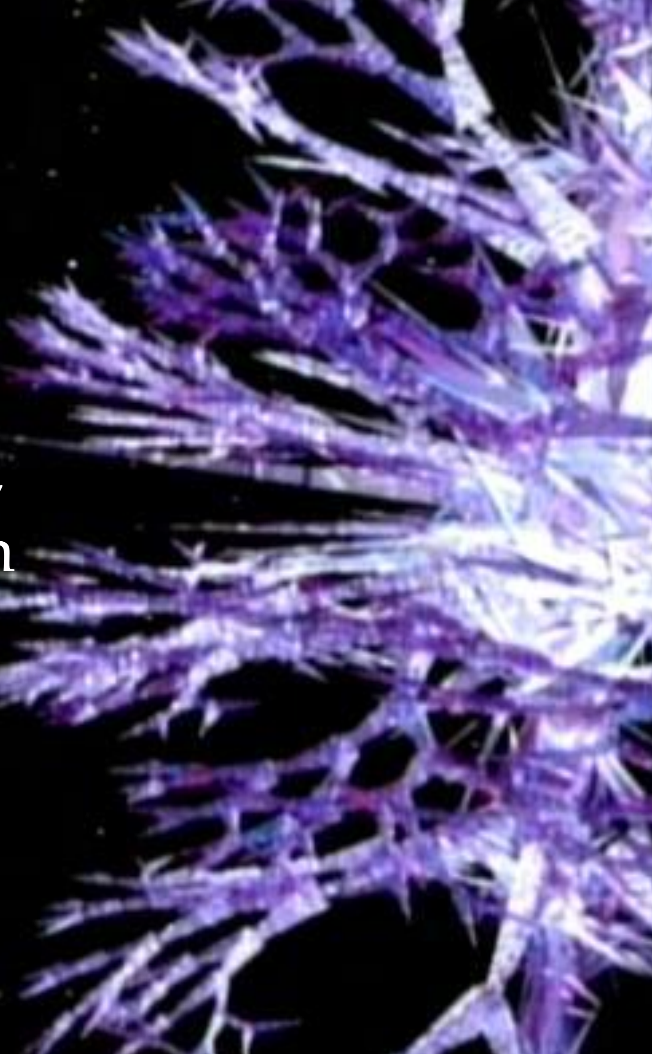
Today in Astronomy 106: alternative forms of life and life in the inner solar system

- ❑ Clays and crystals as catalysts for biomolecules
- ❑ Alternatives to carbon.
- ❑ Alternatives to water.
- ❑ Alternatives to atoms.
- ❑ Status of the Drake-equation input: f_ℓ , the fraction of habitable planets which give rise to life.
- ❑ No life on Mercury or the Moon.
- ❑ No life on Venus.

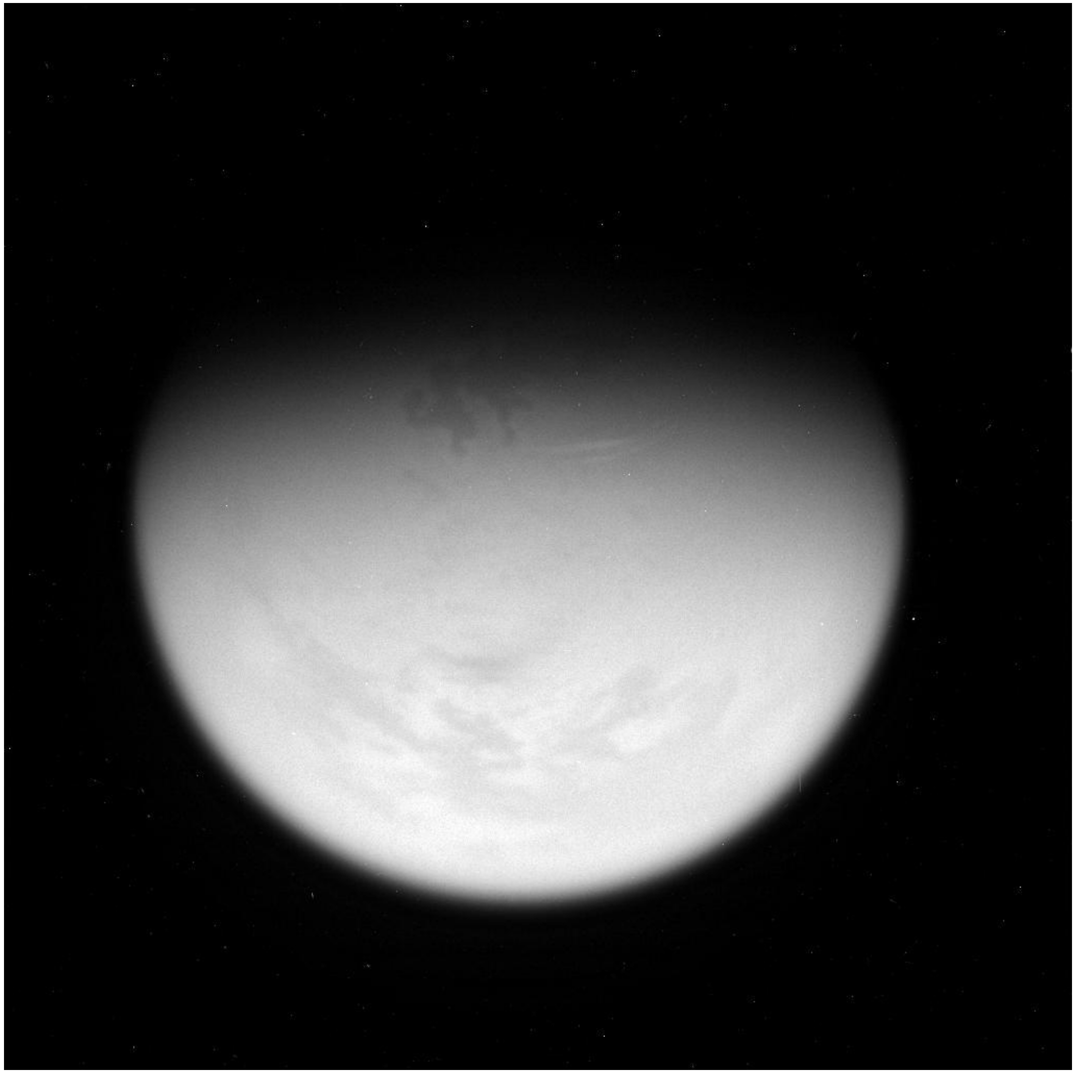


Enterprise vs. the Crystalline Entity (Paramount)

Alternatives

So far the story seems dominated by our Earth bias.

- Why develop life *in situ* on Earth?
- Why molecules?
- Why carbon?
- Why water?
- Why atomic matter at all?

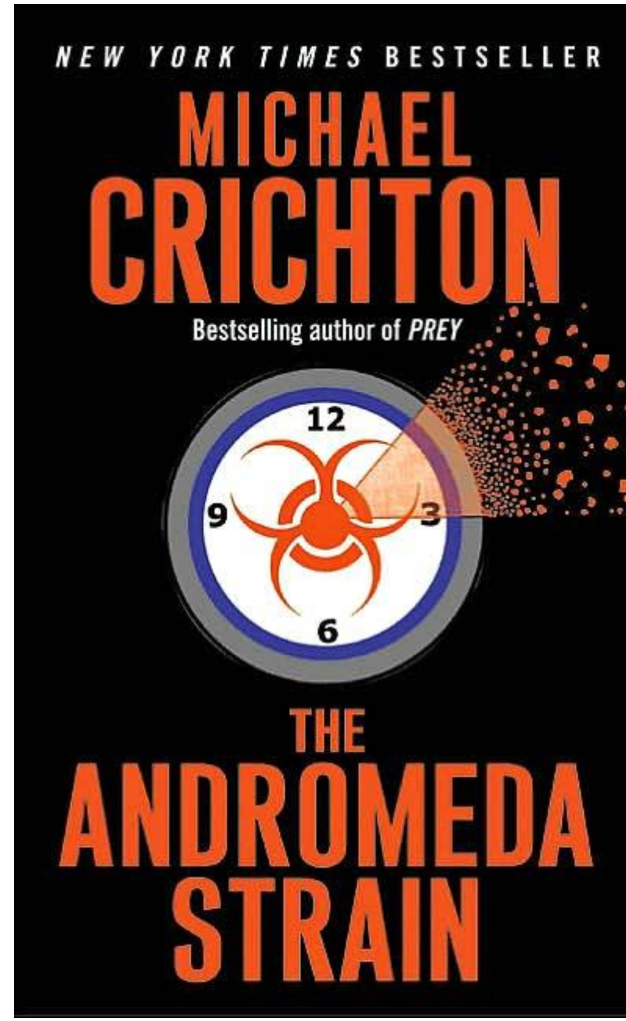


Titan's North-Polar Great Lake (Cassini/ JPL/ NASA)

Why go to the trouble? Panspermia is easier…

What if functioning biomolecules were brought to the protoplanetary disk from somewhere else, frozen onto the surfaces of dust grains?

- ❑ No evidence of this in meteorites or comets, or from extrasolar dust grains.
- ❑ Hoyle's suggestion that the 1918 flu epidemic had an extraterrestrial source does not pass medical tests.
- ❑ Also begs the question of how *that* life began.



Why molecules? Clay and crystals as catalysts.

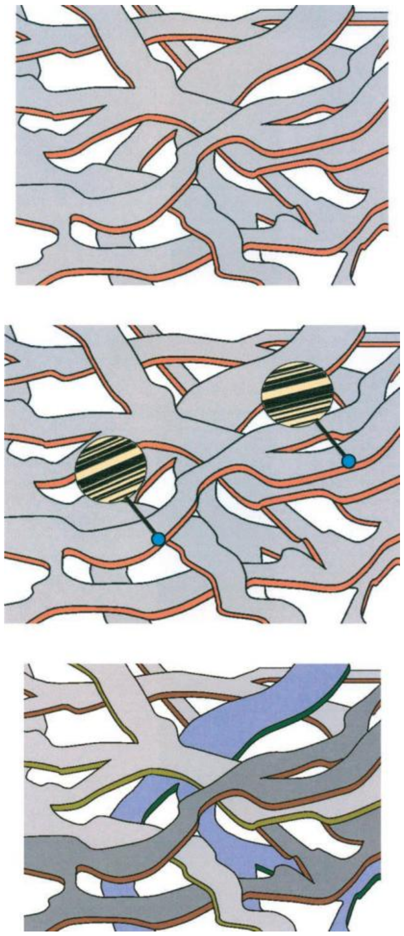
Certain solid surfaces are good at trapping molecules, and so have the potential to catalyze the polymerization of amino acids and nucleotides.

- Any trapping surface OK from this viewpoint with the Dyson (1995) disorder-order-transition model of polymerization, discussed last time.
- And some of the available solid surfaces are orderly: even periodic over dimensions large compared to amino acids or nucleotides.
- We know that crystalline solids form very early in the life of protoplanetary disks and are present throughout the development of life. Can they serve as templates for the first biopolymers?

Clay and crystals as catalysts (cont'd)

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

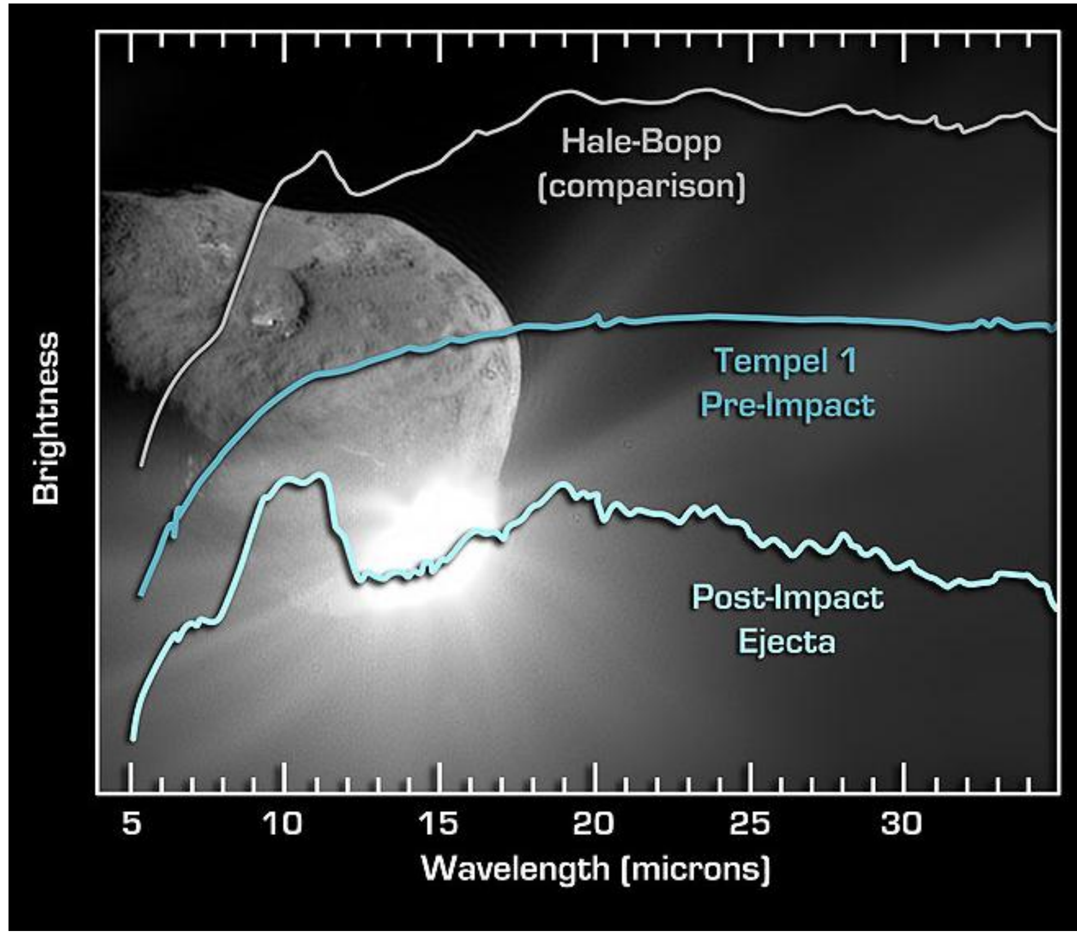
- ❑ Molecules in the interlayer would have many sites in which to be trapped, and there would be patterns of such traps at the spacing of the crystal lattices of the two layers, and at the sum and difference of the two spacings.
- ❑ It is conceivable that such varieties of spacings will promote the assembly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



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

Clay and crystals as catalysts (cont'd)

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

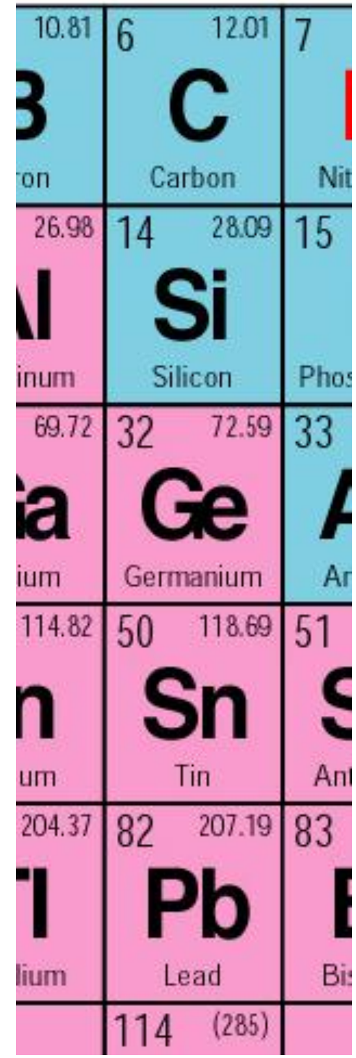


[Lisse et al. 2006]

Why carbon? Other tetravalent atoms

To lead to life – especially the intelligent sort – the chemical basis needs to be capable of holding a lot of information, which means if it's molecular it needs to make complex molecules, like carbon.

- Carbon's complexity is due to its tetravalence, meaning that the atom has four electrons that can make chemical bonds. These elements are all in the same column of the periodic table. Atoms in other columns make fewer bonds.
- By far the most abundant besides carbon is silicon. Silicon life is a favorite of science-fiction writers when considering alternative forms of life.



Other tetravalent atoms (continued)

Unfortunately, Si-containing molecules don’t seem to be very promising as originators or a dominant life form.

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

Other tetravalent atoms (continued)

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

- In Earth’s crust, silicon is hundreds of times more abundant than carbon, yet life on Earth wound up based on carbon.
- If silicon life couldn’t beat carbon life with that much of an edge, how would it do so under cosmically-normal conditions, with carbon a factor of ten *more* abundant than silicon?
- Keep in mind the possibility of non-primitive silicon life, though, like sentient computers, which are based upon crystalline silicon. Maybe we are just an evolutionary stage on the way to silicon life…

Why water? Other solvents

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

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

Other solvents (continued)

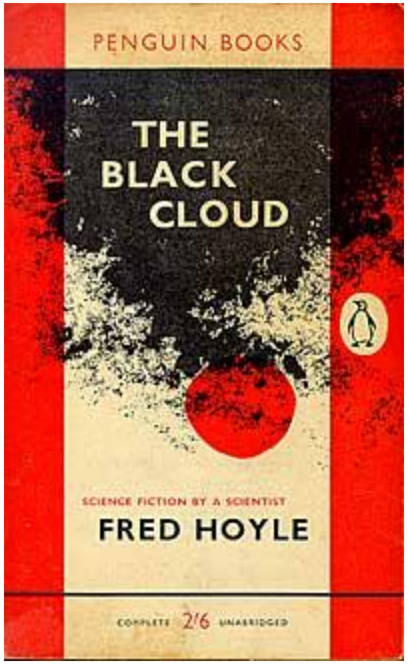
- Cosmically speaking, water is the most abundant of these, by quite a lot.
- All but methane and ethane are **polar** solvents, like water, meaning that one end of the molecule tends always to have a positive electric charge, and the other negative.
- So they tend to dissolve things the same way water does.
- However, water can dissolve more than all the others, by significant amounts.
- Water also has a larger heat capacity and is a more efficient evaporative cooler than the others, which is valuable in regulation of temperature.
- So wherever it is liquid, water is probably life's polar solvent.

Other solvents (continued)

On the other hand,

- the others are liquid at lower temperatures than water: they could support life outside the habitable zone as usually defined.
  - Can’t make the temperature too low, though, or chemical reactions will be too slow.
- methane and ethane are **nonpolar** solvents.
  - Some molecules (e.g. oils) dissolve more easily in nonpolar solvents than in polar ones.
  - No zwitterions made in nonpolar solvents!
  - So these solvents would support very different biochemistries, about which we can only speculate.

Why atomic matter at all?



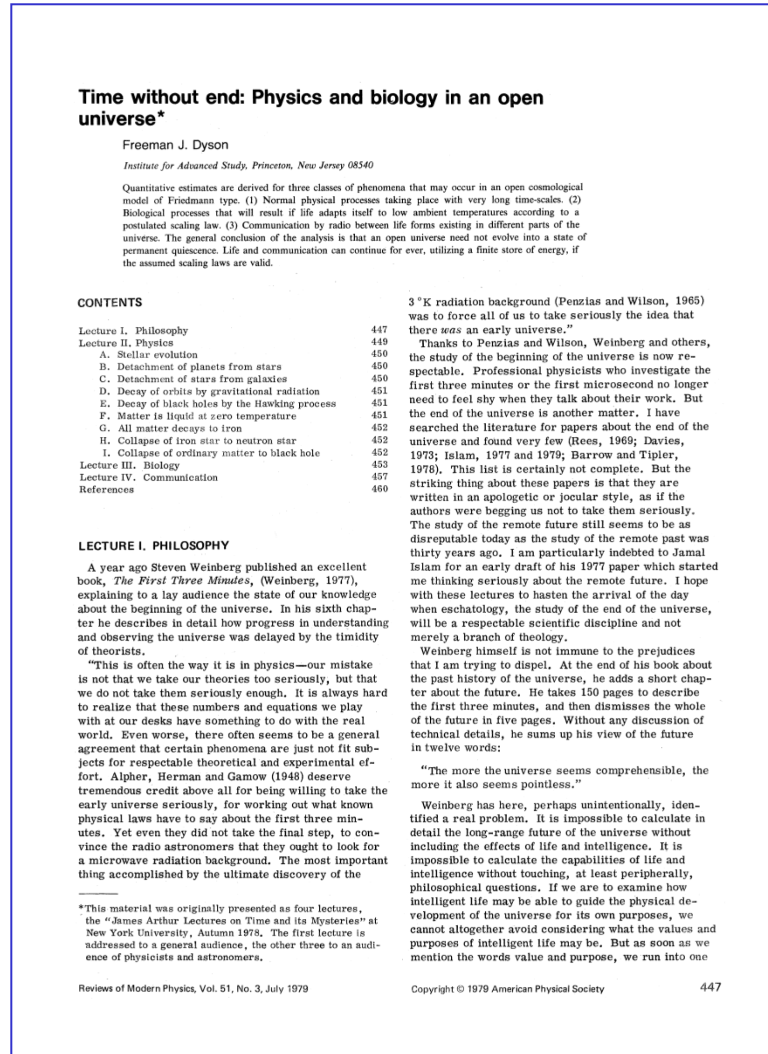
It would take too long to discuss all the possible non-matter-based life forms raised by science-fiction writers; here are a few motifs.

- "**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, not less, to organize.

Why atomic matter at all? (continued)

This is not to say that "pure energy" life would never become important; just not in the beginning. But if you have a loooooong 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's possible to conceive even intelligent life under those circumstances.



Time without end: Physics and biology in an open universe*

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Quantitative estimates are derived for three classes of phenomena that may occur in an open cosmological model of Friedmann type. (1) Normal physical processes taking place with very long time-scales. (2) Biological processes that will result if life adapts itself to low ambient temperatures according to a postulated scaling law. (3) Communication by radio between life forms existing in different parts of the universe. The general conclusion of the analysis is that an open universe need not evolve into a state of permanent quiescence. Life and communication can continue for ever, utilizing a finite store of energy, if the assumed scaling laws are valid.

CONTENTS

LECTURE I. PHILOSOPHY

A year ago Steven Weinberg published an excellent book, *The First Three Minutes*, (Weinberg, 1977), explaining to a lay audience the state of our knowledge about the beginning of the universe. In his sixth chapter he describes in detail how progress in understanding and observing the universe was delayed by the timidity of theorists.

"This is often the way it is in physics—our mistake is not that we take our theories too seriously, but that we do not take them seriously enough. It is always hard to realize that these numbers and equations we play with at our desks have something to do with the real world. Even worse, there often seems to be a general agreement that certain phenomena are just not fit subjects for respectable theoretical and experimental effort. Alpher, Herman and Gamow (1948) deserve tremendous credit above all for being willing to take the early universe seriously, for working out what known physical laws have to say about the first three minutes. Yet even they did not take the final step, to convince the radio astronomers that they ought to look for a microwave radiation background. The most important thing accomplished by the ultimate discovery of the 3 °K radiation background (Penzias and Wilson, 1965) was to force all of us to take seriously the idea that there *was* an early universe."

Thanks to Penzias and Wilson, Weinberg and others, the study of the beginning of the universe is now respectable. Professional physicists who investigate the first three minutes or the first microsecond no longer need to feel shy when they talk about their work. But the end of the universe is another matter. I have searched the literature for papers about the end of the universe and found very few (Rees, 1969; Davies, 1973; Islam, 1977 and 1979; Barrow and Tipler, 1978). This list is certainly not complete. But the striking thing about these papers is that they are written in an apologetic or jocular style, as if the authors were begging us not to take them seriously. The study of the remote future still seems to be as disreputable today as the study of the remote past was thirty years ago. I am particularly indebted to Jamal Islam for an early draft of his 1977 paper which started me thinking seriously about the remote future. I hope with these lectures to hasten the arrival of the day when eschatology, the study of the end of the universe, will be a respectable scientific discipline and not merely a branch of theology.

Weinberg himself is not immune to the prejudices that I am trying to dispel. At the end of his book about the past history of the universe, he adds a short chapter about the future. He takes 150 pages to describe the first three minutes, and then dismisses the whole of the future in five pages. Without any discussion of technical details, he sums up his view of the future in twelve words:

"The more the universe seems comprehensible, the more it also seems pointless."

Weinberg has here, perhaps unintentionally, identified a real problem. It is impossible to calculate in detail the long-range future of the universe without including the effects of life and intelligence. It is impossible to calculate the capabilities of life and intelligence without touching, at least peripherally, philosophical questions. If we are to examine how intelligent life may be able to guide the physical development of the universe for its own purposes, we cannot altogether avoid considering what the values and purposes of intelligent life may be. But as soon as we mention the words value and purpose, we run into one

*This material was originally presented as four lectures, the "James Arthur Lectures on Time and its Mysteries" at New York University, Autumn 1978. The first lecture is addressed to a general audience, the other three to an audience of physicists and astronomers.

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Why atomic matter at all? (continued)

- **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're certainly dense and long lived…

  Hard to evaluate this as it's 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. Discussed, though, by Don Goldsmith and Toby Owen in *The search for life in the Universe* (2002).

Why atomic matter at all? (continued)

- **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.
  - Up side: huge numbers of internal rearrangements possible, and time doesn't really enter the problem.
  - Down side: the arrangements do not seem to be deterministic, and are instead ruled by probability. So as they interact with their surroundings they would spontaneously switch between alive and dead. Memory would be hard to imagine.
- Favorite example: the wormhole beings in Star Trek: Deep Space Nine, discussed in AST 102.

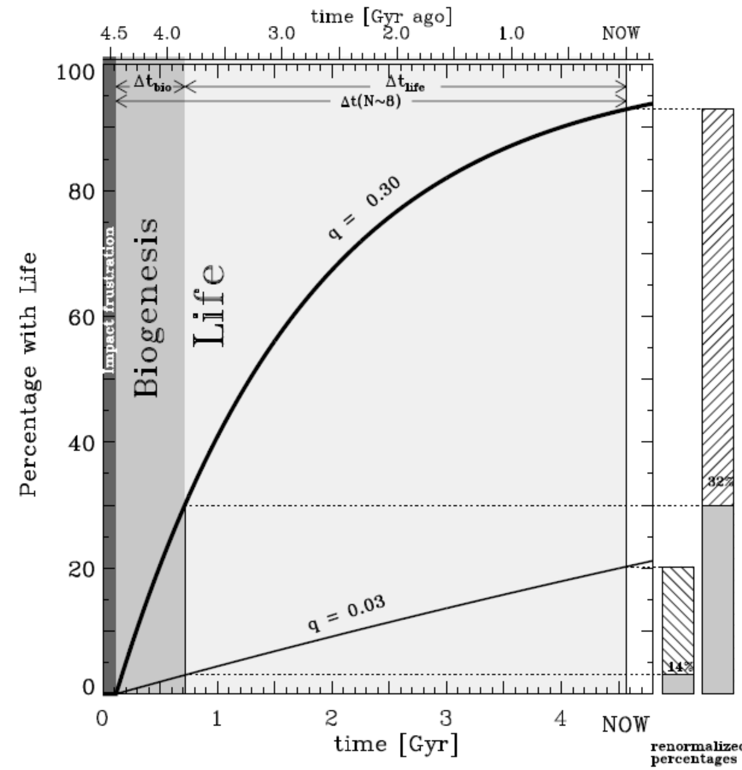
Summary

Thus it looks as if carbon-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 reasonably quickly.

- Simulations show that life on Earth could have arisen in this fashion within a few hundred Myr, which agrees with observations of when life actually did appear here.
- If RNA developed first – rather than proteins – a "genetic takeover" wouldn't have had to occur to produce the nucleic-acid version of life we know now.

The fraction of habitable planets on which life develops, f_ℓ

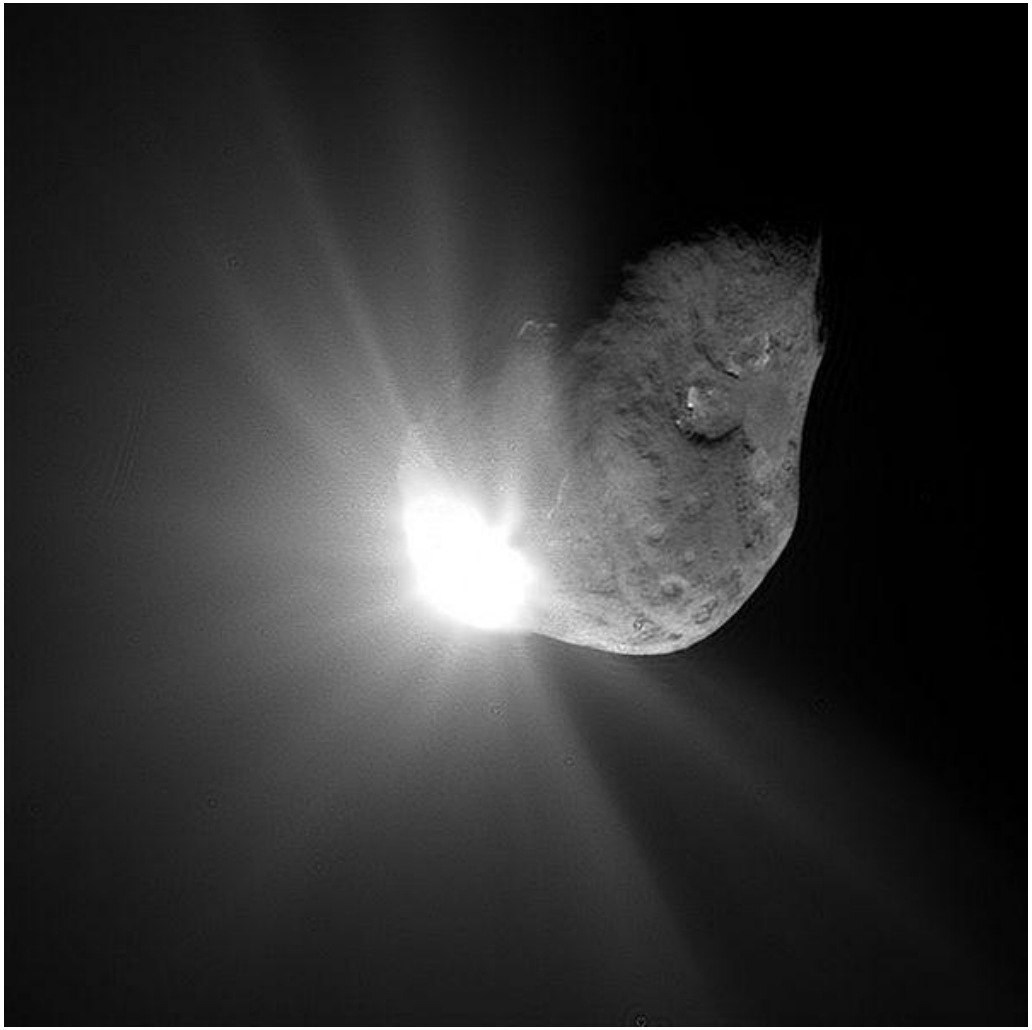
- Using RNA world and the observed timescale of Earth's biogenesis as the paradigm, [Lineweaver and Davis (2004)]() currently estimate that 36% of terrestrial planets that are at least 1 Gyr old have life, at 95% confidence: **f_ℓ = 0.36.**
- If we turn out to have been lucky this could be less; accounting for different mechanisms the number could turn out larger.



Lineweaver and Davis (2004)

Mid-lecture Break.

- Homework #3 is now on WeBWork and is due next Thursday.



The Deep Impact probe blasts a crater in Comet 9P/Tempel.

The terrestrial planets and the Moon

All the **terrestrial** bodies inside the snow line probably started off with the same variety of volatile and organic chemicals, crash-landed on their surfaces by comets or released from rocks by various processes collectively called **outgassing**.

- Little hydrogen and helium was around, as these light species would escape the gravity of small planets quickly.

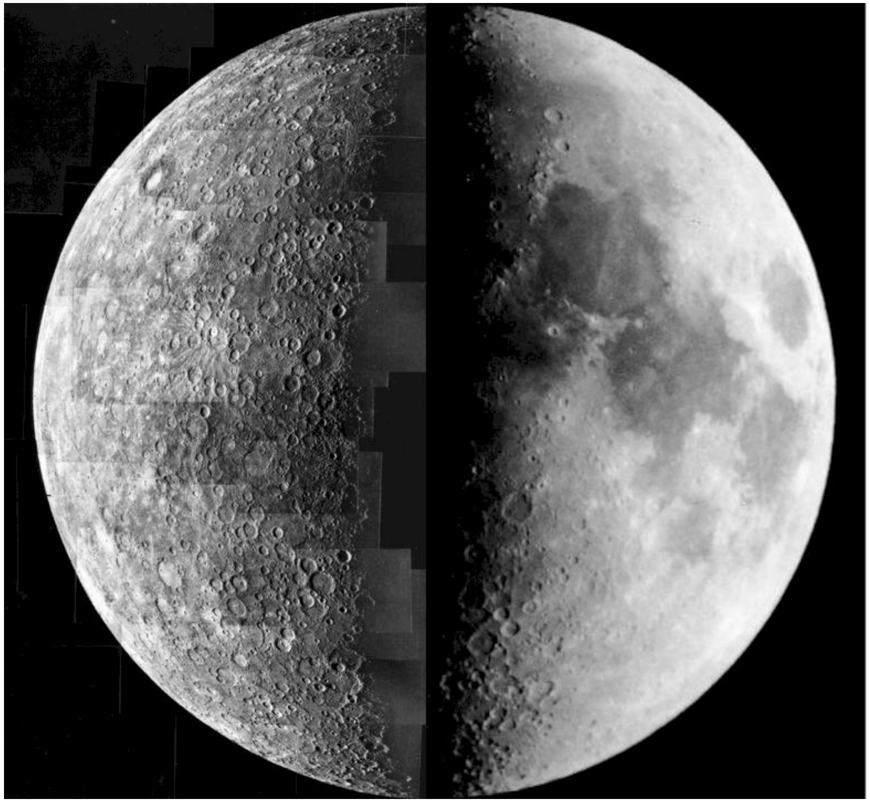
Body	Mass (Earth masses)	Radius (Earth radii)	Average density (gm cm^{-3})
Mercury	0.055	0.38	5.43
Venus	0.81	0.95	5.24
Earth	1	1	5.52
Moon	0.012	0.27	3.35
Mars	0.11	0.53	3.93

Carbonate minerals	2.5
Silicate rocks	3.3
Iron	8.0

The airless worlds

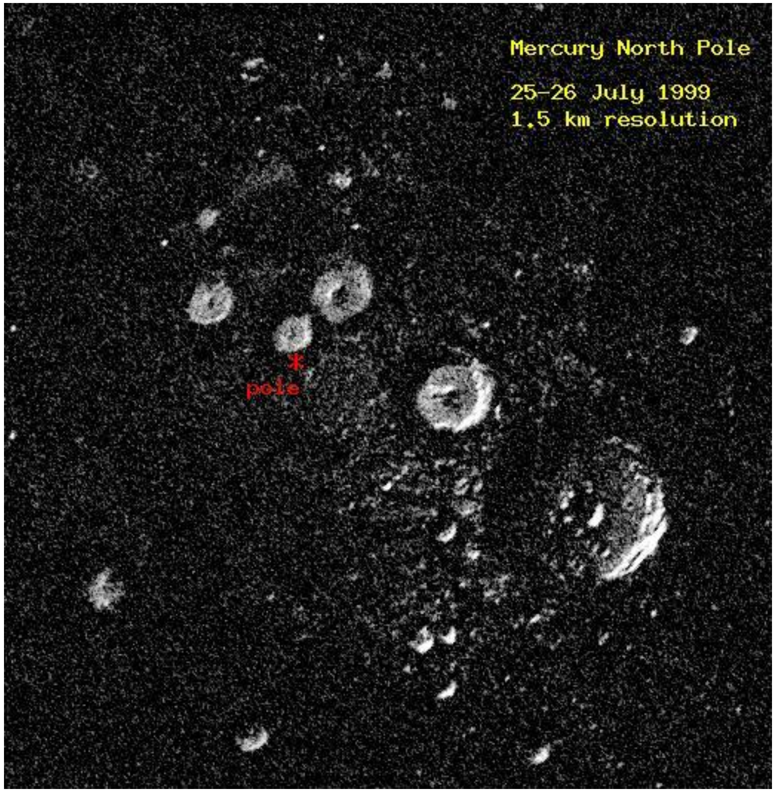
Mercury and the Moon aren't massive enough to retain the volatiles gravitationally, so they evaporated and escaped.

- Both still have a little water below the surface, due to billions of years of bombardment by the solar wind: the high-energy protons penetrate the surface, neutralize to become ordinary hydrogen, and combine with oxygen.



Half Mercury, half Moon. (Image from Mariner 10, NASA.)

The airless worlds (continued)



Radar-reflectivity image of the north pole of Mercury (Harmon et al. 2001)

- More famously, they have some surface water ice, within permanently-shaded polar craters.
  - Discovered first on Mercury; only recently discovered on the Lunar north pole after several dubious claims on the south pole.
- Not enough water anywhere to lead to primordial "ponds", surface subterranean.

Venus and the greenhouse effect

By our admittedly crude rules about habitability, none of the terrestrial planets are habitable, as they are either too cold or way too hot.

- The one that comes the closest is Venus. Under our definition, which employs an albedo smaller than Venus's, the planet even lies within the Solar system's habitable zone.
- But really $T = 735$ K, so life on Venus is a non-starter.
- So how is it that its surface is hotter than that of Mercury, which is much closer to the Sun?

Body	From Sun (AU)	Al-bedo	$T = 279\text{ K} \times \sqrt{\frac{1-A}{(r\,[\text{AU}])^2}}$	Average surface tempera-ture (K)
Mercury	0.387	0.12	676	100-720
Venus	0.723	0.59	247	735
Earth	1	0.39	218	287
Moon	1	0.11	263	100-390
Mars	1.52	0.15	169	227

What constituent of Earth's atmosphere makes the largest contribution to the greenhouse effect?

A. Carbon dioxide B. Methane C. Ozone D. Nitrogen
E. Water

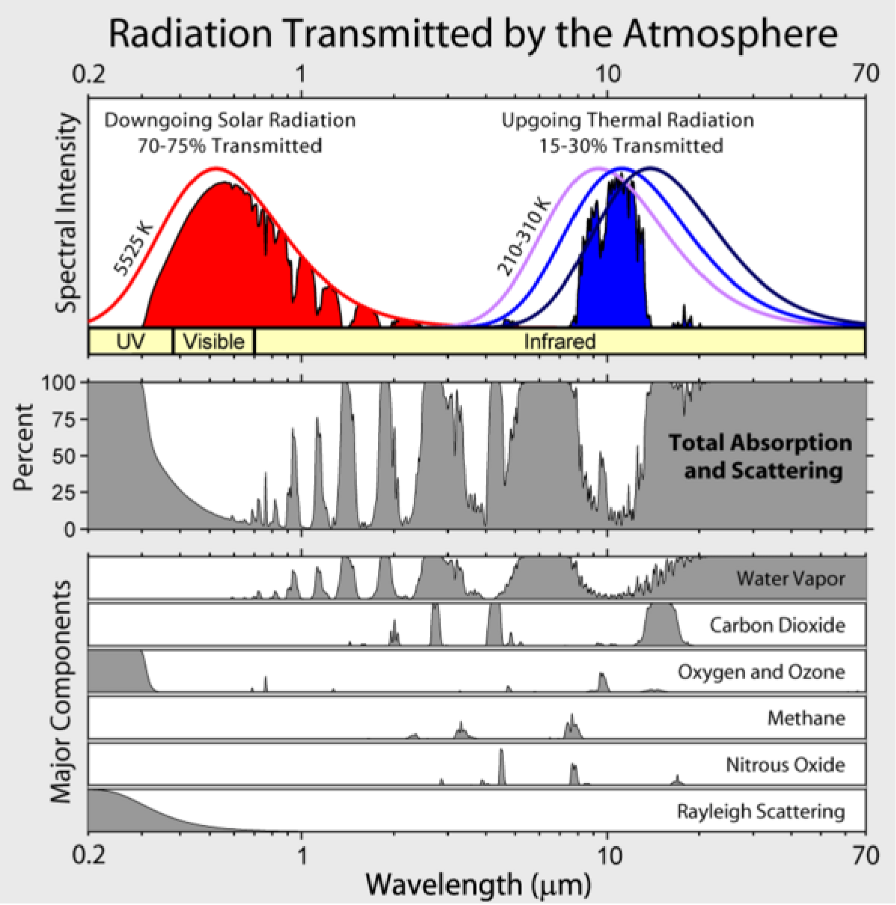
Venus and the greenhouse effect (continued)

At

$$T = 279\ \mathrm{K}\sqrt{(1-A)/\left(r[\mathrm{AU}]\right)^2},$$

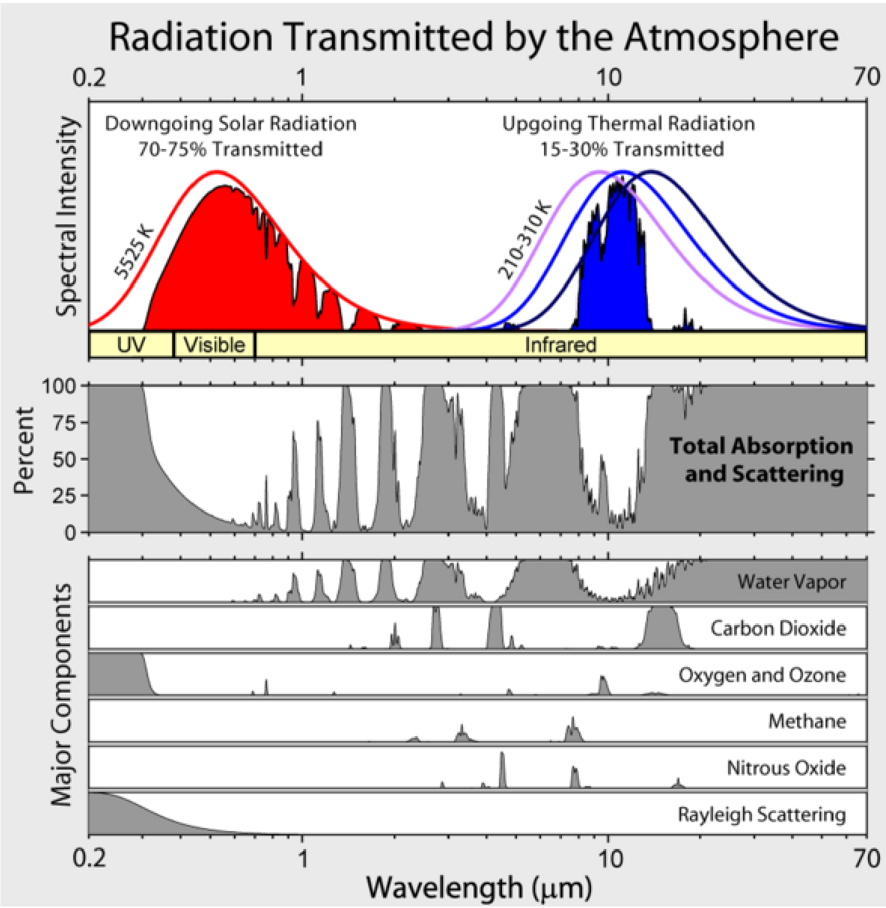
the terrestrial planets emit most of their light at infrared wavelengths.

- They would all be brightest near a wavelength of 10 μm.
- Solar heating arrives mostly at visible wavelengths, at which the atmosphere is quite transparent.



Created for Global Warming Art by Robert A. Rohde

Venus and the greenhouse effect (continued)

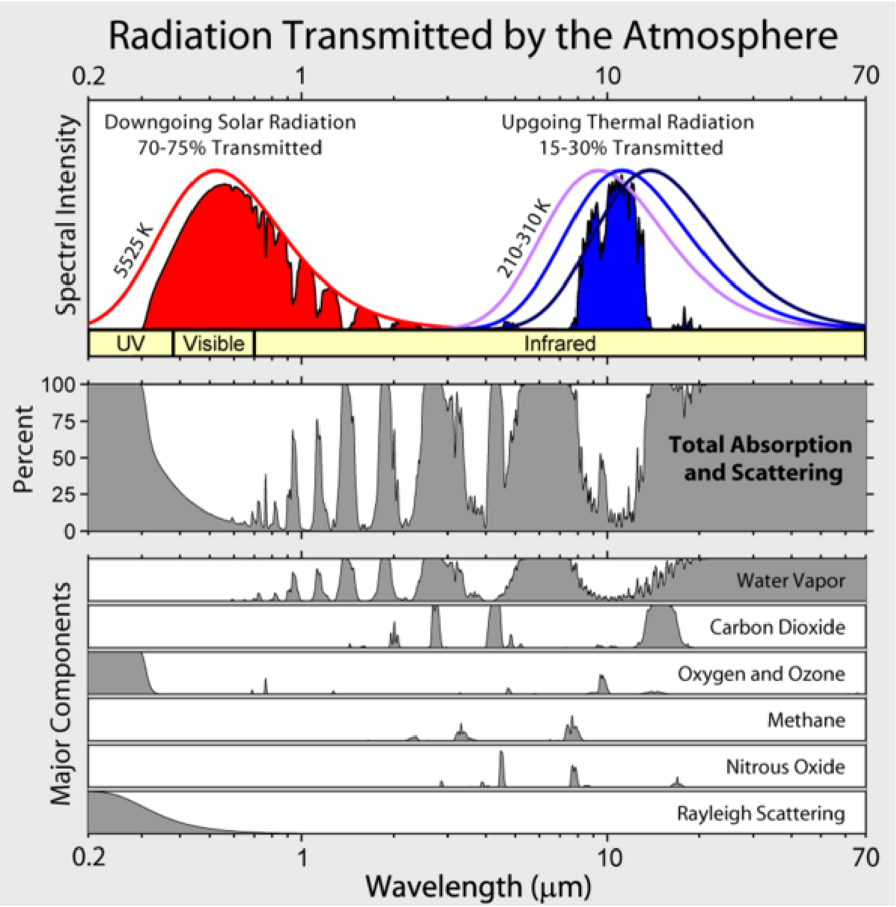


Created for [Global Warming Art] by [Robert A. Rohde]

- ❑ Infrared light is absorbed very strongly by molecules in the atmosphere, notably by water and CO_2.
- ❑ Light can only escape directly to outer space through "windows", of which the most important lie at wavelengths 8-13, 4.4-5, 3-4.2, 2-2.5, 1.5-1.8, and 1-1.4 µm.

Venus and the greenhouse effect (continued)

- ❑ Hotter blackbodies shine more at shorter wavelengths, so if not enough light escapes at 8-13 μm, the surface heats up until enough of the emission leaks out in the shorter-wavelength windows.
- ❑ This warmed all three of the atmosphere-bearing planetary surfaces, but Venus got the most.



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Venus and the greenhouse effect (continued)

- If kept within bounds, and if there's liquid on the surface, this effect is self stabilizing, as water droplets form clouds.
  - Temperature rises → more water evaporates into atmosphere → more clouds form → albedo increases → less sunlight reaches surface → temperature drops.
- But on Venus, the greenhouse effect was sufficient to evaporate all of the water, leaving no liquid bodies on the surface.

Earth and Venus, from the Galileo and Magellan missions, respectively (JPL/NASA).

Venus and the greenhouse effect (continued)

- Liquid water dissolves carbon dioxide, both from the atmosphere and from gradually-dissolving rocks. From there the carbon dioxide can be incorporated in carbonate minerals that can form readily in liquid water.
  - These days, this is done most readily on Earth by ocean-dwelling organisms.
- Thus if there is a lot of liquid water, carbon dioxide will be locked up in carbonate minerals, rather than allowed to be present in the atmosphere.
  - This is the case, for example, on Earth.
  - On Venus, though, the lack of liquid water let a lot of the carbon dioxide remain in the atmosphere. This made the greenhouse effect even worse.

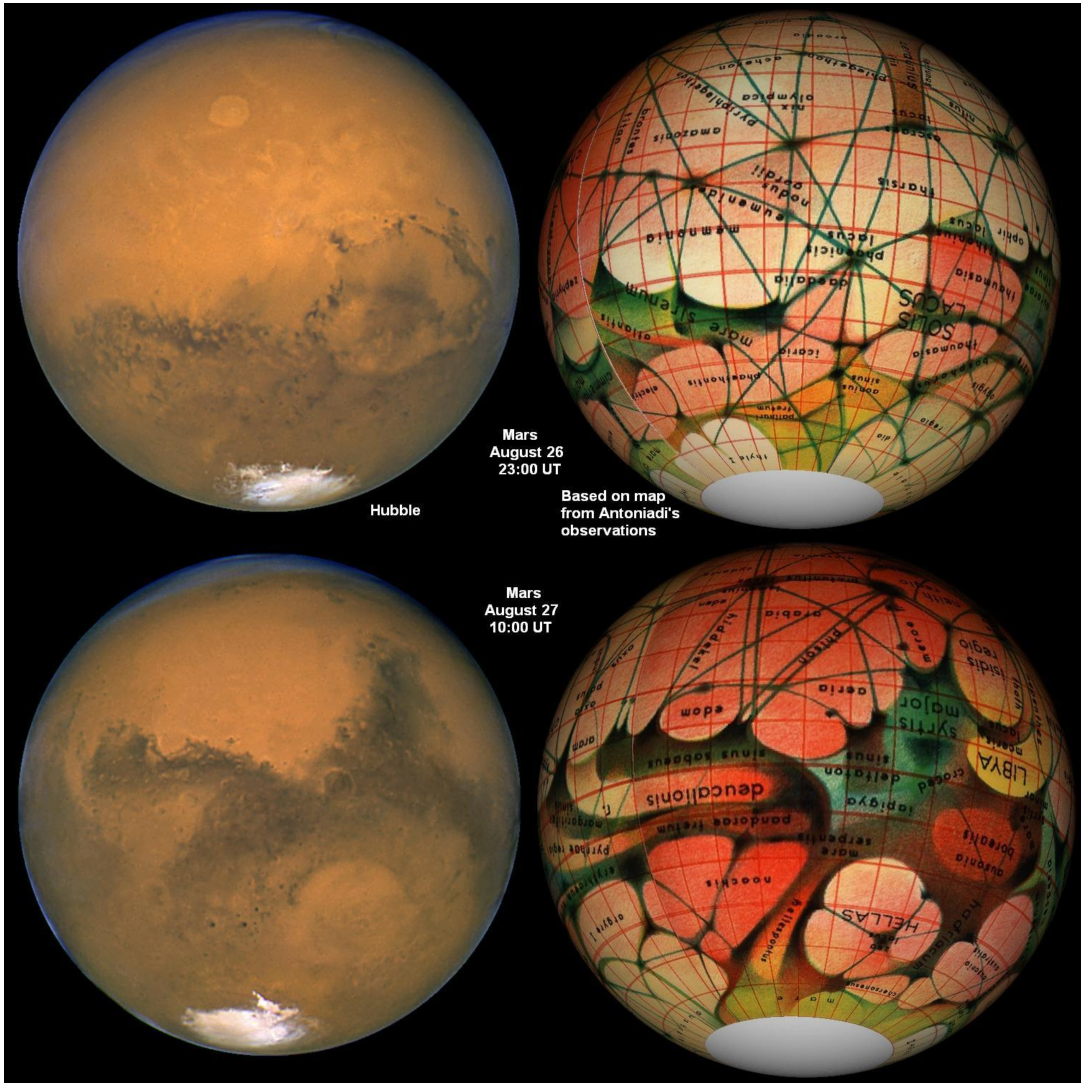
Venus and the greenhouse effect (continued)

- Under solar ultraviolet illumination, water molecules high in the atmosphere dissociate readily, producing hydrogen and oxygen.
  - Oxygen goes on to react with other elements like carbon, nitrogen, and sulfur.
- Hydrogen is too light to be retained by Venus's gravity, so it escapes quickly.
  - No more water, or possibilities for making any more water! A dead world.

Radar map of Venus at 180º longitude by the *Magellan* mission (JPL/NASA).

Mid-lecture Break.

- Homework #3 is now on WeBWorK; due Monday after Spring Break (15 March).
- Recitation today, 4:50 PM, B&L 315, conducted by Carol.



HST images of Mars, and maps drawn in the late 19th century by Eugene Antonaldi, rendered and scaled by Tom Ruen.

The similarities between Earth and Mars

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

- an atmosphere and reasonable surface gravity.
- a day length and an obliquity (seasons) almost the same as Earth.
- terrestrial composition, even terrestrial appearance.
- not much in the way of surface impact cratering.
- strong evidence of past volcanism and some faulting and other geological activity (though no plate tectonics).
- surface color variegation that, for a time, was thought possibly to reveal vegetated areas, fancifully connected by "canali" in the view of early observers.

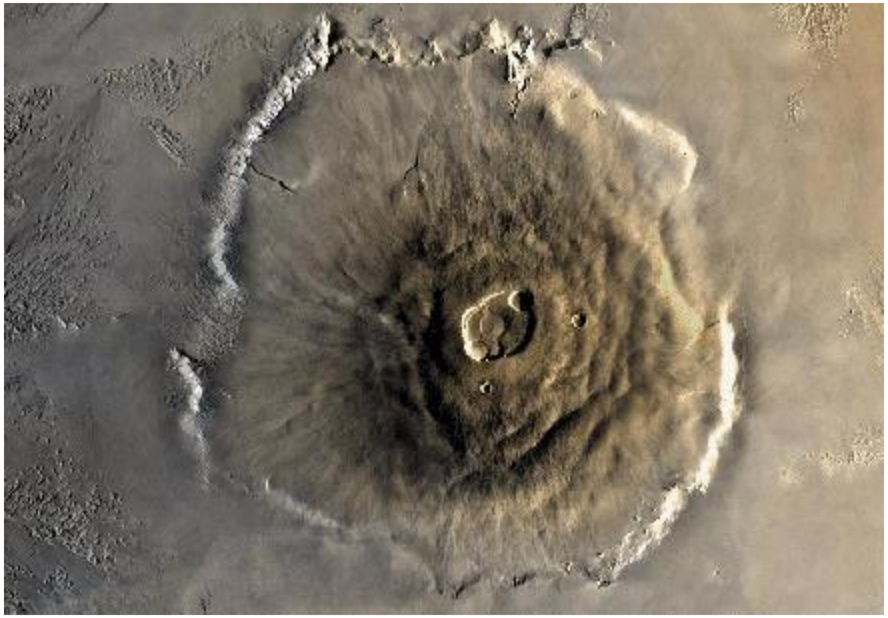
The similarities between Earth and Mars (cont’d)


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

Martian volcanism

On the same scale: the largest volcanoes on Earth and Mars.

The Big Island of Hawai'i, with Mauna Loa, Mauna Kea, Kilauea: 10.6 km high from base (4 km from sea level), 350 km across (140 km on coast)



Olympus Mons: 24 km high, 550 km across (Viking 2 Orbiter/NASA)

The differences between Earth and Mars

The differences outweigh the similarities, though; Mars is in almost every sense intermediate between Venus/Earth and Mercury/Moon.

- It's low in mass density.
- The atmosphere is thin and dominated by heavy molecules (probably because of its low mass).
- Despite a healthy greenhouse effect, it's cold; too cold for liquid water on the surface.

So it has not been terribly surprising that the Viking landers (and Pathfinder and MER rovers) have found no evidence of life, nor that the claims of fossil microorganisms in Martian meteorites are widely disputed.