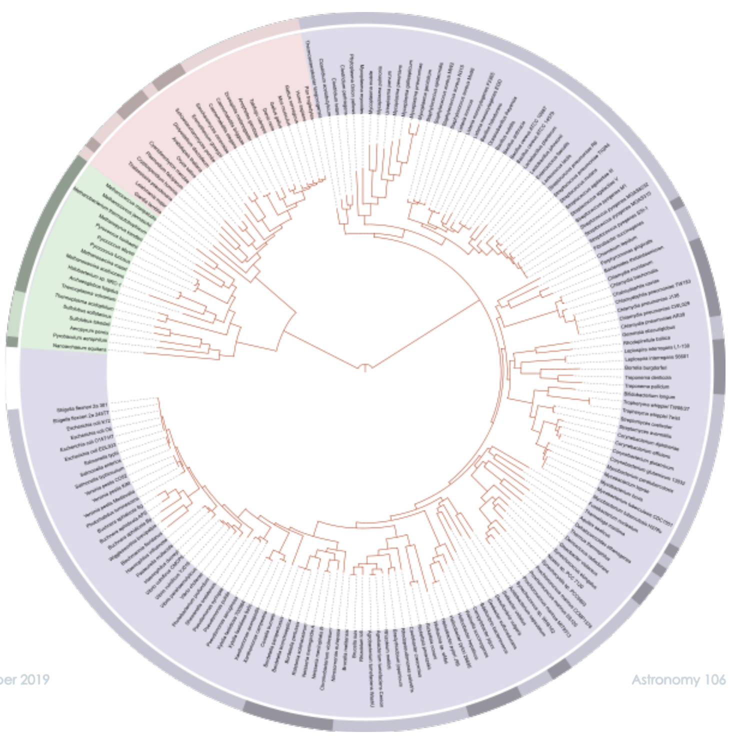
29 October 2019

POSSIBILITIES FOR EXTRATERRESTRIAL LIFE IN THE SOLAR SYSTEM & EVOLUTION OF LIFE ON EARTH

Homework 6 on WeBWorK due November 6 at 7pm
Halloween extra credit!

1



Possibilities for extraterrestrial life in the Solar System & Evolution of life on Earth

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

The accurate measurement of ages through Earth's history

Phylogeny

The fossil record and the increasing diversity of life: biological evolution

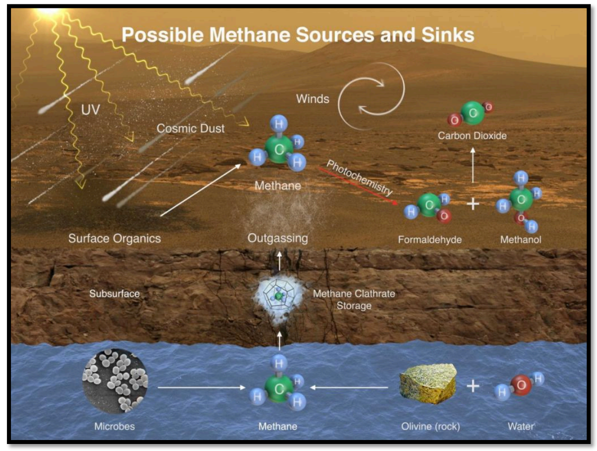
2

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.

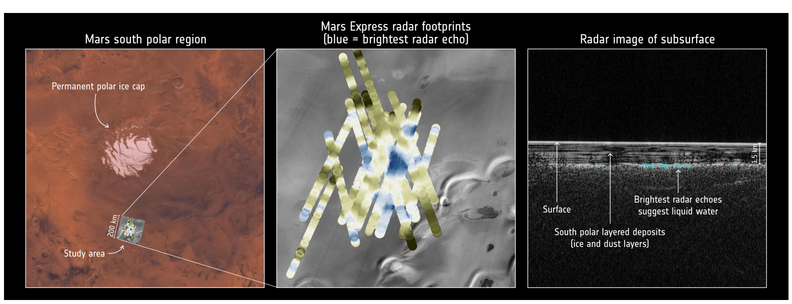


3

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

4

Acquiring Martian meteorites

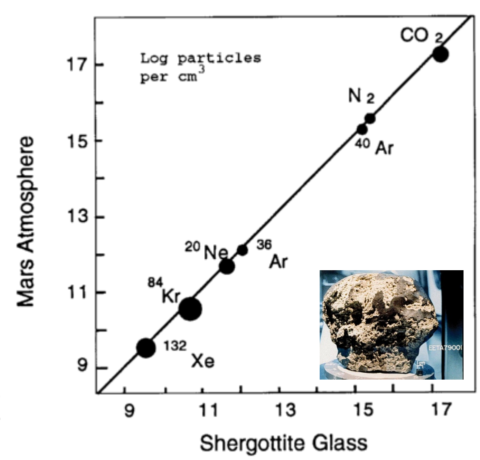
Some samples have been delivered to us already, free of charge, and still look at least as interesting.

5

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

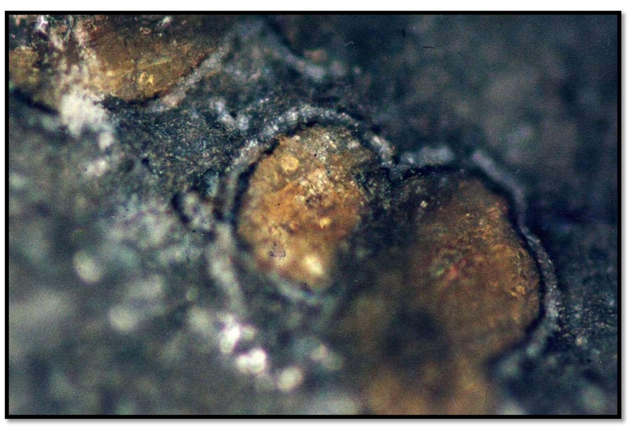
By far the oldest one is ALH84001:

- 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

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).



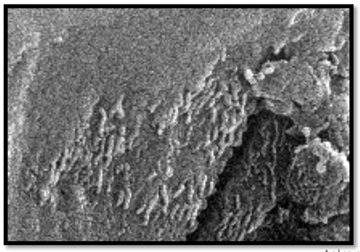
Romanek et al. (1994)

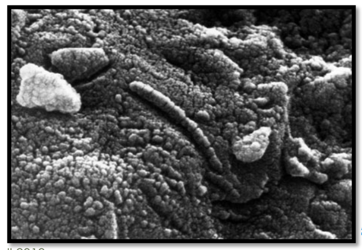
Life in ALH84001?

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

They are too small, though: 30×130 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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What is the best evidence that Mars might have harbored or currently has life?

Question!

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.

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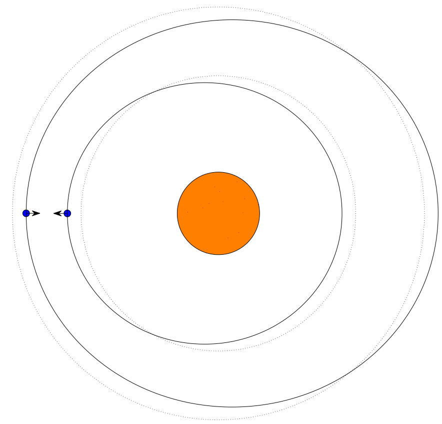
Orbital resonances & tidal heating

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.



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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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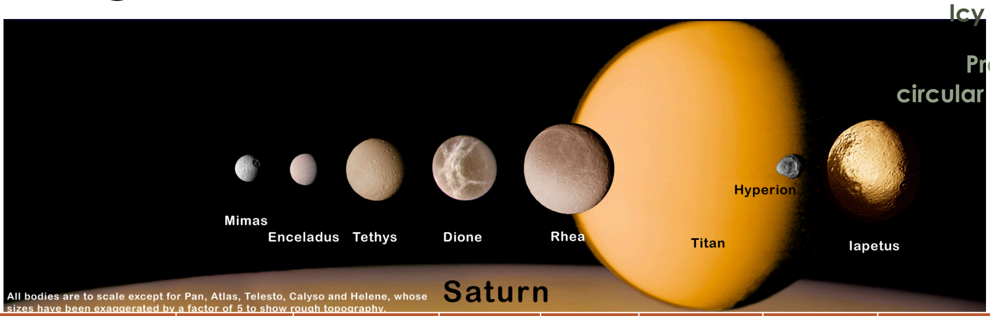
The large moons of Saturn

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

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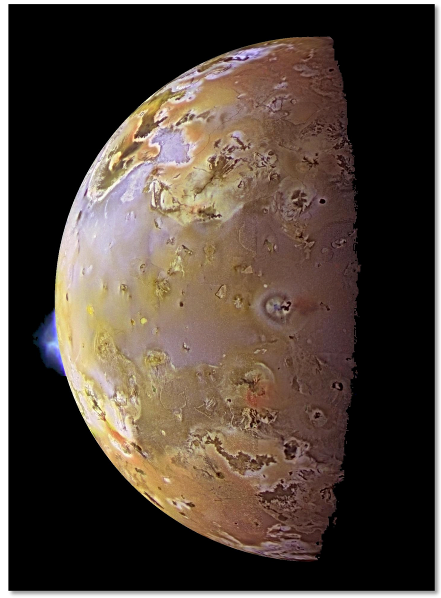
The extremes: Io

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.



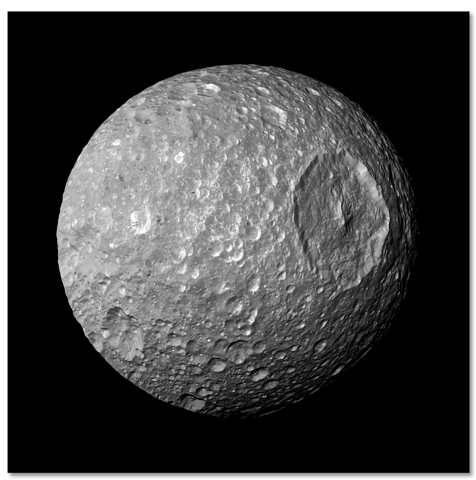
The extremes: Mimas

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.

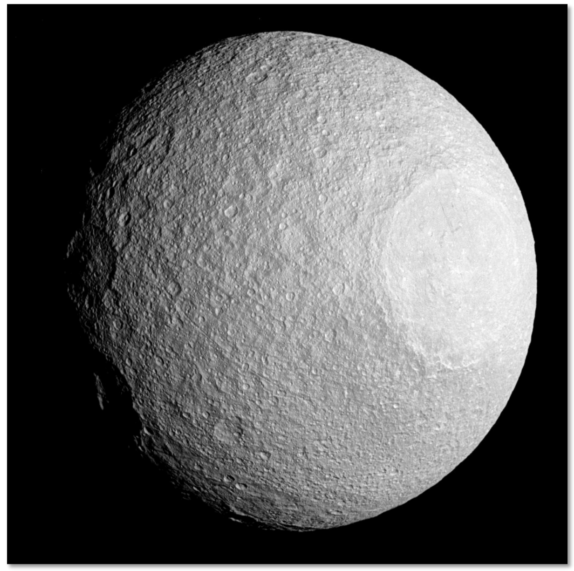
Planetary scientists call this odd situation the **Mimas paradox**.



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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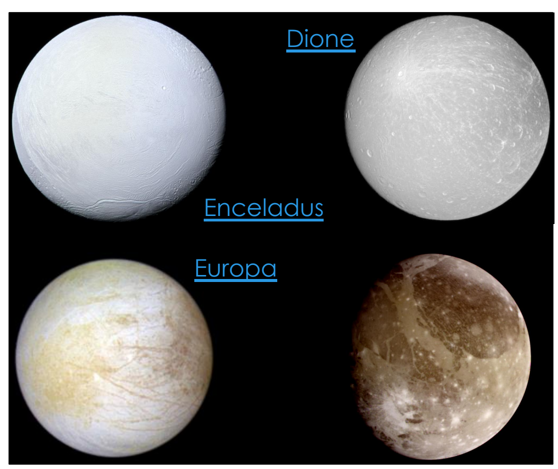
Which explanation is more likely?

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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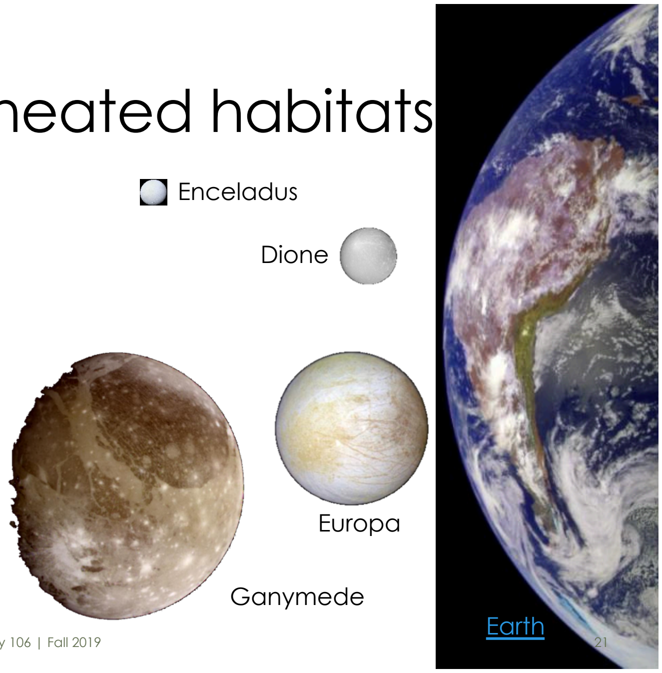
Potentially tidally-heated habitats

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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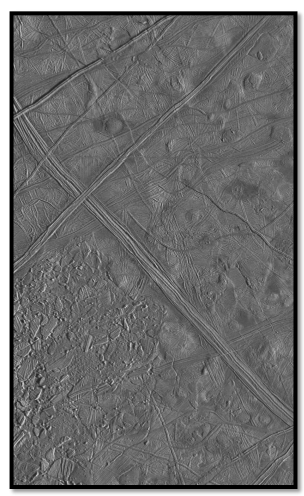
Europa's global subsurface ocean

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

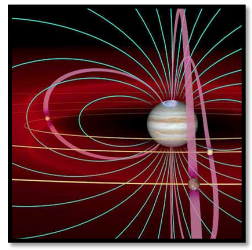
Can we sense liquid under the ice? **Yes**

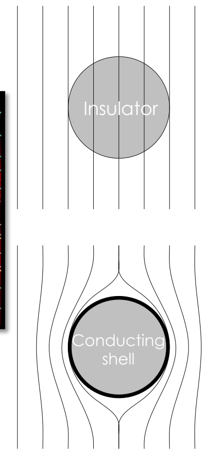
Jupiter has a strong bar-magnet-like magnetic field, within which its moons orbit.

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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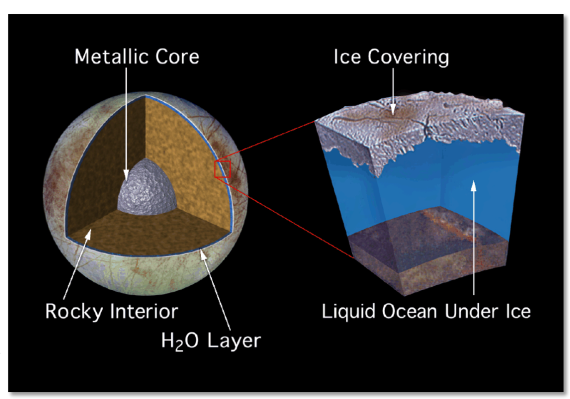
Europa's global subsurface ocean

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.

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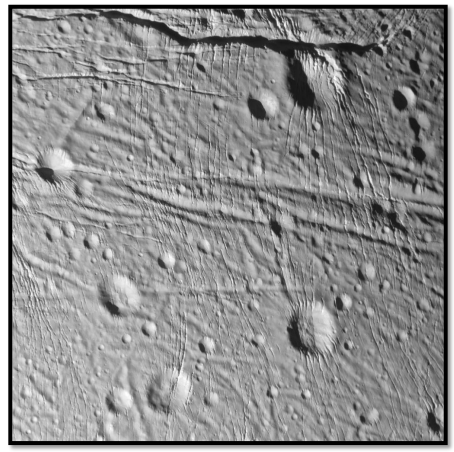
Enceladus' global subsurface ocean

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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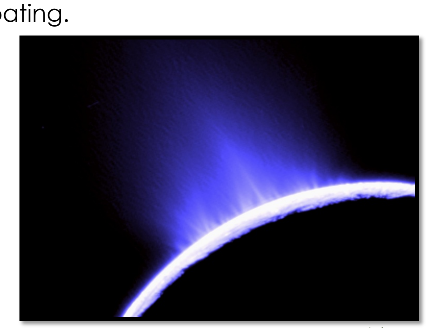
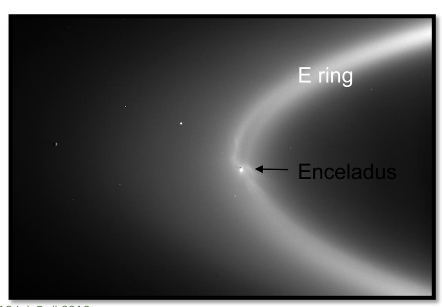
Enceladus' global subsurface ocean

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.





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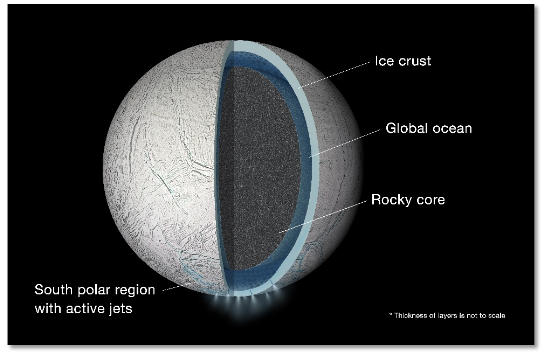
Enceladus' global subsurface ocean

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.



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Ganymede & Dione

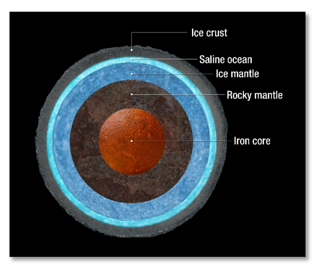
Ganymede and Dione mostly create the eccentricities that provide Europa and Enceladus with tidal heating. In turn, their orbits are also eccentric, but they are far enough from their planets that the tidal heating is much less.

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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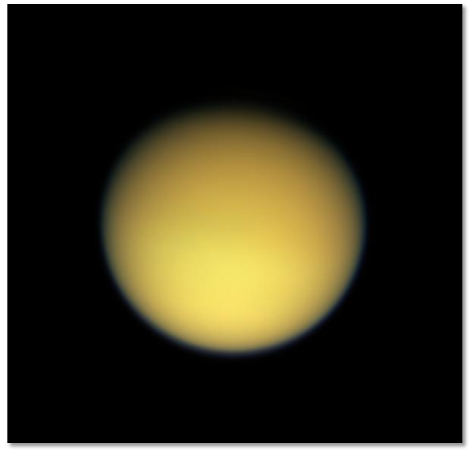
Titan's hydrocarbon lakes

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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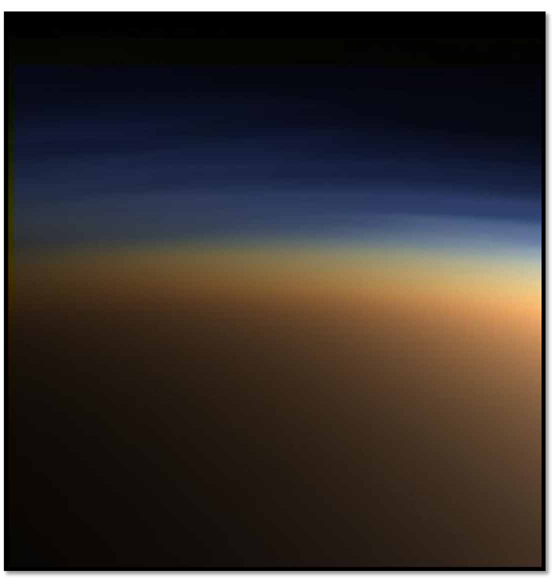

Titan's hydrocarbon lakes

Haze in Titan's upper atmosphere

Photochemical smog below

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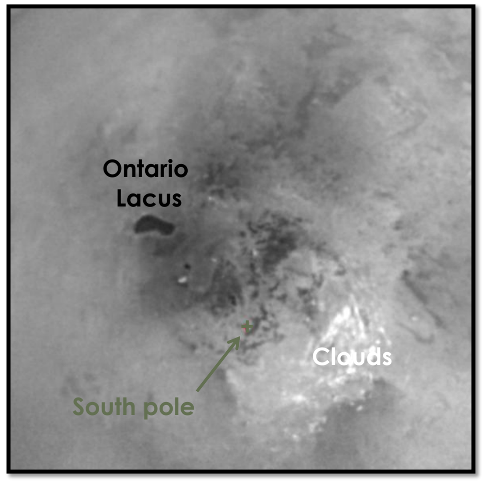
Titan’s hydrocarbon lakes

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.



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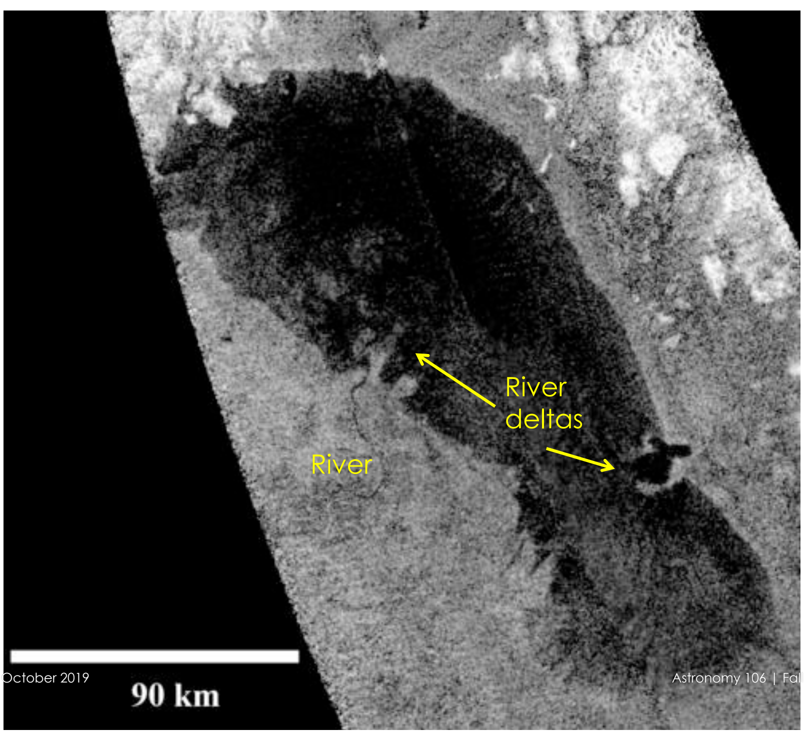

Titan’s hydrocarbon lakes

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

Note the rivers – rivers imply rain!

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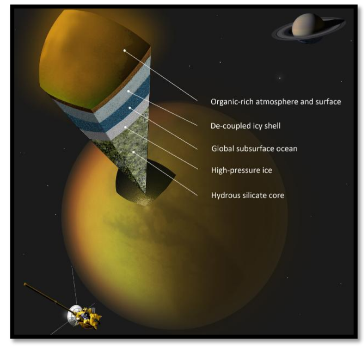
Titan's global subsurface (water) ocean

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.

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

Back to Life on Earth: more on age measurement

Now that we know how life evolves from prebiotic organic molecules and water, what happens next?

This can be determined experimentally by examining the **fossil record**: the state of living things on Earth as a function of time since the formation of the Solar System.

- As usual, the chronology is the most important thing to establish.

Then, the steps can be illuminated in finer detail by **phylogeny**: the structural classification of different forms of life, and comparison of genetic material among the forms that still exist.

- Measurement of "genetic distance" can be hooked through the fossil record to chronology.

Age of Earthly objects

We already know how to measure the ages of old igneous rocks and meteorites using Rb-Sr radioisotope dating of their minerals. Several similar methods give redundancy to check each other, or better precision over different age ranges.

Radionuclide	Daughter	Stable reference	Half life [Gyr]
^{147}Sm	^{143}Nd	^{144}Nd	106
^{87}Rb	^{87}Sr	^{86}Sr	50
^{187}Re	^{187}Os	^{186}Os	43
^{176}Lu	^{176}Hf	^{177}Hf	35
^{232}Th	…^{208}Pb	^{204}Pb	13.9
^{238}U	…^{206}Pb	^{204}Pb	4.5
^{40}K	^{40}Ca	^{44}Ca	1.5
^{235}U	…^{207}Pb	^{204}Pb	0.71

Age of Earthly objects – K-Ar dating

There are also a couple of interesting methods that do not involve mineral chemistry *per se*.

Potassium-argon. Normal potassium is ^{39}K. About 0.01% of potassium exists as ^{40}K, which can decay radioactively by two means: ordinary beta decay and electron capture.

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \upsilon_e \quad 88.8\% \text{ of decays}$$
$$^{40}\mathrm{K} + e^- \rightarrow {}^{40}\mathrm{Ar} + \upsilon_e \quad 11.2\% \text{ of decays}$$

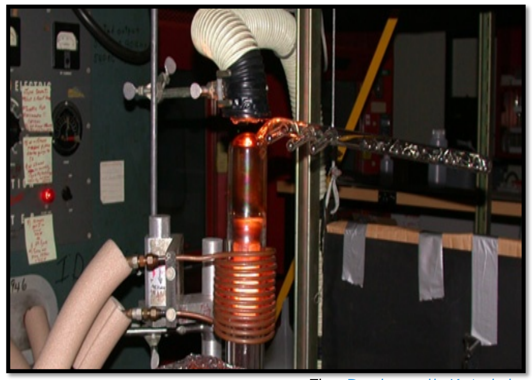
The half-lives are 1.5 Gyr (see previous chart) and 11.9 Gyr.

- Argon, though not a gas and not chemically bound to the mineral, does not escape from the site it occupied as a K atom unless the rock is sufficiently heated.
- The rock would otherwise contain no argon.

Age of Earthly objects – K-Ar dating

- Therefore, counting the trapped argons gives an accurate number of decays since the rock was formed, and this can be done by baking the rock to release the gas.
- The potassium must still be counted, though. The slickest way to do this is to subject the sample to a neutron beam from a nuclear reactor. This quickly converts all the ^{39}K to ^{39}Ar, which can be baked out and counted either separately or along with the ^{40}Ar.
- The analysis works the same as Rb-Sr.

This gives accurate ages in the 50,000 year – 1 Gyr range, nicely extending the range of Rb-Sr to younger ages.



The Dartmouth K-Ar lab

Age of Earthly objects – ^{14}C dating

In the atmosphere, cosmic rays transmute a tiny fraction of the normal isotope of nitrogen, ^{14}N, into the radioactive form of carbon, ^{14}C.

- The half-life of ^{14}C is shorter than any of the other radioactive clocks considered so far: **5730 years**. Consequently, it is only good for measuring young ages, $\sim 100 - 60{,}000$ years.
- The atmospheric concentration of ^{14}C is roughly constant throughout time: **^{14}C/total C $= 1.18 \times 10^{-12}$**.

Age of Earthly objects – ^{14}C dating

- The carbon in plants comes from atmospheric CO_2, so live plants have this same fraction of their carbon in ^{14}C.
- The carbon in animals comes from plants, so live animals also have their ^{14}C in the atmospheric abundance.
- As soon as the plant or animal stops either photosynthesizing or eating, the ^{14}C stops being replenished: dead things have less ^{14}C than the atmosphere by amounts directly related to how long they have been dead.
- Caveats: the atmospheric concentration of ^{14}C does vary with such things as the Solar sunspot cycle. For high accuracy, ^{14}C dates must be corrected by comparison to other methods (e.g. ^{14}C dates of tree rings, which go back about 9000 years).

Calculating ^{14}C ages

Ignoring corrections, the concentrations of ^{14}C are given by the master equations for radioactive decay:

$$\text{Concentration: } n(t) = n_0 e^{-t \ln 2 / t_{1/2}}$$

$$\text{Decay rate: } \quad r(t) = \frac{\ln 2}{t_{1/2}} n(t)$$

which can be rearranged to yield

$$\boxed{t = \frac{t_{1/2}}{\ln 2} \ln\left(\frac{n_0}{n(t)}\right) = \frac{t_{1/2}}{\ln 2} \ln\left(\frac{r_0}{r(t)}\right)}$$

You need to understand how to use this formula.

where

- $n_0 = 1.18 \times 10^{-12}$
- $r_0 = 13.56$ decays per minute per gram of C
- $t_{1/2} = 5730$ years

Nobel prize in chemistry (1960) to Willard Libby for the invention of radiocarbon dating

The ^{14}C concentration in a prehistoric corpse is ¼ that of the atmosphere. How long ago did it die?

Question!

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The ^{14}C concentration in a prehistoric corpse is measured to be 3.39 decays per minute per gram of C from the corpse. How long ago did it die?

Question!

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The dating of sedimentary-rock strata

Currently, we have a good way of measuring the ages of
- Igneous rock of just about any age
- Corpses of plants and animals that died within the last 60,000 years.

Unfortunately, fossils are
- not organic: their material has been replaced by inorganic material. So, ^{14}C dating would not work, even if it could reach very old.
- only found in sedimentary rocks. Sedimentary rocks are made of granules of other sorts of rock whose solidification ages bear no natural resemblance to one another.

The dating of sedimentary-rock strata

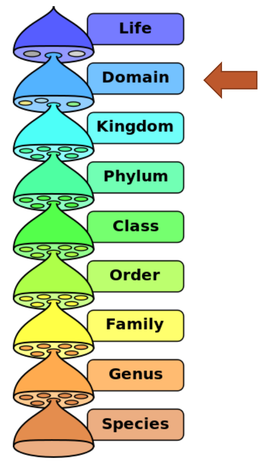
Fortunately, the Earth is volcanic, and there are sheets of sedimentary rock hundreds of miles across that have been horizontal since formation on ancient ocean floors.
- Sedimentary strata are overlain and underlain with igneous rocks whose ages can be measured by radioisotope means (most frequently K-Ar or K-Ca).
- Sediments build from the bottom up, so older sediments were buried by newer ones and now lie at a lower elevation or greater depth. Paleontologists call this the **principle of superposition**.
- Fossil ages can therefore be measured with a few-percent accuracy, and we can construct the **fossil record**: the census of living things through the last few Gyr.

The structure of fossils and life forms: phylogeny

To go with our accurate measures of time, we characterize the structure and, nowadays, the **genetic content**, of organisms.

This study is called **phylogeny** and was invented by Carl Linnaeus in the early 1700s.

The broadest classification is the **domain**. It is based on the distinction between cells that have organelles like nuclei, mitochondria, etc. (**eukaryotes**) and those that do not (**prokaryotes**, divided into **eubacteria** and **archaea**).



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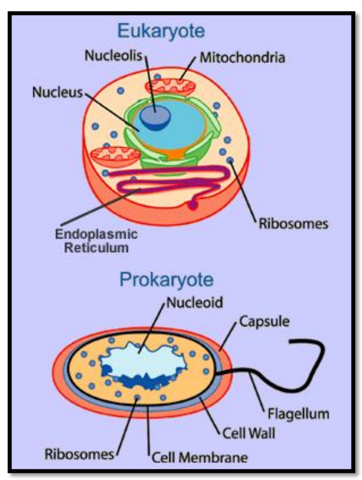
The structure of fossils and life forms: phylogeny

Archaea were first identified among the extremophiles; later, they were found genetically to be much different from eubacteria in their ribosomal RNA. (They still have essentially the same genetic code as other Earthly organisms, though.)

Evolutionary sequence of archaea → eubacteria → eukaryotes seems clear:

- Complexity and diversity increase in this direction
- Some organelles, particularly mitochondria and plastids, look like prokaryotes that assimilated into the structure of eukaryotes



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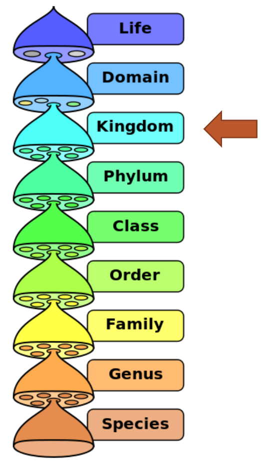
The structure of fossils and life forms: phylogeny

So far, all types can either manufacture their own nutrients out of monomers in the environment (**autotrophs**, the forerunners of plants) or need to eat processed nutrients or other life forms (**heterotrophs**).

The eukaryotes are the most diverse and are thus further sorted into **kingdoms**:

- **Animalia**: multicellular heterotrophs
- **Plantae**: multicellular autotrophs
- **Fungi**: multicellular symbionts
- **Protista**: unicellular eukaryotes



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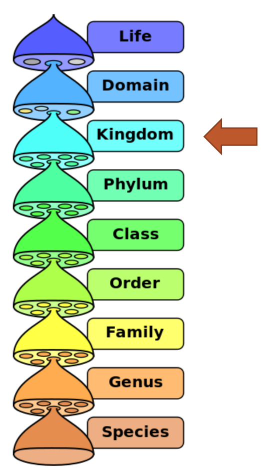
The structure of fossils and life forms: phylogeny

Within kingdoms comes an internal, genetic differentiation: **ploidy**, the number of copies of the nucleic-acid structures each cell contains.

- **Genes**: nucleic acid sequences that code proteins
- **Chromosomes**: structures containing genes
- **Haploids**: Life forms (permanently) containing only one copy of each chromosome
- **Diploids**: Life forms containing two copies of each chromosome. We are diploids.

Importance: this leads to a non-mutation means of having reproduction lead to greater diversity of each multi-ploid life form. We call this, of course, **sexual reproduction**.



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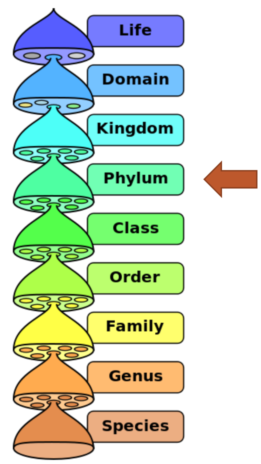
The structure of fossils and life forms: phylogeny

Each kingdom is further sorted into **phyla**.

- For example, the kingdom animalia is divided into 35 different phyla.
- We belong to the phylum chordata, those animals with spinal chords (though not necessarily spines).
- Plants are usually divided into 11 phyla, fungi into 6.
- Phyla first appeared 550 Myr ago: in the Cambrian Explosion, of which the Burgess Shale provides the most examples.



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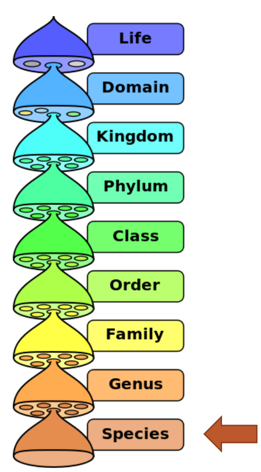
The structure of fossils and life forms: phylogeny

And so on, down to genus and species. Examples:

Human	Giant sequoia redwood
Eukarya	Eukarya
Animalia	Plantae
Chordata	Pinophyta
Mammalia	Pinopsida
Primatae	Pinales
Hominidae	Cupressaceae
Homo	Sequoiadendron
sapiens	giganteum



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Myr ago	Era	Fossil group	Event
Now	Cenozoic		
	Mesozoic		
		Burgess Shale	
	Paleozoic		Macroscopic life
		Ediacara	
			Snowball Earth
	Precambrian		
1000		Bitter Springs	Worm tracks (?)
			Multicellular algae
		Beck Spring Dolomite	
			Eukaryotes certain
		McArthur Group	Sexual reproduction (?)
2000		Gunflint chert	Eukaryotes possible
	Proterozoic		Oxygen-rich atmosphere
			Snowball Earth
			Formation of continents
3000		Bulawayan	
		Fig Tree	
		Onverwacht	
		Warrawoona	Autotrophs-Stromatolites
	Archean		Life begins (?)
			(Prokaryote heterotrophs)
4000			Formation of oceans
			Bombardment decreases
			Frequent impacts
	Hadean		Formation of Earth
5000			

The fossil record

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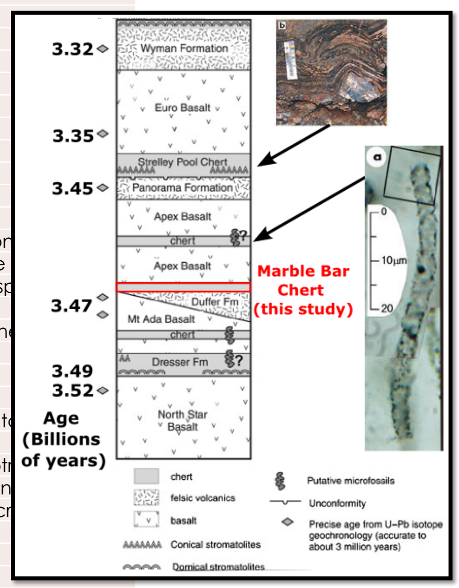

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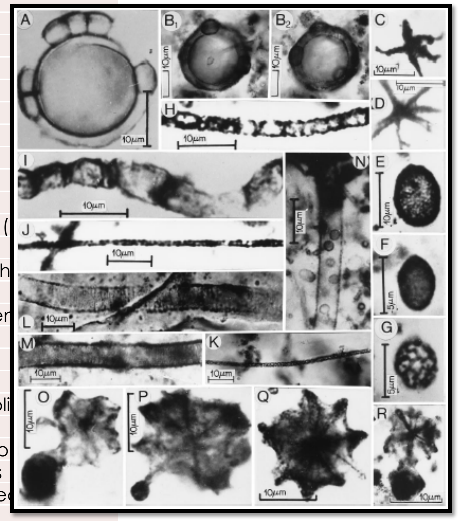

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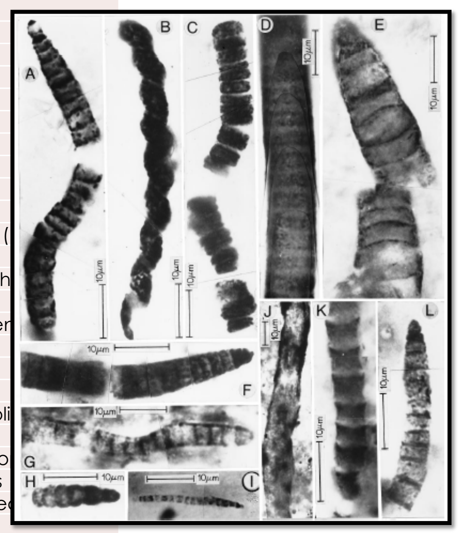

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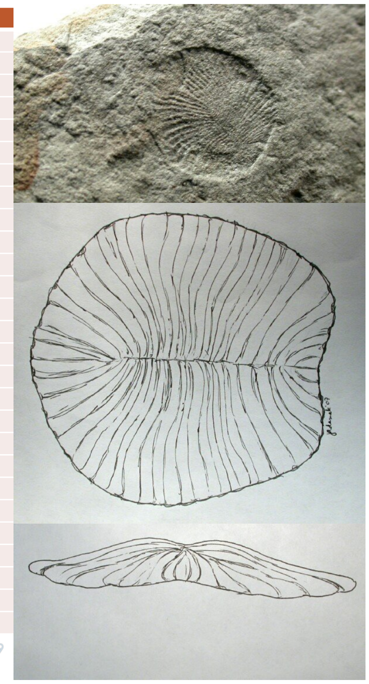

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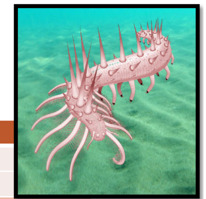
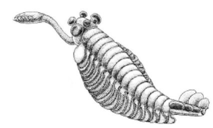
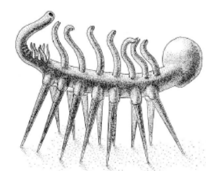
The fossil record 0-800 Myr ago: the Cambrian Explosion and its descendants



Era	Period	Myr ago	Life forms	Events
Cenozoic	Quaternary	2	H. sapiens	Ice ages
	Tertiary	65	Primates	Extinction of dinosaurs
Mesozoic	Cretaceous	136	Birds	South Atlantic open to 1900 miles
	Jurassic	190		North Atlantic open to 600 miles
	Triassic	225	Mammals	Continental drift
Paleozoic	Permian	280	Reptiles	Pangaea breaks up
	Carboniferous	345	Amphibians	Formation of coal
	Devonian	395	Insects	
	Silurian	430	Land plants	
	Ordovician	500	Fish (Chordata)	Burgess Shale forms
	Cambrian	543	Trilobites	
Precambrian		545	Small shelly fossils	*Appearance of phyla*
		580	Ediacarans	
		600-80		Snowball Earth episodes
		0		
			Multicellular life	





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Summary of fossil record

Cellular life has been around for at least 3 Gyr.

Simple organisms developed first, more complex ones later: prokaryotes, then eukaryotes, then multi-cells.

Deterministic "progress" of families is not observed:

- Many organisms develop and become extinct with no links to successors.
- Some families develop greater diversity, but many stay about the same complexity (e.g. bacteria).

General increase in complexity and diversity of life forms, though:

- Huge animal boom in the Cambrian Explosion.
- Plant boom in the last 150 Myr, driven by flowering plants and insect hosts.

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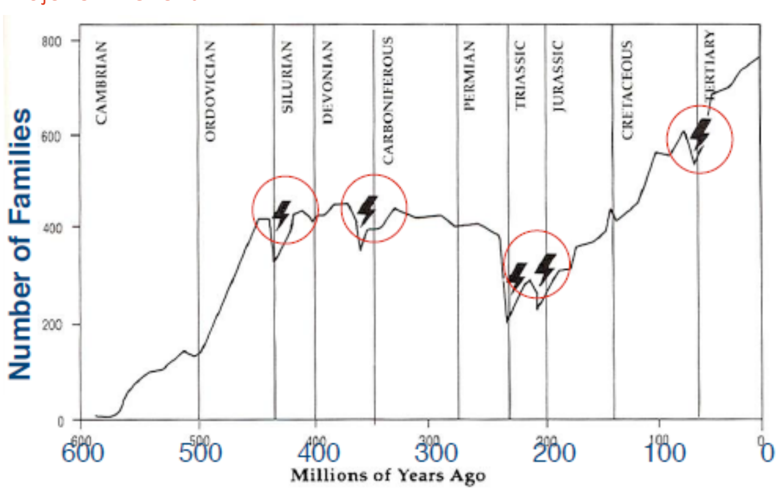
Major extinctions



Diversity rising

"Biological diversity has increased slowly over geological time, with occasional setbacks through mass global extinctions. There have been five such extinctions so far, indicated here by lightning flashes. The data given are for families (groups of related species) of marine organisms. A sixth major decline is now underway as a result of human activity." - E.O. Wilson, *The Diversity of Life*

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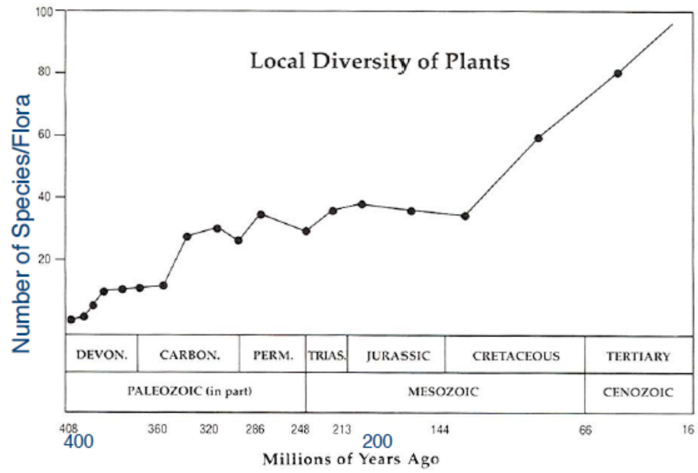

Local diversity of plants

"The average number of plant species found in local floras has risen steadily since the invasion by plants 400 million years ago. The increase reflects a growing complexity in terrestrial ecosystems around the world." - E.O. Wilson, *The Diversity of Life*

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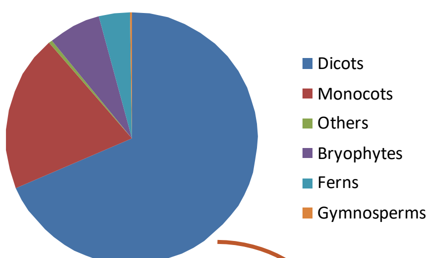
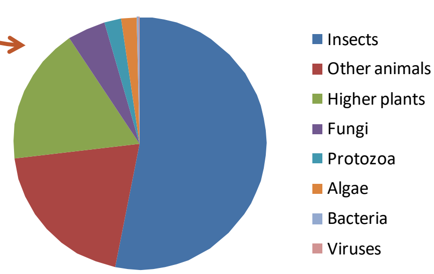


Higher plants on land: about 300,000 species total

Biodiversity today



All known species: about 2,000,000, mostly on land. Vast numbers remain to be discovered, particularly among the small wedges.

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Biological evolution

Features of the fossil record:

- Change of Earth's population with time over billions of years
- Development of greater structural complexity and diversity of fossils as time goes on
- Clear developmental patterns among species within many families as time goes on

These features are all experimental facts. Thus, **biological evolution is also an experimental fact** to go with all the other cosmic evolutions we have found so far.

The Burgess Shale formation in British Columbia is the richest source of Cambrian-era fossils.