What is so special about exomoons?

Surfaces conditions on moons are amazingly different from those on planets. Besides the star, the planet acts as a second light source, and once per orbit around the planet, a satellite can be subject to eclipses. Since moons are tidally locked to their planet, their day is as long as their orbital period about the planet, and if the planet has a significant obliquity with respect to the star, then the moon will also have an obliquity because it orbits the planet in its equatorial plane. The detection of dozens of Super-Earth and Jupiter mass planets in the stellar habitable zone naturally makes us wonder about the habitability of their moons. So far, no exomoon has been confirmed, but dedicated surveys are underway [1]. Here we present a concept to assess the habitability of extrasolar moons based on their global, orbit-averaged energy flux. We consider:

- Direct stellar light
- Reflected light from the planet
- Thermal emission from the planet
- Tidal heating in the moon

and explore the effects of eclipses, which cool the satellite.

Surface illumination and hypothetical exomoons about Kepler-22b

Imagine a moon orbiting a planet in its equatorial plane. If the planet’s spin axis is perpendicular to the circumstellar orbit, then the moon will go through the planet’s shadow once per orbit, i.e. it experiences eclipses. Imagine further that the satellite is tidally locked to the planet. Then one hemisphere faces the planet permanently and it will always be the same hemisphere that is directed towards the star during eclipse. In turn, the antiplanetary hemisphere of the moon will never experience eclipses. Hence, averaged over one orbit about the planet, the antiplanetary hemisphere on the moon will be cooler than the “backside” (as seen from the planet).

Now imagine that the planet has an obliquity. Then the moon’s orbit will have an inclination \( i \neq 0^\circ \) with respect to the circumstellar orbit and possibly does not pass the planet’s shadow. The moon’s antiplanetary hemisphere will then not be cooled but in fact be warmed by the additional illumination from the planet – counter to the satellite’s anti-planetary side.

The figure above indicates these illumination phenomena for a putative moon about the extrasolar planet Kepler-22b, known to orbit its Sun-like host star in the habitable zone [2]. The subplanetary point on the moon, i.e. the location at which the planet is always in the zenith, is indicated with a white cross at longitude \( \Phi = 0^\circ \) = latitude \( \Theta \). The antiplanetary point is at \( (\Phi = 180^\circ, \Theta = 0^\circ) \). Average illumination is given in W/m².

In the left panel, the moon is at a distance of 20 planetary radii (20 \( R_p \)) from Kepler-22b and has an inclination of 0°. Eclipses make the subplanetary point the “coolest” place on the moon. With no seasonal variation of irradiation, the poles at \( \Theta = 90^\circ \) and \( \Theta = -90^\circ \) never receive light. In the right panel, the satellite is again at 20 \( R_p \) but with an inclination of 45°. Now eclipses are omitted and planetary illumination makes the subplanetary point the “warmest” place on the moon. Moreover, the moon is now subject to strong seasonal variations of stellar irradiation, which smooth the latitudinal distribution of the average surface illumination. With an eccentricity of \( e_{ps} = 0.05 \), tidal heating contributes 42 W/m² in both panels.

Habitable orbits for exomoons

We use a semi-analytical atmosphere model [3] to compute the critical average flux \( F_{cr} \) at which a moon turns into a runaway greenhouse and becomes uninhabitable. The equations for the satellite’s orbit-averaged global flux \( F_{glob}^{ps} \) are developed in our two recent studies [4,5]. It depends on the moon’s orbital semi-major axis \( a_{ps} \) about the planet, its orbital eccentricity \( e_{ps} \) and on the planet’s mass \( M_p \) amongst others.

In the figure to the right we show the limiting orbits about a planet at which the respective satellite becomes uninhabitable, i.e. where \( F_{cr} = F_{glob}^{ps} \). We call these orbits the “habitable edges”. Satellites closer to the planet than the habitable edge are uninhabitable due to strong tidal heating and strong illumination from the planet.

Blue lines indicate an Earth-like moon and black lines a Super-Ganymede with a mass ten times that of Ganymede, which is \( \approx 1/4 \) of the Earth’s mass. Each contour represents a given eccentricity \( e_{ps} \). For increasing eccentricity, as well as for increasing stellar mass, a satellite needs to be further away from the planet to remain habitable. Due to their higher critical flux \( F_{cr} \), more massive moons are habitable closer to the planet. This is a purely atmospheric effect.

Conclusions

Variation of illumination on moons is odd. Depending on whether a moon is subject to eclipses behind the planet, the subplanetary point becomes the coldest or the warmest point on its surface. Our orbit-averaged flux model allows for evaluations of exomoon habitability once they will be discovered.

References