Exomoons: from icy to temperate worlds

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Moons of giant exoplanets may comprise a population of small rocky, terrestrial objects characterized by a range of surface and subsurface environments.

Giant planets may host significant populations of moons. In our own solar system, Jupiter and Saturn together harbor over 120 natural satellites, six of which have diameters between 1500 and more than 5000km. Planet-formation models imply that most such moons probably form in situ (unlike the collisional origin of the Earth’s moon) and may therefore have very significant water and volatile contents (see Figure 1). Of particular interest for exoplanetary science is the possible existence of moons with favorable environments for life to succeed and compositional and thermodynamic conditions like those of terrestrial planets.

The orbital configurations of moons can create unique circumstances where, in addition to energy input from stellar radiation, a significant amount of energy may be dissipated through gravitational tidal effects (as seen on Io in our solar system). Can such conditions exist for moons orbiting the increasingly large population of known planets associated with other stars? I provide a preliminary estimate of the possible range of thermal characteristics, particularly for temperate moons that could be effective Earth analogs in terms of suitability for life. These results have implications for future efforts to detect exomoons, both directly and indirectly.

Known exoplanets exhibit an extraordinary diversity in mass and orbital configuration, with a wide range in eccentricity (ellipticity) and periods, from days to years. We first need to determine the range of stable orbital terrain for exomoons. Within approximately 0.6 astronomical units (AU, the Earth’s distance from the Sun) of a solar-mass star, stellar gravitational tides will cause spin synchronicity in planets. In this case, no long-term stable satellite orbits exist, and moons will spiral in and be shredded by the planetary tides. Beyond this distance, orbits are only stable between a planet’s inner Roche limit (where tides will disrupt objects) and some fraction (typically of order one third) of the planetary Hill radius (the distance at which the effects of the competing gravitational fields of the planet and star become comparable).

It is relatively straightforward to derive the time-averaged stellar irradiation on moons, their potential surface temperature (both with and without an atmosphere), and how important tidal heating caused by flexure by the planetary gravitational field may be. Using a number of simplified physical models of orbital dynamics and stellar and tidal energy fluxes, I have made a preliminary study addressing these questions.

For known exoplanets with robust orbital information and orbits that remain further than 0.6AU from the parent star, ~60% of these worlds can harbor stable satellites in orbital bands up to ~0.04AU wide, compared to the ~0.12-0.15AU stable bands

Figure 1. Some of the potential ranges of exomoon characteristics, governed by moon mass and distance from the parent star. The classical habitable zone is the orbital distance within which a terrestrial-type planet could maintain a surface temperature between the freezing and boiling point of water (at a pressure of 1atm). Moons with masses greater than about a tenth of an Earth mass could maintain such conditions over a broader orbital range if tidal heating occurs.

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for Jupiter and Saturn. All sample planets have bands >0.02AU wide. The Galilean moons (the four largest moons of Jupiter) actually only occupy a band of ~0.013AU. Putting aside questions of formation, known exoplanets may, therefore, indeed harbor long-term stable moons. In the context of stellar insolation, using detailed orbital parameters I estimate that 15–27% of all known exoplanets may be able to harbor ice-shrouded moons (i.e., with mean temperatures below the fast-sublimation point of water in a vacuum: ~170K).

Using a simplified, zeroth-order, energy-balance model incorporating both an IR transmission factor for a ‘greenhouse’ atmosphere and a surface energy flux due to tidal heating (assuming tidal dissipation functions and elastic rigidity commensurate with a rock-ice composition), I examine the possibility of massive (> 0.1 Earth-mass) moons where a surface temperature between 273 and 373K is sustained through stellar and tidal heating. I conclude that for known exoplanets such conditions could exist with tidal dissipation ranging from 1–100 times that presently seen on Io. Large moons have long been discussed owing to the expectation that they retain a thick atmosphere over geophysically important timescales of billions of years. Intriguingly, such dissipation in moons could be produced through orbital ‘pumping’ caused by stellar tides, where the ultimate energy source is the planetary orbit itself.

The ongoing revolution in exoplanetary science, driven by major advances in optical control and spectroscopy in astronomical instruments, has revealed a diversity of new worlds. Many of these planets likely host significant numbers of moons. I show that the stable orbital terrain and stellar and tidal energy input expected in known exoplanetary systems allows for water-rich but icy moons or even temperate, Earth-like worlds. Present and future astronomical instruments and space missions (e.g., the Kepler satellite and giant ground-based telescopes with advanced adaptive optics) should allow us to probe beyond even exoplanets and into these potential classes of exomoons.

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Caleb Scharf received a PhD in astronomy from the University of Cambridge. He is currently the director of Columbia University’s multidisciplinary Astrobiology Center. He is the author of the undergraduate textbook *Extrasolar Planets and Astrobiology* (University Science Books).

References