Less likely places to find life in our Solar System

In the main lectures we talk about Mars, Europa, and some of the other decent bets to find extraterrestrial life in our Solar System. Here, for completeness, we talk about a few other places.

Our Moon

The Moon is the closest astronomical object to the Earth, and the only one on which we can see significant surface features with our naked eyes (the Sun is too bright, and everything else is pointlike or, like the Andromeda galaxy, too dim). As a result, it has from time immemorial inspired many fanciful notions, including that the Moon is inhabited. In fact, life on the Moon was the subject of one of the most famous hoaxes ever perpetrated.

On August 25, 1835 the New York Sun, a small newspaper with a daily circulation of about 4,000, printed a remarkable story on page 2. According to them Sir John Herschel (son of the discoverer of Uranus) had been observing the Moon with a new telescope based in South Africa. The results were astounding. He had seen herds of bison, many beavers, a rich variety of plants, and, most intriguingly, traces of artificial features with smoke coming out of them. The newspaper continued in a series of stories, and on the fourth day revealed the discovery of intelligent life: "They averaged four feet in height, were covered, except on the face, with short and glossy copper-colored hair, and had wings composed of a thin membrane, without hair, lying snugly upon their backs from the top of the shoulders to the calves of their legs." On this day the circulation reached 19,360, tops of any newspaper in the world. Tragically, however, as their readers held their breaths in anticipation of the next revelations, the Sun reported that the South African telescope had been destroyed and thus future observations would be delayed.

On September 16, 1835, the Sun admitted that it had all been a hoax. Remarkably, however, its readers took this as an amusing joke and the newspaper reached 30,000 circulation the next year.

This incident reveals a great deal about the psychology of the public but also about the interest in life elsewhere. If you had lived at the time, would you have believed in this story? Remember that one of the goals of this course is to develop your skeptical faculties. In this case, you would want to check whether the purported observations were possible at all. **Hint:** how large a telescope would you need to resolve details of human-sized creatures as far away as the Moon?

As the 1800s and 1900s proceeded, telescopes became successively better until it became clear that the Moon is a pretty barren place. It has no atmosphere, which is as expected because the Moon's surface gravity is only 1/6 of Earth's and it can't hold on to any significant amount of gas. There is also no evidence for liquids on the surface. Landings by astronauts starting in 1969 confirmed the bleak outlook when they brought back rocks and found no evidence for complex organic molecules, let alone life.

Recent news hasn't been all bad, though. In 1996 it was reported that data from the Clementine satellite suggested that water ice is present in some permanently shadowed parts of polar craters on the Moon. This is the only surface location that could host water in any form: ice exposed to sunlight would sublime (turn directly into vapor) and would be lost quickly due to the Moon's weak gravity, and liquid or gaseous water would also drift away. The data themselves, which rely on the reflective properties of the surface, were confirmed by the Lunar Prospector mission two years later. However, the interpretation is controversial, with some scientists believing that the high reflectivity is caused by roughness of the surface instead of by water ice. If it is ice, this likely is the remnant of ice produced by occasional cometary impacts.

Another consideration is that seismometers left on the Moon have confirmed that, as expected, the Moon does not have a liquid center. There are moonquakes, but these are caused by occasional impacts, by tides from the Sun and Earth, and by heating of the surface rather than by tectonic activity. To the degree that we believe tectonics have been important for life on Earth, this element is missing on the Moon.

In terms of our checklist, we can say that the Moon is a little light on elements such as carbon, nitrogen, and oxygen. It has them, though, so this might not be a disqualifier. The source of energy is pretty abundant: our Sun shines as brightly at the Moon as at the Earth. Liquids are not at all present on the surface of the Moon, and the rocks brought back by the astronauts are absolutely bone dry. In terms of stability, the Moon has a 29 day "day", where the average temperature in the Sun is 107°C and the average temperature at night is −153°C.

Given all this, how do you assess the prospects for life on the Moon? Complex or intelligent life seems pretty well ruled out. Can we say the same thing about microbial life? Might it be that some liquid water lurks beneath the surface and that some tenacious microbes are holding on there? What do you think?

Mercury

Mercury is the closest planet to our Sun and is far inside the habitable zone. Still, let's give it an objective look!

In 1974 the Mariner 10 spacecraft did a flyby of Mercury. This means that it did a hit-and-run rather than orbiting the planet (actually, due to its complicated trajectory, it managed three flybys). This yielded photographs of about 45% of the surface. It made some interesting discoveries, including that Mercury does have a tenuous atmosphere made mainly of helium, and that it has a magnetic field. Given that the core of Mercury is thought to be solid, this field cannot be generated the way it is for the Earth (i.e., can't be a dynamo), so some people think that it is more like a permanent magnet, in which magnetic domains in iron line up. The MESSENGER mission recently completed its 2,000th orbit around Mercury, so we will continue to learn about the geology and history of our smallest planet.

Mercury is close enough to the Sun that tidal effects have put it in a special configuration. Its day (as measured relative to the distant stars) is almost exactly 2/3 of its year. Given that it rotates in the same direction that it orbits, this implies that the "day" as measured from one sunrise to the next is actually 176 days, twice the length it takes to orbit around the Sun. This very long time and Mercury's lack of a substantial atmosphere mean that the day-night temperature variations are enormous: from $-183°$C at night to more than $+400°$C in the daytime. Its surface is cratered like the Moon, indicating an old surface not affected by plate tectonics (this is expected, given the small size of Mercury). MESSENGER found evidence that in some permanently shadowed polar craters there is water ice(!), which might seem surprising but which is consistent with the extremely cold nighttime temperatures. Could there be some very narrow boundary regions in which liquid water exists? The problem is that Mercury's lack of an atmosphere probably means that if any surface liquid water is produced, it almost certainly evaporates right away. Still, we could be open-minded enough to imagine that subsurface liquid water could be somewhere on Mercury.

Consulting once again our checklist for life, we note that in terms of chemical building blocks Mercury is pretty poor: it is 70% metallic and about 30% made of silicon compounds. It has very little carbon, nitrogen, or oxygen that isn't bonded with silicon. Some people think these elements may have been lost in a large collision, but this is difficult to tell. There is abundant energy, to put it mildly, given how close it is to the Sun. No liquid has been detected, but as we said there might possibly be some in the polar craters.

With all this in mind, I'm more optimistic than I was a few years ago before water ice was detected, but I still would put the odds of current life (even microbial life) below 50%. What do you think?

The moons of Mars

Mars has two small moons, called Phobos (fear) and Deimos (terror). They are in fact small enough (some 10-30 km in size) that their gravity is not sufficient to squeeze them into spheres. Instead, they are irregularly shaped. They are thought by many astronomers to be captured asteroids, but the mechanism of capture has not been worked out fully.

The moons have the peculiarity that they were "predicted" by Jonathan Swift in Gulliver's Travels! In his voyage to Laputa, Gulliver notes of the Laputan astronomers that "They have likewise discovered two lesser Stars, or Satellites, which revolve about Mars; whereof the innermost is distant from the Center of the primary Planet exactly three of his

Diameters, and the outermost five; the former revolves in the space of ten Hours, and the latter in Twenty-one and an Half." This corresponds to an orbital radius of 13,600 km for the inner moon Phobos (real value 6,000 km) and an orbital radius of 27,200 km for the outer moon Deimos (real value 20,100 km). The impressive thing is that Gulliver's Travels was written in 1726, but the moons were actually discovered in 1877!

It's a bit of a diversion, but how could Swift have known about the moons? You won't be surprised to hear that some people take this as evidence of aliens talking with Swift, or other such nonsense. It turns out that the origin of this idea came from a mistake by Johannes Kepler.

In the 1600s it was common for scientists to "pre-announce" a discovery by sending it out in anagram form. Then, when they had confirmed their work, they would announce it properly and be able to back-date their discovery. In this case, in 1610 Galileo Galilei sent out the anagram "s m a i s m r m i l m e p o e t a l e u m i b u n e n u g t t a u i r a s" which has the correct solution (in Latin) of "Altissimum planetam tergeminum observavi", meaning "I have observed the most distant planet [Saturn] to have a triple form." That is, he was announcing the discovery of rings around Saturn. Kepler, however, thought the announcement was "Salue umbistineum geminatum Martia proles", meaning "Hail, twin companionship, children of Mars", which naturally implied two moons. This propagated down to the time of Swift. Of such things are urban legends born...

In any case, the moons themselves are carbonaceous, meaning that they have plenty of carbon. In principle, this means that the chemical building blocks are there. In addition, since they are at basically the same distance from the Sun as Mars is, they have reasonable sunlight and thus reasonable amounts of energy (although the average temperature is $-40°C$). However, there are no liquids on their surfaces and (obviously) no atmosphere, because they are tiny compared to our Moon and even our Moon isn't able to hang on to an atmosphere. The environment is pretty stable, but with such small objects it is difficult to imagine life originating there either. Can you think of any way out?

Venus

Science fiction stories have frequently portrayed Venus as a steamy tropical planet with dense jungles and frequent rain. To some extent this can be traced back to a 1918 statement by Nobel Prize winning chemist Svante Arrhenius, who decided that Venus's thick cloud cover could only be water vapor. This gave rise to a large number of stories, such as the Ray Bradbury classic "All Summer in a Day" (1954), in which a girl recently arrived from earth is trapped in a closet by her cruel classmates and thus misses the two hours in a seven year period when the clouds part and the sun is seen.

However, as early as 1922 these visions already appeared unrealistic. At that time, two astronomers used a spectroscope to view Venus. They did not find any evidence for oxygen or water, and as a result proposed that Venus was actually a desert. Nonetheless, science fiction writers and the general public clung to the idea of an "early Earth"-like Venus with its jungles, and the illusion was only finally shattered when the satellites Venera 4 (Soviet) and Mariner 5 (American) reached Venus on October 18 and 19, 1967 and confirmed beyond doubt that the atmosphere contained almost no water.

In fact, it is much worse than that. As realized early by Carl Sagan and others, the prevalence of carbon dioxide in Venus's atmosphere means that it is a superb example of the greenhouse effect. That is, light enters and is absorbed by the surface, but the reradiated light (in infrared) is trapped by the carbon dioxide. This raises Venus's surface temperature to the highest of all planets, even though it is only the second closest to the Sun (Mercury is closer). Recall that atmospheres allow the distribution of temperature around the surface; the Moon and Mercury, with zero or little atmosphere, have huge variations between day and night, whereas Earth has more moderate temperature swings. With those examples you might expect Venus, which has an atmosphere that is 90 times denser than Earth's, would really be constant.

You'd be right: the surface temperature is just above 460°C everywhere. That's true whether it is day or night, at the poles or at the equator. The only variation is in altitude. This is true even though Venus's rotation period is an amazingly long 243 days (longer than its 225 day year!!). By the way, Venus actually rotates *backward* relative to its orbit; this is thought by some to be due to a gravitational interaction between Earth and Venus's thick atmosphere. Unlike Earth, Venus has no moon.

Other than these huge differences, Venus is close to a twin of Earth. It has a radius that is 95% that of Earth, for one. It also has frequent lightning. It might even have volcanic activity (it has 167 volcanos more than 100 km across!). However, there are no lava fields visible and no craters older than about half a billion years. It is thought that Venus's crust is thicker than Earth's (because Venus is smaller, it cooled off faster) as well as structurally stronger (because it doesn't have water to make the crust malleable). Therefore, Venus doesn't currently have plate tectonics, and instead it might be that heat builds up until the whole crust resurfaces, leading to the granddaddy of all volcanic episodes. Not good for life!

The atmosphere itself is not just dense and dry. It has rains of sulfuric acid as well. Oddly, these don't appear to erode the mountains (up to 11 km high) or craters much, because water is important in such erosion.

What does this tell us about the prospects for life on Venus? To be systematic, let us once again go through our checklist. Venus has plenty of the required chemical building blocks: carbon, nitrogen, and oxygen. It also has lots of sunlight, which could be a fine energy source, although the great heat would pose some difficulties for complex molecules as we are used to them on Earth. The surface appears completely dry, so no liquid water. Finally, it is arguably the most stable planet in the solar system, at least now: no variation in temperature, and no surface activity.

The high temperature seems pretty fatal to life now, and unlike with Mercury there is no escaping to shaded polar regions. However, recall that stars become more luminous as they age, and our Sun was about 30% less luminous when it was born than now. Venus was in the habitable zone then, and if it avoided a runaway greenhouse in the first billion years it does seem possible that life evolved then.

Indeed, it has even been suggested that this early life might have been able to gradually move up into the atmosphere as the planet heated up. Unfortunately, the lack of water, the presence of sulfuric acid drops, and the enormous temperature combined with a high flux ultraviolet radiation all make it tough for such life, or Earth microbes transported by impacts, to make good. What do you think? Should we give up on Venus? If so, this leaves just one more location in the inner solar system for extraterrestiral life: Mars, which we treat in one of our main lectures.

Saturn's moons Titan and Enceladus

On to the next planet! Saturn is the second-largest planet in the solar system, with about 95 times Earth's mass. It is also about ten times as far away from the Sun as Earth is, meaning that it receives only 1/100 of the illumination. Not only that, but it only has one very large moon, Titan. Therefore, unlike with Jupiter's big moons, there is not a prospect of resonances and tidal heating. Game over, right?

Not quite. Titan is the second biggest moon in the solar system. Like Ganymede it has a larger radius than Mercury, but a smaller mass because of its low density. Even so, at Earth's orbital radius Titan would have no atmosphere, because its gravity is insufficient to hold on at our temperature.

However, at the large distance of Saturn, Titan's gravity is plenty for an atmosphere. In fact, its atmosphere is about 50% thicker than ours, although composed 90% of nitrogen and about 10% methane, with no oxygen. This is facilitated by the remarkably cold temperature: only 93 K ($-180°$C). In fact, there appears to be an anti-greenhouse effect going on: the thick atmosphere blocks a good fraction of the Sun's light but allows the heat from the surface to escape.

Nonetheless the temperature is high enough, and the atmospheric pressure is also high enough, that liquid methane could exist on the surface. In fact, when the Huygens probe landed on Titan, it returned pictures showing channel-like features that were probably carved by liquid methane. However, no streams or pools were seen directly, and the probe was not a rover, so this is still not certain. There are some pretty cool-looking ice boulders, though, and at 93 K that ice is hard as a rock.

We can now go through our usual checklist for life to evaluate the prospects on Titan. The chemical components are no problem: carbon and nitrogen at least are there in abundance. Liquids are probably covered by methane, and the environment is likely extremely stable. The difficulty is in energy. We don't know how much energy is needed to drive life, but Titan has neither the solar illumination so important on Earth nor the tidal squeezing and geothermal heating that is crucial to Europa and possibly Ganymede. Certainly life on Earth would not be able to reproduce and grow there.

Perhaps this is more of a quantitative problem. After all, life on Earth makes use of enzymes that facilitate biochemical reactions that would otherwise take essentially forever at terrestrial temperatures. If life can emerge in the cold tempeatures of Titan, one might imagine that enzymes in that environment could be even more effective in speeding up reactions. My personal feeling, though, is that the low temperatures and minimal energy probably mean that even if Titan has life, it is likely to be similar to life on Earth with little access to energy. In our case, these are the endoliths (organisms living in deep rock cracks), which you recall reproduce as seldom as once per century. If so, multicellular life, let alone intelligent life, seems a dim prospect on Titan.

Saturn's sixth largest moon, Enceladus, has actually received a decent amount of attention recently as a prospective home for life. The reason is that in 2008 the Cassini spacecraft discovered water vapor emerging from Enceladus' south polar region. This suggests that beneath its ice, the moon has liquid water. Enceladus is only 500 km in diameter, so the heat to produce that water must come from tidal heating and radioactive decay (as in some of Jupiter's moons) rather than from the cooling heat of formation.

The moons of Uranus and Neptune

These don't offer much hope for life, so we'll go through them quickly. Uranus is twice again as far from the Sun as Saturn is, and thus receives a mere 1/400 of the illumination that we do. It has no large moons; the biggest are Oberon and Titania, but neither of them has more than 1/20 of the mass of our Moon. They have no atmosphere and no liquid. They are completely dead.

Neptune is 50% farther from the Sun than Uranus is. It has one large moon, Triton, but this is only about the mass of our own Moon. Nonetheless, Triton does have a thin atmosphere. This was discovered with the Voyager 2 spacecraft during its 1989 flyby; there were some remarkable pictures of drifting smoke from nitrogen geysers. However, there is no liquid on the surface and Triton has long since cooled, so it is not a good prospect either.