Exomoons: Their Scientific Potential, Urgent Need and JWST's Unique Opportunity

Thematic Areas (Check all that apply):

☒ (Theme A) Key science themes that should be prioritized for future JWST and HST observations
☐ (Theme B) Advice on optimal timing for substantive follow-up observations and mechanisms for enabling exoplanet science with HST and/or JWST
☐ (Theme C) The appropriate scale of resources likely required to support exoplanet science with HST and/or JWST
☐ (Theme D) A specific concept for a large-scale (∼500 hours) Director's Discretionary exoplanet program to start implementation by JWST Cycle 3.

Summary: Although the existence of exoplanets was largely anticipated, their discovery shattered our views on planet formation and has returned incalculable scientific insights. Similarly, we can be assured that not only do exomoons exist but that their untapped potential to reveal how planetary systems form and evolve is unparalleled. Notably, their detection would test models for in-situ formation from circumplanetary disks, as well as giant impact/capture scenarios. Exomoons may be frequent habitable worlds, and/or affect the habitability of their parent planets and thus their detection is crucial to understanding the occurrence rate of habitable worlds; a value urgently needed for the design of future imaging missions. Finally, we highlight that moons may be a major source of biosignature false-positive for imaging telescopes like LUVOIR/HabEX/HWO, since they exist in chemical disequilibrium with their parent planet. Discovering exomoons is thus not only a probable scientific goldmine, but represents an urgent need for future mission design. JWST is the only machine capable of detecting solar system analog exomoons and delivering this historic breakthrough.

Anticipated Science Objectives: We presently have little observational data concerning the abundance, formation, evolution or properties of exomoons. To date, searches have identified surprisingly large candidates [1, 2] (although none confirmed) and exclusion upper limits typically $\gtrsim M_\oplus$ [3, 4, 5, 6, 7]. Despite this, the existence of exomoons is essentially assured, and understood to be a natural byproduct of giant planet formation forming from their circumplanetary disks [8, 9]. These models predict satellites of order 0.01% that of the planetary mass (or less), and thus Earth-mass moons were in fact hardly expected. Long-period giant planets ($\gtrsim$year) should not only form but maintain Galilean-like moons for many Gyr [10]. Detailed simulation work [11] (see Figure) shows that JWST is not only capable of detecting such moons, but it is, in fact, the only such telescope. We thus advocate for a survey of giant exoplanets that i) could form Galilean-like moons ii) could maintain them for many Gyr iii) would present detectable moon signatures to adequate completeness rates from injection-recovery testing. In addition, moons forming through giant impact upon rocky planets are also expected [12, 13] although the frequency here is less clear. Given the profound connection such moons would have to our own planet's uniqueness, we advocate JWST also search such worlds for Moon analogs. Although numerous methods can and should be investigated (e.g. [14, 15]), transits offer a particularly attractive path to an incontrovertible detection, since the transits repeat but the moon shifts in a predicable yet disparate way each epoch - defining a falsifiable hypothesis [16, 17].

Urgency: Exomoons may significantly influence the frequency of habitable worlds (eta-Earth) [18], as well as representing a biosignature false-positive in direct imaging [19] - both of which affect the design of the HWO concept. Given that the target planets transit infrequently ($\sim$annually or less), there are limited opportunities for JWST to accomplish this goal during its lifetime.

Risk/Feasibility: The formation of Galilean-sized moons is thought to be an inevitable outcome of giant planet formation, whereas giant impact moons around rocky planets are less certain. However, given JWST's ability to detect such moons, a series of non-detections would provide firm upper limits - as well as implying that our solar system is remarkably unusual in having such moons.

Timeliness: JWST is the first machine capable of finding Galilean-like moons and yet their existence is crucial to understand in the design of future flagship missions.

Cannot be accomplished in the normal GO cycle: As an individual search (typical for GO), one upper limit is of little value. The real power is undertaking a search over many objects ($\gtrsim$10) to firmly test moon formation models.

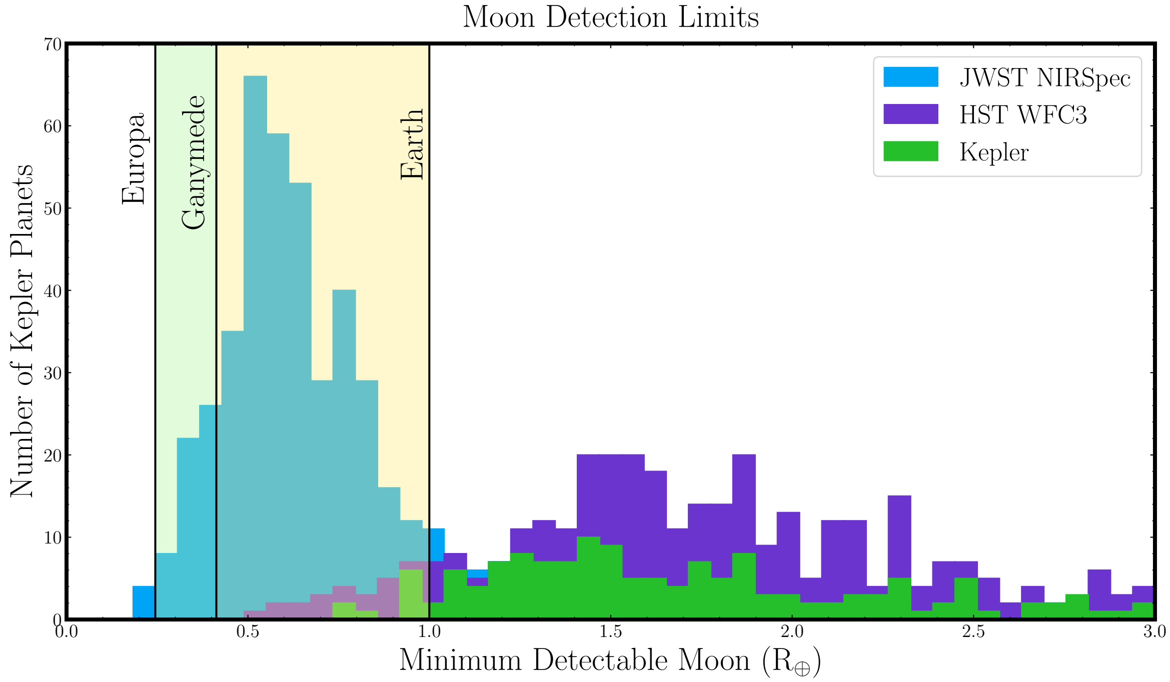

Figure 1: From [11]. For each Kepler planet, we calculate the minimum detectable exomoon radius to SNR=5 using JWST/HST/Kepler. Each moon is ensured to be stable against tidal evolution [10]. JWST is the only mission capable of realistically detecting Ganymede-sized moons.

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