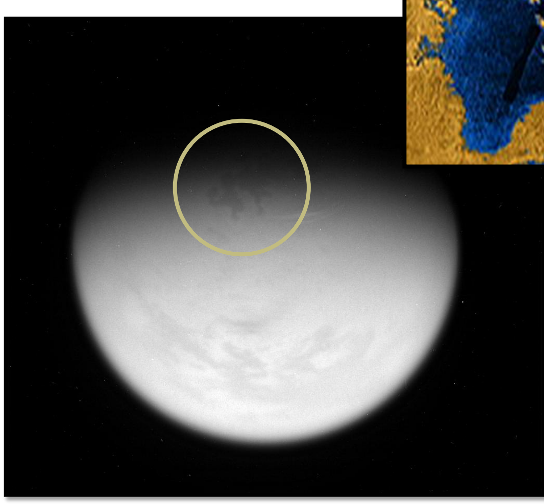

Titan's hydrocarbon lakes

Left: Titan's North-Polar Great Lakes, Kraken Mare and Ligeia Mare. Right: Ligeia Mare on the same scale as Lake Superior.

All together, Titan's lakes contain 40 times the volume of Earth's proven oil deposits.

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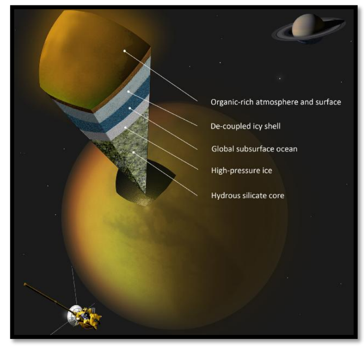
Titan's global subsurface (water) ocean

Titan has several non-LAWKI habitability features in its favor. But for good measure, and despite the lack of significant orbital resonances, it also seems to have a subsurface ocean.

Titan rotates synchronously: the direction of its stretch is constant, but its magnitude varies through its relatively eccentric orbit.

The variation of the tidal stretch through the orbit has been measured by *Cassini* and is a factor of 10 too large for the surface to be solidly connected with the rest (Iess et al. 2012). A subsurface ocean would work fine; **the ocean may be preferentially tidally heated.**

As on Ganymede, the low density of Titan makes it likely that the ocean sits on a water-ice mantle rather than atop the rocky core.



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Summary: AST 106 habitability ratings

Rating these worlds according to supply of water and organics; supply of minerals and inorganics; supply of heat; and consistency of the heat source, on a 100-point scale.

Europa (100)

After cancelling the ambitious Europa Jupiter System Mission, NASA is now planning a Europa orbiter – the "Europa clipper" – carrying nine experiments to characterize Europa's surface and contents noninvasively. Set to launch around 2025. Meanwhile, the European Space Agency (ESA) is planning to get its JUpiter Icy-moons Explorer (JUICE), carrying *ten* experiments to Europa, Ganymede, and Callisto by 2029. Still no landers.

Ganymede (57)

EJSM would have gone here, too, but now it falls to JUICE, and some possible interest by Russia to build an orbiter-lander mission they call Laplas-P (Laplas Posadka = Laplace's Lander). The latter might be coordinated with JUICE for a 2030 arrival, but mission development is at a standstill.

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Summary: AST 106 habitability ratings

Titan (56)

The score includes a 5-point bonus for the hydrocarbon lakes and possible nonpolar-solvent biochemistry. With *Cassini* recently ended and the cancellation of the ambitious Titan Saturn System Mission (TSSM), NASA has done little besides conceptual exercises, such as a mission to place a submarine in the Kraken Mare. Since contributing the *Huygens* lander to the *Cassini* mission and helping their partner NASA cancel TSSM, ESA has expressed little interest; Russia has expressed none.

Enceladus (41)

Worries about the consistency and longevity of its tidal heating source, and a small deduction for being so tiny, have reduced Enceladus' score.

Summary: AST 106 habitability ratings

Mars (40)

Along with Earth-based astronomical detections of methane and water on Mars, NASA has 14 robotic Mars life-search missions in its past, five currently operating, and two in the near-term development stages. ESA currently has one, and two big ones coming up soon. ISRO (India) has an orbiter operating. Including failures and counting the MERs as one: a total of 42 missions.

The Jupiter (Saturn) systems have received six (four) dedicated missions, sharing three of them – Pioneer 11, Voyagers 1 and 2 – and including only one short-lived lander (*Cassini*/*Huygens*, Titan). *Juno* is currently in orbit around Jupiter, but it is studying just the planet and not its moons.

And we hear of doubling down: preparations are underway to send humans to Mars, despite the huge expense and near-certainty of deaths in transit, in the hope that real geologists and biologists will find life where robots could not.

What would be your favorite place to conduct a search for life in the Solar System?

A. Io
B. Europa
C. Ganymede
D. Callisto
E. Mimas
F. Enceladus
G. Tethys
H. Dione
I. Titan
J. Mars

Question!

Review of life prospects in the Solar System

Temperature

Sun's radiation (within habitable zone)
- Only Venus

Additional heating due to atmosphere (greenhouse effect)
- Only present on planets with atmospheres
- Venus is too hot because of the greenhouse effect

Additional heating due to tidal forces (tidal heating)
- Saturnalian and Jovian moons (no planets!)

Too hot for life on at least half of the surface
- Mercury, Venus, Moon

Water

Water only found in permanently-shaded craters
- Mercury, Moon

Evidence of water on or below surface
- Earth, Mars, most of the moons discussed

Evidence of sub-surface water oceans
- Most moons *except* Io and Mimas

Liquid methane and ethane on surface
- Titan