Habitability of Extrasolar Moons
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Why bother about exomoons?

1. Mars-sized moons in the stellar HZs may be as common as terrestrial HZ planets, as suggested by observations of the Kepler telescope (see plot below).
2. Detection methods are now able to find moons a few times the mass of Mars (0.1 M⊕) and as small as Ganymede (0.4 M⊕) in the Kepler data [1,2].
3. Moons are likely tidally locked to their planets. They cannot be tidally locked to the star and thus avoid the danger of unstable atmospheres and climates.
4. Moons give unprecedented insights into planet formation.

Formation scenarios for habitable moons

Even the biggest moon in the solar system, Ganymede, has a mass of only ~0.025 M⊕. Yet, to hold a substantial atmosphere in the HZ, a terrestrial body needs at least the mass of Mars [5]. Such big moons might form around exoplanets via

1. In-situ accretion in the disks around young giant planets. The total mass available for moon formation is ~10⁶ times the planetary mass [6]. To form a Mars-mass moon, a planet with about 5 M⊕ is required.
2. Capture: Massive planets several AU from their stars have large Hill spheres, in which they can capture by-passing objects into moons [7,8].
3. Giant impacts: Projectiles and targets a few times the masses of Mars and Earth, respectively, might create scaled-up versions of the Earth-Moon bary. Mars-sized moons around super-Earths are a compelling scenario given the high abundance of super-Earths (see left-hand plot).

Energy budgets on moons

Planetary habitability is mostly determined by stellar irradiation, which defines the stellar HZ. However, the moons of giant planets also receive

1. (1) stellar reflected light from the planet [9],
2. (2) plus thermal emission from the planet [10],
3. (3) and moons closer than ~10 planetary radii around a gas giant experience substantial tidal heating [11,12], possibly making a moon uninhabitable [13,14].

The plot above shows what we call a circumplanetary exomoon menagerie [10] around a 500 Myr old 13 Jupiter-mass planet 1 AU from a Sun-like star. The planet is in the center, colored shells depict the habitability status of a hypothetical Earth-sized moon with an orbital eccentricity of 0.1. In the Tidal Venus case, tidal heating alone initiates an runaway greenhouse (RG) on the moon. In the Tidal-Illumination Venus case, tidal heating plus illumination (stellar & planetary) trigger a RG. In the Super-Io scenario, tidal heating is ~2 W/m², but the moon could be habitable. In the Tidal Earth shell, tidal heating is ~2 W/m², but still non-zero. In the green orbits, tidal heating is negligible and prograde (light) or retrograde (dark) moons are stable.

References


A new method to find exomoons

The orbital sampling effect (OSE) is visible in the phase-folded light curve of a transiting planet with moons, and it occurs after a few dozen transits [2]. On average, a moon appears more often at large separations from its planet, which creates an extra distortion in the average transit light curve. Each moon creates its own OSE, allowing the characterization of multi-satellite systems. OSE allows detections of sub-Earth-sized moons in the stellar HZs around quiet M and K dwarf stars. The following example shows the average transit light curve of KOI189.01, an almost Jupiter-sized planet candidate in a 30 day orbit at 0.17 AU from a 0.7 R⊙ K star. Gray dots denote Kepler data, white dots with error bars in the lower panel indicate 60-minute binnings. The white dashed line shows our “no moon” model of the phase-folded transit light curve, and the blue solid line shows the OSE model for a hypothetical Earth-sized moon with an orbital semi-major axis of ~15 planetary radii (similar to Ganymede around Jupiter). Note how the blue solid line and the white dashed line in the lower panel deviate after ~6 hours! The decrease in the blue line is due to the moon’s OSE and gives evidence of the satellite radius (by the depth deviation) and distance to the planet (by the start of the brightness decrease).

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