Life in the Solar System
(AST 309L, Scalo)

[Note: Your textbook has excellent discussions of these topics presented independently.]

Our solar system has a large number of objects orbiting the sun—terrestrial planets, Jovian planets, planetary moons, comets, asteroids…We want to narrow down the list for searching for life. Mostly search for places where liquid water could exist; but also Titan, since other biochemistries are possible.

[Good idea to review the general material on our solar system that you encountered in AST 301 here.]

First thing to consider is *general* requirements, and then to see why certain planets in our solar system seem like very low-probability choices for life searches.

Following the textbook, there are 3 general requirements we should consider.

1. Elements H, C, N, O (you should know by now why these are important to have)—these are found everywhere we look, so we have the fortunate coincidence (?) that the just the right elements needed for (our kind of) life are also the very abundant in everything from quasars to comets. Since organic compounds made from these could be delivered by asteroids or comets, any planet could also contain the basic organic building blocks for life (if it can hold onto them and/or not destroy them).

2. Energy source—needed to overcome energy barriers in chemical reactions leading to more complex molecules. But there are many sources.

a. Sunlight—most important on Earth today, and what we used to define “habitable zone.” But for producing organic molecules, probably needed to utilize the Sun’s higher-energy UV radiation.

b. Chemical energy—textbook is a little confusing here—actually means heat sources to get chemical reactions going in a “mixing environment” like atmosphere or ocean. Liquid water probably crucial here.

c. Could use internal radioactive heat on some planets (Venus and Mars) but some bodies (Moon and Mercury) are so small that they have already lost most of their internal heat.

d. Lightning is a possible source on any world with an atmosphere, although we don’t know what controls the amount of lightning you’ll get in a given environment.

e. Tidal heating—some moons of the giant planets are heated this way. It is the subject of ch. 8, to which we’ll return.

3. Liquid medium for transport of chemicals. We have been through this before, but remember that the idea is that if molecules were “just sitting there” on some solid surface, their migration would be *very* slow and they would not react fast enough to produce more complex molecules; a liquid medium provides a “mixing medium” in which the molecules can diffuse, and react, more rapidly.

Exploration of the Solar System.

Read the text on this.

Notice that imaging observations from Earth require very high resolution in order to make out details that might be signatures of processes related to life. This involves some combination of adaptive optics from the ground, a space telescope, and interferometry (which has now advanced into the optical part of the spectrum). Also spectroscopy can identify gases in atmosphere, minerals and ices on surface, obtain the atmospheric temperature, pressure and density, and even probe the weather and climate.

Robotic spacecraft are the method of choice for future NASA missions. Current or recent projects include the Voyager 2 flybys, Mars Orbiter and Lander, Cassini (Saturn) orbiter and lander (Titan). Sending humans to explore (done only for Moon, Apollo 1969-1972) has serious problem that duration of trip means a large payload would be required (supplies for crew), so the fuel requirements and expense become enormous. (Note: Recent 3/2004 Mars findings may change this.)

Moon and Mercury

Small, so have lost most of their internal heat-→ no outgassing and weak gravity-→ no atmosphere.

They are also the least likely to have liquids anywhere.

Could have ices in craters near poles (protected from sunlight by shadow), delivered by comets, but not liquid. Remember, with no atmosphere (or even a very thin one like Mars'), heated ice *sublimes* directly into gas phase, not liquid.

Venus

Very thick CO_2 atmosphere. But at 0.7 AU from sun, temperature so high that water stayed as gas in atmosphere, solar UV photons dissociated them, and the H then escaped. After only a few million years (theoretically), the water was gone. Without liquid water, the CO_2 couldn't dissolve, leaving Venus with a severe runaway greenhouse effect.

However the time for the water to disappear is extremely uncertain. If longer, Venus could have had oceans before the greenhouse effect had heated the planet to inhabitability. Could life have begun during that interval and then adapted to temperatures as large as current surface? We assume not—even extremophiles have limits set by the strength of the strongest molecular bonds. There is some speculation that life could have adapted to the atmosphere, where it is cooler and there might even still be some liquid water (see recent book by Grinspoon). But it does not seem like a good bet, so we are removing it from our list of targets.

Giant Planets

Outer "giant" planets: Jupiter, Saturn, Uranus, Neptune.

Important space missions: Pioneer 10 (Jupiter), 11 (Jupiter, Saturn, 1979); Voyager 1 and 2 (1989; V.2 went on to Uranus and Neptune); Galileo (reached Jupiter in 1995, continued to explore through 2001); Cassini-Huygens (will arrive Saturn 2004; probe through atmosphere of Titan!).

Chemical composition: Cores probably rocky/icy because formed by planetesimal accretion, but most of outer layers is gas accreted from the primordial solar nebula ⇒ mostly hydrogen.

If you let such a gas of "cosmic composition" (90% H + 1% C,N,O,…) react under temperatures that occur in the outer solar system, you get methane (CH_4), ammonia (NH_3), hydrogen sulfide (H_2S), water vapor (H_2O), but overwhelmingly a lot of excess molecular hydrogen. Jupiter and Saturn are so massive and cold that they will always be able to retain this hydrogen. And even though it is very cold at the top of the atmosphere, about 100km down the temperature is warm enough for liquid water droplets. But if a life form wanted to use the layer whose temperature is right for liquid water, it would have to be a "floater" or else it would sink to the hotter depths.

Why pessimistic about life on outer planets?

1. With so much excess hydrogen, the chemical equilibrium favors the formation of *simple* molecules, like those named above, NOT complex molecules that are needed for life (no matter what kind). (This is a weak argument—even with so much excess hydrogen, non-equilibrium chemistry is likely due to sporadic energy sources like lightning.)

2. Jupiter (for example) has no solid surface, so

a) no likely microenvironments (like Earth's tidal pools or transient ponds, where reaction products could become concentrated and undergo more reactions);

b) no opportunity for surfaces to catalyze chemical reactions (think about polymerization on clay minerals on Earth).

3. Vertical convection (mixing, circulation) takes gas between cool upper layers and deeper layers where temperatures exceed $1000\ ^{O}$ C, and where complex molecules would be destroyed.

So the only possibility that has been suggested for life on Jupiter (or other giant planets) is a *buoyant* large gas-filled floater that can stay at the height of the water layer by adjusting its density, inflating and deflating (see below). But how could these have originated? If they began as simpler complex molecules, they would have been destroyed, assuming all the atmosphere gets circulated to hot depths.

But, consider Jupiter's Great Red Spot—a vortex in the upper atmosphere that has persisted for at least centuries, and whose reddish color (still not understood) *may* reflect complex molecules.

The reds, yellows, and brown colors on Jupiter have led to the "color controversy" between those who think they can explain these colors by inorganic compounds (e.g. red from phosphorus compounds) and those who think the colors reflect prebiological orgaqnic chemistry, something like the goo that formed in the Miller-Urey experiment. These controversial reddish-brown substances are usually referred to as "tholins."

Another thing to consider is that water clouds probably do form at a layer where the temperature and pressure are like Earth, and higher in the atmosphere there are ammonia-sulfur clouds. Where there are clouds, there are usually thunderstorms and lightning (observed by Voyager and Galileo spacecraft), so there's a good energy source to get some complex molecules.

In fact, lightning, UV photons from the sun, and heat from Jupiter's interior all probably contribute to forming molecules like hydrogen cyanide (HCN), acetylene (C_2H_2), ethane (C_2H_6), and others, all which have been observed by their spectral lines. The question is: how complex can they get in the presence of the upward-downward convection currents?

C. Sagan & E. Salpeter (1977)—worked out the chemistry/physics of speculative life-forms, "floaters", that might adapt to Jupiter. These giant "gas-bag" creatures use warm hydrogen gas to regulate their buoyancy and rise and fall in the atmosphere, scavenging food (organic molecules) and energy (lightning?) along the way. Hard to see how life could arise on Jupiter, but still can't rule out such creatures on any giant planet until we explore them in detail.

Upshot: Could speculatively see how life might have *adapted* to environments as strange as Jupiter's, but difficult to see how it arose. Can you think of a way?

Mars

(You will update by researching results of recent rover mission.)

Mass of Mars is only ~ 10% Earth's mass. Most of the atmosphere, and water, has escaped—several processes contributed: UV photons dissociating water lead to escape of H; erosion by solar wind; bulk loss during impacts; incorporation into carbonate rocks; runaway glaciation (cold because far from sun), so atmosphere freezes, snows, albedo of planet increases, gets even colder, can never unmelt). Not sure which was most important, but certainly currently not much atmosphere, ~ 1% as thick as Earth's. Composition: 95% CO_2, 3% N_2 , plus traces of others.

Cold! Even at equator, the average temp. is ~ -60 ^{0}C. Low T and low pressure means liquid water would either freeze or boil! This is equivalent to our statement earlier that at low pressure ice, when heated, goes directly from the solid form to the gaseous form (sublimation).

But what about the past? That's the big question for Mars.

[Note: You don't have to memorize the names of any of the scientists mentioned below.]

Geomorphology: 1971 **Mariner** 9: volcanoes, canyons, and many *erosion* features such as gullies, channels, and (apparently) river valleys and valley networks.

There is a very good reason to think that the erosion took place long ago: Much of Mars' surface is >3.5Gyr old (from number of impact craters in different areas). For the *oldest* regions, craters smaller than about 15 km have disappeared, while the larger ones have undergone substantial erosion. But younger craters have not been significantly altered.

[Your textbook has an excellent discussion of the geomorphology of Mars, with many excellent images; be sure to read that.]

Viking (1976)—3 biology experiments fail to find evidence for current life. Details given in text, but students aren't responsible for remembering the names of the experiments or the *details* of their operation. You should however understand the ideas behind each experiment.

But Viking orbiters returned detailed photos that showed "outflow channels" where underground water burst through the permafrost, resulting in floods, producing channels. But only covered about 10% of planet.

There could be *much* more water under the permafrost. But most scientists think no oceans, just occasional lakes that rapidly freeze.

Erosion rates inferred from crater rims indicate there could have been a little water erosion, but only during the "Noachian" (time of late bombardment ending about 3.8 Gyr ago) period—see text for Martian eras).

Tim Parker: searched and found evidence for shorelines in photos. Earliest ocean could have covered half the planet according to this. Again, this is evidence for *early* liquid water.

But Nick Hoffman ("White Mars") claims that all the features could have been produced by the "flow" of CO_2, not water. Hoffman is most outspoken of "anti-water" interpretations of geological forms.

March 12, 2002: Tanaka et al. Use Mars Orbiter Laser Altimeter (MOLA) to reconstruct the Hellas impact basin (1200 mi. wide, 6 mi. deep). Interpret erosional features as flow of liquid CO_2 (not water) during magma eruption. Supports Hoffman, although most appear not to agree.

So the surface geomorphology is ambiguous, and, despite NASA press releases, it is not certain whether there was once extensive liquid water on Mars, although this is certainly possible. More recent results from mineral evidence is listed below.

Atmosphere

Make sure you understand that Mars *could* have have a much thicker atmosphere in the past and why it doesn't now. Could have been warmer in the past due to presence of greenhouse gases like CH_4 or (recently) *clouds of dry ice particles*. So many would agree that there could have been liquid water ~ 3.8 Gyr ago, and some could still exist under the permafrost.

Global Surveyor: images since 1998, some evidence for flooding within the last few *million* years! Was it liquid water from underneath the permafrost?

Mars Odyssey 2002 – gamma ray and neutron detectors. Results: H in top 1 meter of surface. Probably due to water ice. But this still doesn't tell us if there is or was *liquid* water.

Interpretation of recent Mars rover results are crucial.

Recent Spectral and Imaging Results

Recent analyses of spectral results from orbiters concerning surface minerals suggest that if there ever was a *lot* of liquid water on Mars, it must have been when Mars was very young, and that Mars has been cold and dry for 2-3 billion years. The products of extensive weathering expected under a humid climate, such as clays, are showing up in unexpectedly tiny quantities, if at all (using spectrometer TES on orbiting Mars Global Surveyor). Much of surface looks like unaltered basalt (the volcanic rock of Earth's ocean crust; spectrum shown in class). The greenish mineral olivine that has recently been recognized mixed in the basalt should have crumbled away in a few thousand years if there was even a tiny bit of moisture. Early in 2003 the imaging system THEMIS on Mars Odyssey reported dection of olivine-rich basalt at several places that are thought to be at least 0.3 Gyr old.

August 2003: Mars Global Surveyor TES spectrometer detects mineral carbonate in TES spectra (spectra shown in class). Recall that CO_2 dissolves in water to make carbonates (e.g. White Cliffs of Dover). Expect about 20% in martian dust if once humid, but only 2-3% is observed. More: "Desert varnish," a coating that your'd expect if even a little humidity (as found in desolate Dry Valleys of Antarctica) only found in martiam rocks that are older than about a billion years.

Majority consensus at present—Mars has been cold and dry for a very long time. Water does seem to have flowed on the surface briefly, early in martian history (from geological features), and probably gushed to surface in planet's midlife when it seemingly trickled down gullies in the geologically recent past, although the lack of weathering products of this makes it questionable. Mars may have been nearly always cold and dry. The water would be locked up as ice almost all the time except when an exceptional swing of the planet's axis brings extra solar heating to polar regions and brief melting of that snow and flow of resulting water could have shaped the landscape seen today, before the tilt went changed again and returned Mars to complete deep freeze. Ice-ball Mars is the current picture, except for possibly in its earliest billion years. Was this enough time for life to develop? Could it survive in the current frozen dry environment? That's why many astrobiologists are exploring the dry valleys of Antarctica.

Mars Express (Europe) and Mars Exploration Rovers (US) 2004 –Europe's lander Beagle-2 was to dig 2 meters beneath surface at the site of what some people think may have been an ancient sea floor. That should have cleared things up some—but Beagle died upon landing. US Mars rovers apparently scored a big success—I will ask you to research this.

See Figure 7.34 in textbook for illustration of all the plans for Mars exploration into the next decade. These will probably change due to recent events.

And what about life in the past on Mars? This depends on the climate history of Mars. We'll discuss this in class, and your textbook has an excellent discussion on pp. 185-187. The main question whose likely answer(s) you should understand is: did Mars have a thick atmosphere once, and where did it go?

You can find some interesting recent discussion of all these points at some of the links at the course web site.

Life in a Martian Meteorite?

Meteorite ALH84001--oldest of 12 rocks, discovered in 1984, thought to have come from Mars, landed in Antarctica about 13,000 years ago. Weighs about 4 pounds.

Why is it believed to be from Mars?

1. Abundance ratios of oxygen isotopes are the same in all 12 rocks, but different from meteorites from the moon, most Earth rocks, or asteroids.
2. Pockets of gas in the youngest of the 12 have same composition as present Martian atmosphere. (Graphs shown in class—the evidence is *very* convincing.)

The rock's age is about 4.5 billion years (because made of pure pyroxene [not basalt], one of the first solids on an initially molten planet), so dates from earliest era of solar system. Most believe that a 100 km. diameter asteroid hitting Mars about 16 million years ago (from the number of cosmic ray tracks on the rock that show how long it was exposed in space) ejected this rock from the Martian surface. Simulations suggest that this occasionally happens to all the inner planets. Most of these fall into the sun, are kicked out of solar system, or get pulverized in asteroid belt. Some chance of reaching Earth. Older simulations found it would take about 100 million years, but more recent simulations (including effects of Jupiter and Saturn) get about 10 million years. So for 16 million years the rock was undergoing a complicated orbit around the sun, when by chance its orbit intercepted the Earth.

Here's the chronology:

LIKELY HISTORY OF THE MARS METEORITES

0. Rock solidified on Mars 4.5 billion years ago.

1. Pieces of Mars blasted loose by impact of asteroid or comet about 16 Myr ago (date from radiation damage).

2. A small fraction escape Mars' gravity.

3. These particles would orbit the sun in relatively stable orbits for most of their lives, except for gradual orbit alterations by tug of distant planets.

4. Occasionally, a close encounter with inner planets abruptly changes the path.

5. Many of the objects eventually fall into the sun, collide with asteroids, or escape the solar system.

6. A small fraction of the fragments hits the Earth, 13,000 years ago, in Antarctica.

Over 10 to 100 million years, as much as about 7 percent of the original material could find its way to Earth this way. And it goes both ways: some life-bearing rocks from Earth have probably found their way to Mars (and elsewhere).

This brings up the idea of "panspermia" again. Calculations of the probability that rocks like the Martian meteorites have been ejected from our solar system and made their way to another *star* system show that it is *extremely* improbable (as expected) but *still possible*.

Evidence for life in ALH84001

1. Organic molecules that might be associated with life.

a. Carbonates--forms from water and carbon dioxide. On earth, produced by decay or combustion of plants and other organisms. (See below for criticism.)

b. PAH molecules--these are fairly complex organics, but are found on the Earth, in meteorites, and also identified in interstellar dust grains, so this doesn't require biology.

2. Minerals characteristic of biological activity.

Iron sulfide and magnetite--commonly produced by anaerobic bacteria on Earth. Magnetite is especially interesting because it is used by some Earth bacteria to "navigate" through Earth's magnetic field. When bacteria decompose, they leave "magnetofossils" shaped like cubes or teardrops, like some those found in ALH84001.

3. Tubular and egg-shaped structures that resemble fossils of the oldest single-celled bacteria found on Earth.

It *is* believed that liquid water existed on Mars long ago. Mariner 9 (1972) found what looked like dry riverbeds and lakebeds, and the Viking spacecraft provided even stronger evidence for channels and valley networks.

Criticisms (see your text for additional discussion of pros and cons):

1. Possibility of contamination in the last 13,000 years. But life from Mars proponents point out that the PAH concentration increases from surface to interior, opposite from what's expected from contamination.

Dec.1996--Becker et al (UCSD; paper published in Geochimica et Cosmochimica Acta) claim the PAHs are probably contaminants from Antarctic ice. All the PAHs found in the Martian meteorite were found in the ice samples, and also in other Antarctic meteorites, including several that didn't come from Mars. They claim that the PAHs are found deep within fissures because they collect on surfaces of carbonate grains.

2. Carbonates and PAH's could have formed in absence of water. One proposal suggests asteroid smashing into Mars' surface, liquifying the carbon dioxide frost.

3. Two geochemists at U.Colo. claim that the temperature at which the carbonates formed was higher than NASA scientists suggest, possibly hotter than any microorganism could survive. This is crucial because the carbonates are central to the lines of evidence. They derived a temperature of over 600 ^{O}C! But another group, using a different technique, found a formation temperature for the carbonates of only 80 ^{O}C! So still very uncertain.

4. Evidence that the magnetite particles are non-biological. Dec.1996 paper in Geo.Cosmo.Acta by 3 US geoscientists find that the magnetite particles grew "like a tightly wound spiral staircasee" (axial screw dislocation). This form is totally absent in any known magnetite produced by living organisms. They *are* formed at fumaroles (volcanic vents that release hot gases which then condense; need T around 500-800 C for this, agreeing with earlier analysis that carbonate globules must have formed at > 450 C.

5. There should be a large, round crater on Mars from the impact, but none this big have been found. But it could have been a low-angle impact of a much smaller object, creating an elliptical crater. In late 1996 Barlow claimed 2 craters (out of 42,283 Mars craters inspected) as possible sites.

6. Part of the support for biological interpretation was high enrichment in C^{12} over C^{13}. But Oxford geologist Martin Brasier claims repeated freezing and thawing could produce a similar result. (Recall that Martin Brasier is the same person who brought to light the questionable nature of the 3.5 billion year old "fossil" evidence for life on Earth.)

7. The sizes of the purported fossil forms are *tiny*, much smaller than even the smallest prokaryotic cell on Earth. There is severe doubt whether such small objects could contain enough genetic material for even the most primitive of organisms.

Satellites of giant planets

Jupiter's four large satellites :

Io—*very* active volcanoes cover nearly entire surface; amazing variety. Maybe lakes of liquid sulfur. But no evidence for water, and extremely severe radiation environment (Jupiter's radiation belts).

Europa—long lines, many double and triple, appear to be fissures in an icy crust that may (or may not!) cover a layer of *liquid water*.

Ganymede—evidence for plate motions of the crust.

Callisto—lack of large impact craters.

Io's volcanoes and Europa's (possible) liquid water are due to the same effect: changing tidal forces due to interactions with Jupiter *and* with other satellites.

None of these have atmospheres *today*, but could have earlier: they are more massive than Mars, and further from sun (recall that it is almost certain that Mars once had a substantial atmosphere).

Current interest is Europa—Several *Galileo* close flybys show the complex structures of the lines, the "spatter cones,",ice floes, and other structures that might be due to subsurface water; lack of impact craters shows surface is geologically "young". Dark, reddish coloration of cracks⇒ bacteria (or some kind of organic gunk)?? *Galileo* spacecraft's near-infrared spectrometer indicated salts in this dark material, but *no* signature of organic compounds. Under the water: analogues of terrestrial hydrothermal vent organisms?? NASA and astrobiology community is trying to build interest to support a mission sending a probe under the ice. But current calculations are indicating that ice layer thickness is much thicker than hoped.

See text and attend Neal Evans' lecture (Monday) for more detail on this subject.

Titan

Saturn's largest satellite, and the object that may be most interesting for astrobiology: It is massive (like Ganymede and Callisto in the Jupiter system), but Titan has an atmosphere. Why? Apparently the temperature at Jupiter was a little too warm to allow ices that formed the satellites to retain gases like nitrogen, methane, etc. But further away from the sun than Saturn, it is so cold that such compounds would be largely frozen, like on Triton (massive icy moon of Neptune) or Pluto.

Yet Titan is not so massive that it could hold on to the lightest gases, like H_2 (compare with Jupiter). So it has an extremely interesting composition, with many organic molecules, as well as CO_2 and H_2O, observed through spectral lines. The hydrocarbons are formed either from methane (CH_4) or with nitrogen (such as HCN). Much more complex molecules must be present, given the smog layer that totally hides Titan's surface.

Combination of thick atmosphere and dense clouds suggest significant greenhouse. But unlikely that it is enough to allow *liquid* water.

Density = 1.9 g/cm^3 (compare—water=1, rock=3, iron=7), so must be composed largely of ices made from H_2O, CO_2, N_2, CH_4, NH_3, all with densities 1 to 1.5.

Atmosphere: 97% N_2 + 3% combination CO, CH_4,C_2H_6 (ethane).

Temperature: 94 K (-179 C) at surface (cold!).

The methane would be broken up by sunlight if not resupplied $\Rightarrow$ probably by liquid methane (or ethane—see below) oceans or lakes. This can saturate the atmosphere, leading to methane clouds (just as H_2O clouds form on Earth).

Calculations show that what really happens is

CH_4 + photon $\rightarrow CH_2 + CH \rightarrow C_2H_4$, C_2H_2, and H or H_2 which escapes (because so light). So get irreversible conversion of methane into ethane, catalyzed by C_2H_2, so expect ocean of ethane about a km thick.

Is it a global ocean? NO—radar and HST infrared reflectivity show variations, suggesting fixed continents.

Oct. 2003: Campbell et al. (Science) report radar observations indicating many lakes of frozen hydrocarbons.

Liquid water? Too cold at surface now, but early planetesimal bombardment could have meted the early surface ice. But only get ~100 to 1000 yr before it refreezes after each impact.

Life on Titan?

Some think Titan might be a near-ideal site for life's origin; others disagree. Here are some of the arguments.

Against:

a) Liquid methane and ethane don't dissolve compounds easily like water. Organic compounds formed in the atmosphere probably just settle to the bottom.

b) No clays (from silicates) without water. But on Earth, many think that clays were necessary to catalyze polymerization.

c) Probably no silicates at surface anyway—it's almost certainly settled to the core (along with iron, phosphorus). So there is a lack of biogenic elements (Si, Ca, Fe, P) at surface.

For:

UV from the sun and high-energy charged particles from Saturn break bonds in CH_4 and and N_2 ⇒ many hydrocarbons, including HCN and HC_3N (all observed by spectra). These and more complicated molecules will saturate the atmosphere, producing haze (observed), and some will rain a layer of organic products on the surface ⇒ much of Titan may be covered by an "oil slick" 1 to 100 meters thick. With an energy source (lightning?) could get amino acids and organic polymers in high concentrations. One model for the origin of life on *Earth* is a "primordial oil slick," very similar! But current radar observations favor lakes rather than global oil slick (check astrobiology web sites for latest information).

This is why Titan is considered the best natural exobiology laboratory we have. The Cassini-Huygens mission will reach Saturn in 2004, and the Huygens probe will descend and either float on the ocean or land on solid surface. Should be interesting!