Lighting up dark exomoons: observational signatures of tidally induced volcanism in other worlds

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English summary

Are we alone? The search for life elsewere in the universe is a longstanding question of humanity. We can now look for signs of life in other bodies of our solar system; on the Martian surface, and in the hidden, subsurface oceans of the moons of planets in the solar system, like the ones of Jupiter and Saturn.

Solar system moons show great diversity in their physical and orbital characteristics, and some of them are notable for their geological activity. Io, Jupiter's innermost satellite, is the most volcanically active body in the solar system, with hundreds of hotspots across its surface. Enceladus, an icy moon of Saturn, possesses surface fractures, active plumes of water vapor and a global subsurface ocean. A common driver behind these phenomena seen in the solar system moons is tidal heating: as a moon revolves on an eccentric orbit around a planet, changing gravitational pulls flex the body and generate internal heat. Over long timescales this process can maintain water liquid beneath an icy surface, and sustain volcanism. By sustaining liquid water and geological activity, such processes may provide the ingredients and energy sources necessary for habitability. While our solar system gives us nearby test cases, the search for life can also extend far beyond to exoplanet systems around other stars.

Beyond the solar system, the discovery of planets orbiting the pulsar PSR 1257+12 and, soon after, 51 Pegasi b, a giant planet with an orbital period of just a few days, marked the field's turning point. Since then, exoplanet discoveries have expanded rapidly, with thousands of exoplanets known to day. Many of them look nothing like those in our solar system: "hot Jupiters" are Jupiter-like planets on tight orbits. "Super-Earths" (planets with size between that of Earth and Neptune) are widespread, while Earth-sized exoplanets are rarer. Depending on how far they from their stars their orbits are, some of these planets may even resemble the icy moons of our solar system, with cold surfaces and possible internal oceans.

Given the importance of moons in our own solar system, it is natural to ask whether exoplanets also host moons, and whether they too might harbor life. Because every gas giant in the solar system hosts natural satellites, it is reasonable to expect that many of the gas giant exoplanets we have found are also orbited by moons (exomoons). Yet, no exomoon detection has been unambiguously confirmed until today. One of the main reasons is because the signals of moons are faint compared to those of their larger host planets. With exoplanet discoveries spanning a wide parameter space, we must decide which host planets offer the best prospects for a detection, which techniques are most effective, and what moon properties are observable?

The transit method, which is responsible for the most exoplanet discoveries until today, detects planets when they pass in front of their stars and cause a small, periodic dip in their brightness. The planets themselves are not directly visible, but their crossings (transits) are. This technique is sensitive to close-in planets, because the closer a planet is, the greater the chance its orbit will align so that we can see a transit. The latter can have disadvantages for exomoon searches: moons of planets in close-in orbits can be unstable because the star's gravity leaves little room for stable orbits. In addition exomoon searches around transiting exoplanets necessitate a favorable geometry, meaning the planet and its moon need to be lined up just right with our view so their crossings are visible. Finally, long observations are needed in order to catch multiple transits. This motivates a focus on directly imaged (DI) exoplanets, whose orbits are further from their stars. At these wider separations we can suppress the stellar light, and and capture the light from the planet itself.

Observing the light from the planet and detecting faint companions like moons comes with their own difficulties, because the overwhelming brightness of their host stars must be suppressed, and even then the planet itself can outshine its moons. Yet, in infrared wavelengths, where heat emission becomes important, a special class of objects, tidally heated exomoons (THEMs), may stand out. These are analogous to Jupiter's volcanically active moon Io, and provide a unique opportunity: powered by tidal forces, these moons can reach high surface temperatures and, in some infrared wavelength bands, be as bright or brighter than their host planets. Unlike transit observations, direct thermal detection does not depend on a specific orbital phase or repeated events. This opens a search window for identifying moons around giant planets orbiting at large distances from their stars, where other exoplanet detection methods struggle.

The amount of tidal heating a world produces is influneced by, among other factors, its orbit and how its interior materials deform and dissipate energy. Because tidal heating depends on a body's interior properties, studying THEMs is not only a way to detect moons but also a tool to probe their interior structures and properties. Similar approaches have been used in our own solar system: for example, Io's volcanism has long raised questions about whether it harbors a global magma ocean or a partially molten mantle, and measurements of how Io deforms under tidal forces have been key to testing these scenarios. Extending this reasoning to exoplanets and their moons means that, in addition to identifying them, tidal heating can help us infer their internal properties, and the mechanisms with which heat is transported in their interior. These processes are important for astrobiology, and make tidally heated worlds interesting targets for habitability studies, since their internal energy sources could sustain habitable environments independently of whether they receive direct starlight or not.

This thesis focuses on the detectability of THEMs through a variety of methods, while also examining the interior and orbital properties that make them observable. It takes steps toward finding such moons, and explores when tides can heat them enough to glow in the infrared, and whether their brightness or its variability can be measured with current and upcoming telescopes. By combining putative observations with models of tidal heating, the thesis further explores the constraints that can be placed on planetary and satellite interiors. Tidal heating models are finally used to study the interiors of icy exoplanets, that are thought to resemble the icy moons of our solar systems. Here, the focus is on Trappist-1 f, g, and h, examining whether internal heat could sustain subsurface oceans, and whether signs of volcanic activity might be detectable. Together, these studies highlight the role of tidal heating as both a detection pathway and a window into interior processes of extrasolar worlds.

Chapter 2. Exploring the detectability and properties of THEMs around the exoplanet ϵ Eridani b

In this chapter we investigate whether tidally heated exomoons can be bright enough in infrared wavelengths to be detected with the James Webb Space Telescope around nearby giant planets. We use the planet ϵ Eridani b as a test case. We employ models that link a moon's orbit and physical properties to the tidal heat generated inside it and how that heat moves through its layers, until a balance is reached between the heat produced and the heat lost. We test many possible moon scenarios, varying their size, their orbit and incoorporating uncertainties in material properties. Our results show that a moon about twice the size of Io, orbiting the nearby planet ϵ Eridani b, could be detectable if it circles its planet at a distances and with orbital eccentricities comparable to those of solar system moons. Crucially, we show that if the size and orbital distance of a moon were already known from another method, like the transit method, its infrared brightness could be used to place limits on its orbital eccentricity and interior properties, for example, whether it contains layers of molten rock. This means that a successful detection of a THEM could give us direct information about its interior, making THEMs powerful test cases for understanding how interiors and orbits interact.

Chapter 3. Spectroastrometry: a promising method to find exomoons

Even though the previous chapter shows that THEMs can in principle be detectable, current methods are still not sensitive enough to find moons like those we know in the solar system. The ones currently at the detection limits are either bigger, hotter, or both. To move past this "too big or too hot" problem, we explored a method called spectroastrometry. This technique looks for tiny shifts in the apparent position of a planet's light at different colors, caused when an unseen moon contributes to the system's signal. We developed a mathematical description of the spectroastrometric signal produced by a moon in orbit and estimated different sources of noise that could affect such signal, including telescope pointing inaccuracy, background noise, and detector limitations. We then applied this framework to nearby giant planets, using ϵ Indi Ab as an example, to see what kinds of moons can be detected. Our results show that detection is possible with next-generation telescopes like the Extremely Large Telescope for moons similar in size to those in our solar system. In particular, we find that solar system–like moons with moderate surface temperatures, can be detected, pushing detection limits closer to the moons we know in the solar system, compared to the previous chapter. We also show that large icy moons, Mars-sized or greater, might even be observed in the closest planetary systems.

Chapter 4. Adding hotspots to the picture: a new way to find THEMs

In this chapter we explore whether volcanic exomoons, with high temperature surface hotspots, can be discovered by tracking how their brightness changes as they orbit around their planets. The idea is that if a THEM has active volcanoes or hotspots scattered across its surface, like Io, these will make its brightness vary in infrared light as different areas rotate in and out of view. To test this, we simulate moons of different sizes orbiting an isolated planet and explore how they change the system's infrared brightness. We then examine whether these repeating changes can be distinguished as clear signals in the data. We find that volcanic moons with hotspot temperatures like those measured on Io can leave a detectable signature at shorter infrared wavelengths. At longer infrared wavelengths the signal fades, but by comparing observations at two different wavelengths we can separate a moon's contribution from that of its planet. Our results suggest that this method can find Mars-sized volcanic moons within about 10 parsecs, and Earth-sized ones even farther away. This approach broadens the ways we can search for exomoons, particularly around DI or isolated planets, as it is has the potential to detect moons even if their orbits do not line up with our view to produce transits.

Chapter 5. Modeling the interiors and cryovolcanic activity of exoplanets Trappist-1 f, g, and h

In this chapter we explore the interiors of three exoplanets in the Trappist-1 system, the planets f, g, and h, whose surface temperatures and densities suggest they may resemble the icy moons of our solar system. Our goal is to see under what conditions internal heating can sustain subsurface oceans and even power icy volcanoes, called cryovolcanoes. We model how heat is generated inside these planets from two main sources: tidal heating, and radiogenic heating, from the decay of radioactive elements. By linking these heat sources to the thickness of icy shells and oceans, we find which internal structures can keep heat production and loss in balance. Our results show that for Trappist-1f and g, thermal balance is possible only if their outer ice shells are relatively thin, about 4 to 10 kilometers, with underlying oceans around 90 to 120 kilometers thick. Trappist-1h, in contrast, would require a thicker ice shell to stay in equilibrium. We also tested whether volcanic outgassing of water could be detected with the James Webb Space Telescope. Even under the most optimistic assumptions, detection would require a campaign lasting over a decade. This makes detection with current instruments highly unlikely. Future efforts may have better chances by targeting exoplanets with more eccentric orbits, where stronger tidal heating can boost water outgassing rates to detectable levels.