EXOMOON HABITABILITY IN LOW-MASS STAR SYSTEMS

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ABSTRACT

The topic of extrasolar planet habitability has been a subject of much debate in recent decades. During this time, however, consideration for potentially massive satellites around these planets has seen relatively little attention. The detection of massive exomoons has now become feasible, which naturally leads to questions about their habitability. Previous studies have suggested that exomoons in M dwarf star systems cannot possibly host habitable moons in the stellar habitable zones due to stability and tidal heating considerations. However, these studies did not include a model that couples gravitational scattering with tidal evolution. In this paper we report on our development of a computation model which efficiently calculates self-consistently the tidal, spin, and dynamical evolution of a satellite system. Using the model we simulate three-body interactions between M dwarf stars and their hypothetical planet-moon binaries in the steller habitable zones. Our results tend to confirm that exomoons in M dwarf star systems are indeed most likely uninhabitable.

1. INTRODUCTION

The first definitive extrasolar planet (exoplanet) detection was achieved over two decades ago (Wolszczan & Frail 1992). It's interesting to remember that this detection involved a planet orbiting close to a pulsar. As such, the exoplanet undoubtably experiences an environment unlike any planet in our own Solar System. Today, thousands of extrasolar planets and planet candidates have been found[1] (Wright et al. 2011), exposing astronomers to many more examples of previously unanticipated planetary environments.

Now that searches for extrasolar systems are being conducted with ever increasing detail, a new class of extrasolar objects may soon become accessible, that of extrasolar moons (exomoons). These are the moons of extrasolar planets. No exomoon has yet been discovered, but the first exomoon surveys are underway (Kipping et al. 2012) and their detection is believed to be on the horizon. It is therefore conceivable to question the characterization of such moons, the results of which could prove valuable for those conducting detection searches.

Given the diversity and quantity of Solar System moons, we can envision a likewise abundant population of natural satellite around extrasolar planets. While Solar System moons cannot possibly sustain liquid surface water for extended periods, exomoons could be abundant hosts for surface habitats (Reynolds et al. 1987; Williams et al. 1997; Heller & Barnes 2013). Since exomoon detections require high-accuracy observations and vast amounts of computing power, a priority list of targets is required.

2. BACKGROUND

Discussions of extrasolar planet habitability began well before the first exoplanet detection (Huang 1959), and has since received much consideration (Hart 1978; Kasting et al. 1993; Underwood et al. 2003; von Bloh et al. 2007; Selsis et al. 2007; Kaltenegger & Sasselov 2011).

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[1] For this study we refer to the online exoplanet database at exoplanets.org

Habitability is typically defined as the ability to maintain the presence of liquid water on the surface of a terrestrial planet. The primary consideration for habitability is surface temperature, with the major energy contribution coming from the radiation received by a host star. This consideration has lead to the definition of a habitable zone (HZ) as the region around a star where a terrestrial-mass planet with a CO_2-H_2O-N_2 atmosphere and a sufficiently large water content can sustain liquid water on its surface.

For our study, we utilize an updated HZ model proposed by Kopparapu et al. (2013), which provides generalized expressions to calculate HZ boundaries around F, G, K, and M stellar spectral types. In particular, we use their conservative estimates where the inner edge is based on the "moist-greenhouse" (or water-loss) limit and the outer edges is based on the "maximum greenhouse" (or CO_2 condensation) limit. From their estimates, the conservative HZ for our Sun ranges from 0.99 AU to 1.67 AU. Out of the many confirmed exoplanet detections, several HZ candidates have already been identified (Udry et al. 2007; Pepe et al. 2011; Borucki et al. 2011, 2012; Vogt et al. 2012; Tuomi et al. 2013), and the number of HZ planet detections is expected to significantly increase with time (Batalha et al. 2013).

In recent years, the M dwarf spectral class of stars has received growing attention from planet hunting groups. Compared to the Sun, M dwarf stars are smaller, cooler, and lower-mass. Nonetheless, they are the predominant stellar population of our Galaxy. They range in mass from ∼0.075 $M_\odot$ to ∼0.5 $M_\odot$ (where $M_\odot$ is one solar mass), and have surface temperatures typically less than 4,000 K. These low-mass stars are intrinsically fainter than solar-type stars, and as such, there are no M dwarf stars visible to the naked eye.

As a consequence of their low mass, their thermonuclear fusion rate is significantly less than Sun-like stars. M dwarfs therefore develop very slowly and once they reach the main sequence are capable of maintaining a constant luminosity and spectral type for some trillions of years (Laughlin et al. 1997). Their lower core temper-
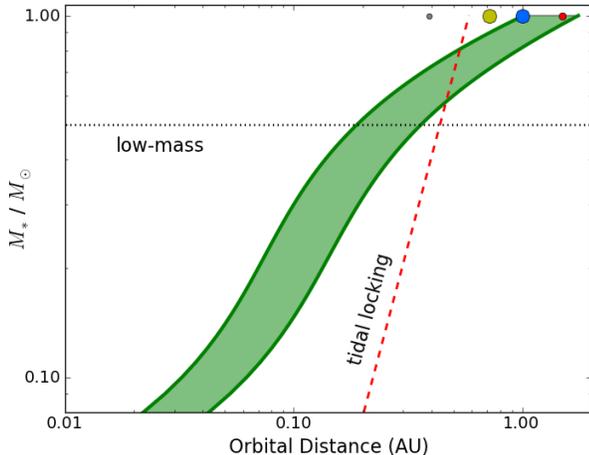
Figure 1. Habitable zones with planet mass. The black dotted line represents the upper M dwarf (low-mass) star boundary. The red dashed line represents the tidal locking radius. The colored circles represent the orbital distances of Mercury, Venus, Earth, and Mars. The size of each circle is scaled to the relative size of the planet with Earth (but not to scale with the horizontal coordinates).

Figure 2. An artist's impression of a planet with two exomoons orbiting in the habitable zone of a red dwarf. Image credit: D. Aguilar/Harvard-Smithsonian Center for Astrophysics

ature and decreased energy output result in a HZ that is much closer to the star. An illustration of the change in HZ boundaries with stellar mass is provide in figure 1.

The inherent faintness of M dwarfs produce technological challenges for exoplanet detection surveys. However, it is estimated that 75% of the stars within 10 pc of Earth are M dwarfs (Henry et al. 2006). Due to their large numbers, low-mass stars may be the most abundant planet hosts in our Galaxy. In addition, the proximity of the HZ to the host star provides certain detection advantages for planets in the HZ. Close planets have shorter orbital periods, allowing for more orbital phases to be sampled in a fixed amount of time. The shorter distance of the HZ combined with the low stellar mass also results in a higher, more discernable, radial velocity signal for the star. Moreover, tighter planetary orbits provide a higher probability that a planet will transit in front of the star relative to the line-of-sight from Earth. In which case the transit would also experience a deeper dip in the stellar light curve.

While M dwarf stars provide attractive candidates for HZ planet detections, they also present concerns for habitability that are somewhat unique to this class of stars. Due to the short distance of the HZ, one of the main arguments against potentially habitable planets is the issue of tidal locking. Tidal interactions between the planet and star will most likely cause the rotation of the planet to synchronize with its orbital period around the star. This results in the same side of the planet always facing the star. The distance at which tidal locking is most likely to occur, in relation to stellar mass, is known as the tidal locking radius. This distance is included in figure 1, in which it can be seen that the entire HZ of low-mass stars is well within the locking radius. The consequence being, that an atmosphere can freeze out on the dark side of the planet, thus restricting proper heat transfer throughout the surface.
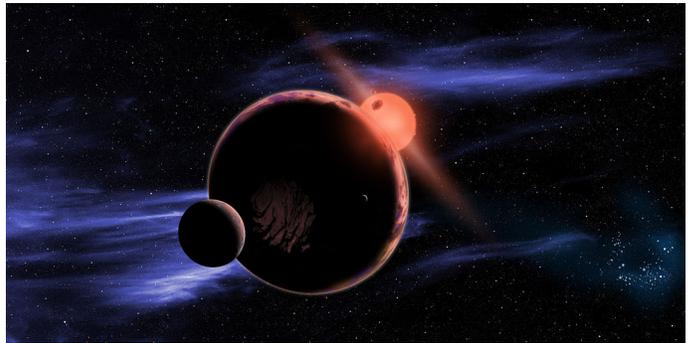
3. MOTIVATION FOR EXOMOONS

Heller & Barnes (2012) recently considered the question as to why we should bother with the habitibility of exomoons when it is yet so hard to characterize even planets. Some of their reasons include:

(i) If they exist, then the first detected exomoons will be roughly Earth-sized, i.e. have masses $\gtrsim 0.2 M_\oplus$ (where $M_\oplus$ is the mass of Earth) (Kipping et al. 2009).

(ii) Moons are expected to become tidally locked to their host planet, as a result, exomoons in the HZ have days much shorter than the stellar year. This is an advantage for their habitability compared to terrestrial planets in the HZ of M dwarfs, which become tidally locked to the star.

(iii) Massive host planets of satellites are more likely to maintain their primordial spin-orbit misalignment than small planets (Heller et al. 2011). An extrasolar moon in the stellar HZ will likely orbit any massive planet in its equatorial plane (Porter & Grundy 2011), thus, it is much more likely to experience seasons than a single terrestrial planet at the same distance from the star.

In addition, moons have been proposed as tracers of planet formation (Sasaki et al. 2010). Therefore, an increased population sample through the detection of many extrasolar satellite systems could fundamentally reshape our understanding of the formation of both planets and moons.

Heller (2012) has suggested that low-mass stars cannot possibly host habitable moons in the stellar habitable zones because these moons must orbit their planets in close orbits to ensure Hill stability. In these close orbits they would be subject to devastating tidal heating, which would trigger a runaway greenhouse effect and make any initially water-rich moon uninhabitable. This tidal heating was supposed to be excited, partly, by stellar perturbations. While tidal processes in the planet-moon system would work to circularize the satellite orbit, the stellar gravitational interaction would force the moon's orbital eccentricity around the planet to remain non-zero. We here set out to explore the three-body interaction between stars and their hypothetical planet-moon binaries in the HZ of low-mass stars to find ultimate constraints on the potential for massive, potentially habitable moons to have liquid surface water.

4. TIDAL HEATING AND HABITABILITY

It is not generally recognized that the same tidal forces which can lead to synchronous rotation can also be effective in circularizing the orbits. This occurs when orbital energy is converted to heat energy through the process known as tidal heating. The exact mechanisms of tidal dissipation are poorly understood (Barnes et al. 2009), but several quantitative models have been suggested (e.g., Hut 1981; Efroimsky & Lainey 2007; Ferraz-Mello et al. 2008; Hansen 2010). A conventional model quantifies the tidal heating (H) of a moon as

$$H = \frac{63}{4} \frac{(GM_P)^{3/2} M_P R_{sat}^5}{Q'_{sat}} a^{-15/2} e^2, \qquad (1)$$

where G is the gravitational constant, M_P is the mass of the host planet, R_{sat} is the moon radius, and Q'_{sat} is the "tidal dissipation function" which encapsulates the physical response of the moon to tides (Peale et al. 1979; Jackson et al. 2008). This equation shows the strong dependence on the semi-major axis (a) and the eccentricity (e) of the satellite. Note that tidal heating ceases once the orbit has been circularized (at $e = 0$).

Equation 1 represents the energy being tidally dissipated by a satellite. However, to assess the surface effects of tidal heating on a potential biosphere we must consider the heat flux through the satellite's surface. The surface heat flux (h) is represented as $h = H/4\pi R_{sat}^2$. Barnes et al. (2009) considered the effects of tidal heating in planetary bodies and provided some habitability limits on heat flux, which we adopt for this study. They start by pointing out that the Solar System moon Io has $h = 2$ W m^{-2} (from tidal heating; McEwen et al. 2004), which results in intense global volcanism and a lithosphere recycling timescale on order of 10^5 years (Blaney et al. 1995; McEwen et al. 2004). Such rapid resurfacing most likely precludes the development of a biosphere, so they assume that heating rates larger than this will certainly result in uninhabitable environments, and thus set $h_{max} \equiv 2$ W m^{-2}.

Barnes et al. (2009) also set a lower limit of $h_{min} \equiv 0.04$ W m^{-2} by considering that internal heating can also drive plate tectonics. Although the processes that drive plate tectonics on Earth are not fully understood (Walker et al. 1981; Regenauer-Lieb et al. 2001), it is accepted that an adequate heat source is essential. This phenomenon is considered important for habitability because it drives the carbon-silicate cycle, thereby stabilizing atmospheric temperatures and CO_2 levels on timescales of $\sim 10^8$ years.

5. METHODS

Equation 1 is useful to calculate the instantaneous heat being dissipated in a satellite. However, for our study we desired a model that would allow us to calculate the immediate effects on the motion of a planet-moon binary due to tidal interactions. With this information we could then simultaneously consider gravitational perturbations to the motion at any point during a moons orbit in order to evaluate both the long-term dynamical and tidal evolution of the system. To this end, useful derivations were presented by Eggleton et al. (1998). Based on the 'equilibrium tide' model, they derived from first principles equations governing the quadrupole tensor of a star distorted by both rotation and the presence of a companion in a possibly eccentric orbit. They also found a functional form for the dissipative force of tidal friction. Their work was based on the principles that (a) the rate of dissipation of energy should be a positive definite function of the rate of change of the tide, as viewed in a frame which rotates with the star, and (b) the total angular momentum is conserved.

Mardling & Lin (2002) later used the formulation devised by Eggleton et al. (1998) to present an efficient method for calculating self-consistently the tidal, spin, and dynamical evolution of a many-body system. Their work had a particular emphasis on planets. An important point to their method was that there was no dependence on mass ratio and that the scheme could be used for any system of bodies. We therefore adopted their method to perform the first attempt to evaluate exomoon habitability with a coupled secular-tidal orbital evolution model. To achieve this goal we developed a computational simulation that can integrate the evolution of a satellite system over several million years.

We limited our initial study to 3-body, star-planet-moon systems. The moon and planet were endowed with structure while the star was treated as a point mass. The motivation for this setup was that the dominant source for tidal evolution of a moon would be through tidal interactions with the planet. The star masses covered the mass range for M dwarfs (0.075 $M_\odot$ to 0.5 $M_\odot$).

We considered two different models for the physical characteristics of the planet, one being Jupiter-like and the other a Saturn-like planet. In all cases, the planet was given a circular orbit with zero inclination and obliquity, as well as a synchronous rotation about the parent star. The planet was placed near the inner edge of the stellar HZ at an Earth-equivalent orbital distance.

The physical characteristics of the moon were modelled after the Solar System planet Mars. This choice was based on support from formation theory (Porter & Grundy 2011; Williams 2013) and also considering that at roughly 10% the mass of Earth, such moons are near the current detection limit for exomoons. The orbital distances were based on orbits of Solar System moons, mainly, Io, Europa, Ganymede, and Titan. These equate to semi-major axis values of 5.9, 9.6, 15.3 and 21.0 times the radius of the host planet, respectively. Due to the perturbing influence of the star, the initial conditions for the moon were chosen so that its orbit-averaged eccentricity was as close to 0.1 as possible. All simulations were started with the moon already tidally locked to the planet, with zero inclination and obliquity relative to the planet's equatorial plane. The motivation being for the tidal evolution to depend primarily on the eccentricity and semi-major axis of the orbit. For each 3-body system considered, a corresponding 2-body simulation was performed involving just the planet-moon binary. These simulations allow for direct comparison of the effects of stellar perturbations on the moon's long-term tidal evolution.

To calculate the orbits we used hierarchical (Jacobi) coordinates with the planet as the initial reference point. This coordinate system has the advantage that the relative moon orbit is simply a perturbed Keplerian orbit so that the corresponding orbital elements are easy to calculate (Murray & Dermott 1999). The simulation code

Table 1
Stability summary for moon orbital distances in different stellar systems. A mark of 'J' means the moon was stable around a Jupiter-like planet, an 'S' for a Saturn-like planet.

Star Mass	$5.9R_P$	$9.6R_P$	$15.3R_P$	$21.0R_P$
$0.2~M_\odot$	J, S	-	-	-
$0.3~M_\odot$	J, S	J	-	-
$0.4~M_\odot$	J, S	J, S	-	-
$0.5~M_\odot$	J, S	J, S	J	-

was written in c++ and used a Bulirsch-Stoer integrator with an adaptive timestep. About 7 integration steps per moon orbit were required to maintain a maximum relative error of 10^{-9} for the total angular momentum.

6. RESULTS

An analysis of orbital stability for the moon showed that no star system less than $0.2~M_\odot$ was able to maintain a stable moon orbit for even the smallest, Io-like, orbital distance. This result can be explained by the reduced Hill radius (R_{Hill}) of the planet for the close-in stellar HZ. Overall, only simulations for which the moon's semi-major was $\lesssim 0.4R_{Hill}$ were able to maintain stability, which is in agreement with other stability studies of satellite systems (Domingos et al. 2006). A summary of moon stability for parent stars with $0.2~M_\odot$ and above is given in table 6. From the table it's interesting to note that no stable systems occurred for the equivalent orbital distance of titan ($21.0~R_P$) and only one star system was stable for a Ganymede-like orbit ($15.3~R_P$).

The energy dissipated by tidal heat in the planet and moon result in the slow decay of the moon's orbital eccentricity around the planet. The time required for the eccentricity to reach a minimum value was widely varied depending on the moon's orbital distance, yet, several million years were necessary for even the shortest orbit. For the largest stable orbit considered ($15.3~R_P$ around
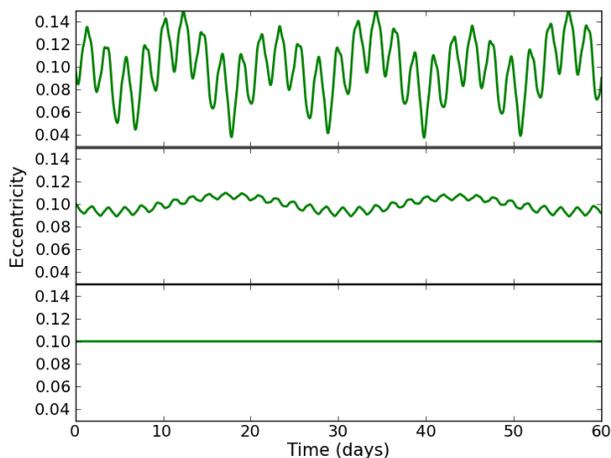

Figure 3. Comparison of satellite eccentricity for three different systems. The top and middle plots show results for 3-body simulations. The system shown in the top plot included a close-in planetary orbit around a $0.2~M_\odot$ star while the middle plot had a wider planetary orbit around a $0.5~M_\odot$ star. The bottom plot represents an isolated planet-moon system without the influence of a star.

a Jupiter-like planet), the tidal dissipation proved much less effective and very little change to the satellite's orbit occurred after 15 Myrs.

On much shorter timescales, the instantaneous eccentricity fluctuated significantly for the 3-body systems. An example of this is provided in figure 3. The figure shows two different 3-body simulations (top and middle plots) in comparison to an isolated planet-moon simulation (bottom plot). The top plot included a $0.2~M_\odot$ star which resulted in a tight orbit for the planet due to the short distance of the HZ at this low stellar mass. The middle plot represents a noticeably larger HZ distance for a $0.5~M_\odot$ star. Higher frequency oscillations in the eccentricity amplitude correspond to the moon's orbit about the planet, while lower frequency oscillations in the overall behavior correspond to the planet's orbit about the star.

The diminishing influence of the star at wider HZ distances is clearly seen in the different amplitudes of the eccentricity fluctuations. When the star's influence is removed completely, as represented by the bottom plot of figure 3, the moon's orbit remains quite stable. Due to the strong dependence on eccentricity for tidal heating, corresponding fluctuations also occur for the tidal dissipation. For this reason, we report the orbit-averaged eccentricity and tidal heating values in the remainder of this paper.

An example of the tidal evolution for a satellite is shown in figure 4. The figure represents a Mars-like satellite with an Io-like orbit around a Saturn-like planet. The two curves in the figure represent two different simulated systems. The blue curve is for an isolated planet-moon simulation (2-body). The red curve represents the same planet-moon binary orbiting in the HZ of a $0.4~M_\odot$ dwarf star (3-body). The perturbing effects of the star can be clearly seen in the long-term evolution of the star-planet-moon system as compared to the isolated planet-moon system.

A complete summary of all the simulated systems is provided in table 2. The table includes only stable systems. The tidal heating and eccentricity values represent the orbit-averaged values at the end of each integration. For Io and Europa-like orbital distances (5.9 and $9.6~R_P$, respectively) the integrations were run long enough for the surface heat flux (and effectively the eccentricity) to approach a minimum average value for the 3-body systems. For the sake of comparison, the results of an isolated planet-moon simulation is also included for each planet-moon binary considered.

7. DISCUSSION

An important comparison can be made between the 2-body and the 3-body integrations. As expected, the isolated planet-moon systems are allowed to evolve toward the eventual circulation of the moon's orbit, and correspondingly, an end to tidal heating. While in the 3-body simulations, the stellar perturbations act to continually excite the eccentricity and result in a non-zero, minimum value for the surface heat flux.

In section 4 we explained our adoption of habitability limits for surface heat flux, $h_{min} \equiv 0.04$ W m^{-2} and $h_{max} \equiv 2$ W m^{-2}. Table 2 shows that every 3-body system considered, save one, approached a tidally evolved, minimum average for the heat flux which ex-
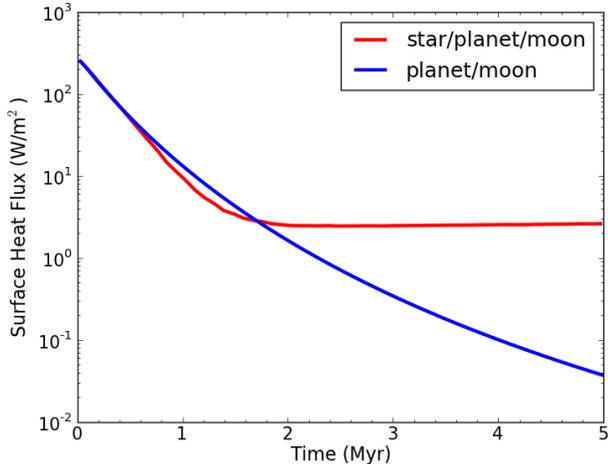
Figure 4. Comparison of tidal evolution between an isolated planet-moon system and the same planet-moon binary in the HZ of an M dwarf star.

Table 2
Summary for stable systems at Earth-equivalent distances in the HZ of M dwarf stars. The surface heat flux (h) and eccentricity values represent the orbit-averaged values at the end of each integration. A '-' value for the star mass indicates results for isolated planet-moon systems, which show what the evolution would be without the perturbing effects of the star.

Jupiter-like Host Planet				
Orbital Distance (R_P)	Sim. Time (Myr)	Star Mass ($M_\odot$)	Final h (W/m^2)	Final Ecc.
5.9	5	-	0.00	0.00
		0.2	59.7	0.025
		0.3	12.9	0.012
		0.4	3.06	0.006
		0.5	0.630	0.003
9.6	15	-	1.00	0.019
		0.3	16.8	0.072
		0.4	2.86	0.034
		0.5	1.31	0.021
15.3	15	-	0.8134	0.092
		0.5	1.39	0.100

Saturn-like Host Planet				
5.9	5	-	0.038	0.003
		0.2	53.0	0.038
		0.3	11.3	0.017
		0.4	2.62	0.008
		0.5	0.582	0.004
9.6	15	-	0.742	0.030
		0.4	3.66	0.068
		0.5	1.12	0.038

ceeds the maximum value for surface habitability. The only exception was the longer period, Ganymede-like orbit around a Jupiter-like planet with a host star whose mass is at the upper limit for M dwarf stars. However, the heat flux for this system does not represent a tidally evolved minimum due to the extremely slow evolution rate. This result is therefore somewhat arbitrary based on our choice for the initial eccentricity of the system. It does, however, suggest that tidal heating alone does not

preclude habitability for such a system. Although, it's worth reemphasizing that the system is already near the outer limit for stability and so small perturbations could destabilize the system, like those from other planets or tidal torques not considered here.

As future extensions to this work, we would like to consider the overall global energy flux received by the moon at different distances throughout the stellar HZ. It may be that reasonably high rates of tidal heating can act to extend the HZ for satellites in comparison to planets. Also, it would be worthwhile to consider the inflation of a moon's radius due to significant dissipation of tidal heat since the heat rate actually depends on the satellite's radius (see equation 1).

8. CONCLUSION

In this paper we report the first attempt to evaluate the long-term habitability of exomoons in low-mass M dwarf star systems, in which we considered Mars-like terrestrial moons around gas-giant planets. Our coupled secular-tidal simulations show, for the first time, concrete evidence that moons orbiting giant planets at Earth-equivalent distances in the habitable zones of low-mass stars are most likely uninhabitable based on stability and tidal evolution alone. As such, they do not represent promising targets for those conducting searches for habitable exomoons.

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