The moons of the outer planets

Last lecture we explored Mars, which is the best bet among the other terrestrial planets to host life. In this lecture we will explore the outer planets. Given that the closest of these, Jupiter, is outside of our official habitable zone by a large factor (Jupiter is 5.2 AU away from the Sun, so it receives only 1/27 of the illumination that the Earth does), we might think that the prospects for life are bleak. However, surprisingly, some of the very best prospects for life outside Earth are in these very systems. The reason is that although the giant planets themselves may not host life (although we should as always be open-minded), some of their moons may well do so. We'll start with the satellite system of Jupiter and move out.

The Jovian moon system

Jupiter is the king of the planets, with two and a half times the mass of all the rest put together. One reason for its size is that it formed outside the "frost line" where water ices can form. These ice grains incorporated hydrogen (the most common element), hence a substantial amount of mass came together. Eventually the mass was large enough to start pulling in gas from the surrounding protoplanetary nebula and grow by direct gravitational accumulation instead of by the collisions between protoplanets that we think played a major role for terrestrials. One result of this is that whereas Earth is highly enriched in heavy elements such as iron and silicon, Jupiter's composition is close to that of the Sun and thus of the nebula.

Jupiter has four large moons and a host of much smaller ones (more than sixty total at last count). Galileo, who discovered the big moons, called them the "Medicean satellites" in an effort to curry favor with his patrons the Medicis. Posterity would have none of this, however, so they are collectively called the Galilean moons instead. In order from closest in to farther out, they are Io, Europa, Ganymede, and Callisto. Ganymede is the largest moon in the solar system, and in fact has a larger diameter than Mercury (although a smaller mass, due to Mercury's higher density). These four satellites are a microcosm of the solar system itself. Their average densities are greater closer in, suggesting that the heat was larger there in the protojovian disk and thus it was more difficult to capture things with lower melting points.

Of special relevance to our investigation is the orbital periods of the inner three of these. Io goes around Jupiter once every 1.77 days; Europa every 3.55 days; and Ganymede every 7.15 days. If you look at these numbers you will realize that these are very close to a 1:2:4 ratio. Coincidence? No! Indeed, this close ratio turns out to be the reason why Europa, and possibly Ganymede, are considered good prospects for life. This is due to the gravitational tidal effects of Jupiter on the satellites and the satellites on each other. This is important enough that we will now go into some detail about this system.

Tidal effects

Tides on the Earth are caused primarily by the gravity of the Moon, and secondarily by the gravity of the Sun. Basically, the part of the ocean that faces the Moon is closer to it than the Earth on average. Therefore, that part is pulled more strongly, leading to water that is slightly raised, i.e., a tide. What is less intuitive is that there is also a tide on the *opposite* side of the Earth. That water is *farther* from the Moon than the Earth on average, so the Earth on average is pulled more strongly than the far ocean. Thus the Earth is pulled away from the far part of the ocean, so the ocean has a bump there relative to the Earth.

If the Earth rotated at the same rate that the Moon orbits us, then those bulges would always be directly underneath the Moon. In reality, the Earth rotates more rapidly than the Moon orbits (a day is shorter than a month!). Therefore these bulges are carried a bit forward by the Earth's rotation. The bulge nearer the Moon will itself tug on the moon, and since that bulge is forward of the Moon's orbit the tug always increases the angular momentum of the Moon. Orbits with larger radii have larger angular momentum, meaning that this tug moves the Moon out and increases its orbital period. At the same time, Earth's rotation is slowing down (it has to, so that the whole system has a constant angular momentum). Tidal effects decrease in strength quite rapidly as distances increase (like one over the cube of the distance), so when the Earth-Moon system was formed and the Moon was closer than it is now, it moved away more rapidly than it is currently.

Now let's return to Jupiter's moons. Jupiter rotates in just 9.8 hours. That means that the tidal bulges raised by its moons always lead the moons. Therefore, just as with our Moon, the Galilean satellites are moving outwards with time.

Let's suppose that there were only one big moon around Jupiter. The tidal effects would push that moon away. They would also quickly make that moon's orbit circular, and would even more quickly make that moon's rotation period equal to its orbit, so that it always put the same face to Jupiter (as our Moon does to Earth, and indeed as Io and the gang do to Jupiter). But a circular orbit plus synchronous rotation (i.e., same face always to the host planet) means that the tidal effects would not be squeezing and kneading the moon, and hence would not produce any extra heat. As a result, we would expect Io, Europa, and Ganymede to be cold and dead because they are too small to hold onto any significant amount of their heat of formation.

Instead, Io is the most volcanically active object in the solar system. Europa isn't that extreme, but cracks in its ice indicate that there is an ocean of liquid water starting a few miles down in the ice. It is thought that even Ganymede has liquid water, albeit under an even thicker ice layer. What gives?

This is where the 1:2:4 orbital period ratio comes in; it's not a coincidence at all. Remembering that tidal effects are much stronger for closer things, Io was pushed out much faster than Europa and Ganymede. Suppose that Io started out farther inside Europa than it is currently, maybe with a 1:2.6 orbital period ratio. As it moved out this gap closed, to 1:2.4, 1:2.2, and eventually to 1:2. At this stage, Io orbits twice for every single time Europa orbits. As a result, Io and Europa give each other regular gravitational kicks, always at the same phase.

This is the recipe for a *resonance*, by which a large number of small kicks that are at the same location can build up. A familiar example is of pushing a swing. By pushing at the same place each time you can get someone going rather high quite quickly. In contrast, if you pushed at random places during the cycle you would sometimes add energy and sometimes remove it, for not much of a net effect.

The key in the Jovian moon system is that one consequence of these kicks is to make the orbits slightly eccentric instead of exactly circular. These types of resonances, in which the orbits converge towards each other, also stick: once Io and Europa were in a 1:2 resonance, they stayed in that orbital period ratio even though both of them have moved out since. Likewise, when that pair had moved out far enough, they captured Ganymede and they are now in a nice 1:2:4 setup.

The eccentricities that are introduced in this way are crucial for heating the moons. Since Io and Europa are not always at the same distance from Jupiter, the rate at which they orbit also changes and thus they can't keep the same face to Jupiter all the time. Jupiter's tidal force therefore squeezes each of them and warms them up far beyond what they could sustain normally. The same is true, to a lesser extent, for Ganymede.

With this in mind, what can we say about the likelihood of life on the Galilean moons? Io is probably too hot. Europa has liquid water and a geothermal energy source, and is probably plenty stable. This leaves the question about the chemical composition. We know that the outer part is water ice, one of the consequences of being so far from the Sun. We suspect that the inner portion is rocky, but that there is plenty of carbon. If so, then in principle I see no obstacle to there being life on Europa. For all these reasons, Europa is considered to be second only to Mars in terms of potential for life elsewhere in the solar system.

Consequences for life in the universe

Whew! After that discussion, what does it mean for life elsewhere? We obviously don't know how common such moon systems are. In particular, if Io, Europa, or Ganymede were very small moons, the effects would be negligible. Nonetheless, I think the implications are profound. Jupiter is *way* outside of our nominal habitable zone, yet here is at least one moon, possibly two, with likely substantial oceans of liquid water! In addition, the squeezing and cracking of Europa is thought by some to imply that at the bottom of this ocean one would have hydrothermal vents. We know that on Earth these host ecosystems of extremophiles, and it is possibly even more extensive on Europa because the lack of plate tectonics (the temperature is too low for magma) could mean that the locations of these vents might be much more persistent than the locations on Earth.

This may well open up a vast new range of possibilities for life. Could intelligent life emerge? I don't know. There are macroscopic life forms near vents on Earth, so complexity is clearly possible. One could also envision scenarios in which intelligent life evolved but the thick covering of ice prevented them from communicating. There is some discussion of a mission to Europa to drill through the ice and extract samples of the water to search for life. These are fairly pie in the sky at the moment; I invite you, for example, to think about how best to drill through a several mile thick layer of ice (there are ways, but it is not clear how one would then be able to get samples back!).

Saturn's moon Titan

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.

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.

Giant planets in the early solar system

Before departing the outer solar system for good we need to think about what it looked like early. When we discussed the terrestrial planets we stressed that larger planets retain their internal heat more. This is even more so for gas giants, and indeed even today Jupiter radiates more than twice as much energy as it receives from the Sun. The way to think of this is that Jupiter and the other giants are basically balls of gas that are slowly settling and releasing energy as a result.

If we project this back to the first hundred million years of the solar system, at that point Jupiter was radiating more energy and indeed its giant satellites might have received more energy from Jupiter than from the Sun. Could this have meant surface liquid water for Europa during this time?

In a further what-if, we could imagine another stellar system with gas giants a few times larger than Jupiter (many of these have actually been detected). Such a giant would be an even more effective heat source for its satellites, so if the satellites are close enough and big enough they would be warmed enough to sustain liquid water for billions of years. If the satellites themselves were a factor of a few larger, they could retain an atmosphere and possibly be even more favorable to life.

The take-away point is that even in our own solar system, and surely in the universe as a whole, there are many places where life *might* exist. We do not know yet whether life *does* exist anywhere but Earth, but there is reason to stay optimistic.