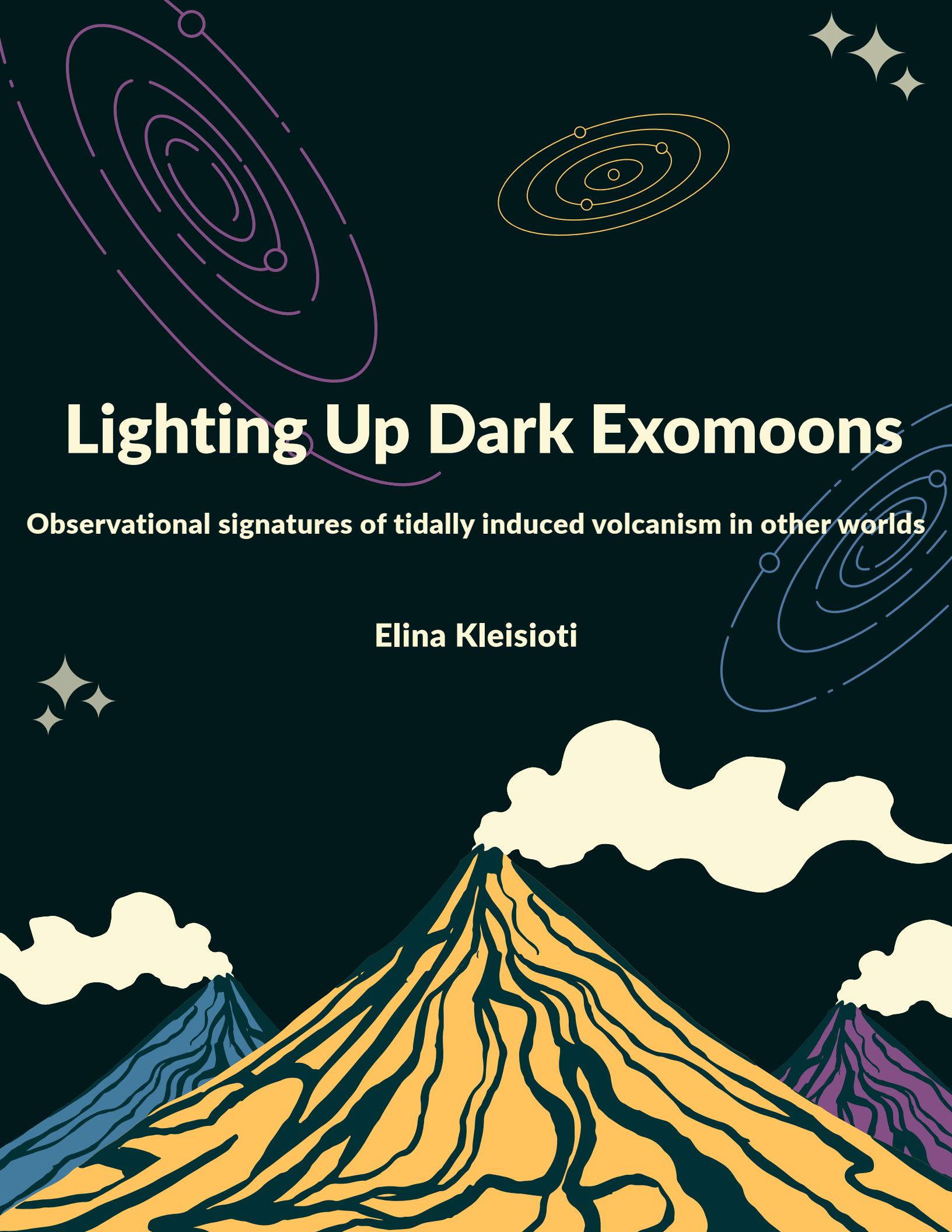


The background is a dark navy blue. In the upper half, there are three stylized orbital systems. One on the left is purple, one in the center is yellow, and one on the right is light blue. Each system consists of concentric ellipses representing orbits, with small circles representing celestial bodies. In the top right and bottom left corners, there are clusters of four-pointed white stars. The bottom half of the image features a stylized landscape of three volcanoes. The central volcano is large and colored orange with dark blue outlines. To its left is a smaller volcano in blue, and to its right is another in purple. All volcanoes have white, billowing smoke or ash clouds rising from their peaks.

Lighting Up Dark Exomoons

Observational signatures of tidally induced volcanism in other worlds

Elina Kleisioti

Lighting up dark exomoons

Observational signatures of tidally induced volcanism in other worlds

Proefschrift

ter verkrijging van
de graad van doctor aan de Universiteit Leiden,
op gezag van rector magnificus prof. dr. ir. H. Bijl,
volgens besluit van het college voor promoties
te verdedigen op donderdag 13 november 2025
klokke 10.00 uur

door

Evangelia Kleisioti

geboren te Athens, Greece
in 1994

Promotor:	Dr. M. A. Kenworthy	
Co-promotor:	Dr. D. Dirkx	TU Delft
Promotiecommissie:	Prof. dr. I.A.G. Snellen	
	Prof. dr. M.R. Hogerheijde	
	Dr. Y. Miguel	
	Prof.dr. C. Dominik	University of Amsterdam
	Dr. S.M. Cazaux	TU Delft

Printed by: Universitair Facilitair Bedrijf

Cover design: Illustrated by Phoebe Athanasopoulos.

An electronic copy of this thesis can be found at <https://openaccess.leidenuniv.nl>.

© Elina Kleisioti, 2025

To my parents

Contents

1	Introduction	1
1.1	Introduction	1
1.2	Detecting extrasolar worlds	3
1.2.1	Exoplanet detection methods	3
1.2.2	Exomoons and their detection methods	6
1.3	Tides	12
1.3.1	Tides and tidal heating: Basic concepts	14
1.3.2	Probing planetary interiors	16
1.4	This thesis	17
	References	20
2	Tidally Heated Exomoons around ϵ Eridani b: Observability and prospects for characterization	27
2.1	Introduction	28
2.2	Models	29
2.2.1	Interior model	30
2.2.2	Tidal model	32
2.2.3	Thermal equilibrium	34
2.3	Observability	36
2.4	Results	38
2.4.1	Interior structure dependence on orbital properties	38
2.4.2	Orbital and interior constraints from observations	41
2.5	Discussion	43
2.5.1	Longevity and mean motion resonance	44
2.5.2	Combination with other exomoon detection methods: Constraining the moon radius and semi-major axis	45
2.5.3	Larger moons	47
2.5.4	Future model validation	47
2.6	Conclusions	48
	References	49
3	The spectroastrometric detectability of nearby Solar System-like exomoons	53
3.1	Introduction	54
3.2	Methods	56
3.2.1	The centroid and the spectroastrometric signal	56
3.2.2	The spectroastrometric signal for closed Keplerian orbits	58
3.2.3	Sources of spectroastrometric noise	58
3.2.4	Consequences for the observation time allocation	61
3.2.5	Minimum required moon flux	61
3.2.6	Model scenario	62

3.3	Results	65
3.3.1	Minimum moon temperature for detectability	66
3.3.2	Eccentricity effects	66
3.3.3	Applicability to distant systems	66
3.4	Discussion	67
3.4.1	Comparison to previous work	69
3.4.2	Limitations on this formulation	69
3.4.3	Spectroastrometric capabilities of current-generation telescopes	71
3.4.4	Detectability of other moon-planet systems	71
3.4.5	Comparing against other moon detection methods	72
3.4.6	Synergies with other methods	73
3.5	Conclusion	73
	References	75
4	Direct detectability of tidally heated exomoons by photometric orbital modulation	79
4.1	Introduction	80
4.2	Photometric signal variability	81
4.2.1	Exo-Io modeled photometric light curves	81
4.2.2	Host modeled photometric light curves	83
4.3	Detectable moon signals in hosts' periodograms	84
4.4	Results	85
4.4.1	Tidally heated exomoons around a 2.5 h variable planet at 3 parsecs	87
4.4.2	Applicability to systems at larger distances	87
4.5	Discussion	88
4.5.1	Other sources of such signals and synergies with other exomoon detection methods	89
4.5.2	Hotspot time variability and spatial distribution on Io and exo-Ios	90
4.5.3	Possibility of hotspot detection around cooler planets	90
4.6	Conclusions	90
	References	92
5	Modeling the interiors of Trappist-1f, g, h: Tidal Heating, Subsurface Oceans, and Cryovolcanic Activity	99
5.1	Introduction	100
5.2	Methods	102
5.2.1	Heat transfer model	102
5.2.2	Tidal response model	103
5.2.3	Interior heat balance and structure calculation	104
5.2.4	Modelling observations of cryovolcanic activity	107
5.3	Results	110
5.3.1	Possible interior structures of the planets Trappist 1 - f,g,h	110
5.3.2	Observations of cryovolcanic activity	112
5.4	Discussion	113
5.4.1	Column density comparison with previous work	113

5.4.2	Water Mass Fraction comparison with previous work	115
5.4.3	Water content in the Trappist-1 system and other possible interior structures	116
5.4.4	Future work	117
5.5	Conclusions	118
	References	119
English summary		127
Nederlandstalige samenvatting		131
Ελληνική περίληψη		137
List of publications		143
Curriculum vitae		145
Acknowledgments		147

1 | Introduction

1.1 Introduction

All gas giant planets in our Solar System are orbited by moons. Jupiter alone hosts nearly 90, while Saturn has more than 200 natural satellites (NASA Planetary Data System, 2025). Even some rocky planets have moons, such as the Earth with our Moon, Mars accompanied by two known moons, and Pluto, a rocky dwarf planet, which hosts five moons, as of the time of writing (NASA Planetary Data System, 2025). These natural satellites exhibit remarkable diversity in size, and surface properties, as can be seen in Figure 1.1, orbital characteristics, composition, interior structures, and the presence or absence of atmospheres.

The moons of the Solar System represent extremes of planetary science: Io, a Jovian satellite, is the most volcanically active body in the Solar System, with over 150 hotspots on its surface (Davies et al., 2015). Meanwhile, the majority of the large moons contain a significant amount of water ice. These -so called- icy moons display a wide range of sizes and characteristics themselves. For instance, even though most of them lack a dense, bound atmosphere, Titan, a large moon of Saturn, stands out. Titan possess a dense methane-rich atmosphere and lakes of liquid ethane and methane. The surfaces of icy moons are cold and icy, and a large number of them, such as Titan, Enceladus and Triton among others, are thought to sustain subsurface water oceans (Soderlund et al., 2024). The rest of the large moons in our Solar System consist mostly of rocky material; examples are Io, and our own Moon. Together, these natural satellites highlight the variety of environments found within our Solar System.

Scientific interest in exploring the moons of our Solar System has grown, particularly following the landmark Voyager 1 and 2 missions. These missions revolutionized our understanding of the outer Solar System by exploring the Jovian and Saturnian systems, including the discovery of active volcanoes on Io (Morabito, 2012). Subsequent missions have built on this foundation. Galileo revealed that Jupiter's icy moon Europa likely harbors a subsurface ocean (Khurana et al., 1998). Cassini uncovered evidence that Saturn's icy moon Enceladus possesses active plumes of water vapor (Dougherty et al., 2006). Before Cassini's observations, Enceladus was thought to be relatively unremarkable, and it was later revealed to host active plumes and a global subsurface ocean (McKinnon, 2015). Juno, focusing on Jupiter, continues to study the Jovian moons and their environment. The recent launches of ESA's JUICE (Jupiter Icy Moons Explorer) and NASA's Europa Clipper underline the high priority placed on exploring icy moons. For instance, Enceladus remains a high priority target for astrobiological studies, as highlighted by ESA's mission priorities in 2024 (Martins et al., 2025). NASA's 2023-2032 decadal strategy likewise emphasizes ocean worlds among the next decade's priority targets (National Academies of Sciences & Medicine, 2023). These missions and the study of moons will play a critical role in advancing our understanding of planetary systems and the potential for life beyond Earth.

One mechanism that plays an important role on the evolution and the current state

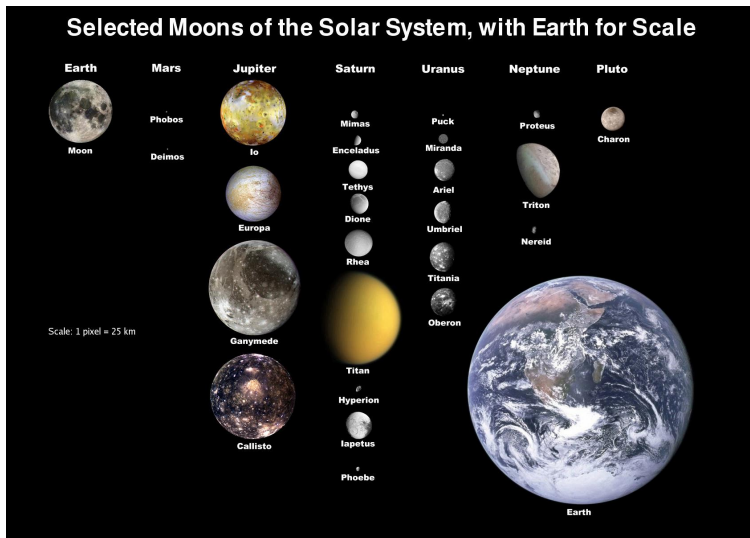


Figure 1.1: The moons of the Solar System show great diversity, in terms of size and composition. The Earth is presented for scale. Image courtesy of NASA

of surface and internal features in satellites is tidal dissipation, caused by tidal forces. A body's response to tidal forces is influenced by various factors, including its orbital parameters. For non-zero eccentricity orbits, tidal forces become stronger when the body is closest to its primary. This causes changes in the tidal bulge throughout the orbit, which generates internal friction and, subsequently, contributes to heating the interior. Tides can significantly influence the formation and maintenance of subsurface oceans, which are crucial for astrobiology, in the interior of moons. In addition, tides drive the extreme temperatures of Io (Segatz et al., 1988), and cryovolcanic plumes, like in the case of Enceladus (Terrile & Cook, 1981).

Moving outside of the Solar System, over the past two decades, more than 5,700 exoplanets have been discovered. Given the prevalence of moons in our Solar System, it is reasonable to expect that exoplanets also host natural satellites (exomoons). Beyond their potential astrobiological significance, the discovery and study of exomoons could provide valuable insights into planetary system formation and evolution, architectures, as well as population dynamics. Yet no exomoon detection has been confirmed, despite extensive searches (Teachey, 2024). With the launch of the JWST looking at the cosmos in infrared wavelengths, the natural question would be to see whether hot moons - from tidal heating, similar to Io - can be detected. And if so, what are the conditions that would make such a detection feasible.

In the following sections I introduce the different proposed exomoon detection methods, placing them in the context of exoplanet detection. In addition, I discuss tidal heating, its implications for Solar System moons, and how it affects our hunt to find moons outside of the Solar System.

1.2 Detecting extrasolar worlds

The discovery of two planets around the pulsar PSR1257 + 12 (Wolszczan & Frail, 1992), and the subsequent discovery of 51 Pegasi b, the first exoplanet discovered orbiting a main-sequence star (Mayor & Queloz, 1995) initiated an enormous growth of the inventory of known exoplanets that occurred over the last two decades. A diverse population of over 5,700 exoplanets has been currently identified, many of which bear little resemblance with the planets of our own Solar System. For example, 51 Pegasi b raised many questions in the scientific community, as it has a mass similar to that of Jupiter and an orbital period of just 4.2 days. Later it would turn out that these planets, named hot-Jupiters, are not uncommon. Currently one of the most common known planet type in our Galaxy is foreign to our Solar System; they have a size between that of the Earth and Neptune and are called super-Earths (Cloutier, 2024). On the contrary, Earth-sized planets represent only a small portion of the planets discovered so far. If the right conditions are met and they are distant enough from their star for water to remain in solid form, these planets can resemble the icy moons of our Solar System. These cold, ocean worlds are the topic of Chapter 5 of this thesis.

The field of exoplanets gives us the capability to place our Solar System and the Earth in the broader context of the population of other planetary systems. We are now at a stage where we can characterize exoplanet atmospheres by detecting molecules, like water, and study their atmospheric dynamics and clouds (see e.g. Helling (2019)). Additionally, by combining measurements of planets' mass and radii we can measure their bulk density, investigate their interior structures by modelling different material compositions, and assess their habitability potential. For this thesis, we are now pushing the boundaries of observational techniques in an effort to detect moons orbiting them. In the following section I will give a brief introduction on exoplanet detection methods, to provide the bases of understanding exomoon detection methods, discussed in Section 1.2.2.

1.2.1 Exoplanet detection methods

Indirect methods

Most of currently known exoplanets have been detected via indirect methods of detection. Their presence is inferred through an effect that they have on their stellar host's signal. The most successful of these methods are the transit and radial velocity methods (RV). Other indirect methods include microlensing, where the light of a distant background star is gravitationally influenced by the presence of the detected planet.

The transit method has been the most successful in finding exoplanets. Particularly, the number of detected transiting exoplanets exploded with the Kepler (Borucki et al., 2010), and TESS (Ricker et al., 2015) missions, which performed accurate photometry of a large number of stars and obtain their lightcurves, a measure of brightness over time. The method is based on detecting the dip caused by an orbiting planet in the lightcurve of their host star. The size of the dip gives the planets radius as a fraction of the star's one, and the time between two consequent transits, is a measure of the orbital period. This method is biased for exoplanets with small orbital periods, as close-in exoplanets com-

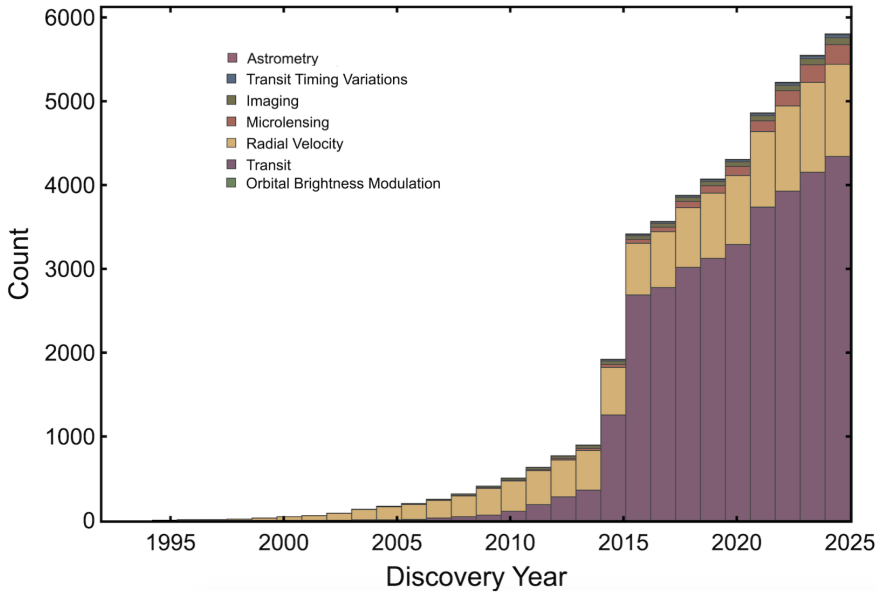


Figure 1.2: Known exoplanets as of March 2025. The graph shows the cumulative distribution of detected exoplanets per year and discovery method. Credit: NASA Exoplanet Archive

plete more transits in a given observation time, but also have higher transit probabilities. An important transiting system is the planet system of Trappist-1, which consists of seven Earth sized planets orbiting an M-dwarf (Gillon et al., 2017). It is the first known system of potentially rocky, terrestrial exoplanets with incident fluxes similar to those of the rocky planets in our Solar System. Three of the Trappist-1 planets lie within the star's habitable zone (HZ), which is the distance from the host star where water can exist in liquid form. As the light from the star passes through the planet's atmosphere during the transit, it gets absorbed at different wavelengths, depending on the atmosphere's chemical composition. When measuring the transit depth at different wavelengths, we can obtain the transmission spectrum of an exoplanet. This method is called transmission spectroscopy and gives the possibility to detect specific chemical compounds in the atmosphere, like H_2O (Tsiaras et al., 2019), and CO_2 (Ahner et al., 2023).

The RV method measures variations in the Doppler shift of the star's spectrum, caused by the presence of an orbiting planet. The method is more sensitive to close-in, massive planets, as the shift in frequency of the spectral features of a planets is larger for more massive planets. The RV method provides us with the lower limit to the planet's mass and its orbital period. When this technique is combined with the transit method, astronomers can measure the bulk density of a planet. Initially the RV method was mostly sensitive to close-in massive planets (like 51 Pegasi b), however modern instruments can detect rocky planets around low mass stars (Suárez Mascareño et al., 2023). Two examples of planets

discovered with the RV method, and discussed in this thesis are ϵ Eridani b (Hatzes et al., 2000) - Chapter 2, ϵ Indi A b (Feng et al., 2018) - Chapter 3.

Another exoplanet detection method is astrometry, where precise measurements of the perturbation of the linear motion of a star, due to the planet's orbit are taken. Astrometry is sensitive to planets with longer orbital periods, as such planets induce larger displacements in their star's position over the course of their orbit. This method has not been as successful as the transit and RV methods in detecting planets, and has resulted in only a handful of detections, as of March 2025. Apart from the high precision requirements that a detection requires, the bias for long period planets necessitates longer observation times (Endl & Cochran, 2007). In addition However, the Gaia mission and its upcoming Data Releases is expected to significantly increase that number (Espinoza-Retamal et al., 2023). Gaia scans the sky taking precise astrometric measurements of stars. Figure 1.2 shows the cumulative distribution of detected exoplanets per year and discovery method as of 2025 for each detection method.

Direct imaging

In contrast to the successful transit and RV methods, 83 exoplanets have been discovered via direct imaging (DI) (see Chauvin, 2024, for an extensive overview). Direct imaging works by suppressing the starlight to reveal the planet's flux. Spatially resolving the planet from the star in this context is challenging, as it requires to tackle the big contrast of the planet with respect to the star, particularly for close-in planets. This is why DI is relatively easier at larger angular separations. Although DI has resulted in relatively few discoveries, the method captures light directly from the planets, rather than merely inferring their presence. This comes with several advantages, as it can allow atmospheric characterization particularly for planets that are far from their stars, where other methods struggle. DI is also sensitive to detecting young exoplanets that are IR-bright and warm from their formation. In addition, unlike the transit method, which requires the orbit of the planet to pass in front of the disk of the star, DI can detect planets regardless of their orbital inclination, which in this context describes the angle between the plane of the orbit relative to the plane of the sky. However, planets on a highly inclined orbits are likely to experience close encounters with the star in the image plane, making detection more challenging. Some directly imaged systems include PDS 70 (two accreting protoplanets), in which a moon-forming disk was directly imaged for the first time (Benisty et al., 2021), and HR 8799 which hosts four wide-orbit giant planets (Marois et al., 2010). Both of these systems can be seen in Figure 1.3. Another notable system is that of YSES-1, which is the first directly imaged planet system around a Sun-like star, with multiple planets (Bohn et al., 2020). In the near future, the combination of adaptive optics and coronagraphs with next-generation large telescopes, such as the ELT, will enable DI and characterization of Earth-like planets (Snellen et al., 2015).

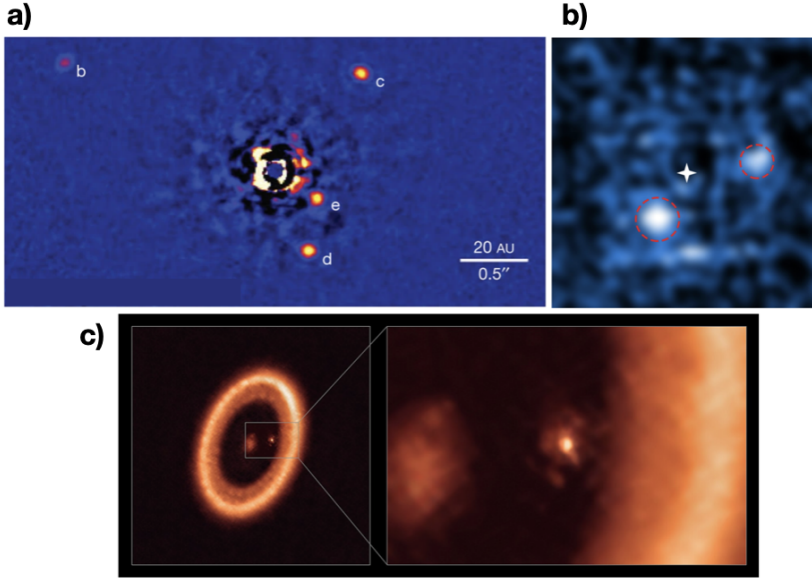


Figure 1.3: Several directly imaged planetary systems. a) The HR 8799 system (Marois et al., 2010) b) The planets PDS 70 b,c (Haffert et al., 2019) c) The circumplanetary disk around PDS 70c (Benisty et al., 2021)

1.2.2 Exomoons and their detection methods

Since every giant planet in the Solar System has a system of moons, it is plausible that exoplanets also host exomoons. While detection methods have become increasingly effective at identifying exoplanets, finding exomoons remains more difficult due to the subtle effects they have on an exoplanet's signal. However, advances in observational astronomy have already identified multiple exomoon candidates (see page 11). A confirmed exomoon detection can be, thus, within reach in the near future (Lazzoni et al., 2022; Teachey, 2024).

Before we dive into the different exomoon detection methods, it would be beneficial to expand on what exactly can be considered as an exomoon. In the case that one of the two orbiting bodies's mass is significantly lower, like in the case of the Galilean satellites, the answer is straightforward. By convention, if the center of mass of the system is outside of the largest body, the system can be considered a binary system. However, when a smaller body orbits an isolated planet or a brown dwarf (BD), the exact terminology remains uncertain. In addition to that, the line between what can be considered a BD or a planet is blurred, especially between the deuterium-burning limit at $\approx 13M_{Jup}$, below which bodies are often characterized as planets (Teachey, 2024), and the hydrogen-burning limit at $\approx 80M_{Jup}$ (Chabrier et al., 2023), the dividing line between stars and BDs. In this thesis

we make use of the term companion and exomoon interchangeably, keeping in mind that the diversity of the worlds can challenge their strict classification.

By studying exoplanets we do not only expand our understanding of distant worlds, but also gain insights into our own. Observations of life on Earth have shown that ecosystems, at the very least, require liquid water, a steady energy source, and a supply of nutrients (Heller et al., 2014). Interestingly, the only bodies in the Solar System that fulfill these habitability requirements apart from the Earth are moons of the gas giant planets. This fact has inspired scientists to move from the conventional planet HZ, to the moon habitability zone, which can significantly increase the potential habitable bodies in the cosmos (Dobos et al., 2017; Heller, 2012). In addition, a moon might play a significant role in making its parent planet inhabited. For example, the Earth's Moon affects tides on Earth, which could have played a role in the development of early life (Benn, 1999).

The explosion of the discovered exoplanets has enabled studies of exoplanet demographics. These indicate that our Solar System might not be very common (Mishra et al., 2023). However, we lack a comparable reference point for moons. Exomoon detections could help shed light into questions such as the prevalence of moons, their properties particularly compared to the Solar System ones, and the rarity of a moon similar to Earth's. In addition, satellites gives us hints on their host planets' formation and dynamical history. For example, the existence and properties of the Galilean moons provide insights on the location of Jupiter's formation and its migration history (Heller et al., 2015). Recently, the existence of an ancient satellite has been proposed to explain the obliquity of Uranus (Saillenfest et al., 2022).

Formation mechanisms

Moon formation is a natural consequence of planet formation (Barr, 2016). Having given several examples of how the existence and properties of moons can affect our interpretation of its host planet formation history, it is now worth exploring the several moon formation theories that have been proposed. The large and regular moons of the gas giants are thought to form in a circumplanetary disk (CPD) of material around the young planet that is accreting gas from the solar nebula, in a similar way that planets form around stars. Satellites formed in this way have orbits that are mostly coplanar with small eccentricity and inclination values. Canup & Ward (2006) suggest that they follow a mass scaling law compared to their hosts of $\approx 10^{-4}$, which is governed by the interplay between the inward delivery of material and the loss of satellites via orbital decay. The latter mass scaling law is in agreement with the mass fractions of the Solar System gas giants' moons.

Another formation scenario, which has been invoked to explain our own Moon is the giant impact scenario (Canup & Asphaug, 2001). Pluto's moon, Charon, is also thought to have formed in this way (Canup, 2010). In the inner Solar System, collisions between planetary embryos frequently occur during the late stages of terrestrial planet formation (Agnor et al., 1999). It is reasonable to assume that terrestrial planets in other systems would also experience similar phenomena. Nakajima et al. (2022) simulated such collisions and found that more massive rocky planets produce a gas-rich disk, which induces drag on moonlets, causing them to return to the planet. This suggests that impacts are more likely to produce fractionally large satellites around less massive rocky exoplanets.

Finally, capture of satellites constitutes a third formation mechanism. The moons formed via this way can be larger than the moons formed in a CPD. Triton, Neptune's largest moon, exhibits orbital characteristics that strongly indicate it was captured (McKinnon et al., 1995). Its retrograde orbit is tilted approximately 157° relative to Neptune's equator, which is indicative of formation via capture. Such an event may have disrupted the original moons of Neptune, assuming one existed prior to the current (Ruffy & Canup, 2017).

We will now expand on the different exomoon detection methods that have been proposed, highlighting their respective strengths and limitations in the context of exomoon discovery.

Exomoon detection methods and candidate systems

Searches for extrasolar satellites are providing either constraints on exomoon properties from non-detections, signs of a moon's presence—such as detected volcanic species or gaps in ring systems—or potential candidate systems. A variety of indirect and direct methods have been proposed for exomoon detection. Indirect methods analyze the impact of a moon on a planet's signal. These include centroid shifts (Agol et al., 2015) (Figure 1.4 a) and Doppler monitoring of directly imaged exoplanets resulting from gravitational interactions between the planet and its companion (Vanderburg et al., 2018). Additional detection techniques involve the dynamical sculpting of circumplanetary disks (Kenworthy & Mamajek, 2015). In this thesis, I explain each method with respect to the corresponding exoplanet detection method to make a clear distinction between the possible ways that an exomoon can be found depending on the exoplanet characterization method, and place the following chapters into context. To aid the explanation, Figure 1.5 presents the exoplanet population found as of March 2025, depending on their orbital period and mass. Some Solar System planets, together with exoplanets discussed in this thesis are also shown.

Exomoon detection around transiting exoplanets

Transiting exoplanets make up the majority of detected exoplanets. There is, thus, a variety of methods proposed to detect satellites around them. The first one was proposed by Sartoretti & Schneider (1999), who show that detecting an exomoon transit in the lightcurve of a transiting exoplanet is possible with an observation time equal to the planet's orbital period, provided that the satellite is large enough (Figure 1.4 b). They suggested that even if the satellite transit is itself not detectable, as an additional dip in the star's lightcurve, the presence of a moon can be inferred by the shift of the planet's transit timing (Transit Timing Variation - TTV (Simon et al., 2007)), caused by the motion of the planet around the planet-moon barycenter. With the launch of the Kepler Space Telescope and the subsequent explosion of detected transiting systems, interest in studying exomoons around transiting planets grew significantly. Kipping (2008, 2009) showed that not only the timing of the planet's transit (Transit Duration Variations - TDVs), but also its duration is affected by the presence of an exomoon. The combination of TTVs and TDVs can give the mass and semi-major axis of a putative satellite. A number of papers

followed investigating the properties of TTVs/TDVs as a detection method for exomoons (see e.g. Kipping (2020), Heller et al. (2016)a), as well as the first systematic program to search for the satellites of extrasolar planets, namely the Hunt for Exomoons with Kepler (HEK). HEK conducted a photodynamical modeling analysis of approximately 60 planets to search for exomoon signatures (Kipping et al., 2012). However, it was in HEK VI (Teachey et al., 2017) that the authors examined 284 planets to investigate the Orbital Sampling Effect (OSE). OSE appears as a characteristic reduction in flux at the edges of a planetary transit when analyzing a time-averaged, phase-folded lightcurve (Heller, 2014),(Heller et al. (2016)b). Given a sufficient number of planet transits, OSE can be used to identify moons as small as Ganymede. HEK VI yielded one exomoon candidate, Kepler-1625b-i, a putative exomoon with size comparable to that of Neptune (Teachey et al., 2017). Kipping et al. (2022) performed a survey around 70 giant transiting exoplanets with Kepler, and identified the candidate Kepler-1708 b-i. The latter is, similarly to Kepler-1625b-i, quite large, ≈ 2.6 Earth radii.

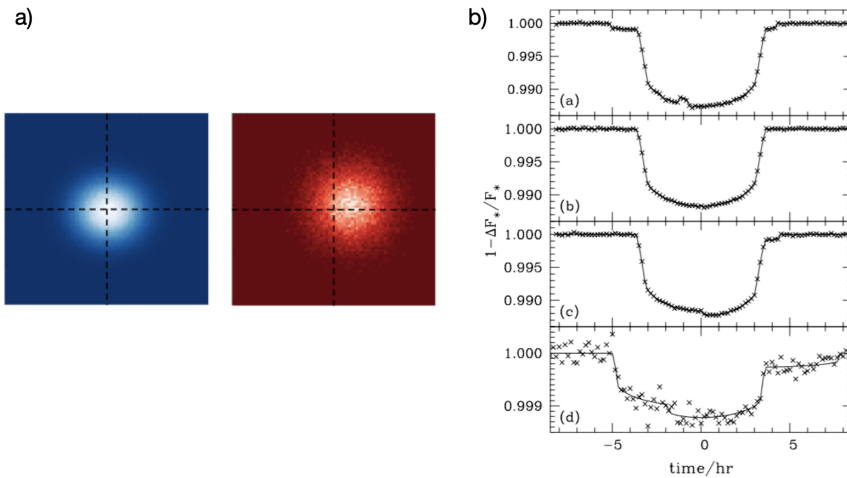


Figure 1.4: Illustrations of two different exomoon detection methods. a) Centroid shifts (Agol et al., 2015): At bluer wavelengths that are dominated by the planet's flux, the centroid aligns with the planet's position. At redder wavelengths that are dominated by a moon, the centroid shifts to the moon's position. b) Exomoon transits (Sartoretti & Schneider, 1999): Several moon transits distinguishable on planet transit lightcurves.

In addition to monochromatic photometric effects, exomoon detection has also been suggested through the spectral analysis of a system. Volcanic material coming from an exomoon similar to Io (exo-Io) can cause detectable signals in the spectrum of a planet (Ben-Jaffel & Ballester, 2014; Gebek & Oza, 2020; Meyer zu Westram et al., 2024). Oza et al. (2019) identified an exomoon candidate around the planet WASP-49b, attributing this to signatures of sodium detected in the planet's transmission spectrum.

Exomoon detection around DI exoplanets

DI has revealed planets at great distances from their host star. This is significant for the hunt of exomoons, as planets further away from their host star are more likely to host moons (Dobos et al., 2021). With DI, the light coming directly from the planet itself can be utilised. This can allow for the direct detection of a companion in wavelengths where the moon is brighter than its host. For example, an Earth-like moon could be brighter than a Jupiter-like planet between 1 and 4 microns, if the latter's atmosphere produces strong methane and water absorption features, suppressing the giant planet's flux in this range (Williams & Knacke, 2004). Direct imaging has given us a candidate that similarly to the two transiting candidates of Teachey et al. (2017) and Kipping et al. (2022) look nothing like the moons of the Solar System. The DI candidate is a 1MJup companion around the low-mass ($10M_{Jup}$) BD DH Tau B (Lazzoni et al., 2020).

Various approaches have been suggested for applying planet detection techniques to the flux of a planet with the goal to reveal exomoons. For instance, radial velocity and astrometry can be utilized (Lazzoni et al., 2022). Additionally, moon transits can be identified through variations in the planet's photometric signal (Cabrera & Schneider, 2007). Although these techniques have not yet yielded promising exomoon candidates, they have helped establish important detection limits. In particular, Vanderburg & Rodriguez (2021) gave the first RV limits of exomoons around HR 8799, which are in the order of Jupiter mass planets. Recently, Ruffio et al. (2023) demonstrated that next-generation high-contrast imaging 30 meter class telescopes combined with spectroscopy will enable the detection of close-in, Solar System-sized moons around nearby brown dwarfs, whereas current-generation telescopes can only identify giant moons, akin to gas giant planets in the Solar System (Vanderburg et al., 2018; Lazzoni et al., 2022; Ruffio et al., 2023; Horstman et al., 2024).

The glare from their host star often obscures directly imaged exoplanets, making exomoon detection difficult with conventional methods. Thus, apart from applying the aforementioned techniques around DI exoplanets or BD around a host, several techniques have been proposed to detect exomoons around isolated planets or BDs (Limbach et al., 2021). Low-period moons can have geometric transit probabilities greater than 10, making their detection more feasible in large-scale surveys. PINES is an ongoing survey aimed at detecting transiting exosatellites around nearly 400 nearby brown dwarfs and free-floating planets (FFPs) (Tamburo et al., 2022a). The survey is capable of identifying exosatellites larger than $2.5 R_{Earth}$ and has detected a $\approx 5 R_{Earth}$ candidate orbiting 2MAS J0835+1953 (Tamburo et al., 2022a,b). In addition, Limbach et al. (2024c) studied 44 archival Spitzer lightcurves, with no significant evidence of satellite transits, sensitive to $0.7 R_{Earth}$ satellites. Limbach et al. (2023) recently introduced the TEMPO survey, a 30-day observation program utilizing the Nancy Grace Roman Space Telescope to search the Orion Nebula Cluster for exomoon transits, with the capability to detect bodies as small as Titan. Finally, Earth-Moon analogs will be detectable for systems within 10 pc with the upcoming HWO (Limbach et al., 2024a).

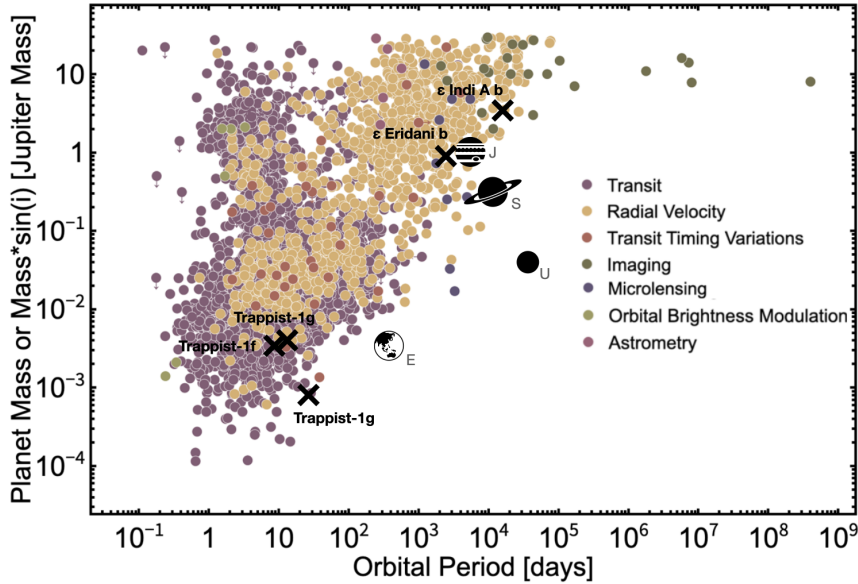


Figure 1.5: A planet mass as a function of orbital period of all the detected exoplanets as of March 2025. Solar System planets are shown on the plot, along with the planets discussed in this thesis. Credit: Adapted from NASA Exoplanet Archive

Exomoon candidates

In this section, I present the exomoon candidates proposed up to 2025, and any controversies surrounding their detection. The candidate systems so far include the following.

1. J1407 b: (Kenworthy & Mamajek, 2015) proposed the presence of putative exomoons from a transit observation of J1407. The transit was linked to a large disk featuring gaps, which were believed to result from the presence of exomoons. Later on it was suggested that J1407 b may not be bound to the star and that it was a free floating system in front of the star (Kenworthy et al., 2020; Mentel et al., 2018).
2. Exomoon candidates found via microlensing, namely MOA-2011-BLG-262 (Bennett et al., 2014), and MOA-2015-BLG-337 (Miyazaki et al., 2018): Detection via microlensing has the disadvantage that observations cannot be repeated. Recently, the MOA-2011-BLG-262 candidate was confirmed to be a low-mass star host with a planet, based on Keck adaptive-optics imaging that directly measured the lens brightness (Terry et al., 2025).
3. Neptune sized moons around transiting gas giants: Kepler-1625 b-i (Teachey & Kipping, 2018) and Kepler-1708 b-i (Kipping et al., 2022) have generated controversy in the literature, with the putative moon signals were found to be fitting (Heller & Hippke, 2024) of data reduction artifacts (Kreidberg et al., 2019). In addition, the

unexpected nature of the candidates themselves has been questioned, particularly regarding their possible formation mechanism (Heller, 2018).

4. WASP-49 b: Sodium absorption observed for the Hot Jupiter WASP-49b was attributed by Oza et al. (2019) to a torus of material that may exist around the host planet. The candidate around WASP-49b remains to be confirmed, as an independent exomoon detection method is needed apart from the indirect method of identifying gases in absorption during the planet's transit. In addition, exomoons around low-period planets are less likely to have stable orbits (Dobos et al., 2021).
5. 2MASS J11193254–1137466 AB: Limbach et al. (2021) claim the detection of a $1.7 R_{Earth}$ moon transit around an isolated planetary mass object. The data exhibit significant variability with amplitudes similar to those of the suspected transit, and follow-up observations are needed to confirm the presence of the putative moon.
6. W1935: Faherty et al. (2024) detected methane CH_4 in the emission of an isolated BD. The authors claim that this could be associated with a temperature inversion in the upper atmosphere, which can potentially be caused by auroras, linked to nearby moons.

Having discussed the disadvantages that exomoon detection around transiting exoplanets may face, we can shift our interest towards targeting DI exoplanets or IPMOs, given their potential for exomoon detection. Direct imaging of heated exomoons presents challenges, as it requires suppressing the star's light while also accounting for the combined flux from both the moon and its host planet. However, tidally heated exomoons (THEMs) (Limbach & Turner, 2013) can outshine their host planet in certain infrared bands due to tidal interactions between the exomoon and the planet. Unlike other methods such as transits, direct detection through thermal spectral energy distribution (SED) does not depend on a specific satellite orbital phase or require multiple observations. This approach provides a detection window for exomoons orbiting gas giant planets at distances of several tens of astronomical units from their parent star. In this thesis, I discuss possible ways to detect THEMs around DI exoplanets or IPMOs. Firstly, I give an introduction on tidal heating, and its implications for the moons of the Solar System.

1.3 Tides

On Earth we experience the effect of tides; the coastline's level changes as a result of the Moon's gravity. Ocean tides have shaped traditions in different cultures, drive one of the world's most biodiverse environments, and can even be used for power generation. But what is causing this phenomenon? As the Moon orbits around the Earth it exerts a tidal force on the entire planet. This force varies across the Earth; it is strongest on the side facing the Moon and weakest on the opposite side. This variation creates a deformation, or a "tidal bulge", on opposite sides of the Earth's surface, resulting in high- and low-tides. It also has an effect on the rocky part of the Earth. Such "Terrestrial tides" can cause, for example, volcanic eruptions.

The same phenomenon does not only occur on Earth. It has big implications in other bodies of the Solar System, in exoplanetary systems, and might be an important factor for the emergence of life in other worlds. In the Solar System tidal forces affect the orbits, interior, and surface properties of various bodies, producing different effects on each. Tidal forces are responsible for the geologic activity of Io, the most volcanically active body in the Solar System (Peale et al., 1979). They drive volcanic eruptions, and plumes of material that contribute to the resurfacing that gives Io a young surface (Geissler et al., 2004). The volcanoes of Io are an active field of research and have been mapped and extensively studied (see e.g. de Kleer & de Pater (2016); Bartolić et al. (2022); Davies et al. (2015)). Figure 1.6 a, d both show images of Io's surface, in visible and IR wavelengths, where the excess heat from the volcanoes are clearly distinguishable.

A surprisingly young surface with cracks and ridges (Figure 1.6c) was also discovered at the Jovian moon Europa, when Voyager encountered it (Smith et al., 1979). It was later proposed that a similar mechanism to Io contributes to the geological activity, and that it can prevent the solidification of a subsurface ocean (Cassen et al., 1979). In 2012, the Hubble Space Telescope captured images providing evidence of plumes erupting from the surface of Europa (Saur et al., 2011; Roth et al., 2014). It is now thought that the supposed plumes originate from either water pockets in the ice or from the water ocean. Similarly, Saturn's moon Enceladus is believed to have a subsurface liquid water ocean, maintained by tidal forces, which drive the water vapor geysers erupting from its surface (Figure 1.6b) (Spencer et al., 2018).

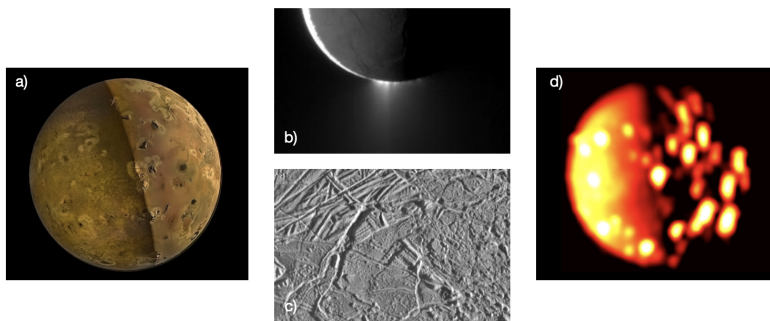


Figure 1.6: Diversity of tidally active moons. a) Image of Io where distinct volcanoes and lava lakes are distinguishable b) Enceladus' plume. Image taken by Cassini Credit: NASA/JPL/Space Science Institute c) Ridges on Europa. Image taken by solid state imaging television camera aboard the Galileo mission Credit: NASA/JPL/University of Arizona Credit: NASA/JPL-Caltech/SwRI/MSSS d) Infrared image of Io's southern hemisphere from data collected by the JIRAM instrument aboard Juno Credit: NASA/JPL-Caltech/SwRI/ASI/INAF/JIRAM

1.3.1 Tides and tidal heating: Basic concepts

Crucially for this thesis, tidal forces can generate heat within the interior of a body. The response of a body to tidal forces depends, among others, on its orbit. When the orbit is elliptical the tidal forces are stronger near periapsis. This results in the tidal bulge to vary over the course of the orbit, as can be seen in Figure 1.7, which in turn generates internal friction heating the interior. The amount of heat that is generated in the interior of a secondary body orbiting a primary depends, among other parameters, on the orbital eccentricity and the semi-major axis of the secondary. In addition to eccentricity driven tides, obliquity tides that arise from the angle between the body's rotational axis and its orbit, can also contribute to tidal dissipation.

The extent of tidal deformation of a body due to tides is parametrized by the Love number k_2 (Love, 1911), which measures amplitude of the tidal response. A higher Love number indicates a more deformable interior. Love numbers are typically complex, except in the case of a perfectly elastic body, where the tidal response is instantaneous. On the other hand, when a body is viscous, the tidal response lags behind the tidal force by a phase angle. This lag, caused by internal energy dissipation, is reflected in the phase of the complex Love numbers (Renaud & Henning, 2018). Together with the tidal quality factor Q , which reflects how dissipative the body is, the ratio $\frac{k_2}{Q}$ is a key parameter in models of tidal heating and orbital evolution (see e.g. Dobos & Turner (2015); Renaud & Henning (2018); Rovira-Navarro et al. (2021))).

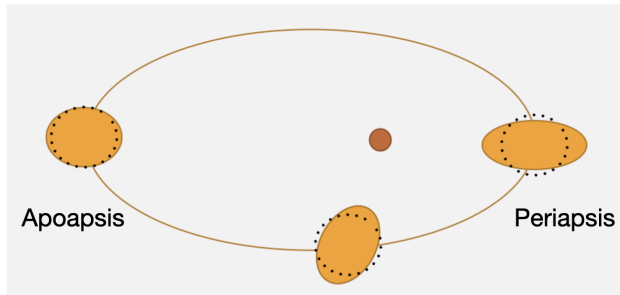


Figure 1.7: Illustration of the tidal bulge evolution throughout an eccentric orbit in a planet-central reference frame. The planet is depicted in brown while the moon in yellow. The tidal bulge is exaggerated for clarity.

In a two body system, as the secondary body interacts gravitationally with the primary body, its interior is heated, with the energy coming from its own orbital and rotational energy. The latter leads to tidal circularization in a two-body system, where an initially elliptical orbit gradually becomes circular. The tidal bulge raised on the secondary by the primary drive this circularisation process, as it is misaligned with the line connecting the two bodies, creating torques that remove energy from the orbit, and thus, leading to eccentricity damping (Peale, 1999). Over time, tidal interactions also slow down the rotation of the secondary body until the latter becomes tidally locked. Tidal locking occurs when the secondary's rotational period matches its orbital period. The tides raised on

the planet by the satellite can cause orbital migration, which plays a fundamental role in the long-term dynamical evolution of satellite systems. In the case that planet's tidal bulge is ahead the satellite, angular momentum is transferred from the planet's spin to the satellite's orbit, causing the satellite to migrate outward. If the bulge lags behind, the orbit decays inward (Goldreich & Soter, 1966).

In more complex systems gravitational forces from additional bodies can perturb the orbit. Instead of the eccentricity decreasing, orbital circularization is prevented, allowing tidal heating to persist over long timescales. This is what happens, for example, in the case of the Galilean moons of Jupiter. In particular, the moons continuously influence each other through periodic gravitational interactions, distorting their orbits. Ganymede, Europa, and Io are in a 1:2:4 Mean Motion Resonance (MMR); for every four orbits of Io around Jupiter, Europa and Ganymede complete two and one, respectively. This resonance causes the moons to gravitationally perturb each other at regular intervals, maintaining increased orbital eccentricities. It is thus a major factor in sustaining Io's extreme volcanic activity. In addition by preventing Europa's orbit to fully circularize it contributes to the maintenance of its subsurface ocean (Cassen et al., 1979). MMRs have also been observed in several exoplanetary systems, like the Trappist-1 system (Teyssandier et al., 2022). In the context of exomoon detections such resonances do not only contribute in sustaining extreme temperatures, but may also imply the existence of additional, unseen moons, in the case that the observed one is tidally heated.

Under the assumption of zero obliquity, which is a reasonable assumption for Io and other regular satellites (Baland et al., 2012), the tidal heat that is generated in the interior of a satellite follows Equation 1.1 (Segatz et al., 1988; Makarov & Efroimsky, 2014):

$$\dot{E} = -\frac{21}{2} \text{Im}(k_2) \frac{(nR)^5}{G} e^2, \quad (1.1)$$

where n is the mean motion, e the orbital eccentricity, R the radius of the satellite, and G the universal gravitational constant. $\text{Im}(k_2)$ is the imaginary part of the k_2 Love number and is a parameter that describes the deformation of the gravitational field of a body in response to tides. $\text{Im}(k_2)$ depends on the interior structure, its material the orbital period of the satellite (Segatz et al., 1988).

One common approach for modeling tidal dissipation is with the so-called fixed Q model, which is broadly used in tidal calculations, and assumes that $\text{Im}(k_2) = \frac{k_2}{Q}$, and that is constant with respect to the orbital frequency and the thermal state of a satellite (Renaud & Henning, 2018; Henning et al., 2009). In the latter expression Q is the tidal quality factor (Kaula, 1964), and measures the fraction of orbital energy lost to dissipation per orbit as a result of internal friction. The fixed- Q model highly underestimates the tidal heat of the body (see e.g. Ross & Schubert (1989)), and does not take into account Q 's dependency on the satellite's orbital period. In addition, it has been shown that material properties of the interior strongly depend on its temperature (Moore, 2003; Fischer & Spohn, 1990). Unlike the fixed Q model, viscoelastic models incorporate the temperature dependence of the body, taking into account the thermal state of a planet and its response to tidal forces. This allows for a more realistic representation of how the planet's interior responds to tides.

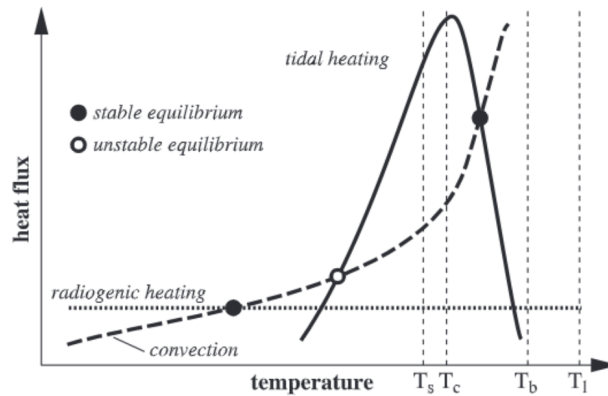


Figure 1.8: Interior heat as a function of mantle temperature. Dashed line: Radiogenic heat Continuous line: Generated tidal heat. Reference: Moore (2003)

The most simple viscoelastic model is the Maxwell model. Because $\text{Im}(k_2)$ is a function of the interior's material properties, namely the rigidity (μ), density (ρ), and viscosity (η), as a result, the generated tidal heat flux also depends on the temperature. As illustrated in Figure 1.8 tidal heat flux (continuous line) reaches its peak at a critical temperature (T_c). Between the solidus (T_s) and liquidus (T_l) temperatures, the material undergoes partial melting. Tidal dissipation increases when the tidal period is near the Maxwell time ($\frac{\eta}{\mu}$). When the forcing period is shorter than the Maxwell time, the body behaves elastically, whereas when the forcing period is greater, the body responds as a viscous fluid. The dashed curve represents the body's convective heat loss. Equilibrium points are marked by circles; for instance, the solid circle between T_c and T_l indicates a stable equilibrium point. If the temperature rises, convective cooling surpasses the tidal heat flux, leading to a temperature decrease. Conversely, if the temperature drops, the tidal heat flux dominates, causing the temperature to rise back to equilibrium.

1.3.2 Probing planetary interiors

Because tidal response depends on the material properties of a body, a connection can be made between the tidal response and the interior structure. For example, the exact interior structure and heat transfer mechanism that takes place in the interior of Io is still unknown; whether Io harbors a shallow, global magma ocean has remained an open question since the discovery of its volcanism. For decades, scientists had speculated that Io's intense tidal heating could be powerful enough to melt a significant portion of its interior, potentially creating a global subsurface magma ocean. Moore (2001) proposed that Io's tidal heat is transported by the advection of melt, for melt fractions of less than 20 percent. There are two end-case scenarios for Io's interior: a partially molten, mostly solid interior, and an interior with a global magma ocean. Measuring Io's tidal response can help shed light into this question. If Io possesses a shallow global magma ocean, its tidal deformation would be larger than in a scenario with a solid, rigid interior, as the decoupling of the liquid layer

leads to an enhanced tidal response. Efforts to determine $\text{Im}(k_2)$ for Io using astrometric observations (Lainey et al., 2009) have constrained its value to 0.015 ± 0.003 . Recently Park et al. (2025) by combining the most recent Juno and previous Galileo Doppler data, constrained Io's k_2 , and proposed that a shallow global magma ocean does not exist, and that their results are consistent with Io having a mostly solid mantle.

Similarly, a connection can be made between an exoplanet's tidal response and its interior properties. There has been several papers investigating theoretically the effect of tidal heating on exoplanet systems using a multilayer approach (Barr et al., 2018; Shoji & Kurita, 2014). Henning et al. (2009) gave an extensive overview of the effect of different rheology models and interior properties for exoplanets and their implications on their tidal heating rates. In addition, the effect of tidal heating is expected to be tremendous on exoplanet habitability (Dobos et al., 2019). These studies have paved the way for the detection of exoplanet volcanism, driven by tidal heating (Peterson et al., 2023).

Direct detection of tidally heated exomoons (THEMs), driven by tidal interactions in eccentric, short-period orbits, has been proposed as a method for identifying these bodies (Limbach & Turner, 2013). This process requires the presence of tidal heating within the moon's interior. Most studies examining the direct detection of THEMs have assumed a uniform temperature distribution across the moon's surface to estimate the temperatures achievable through tidal interactions using a multilayer approach (Dobos & Turner, 2015; Rovira-Navarro et al., 2021). Jäger & Szabó (2021) argue that a THEM's temperature distribution is likely to be uneven, with hotspots similar to those seen on Io. They suggested that this uneven temperature distribution could enhance the direct detectability of THEMs.

1.4 This thesis

The work done during this PhD research, aims to investigate the effect of tidal heating in the observability of extra-solar satellites around exoplanets. More particularly, this thesis focuses on the effects of tidal heating on the detectability of exomoons around directly imaged and radial velocity exoplanets, IPMOs or BDs. The main goal is to identify the physical and/or orbital parameters that would make THEMs detectable with different methods and existing or future instruments. In parallel, we also investigate how well the physical properties of potentially detected exomoons might be characterized according to observational and theoretical constraints. The second part of this thesis uses interior models used in the characterization of Solar System moons, to assess potential interior structures of the likely icy planets of the system Trappist-1. We model the tidal heat produced in their interior and identify the thickness and depth of any potential subsurface oceans. We also conclude on the detectability of cryovolcanism in the system.

Chapter 2: Tidally Heated Exomoons around ϵ Eridani b: Observability and prospects for characterization

We begin with Chapter 2, where we explore the possibility of detecting THEMs in IR wavelengths with JWST. We study as an archetype the system ϵ Eridani b, a nearby system with a distance of 3.2 parsec (see also Figure 1.2). We firstly, model exomoons of

different size for a range of orbital parameters, and conclude on the ones that would make them detectable. To do so, we modelled a radially symmetric, spherical body in which heat moves through magma advection in a partially molten layer and convection in the deeper mantle. We used a combined thermal and tidal model to identify stable equilibrium states where tidal heating balances internal heat transport within a moon. To evaluate detectability with MIRI, we accounted for uncertainties in both the interior composition and tidal dissipation parameters, analyzing the proportion of simulated moons that would exhibit observable signatures. We find that for comparable semi-major axes and eccentricities with the satellites of the Solar System gas giants, Mars-sized exomoons or larger would be detectable.

Chapter 3: The spectroastrometric detectability of nearby Solar System-like exomoons

We continue with Chapter 3, which explores the detectability of THEMs around exoplanets with the method of spectroastrometry. Spectroastrometry uses the spectral variation of the center of light as a result of an exomoons orbit. We derive an analytic expression for the signal, and apply this on the detection of THEMs around exoplanets. We determine the temperatures of THEMs that can be detected with the upcoming ELT, using ϵ Indi Ab as an archetype. We find that the ELT will be able to detect exomoons comparable in size to the Solar System moons of moderate temperatures. In addition, Mars-sized icy moons can be detected in nearby systems with the method of spectroastrometry. Thus, with this method we are sensitive to much colder exomoons with temperatures that are closer to those of Solar System satellites.

Chapter 4: Direct detectability of tidally heated exomoons by photometric orbital modulation

In Chapter 4 we model the effect of hotspots, like the ones observed on Io, on the detectability of THEMs, deviating from the assumption of a uniformly distributed surface temperature, that was taken in the two previous chapters. We introduce the method of photometric orbital modulation for the detection of THEMs. As a moon orbits its host, inhomogeneously distributed volcanic features or hotspots cause a photometric variability on the signal of a planet-moon system. The periodicity of this signal introduces a distinct feature in the frequency domain of the system's time-variable flux. In this Chapter, we investigate the properties of THEMs that would make them observable with JWST around IMPOs. For Mars-sized exomoons, this applies to system distances of up to 10 pc, while Earth-sized exomoons can be detected at even greater distances. Io-sized exomoons may be detectable in extremely close systems, and when hotspot temperatures are on the higher end of the spectrum of the assumed temperatures. Notably, this approach is applicable to non-transiting orbital inclinations, and thus, expands the range of detectable exomoons around IPMOs.

Chapter 5: Modeling the interiors of Trappist-1f, g, h: Tidal Heating, Subsurface Oceans, and Cryovolcanic Activity

We finish the scientific part of this thesis with Chapter 5, where we expand our research on extrasolar volcanism, focusing this time on potentially icy exoplanets. In this Chapter

we investigate the internal heating of Trappist-1f,g, and h, and its effect on the thermal state of their interior. We use models previously used to describe the thermal structure and heat generation on Solar System icy moons, and draw conclusions on the equilibrium thermal states of the planets. We find that if the Trappist-1f and h planets have a subsurface water ocean underneath, they likely possess a thin ice shell, with thicknesses between ≈ 4 and 10 km. We also explore whether the internal heat generation is sufficient to drive detectable cryovolcanic activity. We do so for a configuration where the outgassing is evenly distributed over the surface, and one where geyser-like plumes are concentrated at one pole of the planet. The most optimistic volcanic configurations would require a JWST campaign lasting over a decade. We suggest that the community focus on exploring other planets to observe cryovolcanic activity.

I conclude this introduction with an outlook on the future of exomoon detection. Although no exomoon detection has been confirmed yet, the field of exoplanet research has advanced rapidly over the past decades. Cycle 3 of JWST has included proposals aimed at detecting exomoons; one around a long-period Kepler planet (Cassese et al., 2024), and an Earth-Moon analogue (Pass et al., 2024). With the next generation of telescopes and improved modeling techniques, we may soon achieve exomoon detections. However, it may take some time until the field of exomoons becomes as fruitful in discoveries and as routine as exoplanet detections are today. The path of discovery is hard to predict, and the diversity of worlds that may be revealed in the future might surprise us, and exceed our expectations, if past discoveries are any indication. In any case, detecting and characterizing exomoons will have a profound impact, as we will gain new insights of planetary systems and the potential for life beyond Earth.

Bibliography

- Agnor, C. B., Canup, R. M., & Levison, H. F. 1999, *Icarus*, 142, 219, doi: [10.1006/icar.1999.6201](https://doi.org/10.1006/icar.1999.6201)
- Agol, E., Jansen, T., Lacy, B., Robinson, T. D., & Meadows, V. 2015, *The Astrophysical Journal*, 812, 5, doi: [10.1088/0004-637X/812/1/5](https://doi.org/10.1088/0004-637X/812/1/5)
- Ahrer, E.-M., Alderson, L., Batalha, N. M., et al. 2023, *Nature*, 614, 649, doi: [10.1038/s41586-022-05269-w](https://doi.org/10.1038/s41586-022-05269-w)
- Baland, R.-M., Yseboodt, M., & van Hoolst, T. 2012, *Icarus*, 220, 435, doi: [10.1016/j.icarus.2012.05.020](https://doi.org/10.1016/j.icarus.2012.05.020)
- Barr, A. C. 2016, *Astronomical Review*, 12, 24, doi: [10.1080/21672857.2017.1279469](https://doi.org/10.1080/21672857.2017.1279469)
- Barr, A. C., Dobos, V., & Kiss, L. L. 2018, *AA*, 613, A37, doi: [10.1051/0004-6361/201731992](https://doi.org/10.1051/0004-6361/201731992)
- Bartolić, F., Luger, R., Foreman-Mackey, D., Howell, R. R., & Rathbun, J. A. 2022, *The Planetary Science Journal*, 3, 67, doi: [10.3847/PSJ/ac2a3e](https://doi.org/10.3847/PSJ/ac2a3e)
- Ben-Jaffel, L., & Ballester, G. E. 2014, *The Astrophysical Journal Letters*, 785, L30, doi: [10.1088/2041-8205/785/2/L30](https://doi.org/10.1088/2041-8205/785/2/L30)
- Benisty, M., Bae, J., Facchini, S., et al. 2021, *The Astrophysical Journal Letters*, 916, L2, doi: [10.3847/2041-8213/ac0f83](https://doi.org/10.3847/2041-8213/ac0f83)
- Benn, C. R. 1999, *Earth, Moon, and Planets*, 85, 61, doi: [10.1023/A:1017082925182](https://doi.org/10.1023/A:1017082925182)
- Bennett, D. P., Batista, V., Bond, I. A., et al. 2014, *The Astrophysical Journal*, 785, 155, doi: [10.1088/0004-637X/785/2/155](https://doi.org/10.1088/0004-637X/785/2/155)
- Bohn, A. J., Kenworthy, M. A., Ginski, C., et al. 2020, *The Astrophysical Journal Letters*, 898, L16, doi: [10.3847/2041-8213/aba27e](https://doi.org/10.3847/2041-8213/aba27e)
- Borucki, W. J., Koch, D., Basri, G., et al. 2010, *Science*, 327, 977, doi: [10.1126/science.1185402](https://doi.org/10.1126/science.1185402)
- Cabrera, J., & Schneider, J. 2007, in *Astronomical Society of the Pacific Conference Series*, Vol. 366, *Transiting Extrapolar Planets Workshop*, ed. C. Afonso, D. Weldrake, & T. Henning, 242
- Canup, R. M. 2010, *The Astronomical Journal*, 141, 35, doi: [10.1088/0004-6256/141/2/35](https://doi.org/10.1088/0004-6256/141/2/35)
- Canup, R. M., & Asphaug, E. 2001, *Nature*, 412, 708, doi: [10.1038/35089010](https://doi.org/10.1038/35089010)
- Canup, R. M., & Ward, W. R. 2006, *Nature*, 441, 834, doi: [10.1038/nature04860](https://doi.org/10.1038/nature04860)
- Cassen, P., Reynolds, R. T., & Peale, S. J. 1979, *Geophysical Research Letters*, 6, 731, doi: <https://doi.org/10.1029/GL006i009p00731>
- Cassese, B., Batygin, K., Chachan, Y., et al. 2024, *Revealing the Oblateness and Satellite System of an Extrasolar Jupiter Analog, JWST Proposal. Cycle 3, ID. #6491*
- Cassidy, T. A., Mendez, R., Arras, P., Johnson, R. E., & Skrutskie, M. F. 2009, *The Astrophysical Journal*, 704, 1341, doi: [10.1088/0004-637X/704/2/1341](https://doi.org/10.1088/0004-637X/704/2/1341)
- Chabrier, G., Baraffe, I., Phillips, M., & Debras, F. 2023, *AA*, 671, A119, doi: [10.1051/0004-6361/202243832](https://doi.org/10.1051/0004-6361/202243832)
- Chauvin, G. 2024, *Comptes Rendus. Physique*, 24, 129–150, doi: [10.5802/crphys.139](https://doi.org/10.5802/crphys.139)
- Cloutier, R. 2024, *Exoplanet Demographics: Physical and Orbital Properties*. <https://arxiv.org/abs/2409.13062>
- Davies, A. G., Veeder, G. J., Matson, D. L., & Johnson, T. V. 2015, *Icarus*, 262, 67, doi: <https://doi.org/10.1016/j.icarus.2015.08.003>
- de Kleer, K., & de Pater, I. 2016, *Icarus*, 280, 378, doi: <https://doi.org/10.1016/j.icarus.2016.06.019>
- Dobos, V., Barr, A. C., & Kiss, L. L. 2019, *AA*, 624, A2, doi: [10.1051/0004-6361/201834254](https://doi.org/10.1051/0004-6361/201834254)
- Dobos, V., Charnoz, S., Pál, A., Roque-Bernard, A., & Szabó, G. M. 2021, *Publications of the Astronomical Society of the Pacific*, 133, 094401, doi: [10.1088/1538-3873/abfe04](https://doi.org/10.1088/1538-3873/abfe04)

- Dobos, V., Heller, R., & Turner, E. L. 2017, *AA*, 601, A91, doi: [10.1051/0004-6361/201730541](https://doi.org/10.1051/0004-6361/201730541)
- Dobos, V., & Turner, E. L. 2015, *The Astrophysical Journal*, 804, 41, doi: [10.1088/0004-637x/804/1/41](https://doi.org/10.1088/0004-637x/804/1/41)
- Dougherty, M. K., Khurana, K. K., Neubauer, F. M., et al. 2006, *Science*, 311, 1406, doi: [10.1126/science.1120985](https://doi.org/10.1126/science.1120985)
- Endl, M., & Cochran, W. D. 2007, in *Encyclopedia of the Solar System (Second Edition)*, second edition edn., ed. L.-A. McFadden, P. R. Weissman, & T. V. Johnson (San Diego: Academic Press), 887–902, doi: <https://doi.org/10.1016/B978-012088589-3/50051-7>
- Espinoza-Retamal, J. I., Zhu, W., & Petrovich, C. 2023, *The Astronomical Journal*, 166, 231, doi: [10.3847/1538-3881/ad00b9](https://doi.org/10.3847/1538-3881/ad00b9)
- Faherty, J. K., Burningham, B., Gagné, J., et al. 2024, *Nature*, 628, 511, doi: [10.1038/s41586-024-07190-w](https://doi.org/10.1038/s41586-024-07190-w)
- Feng, F., Tuomi, M., & Jones, H. R. A. 2018, Detection of the closest Jovian exoplanet in the Epsilon Indi triple system. <https://arxiv.org/abs/1803.08163>
- Fischer, H.-J., & Spohn, T. 1990, *Icarus*, 83, 39, doi: [https://doi.org/10.1016/0019-1035\(90\)90005-T](https://doi.org/10.1016/0019-1035(90)90005-T)
- Fox, C., & Wiegert, P. 2020, *Monthly Notices of the Royal Astronomical Society*, 501, 2378, doi: [10.1093/mnras/staa3743](https://doi.org/10.1093/mnras/staa3743)
- Gebek, A., & Oza, A. V. 2020, *Monthly Notices of the Royal Astronomical Society*, 497, 5271, doi: [10.1093/mnras/staa2193](https://doi.org/10.1093/mnras/staa2193)
- Geissler, P., McEwen, A., Phillips, C., Keszthelyi, L., & Spencer, J. 2004, *Icarus*, 169, 29, doi: <https://doi.org/10.1016/j.icarus.2003.09.024>
- Gillon, M., Triaud, A. H. M. J., Demory, B.-O., et al. 2017, *Nature*, 542, 456, doi: [10.1038/nature21360](https://doi.org/10.1038/nature21360)
- Goldreich, P., & Soter, S. 1966, *Icarus*, 5, 375, doi: [https://doi.org/10.1016/0019-1035\(66\)90051-0](https://doi.org/10.1016/0019-1035(66)90051-0)
- Haffert, S. Y., Bohn, A. J., de Boer, J., et al. 2019, *Nature Astronomy*, 3, 749–754, doi: [10.1038/s41550-019-0780-5](https://doi.org/10.1038/s41550-019-0780-5)
- Hatzes, A. P., Cochran, W. D., McArthur, B., et al. 2000, *The Astrophysical Journal*, 544, L145, doi: [10.1086/317319](https://doi.org/10.1086/317319)
- Heller, R. 2012, *AA*, 545, L8, doi: [10.1051/0004-6361/201220003](https://doi.org/10.1051/0004-6361/201220003)
- Heller, R. 2014, *ApJ*, 787, 14, doi: [10.1088/0004-637X/787/1/14](https://doi.org/10.1088/0004-637X/787/1/14)
- Heller, R. 2018, *AA*, 610, A39, doi: [10.1051/0004-6361/201731760](https://doi.org/10.1051/0004-6361/201731760)
- Heller, R., & Hippke, M. 2024, *Nature Astronomy*, 8, 193, doi: [10.1038/s41550-023-02148-w](https://doi.org/10.1038/s41550-023-02148-w)
- Heller, R., Hippke, M., & Jackson, B. 2016, *ApJ*, 820, 88, doi: [10.3847/0004-637X/820/2/88](https://doi.org/10.3847/0004-637X/820/2/88)
- Heller, R., Hippke, M., Placek, B., Angerhausen, D., & Agol, E. 2016, *AA*, 591, A67, doi: [10.1051/0004-6361/201628573](https://doi.org/10.1051/0004-6361/201628573)
- Heller, R., Marleau, G.-D., & Pudritz, R. E. 2015, *AA*, 579, L4, doi: [10.1051/0004-6361/201526348](https://doi.org/10.1051/0004-6361/201526348)
- Heller, R., Williams, D., Kipping, D., et al. 2014, *Astrobiology*, 14, 798–835, doi: [10.1089/ast.2014.1147](https://doi.org/10.1089/ast.2014.1147)
- Helling, C. 2019, *Annual Review of Earth and Planetary Sciences*, 47, 583, doi: <https://doi.org/10.1146/annurev-earth-053018-060401>
- Henning, W. G., O’Connell, R. J., & Sasselo, D. D. 2009, *The Astrophysical Journal*, 707, 1000–1015, doi: [10.1088/0004-637x/707/2/1000](https://doi.org/10.1088/0004-637x/707/2/1000)
- Horstman, K., Ruffio, J.-B., Batygin, K., et al. 2024, RV measurements of directly imaged brown dwarf GQ Lup B to search for exo-satellites. <https://arxiv.org/abs/2408.10299>
- Jäger, Zoltán, J., & Szabó, G. M. 2021, *Monthly Notices of the Royal Astronomical Society*, 508, 5524, doi: [10.1093/mnras/stab2955](https://doi.org/10.1093/mnras/stab2955)

- Kaula, W. M. 1964, *Reviews of Geophysics*, 2, 661, doi: <https://doi.org/10.1029/RG002i004p00661>
- Kenworthy, M. A., & Mamajek, E. E. 2015, *The Astrophysical Journal*, 800, 126, doi: [10.1088/0004-637x/800/2/126](https://doi.org/10.1088/0004-637x/800/2/126)
- Kenworthy, M. A., Klaassen, P. D., Min, M., et al. 2020, *Astronomy & Astrophysics*, 633, A115, doi: [10.1051/0004-6361/201936141](https://doi.org/10.1051/0004-6361/201936141)
- Khurana, K. K., Kivelson, M. G., Stevenson, D. J., et al. 1998, *Nature*, 395, 777, doi: [10.1038/27394](https://doi.org/10.1038/27394)
- Kipping, D. 2020, *Monthly Notices of the Royal Astronomical Society*, 500, 1851–1857, doi: [10.1093/mnras/staa3398](https://doi.org/10.1093/mnras/staa3398)
- Kipping, D., Bryson, S., Burke, C., et al. 2022, *Nature Astronomy*, 6, 367, doi: [10.1038/s41550-021-01539-1](https://doi.org/10.1038/s41550-021-01539-1)
- Kipping, D. M. 2008, *Monthly Notices of the Royal Astronomical Society*, 392, 181, doi: [10.1111/j.1365-2966.2008.13999.x](https://doi.org/10.1111/j.1365-2966.2008.13999.x)
- . 2009, *Monthly Notices of the Royal Astronomical Society*, 396, 1797, doi: [10.1111/j.1365-2966.2009.14869.x](https://doi.org/10.1111/j.1365-2966.2009.14869.x)
- Kipping, D. M., Bakos, G., Buchhave, L., Nesvorný, D., & Schmitt, A. 2012, *The Astrophysical Journal*, 750, 115, doi: [10.1088/0004-637x/750/2/115](https://doi.org/10.1088/0004-637x/750/2/115)
- Kreidberg, L., Luger, R., & Bedell, M. 2019, *The Astrophysical Journal Letters*, 877, L15, doi: [10.3847/2041-8213/ab20c8](https://doi.org/10.3847/2041-8213/ab20c8)
- Lainey, V., Arlot, J.-E., Karatekin, O., & Van Hoolst, T. 2009, *Nature*, 459, 957–959, doi: [10.1038/nature08108](https://doi.org/10.1038/nature08108)
- Lazzoni, C., Desidera, S., Gratton, R., et al. 2022, *Monthly Notices of the Royal Astronomical Society*, 516, 391, doi: [10.1093/mnras/stac2081](https://doi.org/10.1093/mnras/stac2081)
- Lazzoni, C., Zurlo, A., Desidera, S., et al. 2020, *AA*, 641, A131, doi: [10.1051/0004-6361/201937290](https://doi.org/10.1051/0004-6361/201937290)
- Limbach, M. A., Lustig-Yaeger, J., Vanderburg, A., et al. 2024a, *Exomoons Exorings with the Habitable Worlds Observatory I: On the Detection of Earth-Moon Analog Shadows Eclipses*. <https://arxiv.org/abs/2405.02408>
- . 2024b, *Exomoons Exorings with the Habitable Worlds Observatory I: On the Detection of Earth-Moon Analog Shadows Eclipses*. <https://arxiv.org/abs/2405.02408>
- Limbach, M. A., & Turner, E. L. 2013, *The Astrophysical Journal*, 769, 98, doi: [10.1088/0004-637X/769/2/98](https://doi.org/10.1088/0004-637X/769/2/98)
- Limbach, M. A., Vos, J. M., Vanderburg, A., & Dai, F. 2024c, *The Astronomical Journal*, 168, 54, doi: [10.3847/1538-3881/ad4ed5](https://doi.org/10.3847/1538-3881/ad4ed5)
- . 2024d, *Occurrence Rates of Exosatellites Orbiting 3-30M_{Jup} Hosts from 44 Spitzer Light Curves*. <https://arxiv.org/abs/2405.08116>
- Limbach, M. A., Vos, J. M., Winn, J. N., et al. 2021, *The Astrophysical Journal Letters*, 918, L25, doi: [10.3847/2041-8213/ac1e2d](https://doi.org/10.3847/2041-8213/ac1e2d)
- Limbach, M. A., Soares-Furtado, M., Vanderburg, A., et al. 2023, *Publications of the Astronomical Society of the Pacific*, 135, 014401, doi: [10.1088/1538-3873/acafa4](https://doi.org/10.1088/1538-3873/acafa4)
- Love, A. E. H. 1911, *Some Problems of Geodynamics* (Cambridge University Press)
- Makarov, V. V., & Efroimsky, M. 2014, *The Astrophysical Journal*, 795, 7, doi: [10.1088/0004-637X/795/1/7](https://doi.org/10.1088/0004-637X/795/1/7)
- Marois, C., Zuckerman, B., Konopacky, Q. M., Macintosh, B., & Barman, T. 2010, *Nature*, 468, 1080, doi: [10.1038/nature09684](https://doi.org/10.1038/nature09684)
- Martins, Z., Bunce, E. J., Grasset, O., et al. 2025, in *Proceedings of the VIII Iberian Congress on Planetary Sciences and Solar System Exploration*, 35
- Mayor, M., & Queloz, D. 1995, *Nature*, 378, 355, doi: [10.1038/378355a0](https://doi.org/10.1038/378355a0)

- McKinnon, W. B. 2015, *Geophysical Research Letters*, 42, 2137, doi: <https://doi.org/10.1002/2015GL063384>
- McKinnon, W. B., Lunine, J. I., & Banfield, D. 1995, in *Neptune and Triton*, ed. D. P. Cruikshank, M. S. Matthews, & A. M. Schumann, 807–877
- Mentel, R. T., Kenworthy, M. A., Cameron, D. A., et al. 2018, *AA*, 619, A157, doi: [10.1051/0004-6361/201834004](https://doi.org/10.1051/0004-6361/201834004)
- Meyer zu Westram, M., Oza, A. V., & Galli, A. 2024, *Journal of Geophysical Research: Planets*, 129, e2023JE007935, doi: <https://doi.org/10.1029/2023JE007935>
- Mishra, L., Alibert, Y., Udry, S., & Mordasini, C. 2023, *AA*, 670, A68, doi: [10.1051/0004-6361/202243751](https://doi.org/10.1051/0004-6361/202243751)
- Miyazaki, S., Sumi, T., Bennett, D. P., et al. 2018, *AJ*, 156, 136, doi: [10.3847/1538-3881/aad5ee](https://doi.org/10.3847/1538-3881/aad5ee)
- Moore, W. B. 2001, *Icarus*, 154, 548, doi: <https://doi.org/10.1006/icar.2001.6739>
- . 2003, *Journal of Geophysical Research: Planets*, 108, doi: <https://doi.org/10.1029/2002JE001943>
- Morabito, L. A. 2012, *Discovery of Volcanic Activity on Io. A Historical Review*. <https://arxiv.org/abs/1211.2554>
- Nakajima, M., Genda, H., Asphaug, E., & Ida, S. 2022, *Nature Communications*, 13, 568, doi: [10.1038/s41467-022-28063-8](https://doi.org/10.1038/s41467-022-28063-8)
- NASA Planetary Data System. 2025, *Planetary Fact Sheet*, NASA Goddard Space Flight Center. Accessed 2025-04-04. <https://nssdc.gsfc.nasa.gov/planetary/factsheet/>
- National Academies of Sciences, E., & Medicine. 2023, *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032* (Washington, DC: The National Academies Press), doi: [10.17226/26522](https://doi.org/10.17226/26522)
- Nogueira, P. H., Lazzoni, C., Zurlo, A., et al. 2024, *Astrometric and photometric characterization of η Tel B combining two decades of observations*. <https://arxiv.org/abs/2405.04723>
- Oza, A. V., Johnson, R. E., Lellouch, E., et al. 2019, *The Astrophysical Journal*, 885, 168, doi: [10.3847/1538-4357/ab40cc](https://doi.org/10.3847/1538-4357/ab40cc)
- Park, R. S., Jacobson, R. A., & Gomez Casajus, L. e. a. 2025, *Nature*, 638, 69, doi: [10.1038/s41586-024-08442-5](https://doi.org/10.1038/s41586-024-08442-5)
- Pass, E., Bean, J. L., Charbonneau, D., Cherubim, C., & Garcia-Mejia, J. 2024, *A Search for Exoplanet Satellites that are the Same Size as the Earth's Moon*, JWST Proposal. Cycle 3, ID. #6193
- Peale, S. J. 1999, *Annual Review of Astronomy and Astrophysics*, 37, 533, doi: [10.1146/annurev.astro.37.1.533](https://doi.org/10.1146/annurev.astro.37.1.533)
- Peale, S. J., Cassen, P., & Reynolds, R. T. 1979, *Science*, 203, 892, doi: [10.1126/science.203.4383.892](https://doi.org/10.1126/science.203.4383.892)
- Peterson, M. S., Benneke, B., Collins, K., et al. 2023, *Nature*, 617, 701, doi: [10.1038/s41586-023-05934-8](https://doi.org/10.1038/s41586-023-05934-8)
- Renaud, J. P., & Henning, W. G. 2018, *The Astrophysical Journal*, 857, 98, doi: [10.3847/1538-4357/aab784](https://doi.org/10.3847/1538-4357/aab784)
- Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, *Journal of Astronomical Telescopes, Instruments, and Systems*, 1, 014003, doi: [10.1117/1.JATIS.1.1.014003](https://doi.org/10.1117/1.JATIS.1.1.014003)
- Roccetti, G., Grassi, T., Ercolano, B., et al. 2023, *International Journal of Astrobiology*, 22, 317–346, doi: [10.1017/S1473550423000046](https://doi.org/10.1017/S1473550423000046)
- Ross, M., & Schubert, G. 1989, *Icarus*, 78, 90, doi: [https://doi.org/10.1016/0019-1035\(89\)90071-7](https://doi.org/10.1016/0019-1035(89)90071-7)
- Roth, L., Saur, J., Retherford, K. D., et al. 2014, *Science*, 343, 171, doi: [10.1126/science.1247051](https://doi.org/10.1126/science.1247051)

- Rovira-Navarro, M., van der Wal, W., Steinke, T., & Dirkx, D. 2021, 2, 119, doi: 10.3847/psj/abf6cb
- Ruffio, J.-B., Horstman, K., Mawet, D., et al. 2023, *The Astronomical Journal*, 165, 113, doi: 10.3847/1538-3881/acb34a
- Rufu, R., & Canup, R. M. 2017, *The Astronomical Journal*, 154, 208, doi: 10.3847/1538-3881/aa9184
- Saillenfest, M., Rogoszinski, Z., Lari, G., et al. 2022, *AA*, 668, A108, doi: 10.1051/0004-6361/202243953
- Sartoretti, P., & Schneider, J. 1999, *A&AS*, 134, 553, doi: 10.1051/aas:1999148
- Saur, J., Feldman, P. D., Roth, L., et al. 2011, *The Astrophysical Journal*, 738, 153, doi: 10.1088/0004-637X/738/2/153
- Segatz, M., Spohn, T., Ross, M. N., & Schubert, G. 1988, *Icarus*, 75, 187, doi: 10.1016/0019-1035(88)90001-2
- Shoji, D., & Kurita, K. 2014, *ApJ*, 789, 3, doi: 10.1088/0004-637X/789/1/3
- Simon, A., Szatmáry, K., & Szabó, G. M. 2007, *AA*, 470, 727, doi: 10.1051/0004-6361:20066560
- Smith, B. A., Soderblom, L. A., Johnson, T. V., et al. 1979, *Science*, 204, 951, doi: 10.1126/science.204.4396.951
- Snellen, I., de Kok, R., Birkby, J. L., et al. 2015, *A&A*, 576, A59, doi: 10.1051/0004-6361/201425018
- Soderlund, K. M., Rovira-Navarro, M., Le Bars, M., Schmidt, B. E., & Gerkema, T. 2024, *Annual Review of Marine Science*, 16, 25, doi: <https://doi.org/10.1146/annurev-marine-040323-101355>
- Spencer, J. R., Nimmo, F., Ingersoll, A. P., et al. 2018, in *Enceladus and the Icy Moons of Saturn*, ed. P. M. Schenk, R. N. Clark, C. J. A. Howett, A. J. Verbiscer, & J. H. Waite (University of Arizona Press), 163, doi: 10.2458/azu_uapress_9780816537075-ch008
- Suárez Mascareño, A., González-Álvarez, E., Zapatero Osorio, M. R., et al. 2023, *A&A*, 670, A5, doi: 10.1051/0004-6361/202244991
- Tamburo, P., Muirhead, P. S., McCarthy, A. M., et al. 2022a, *The Astronomical Journal*, 163, 253, doi: 10.3847/1538-3881/ac64aa
- . 2022b, *The Astronomical Journal*, 164, 252, doi: 10.3847/1538-3881/ac9a52
- Teachey, A. 2024, *Detecting and Characterizing Exomoons and Exorings (Handbook of Exoplanets, 2nd Edition)*. <https://arxiv.org/abs/2401.13293>
- Teachey, A., & Kipping, D. M. 2018, *Science Advances*, 4, eaav1784, doi: 10.1126/sciadv.aav1784
- Teachey, A., Kipping, D. M., & Schmitt, A. R. 2017, *The Astronomical Journal*, 155, 36, doi: 10.3847/1538-3881/aa93f2
- Terrile, R. J., & Cook, A. F. 1981, in *Lunar and Planetary Science XII, Supplement A. Satellites of Saturn. Abstracts Presented at a Session of the Twelfth Lunar and Planetary Conference, Vol. LPI Contribution 428 (3303 Nasa Road 1, Houston, TX 77058: Lunar and Planetary Institute)*, 10
- Terry, S. K., Beaulieu, J.-P., Bennett, D. P., et al. 2025, *The Astronomical Journal*, 169, 131, doi: 10.3847/1538-3881/ad9b0f
- Teyssandier, Libert, A.-S., & Agol, E. 2022, *A&A*, 658, A170, doi: 10.1051/0004-6361/202142377
- Tobie, G., Mocquet, A., & Sotin, C. 2005, *Icarus*, 177, 534, doi: <https://doi.org/10.1016/j.icarus.2005.04.006>
- Tsiaras, A., Waldmann, I. P., Tinetti, G., Tennyson, J., & Yurchenko, S. N. 2019, *Nature Astronomy*, 3, 1086, doi: 10.1038/s41550-019-0878-9

- Van Hoolst, T., Tobie, G., Vallat, C., et al. 2024, *Space Science Reviews*, 220, 54, doi: [10.1007/s11214-024-01085-y](https://doi.org/10.1007/s11214-024-01085-y)
- Vanderburg, A., Rappaport, S. A., & Mayo, A. W. 2018, *The Astronomical Journal*, 156, 184, doi: [10.3847/1538-3881/aae0fc](https://doi.org/10.3847/1538-3881/aae0fc)
- Vanderburg, A., Rappaport, S. A., & Mayo, A. W. 2018, *AJ*, 156, 184, doi: [10.3847/1538-3881/aae0fc](https://doi.org/10.3847/1538-3881/aae0fc)
- Vanderburg, A., & Rodriguez, J. E. 2021, *The Astrophysical Journal Letters*, 922, L2, doi: [10.3847/2041-8213/ac33b4](https://doi.org/10.3847/2041-8213/ac33b4)
- Williams, D., & Knacke, R. 2004, *Astrobiology*, 4, 400, doi: [10.1089/ast.2004.4.400](https://doi.org/10.1089/ast.2004.4.400)
- Wolszczan, A., & Frail, D. A. 1992, *Nature*, 355, 145, doi: [10.1038/355145a0](https://doi.org/10.1038/355145a0)
- Yahalomi, D. A., Kipping, D., Agol, E., & Nesvorný, D. 2024, *The Exoplanet Edge: Planets Don't Induce Observable TTVs Faster than Half their Orbital Period*. <https://arxiv.org/abs/2411.09752>

2 | Tidally Heated Exomoons around ϵ Eridani b: Observability and prospects for characterization

Adapted from

E. Kleisioti, D. Dirkx, M. Rovira-Navarro, and M. A. Kenworthy

Astronomy & Astrophysics, 675, A57 (2023)

Context. Exomoons are expected to orbit gas giant exoplanets just as moons orbit Solar System planets. Tidal heating is present in Solar System satellites, and it can heat up their interior, depending on their orbital and interior properties.

Aims. We aim to identify a tidally heated exomoon's (THEM) orbital parameter space that would make it observable in infrared wavelengths with MIRI/JWST around ϵ Eridani b. We study the possible constraints on orbital eccentricity and interior properties that a successful THEM detection in infrared wavelengths can bring. We also investigate what exomoon properties need to be independently known in order to place these constraints.

Methods. We used a coupled thermal-tidal model to find stable equilibrium points between the tidally produced heat and the heat transported within a moon. For the latter, we considered a spherical and radially symmetric satellite with heat being transported via magma advection in a sublayer of melt (asthenosphere) and convection in the lower mantle. We incorporated uncertainties in the interior and tidal model parameters to assess the fraction of simulated moons that would be observable with MIRI.

Results. We find that a $2R_{Io}$ THEM orbiting ϵ Eridani b with an eccentricity of 0.02 would need to have a semi-major axis of 4 planetary Roche radii for 100% of the simulations to produce an observable moon. These values are comparable with the orbital properties of the satellites of the Solar System gas giants. We placed similar constraints for eccentricities up to 0.1. We conclude that if the semi-major axis and radius of the moon are known (e.g., with exomoon transits), tidal dissipation can constrain the orbital eccentricity and interior properties of the satellite, such as the presence of melt and the thickness of the melt-containing sublayer.

2.1 Introduction

Since all giant planets in the Solar System host moon systems, it is plausible that exomoons orbit exoplanets as well. Even though detection techniques have shown tremendous success in identifying over 5000 exoplanets, exomoon detection is more challenging because the deviation on the exoplanet's signal caused by their presence is relatively small. However, progress in observational astronomy has made the detection of exomoons a possibility for the near future (Lazzoni et al., 2022; Teachey & Kipping, 2018; Heller, 2017; Heller et al., 2016).

Several indirect and direct methods have been proposed for the detection of exomoons. Indirect detection methods study the effect that a moon has on a planet's signal. These methods include Transit Timing Variations (TTV; Kipping, 2009; Simon, A. et al., 2007; Sartoretti & Schneider, 1999), Transit Duration Variations (TDV; Kipping, 2009), and other photometric effects on the stellar signal (Heller, 2014), centroid shifts (Agol et al., 2015), and Doppler monitoring of directly imaged exoplanets (Ruffio et al., 2023; Vanderburg et al., 2018) caused by the gravitational interaction between the planet and its companion. Other methods for exomoon detection include dynamical sculpting of the circumplanetary disk (Kenworthy & Mamajek, 2015) and the detection of planet-satellite mutual eclipses (Cabrera, J. & Schneider, J., 2007).

Though there have been several tentative detections (see e.g., Kipping et al. (2022); Oza et al. (2019); Teachey & Kipping (2018); Kenworthy & Mamajek (2015)) and despite the numerous known exoplanets and the surveys searching for companions around them (Kipping et al., 2022, 2012), no exomoon detection has been confirmed yet. Apart from being due to their small signal, this may also be due to the biases of detection methods to detect exoplanets closer to their host star, meaning that any potential satellite would be stripped off during the planet's migration (see e.g., Dobos et al. (2021); Trani et al. (2020)).

Direct imaging, which is sensitive to young exoplanets further out from their host star, could offer an observational window to far out systems. Only recently, Benisty et al. (2021) directly imaged the thermal emission from a circumplanetary disk at sub-millimeter wavelengths in the PDS 70 system, a strong prerequisite for exomoon formation. Direct imaging of tidally heated exomoons (THEMs) is challenging because, except for the need to suppress the star's light, the final signal contains both the flux from the moon and the planet. However, THEMs (Limbach & Turner, 2013) can be brighter than their host planet's signal in some infrared bands, due to tidal interactions between the exomoon and the host planet. A direct detection via thermal spectral energy distribution (SED), in contrast to other proposed methods such as transits, does not rely on a specific satellite orbital phase nor require multiple observations. This method offers a detection window for exomoons around gas giant planets at distances of several tens of astronomical units from the parent star. The method can also directly measure the flux emitted from the surface, which under the assumption of thermal equilibrium can be equal to the tidal heat flux produced in the interior. Even though the mass of the satellite is not measurable via this method, the advantage of constraining the tidally generated flux can offer possibilities for characterization because the latter depends on the interior structure and orbital properties of the moon.

Tidal models with a broad range of complexity have been used to model Solar System bodies and moons (Rovira-Navarro et al., 2022; Steinke et al., 2020; Bierson & Nimmo, 2016; Castillo-Rogez et al., 2011; Hussmann & Spohn, 2004; Fischer & Spohn, 1990; Reynolds et al., 1987) and have already been applied to exoplanets (Barr et al., 2018; Shoji & Kurita, 2014; Henning et al., 2009). For the first time, Dobos & Turner (2015) modeled THEMs while taking into account viscoelasticity, a characteristic that describes the tidal response of the material making up the interior of planetary bodies. Rovira-Navarro et al. (2021) used a coupled thermal-orbital evolution model and compared the effect that different rheological models have on THEM surface temperatures while studying their longevity. Finally, Jäger & Szabó (2021) took into account the presence of a hotspot on the surface of homogeneous THEMs without melt and modeled the increased radiation in thermal wavelengths to infer detectability.

In this work, we study the effect of tidal heating on the direct imaging observations of exo-Ios. We define an exo-Io as an exomoon with the same density and interior structure as the moon Io, that is, with a thin, melt-containing asthenosphere beneath the lithosphere (Moore, 2001). We use models developed to describe Io's tidal heat flux (Rovira-Navarro et al., 2021; Moore, 2003) and apply them to THEMs with the assumption of thermal equilibrium. We use ϵ Eridani b as a test case for a potential host planet. The exoplanet ϵ Eridani b is a close-by gas giant with a distance of 3.2 parsec (MacGregor et al., 2015) and a minimum mass of 0.65 - 0.78 M_J (Rosenthal et al., 2021; Llop-Sayson et al., 2021; Mawet et al., 2019), making it a plausible host to relatively large satellites (Canup & Ward, 2006). In Section 2.2, we explain the tidal-thermal model and the interior structure used in this work as well as the algorithm that solves for the surface temperature of moons in thermal equilibrium. In Section 2.3, we describe how we define an observable moon around ϵ Eridani b. In Section 2.4, we present the orbital-interior configurations that would lead a THEM around ϵ Eridani b to be detectable with MIRI under the assumptions of our model. We then extend this analysis through a sensitivity analysis of the various free parameters of our interior model, which allows us to quantify the interior constraints a detection may provide. Finally, in Section 2.5, we discuss possible ways to validate our analysis; factors that could affect the interpretation of our results, such as the presence of moon atmospheres and different moon sizes; and exomoon constraints that our method can yield in combination with other exomoon detection methods.

2.2 Models

To evaluate a THEM's detectability and infer its surface heat flux, we used an interior model that describes the moon's layers and heat transfer mechanisms and a tidal model that calculates the tidal dissipation given the interior structure and orbital parameters. A schematic overview of how these two models interact is given in Figure 2.1.

We modeled THEMs using models initially developed to describe Io's interior, which have been shown to be compatible with Io heat flux observations (Spencer et al., 2000; Veeder et al., 1994). In our model, we assumed a metallic core, a solid silicate mantle, and a partially molten sublayer of melt beneath a stiff lithosphere. The moons are assumed to be spherically symmetric, and the properties of each layer are uniform. We assumed that

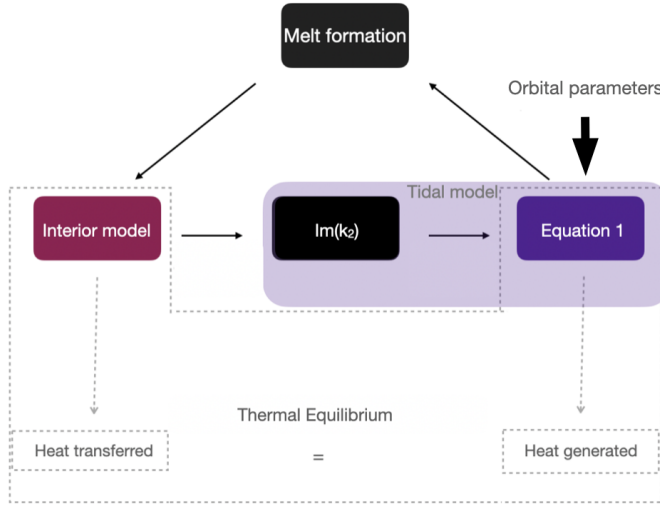


Figure 2.1: Feedback between the heat transfer and the tidal models. The interior structure affects the $Im(k_2)$ value, which the tidal dissipation depends on. High tidal dissipation can cause the formation of melt, leading to a new sublayer (new interior structure; see the black arrows in the upper part of the plot). Thermodynamic equilibrium is reached when the moon’s interior transfers the same amount of heat as what is generated via tidal interactions (see the grey arrows in the lower part of the plot).

tidal heat is generated in the deep mantle and asthenosphere (viscoelastic layers) and that the lithosphere behaves elastically. Our model implementation was adapted from Rovira-Navarro et al. (2021). In the following subsections, we introduce both the interior and tidal models we used.

2.2.1 Interior model

We assumed that different heat transfer mechanisms are present in the interior layers of the exo-Ios (see Figure 2.2). The heat that is generated through tidal friction in the viscoelastic layers (mantle, asthenosphere) is ultimately emitted via radiation from the surface. We assumed that the heat is transported via convection in the lower mantle and via conduction in the stiffer lithosphere, compatible with bodies in a stagnant lid regime (e.g., Reese et al. (1999); Schubert et al. (1979)).

For high tidal heating rates, the interior temperature rises and a partially molten sublayer, the asthenosphere, forms beneath the moon’s lithosphere. As introduced by Moore (2001), we modeled the heat transport in the asthenosphere with melt segregation. This model successfully describes Io’s current state. If no melt segregation is assumed, convection alone cannot explain the observed heat flux of Io when assuming thermal equilibrium (Moore, 2003). As such, the exo-Ios discussed in our work are modeled with the same

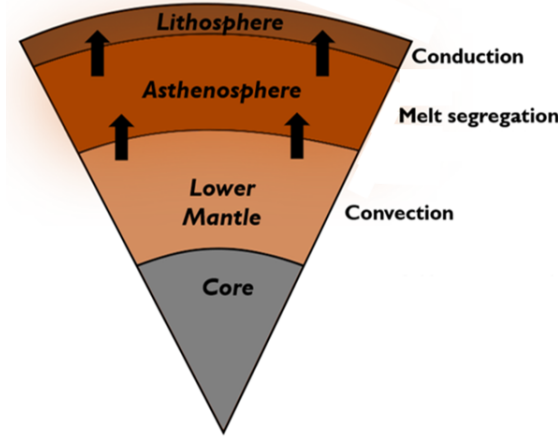


Figure 2.2: Interior layers and the corresponding heat transfer mechanisms assumed in our model.

mechanism.

Overall, the parameters of our interior model are shown in Figure 2.3. We assumed a core of radius R_c equal to $0.52 \times R$ (Anderson et al., 1996), where R is the moon radius, with density ρ_c ; a mantle with density ρ_m ; a shear modulus μ_m ; solidus viscosity $\eta_{s,m}$; and a temperature T_m . The dependence of the mantle viscosity (η_m) on the temperature was parameterized with the activation energy E_a (Equation 2.1a). The asthenosphere's viscosity (η_α) also depends on the presence of melt through the B parameter, as shown in Equation 2.1b (Mei et al., 2002). Finally, the melt segregation is a function of the permeability exponent n and the scale velocity γ .

$$\eta_m = \eta_{s,m} \exp\left(\frac{E_a}{R_g T_s} \left(\frac{T_s}{T_m} - 1\right)\right), \quad (2.1a)$$

$$\eta_\alpha = \eta_{s,m} \exp\left(\frac{E_a}{R_g T_s} \left(\frac{T_s}{T_m} - 1\right)\right) \exp(-B\phi_\alpha), \quad (2.1b)$$

where R_g is the ideal gas constant, ϕ_α is the melt fraction of the asthenosphere, and T_s is the average of the mantle solidus temperature. The input values used can be found in Table 2.1. Table 2.3 shows the parameters included in our sensitivity analysis (see Section 2.4.2).

The interior model output parameters, which were obtained once thermal equilibrium was reached (also listed in Table 2.2), consist of the asthenosphere thickness (h_α) and the melt fraction needed to transfer $\dot{Q}_s$ heat via melt segregation for a value of T_m . The material properties that make up the moon's interior are temperature dependent. Thus, all the output parameters listed in Table 2.2 and Figure 2.3 are a function of T_m . Rovira-Navarro et al. (2021) explain the interior properties' dependency on the melt fraction and temperature in detail, and they include a detailed description of the heat transfer model

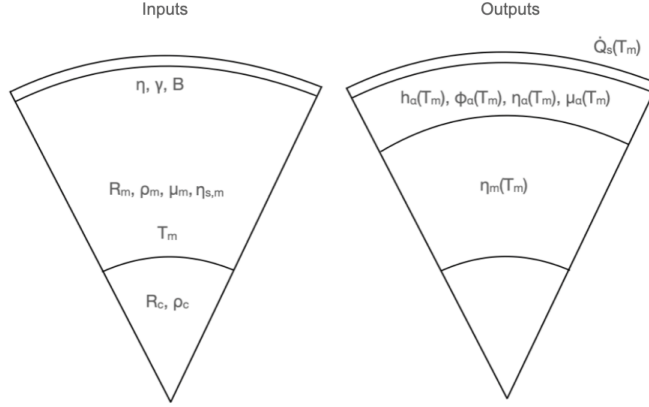


Figure 2.3: Input and output parameters used in the thermal model. Descriptions of these values can be found in Tables 2.1, 2.2 and 2.3.

Table 2.1: Interior parameters – Inputs.

Parameter	Symbol	Value	Units
Core radius	R_c	$0.52 \times R$	
Mantle density	ρ_m	3542	$kg\ m^{-3}$
Core density	ρ_c	5150	$kg\ m^{-3}$
Activation energy	E_a	300	$kJ\ mol^{-1}$

(including convection and conduction). We highlight that when the mantle temperature crosses a threshold, which corresponds to the fraction of melt in the asthenosphere rising above 0.45 (Moore, 2003), the rheology of the mantle is no longer adequately described using viscoelasticity and is more accurately portrayed as a magma ocean, a regime that is not modeled in our work. We only discuss the relevance of a magma ocean regime qualitatively in terms of detectability.

2.2.2 Tidal model

The amount of tidal heat dissipated in the interior of a moon with zero obliquity is given through (e.g., Segatz et al. (1988); Makarov & Efroimsky (2014)):

$$\dot{E} = -\frac{21}{2} \text{Im}(k_2) \frac{(nR)^5}{G} e^2, \quad (2.2)$$

where n is the mean motion, e the orbital eccentricity of the satellite, and G the universal gravitational constant. We assumed synchronous rotating moons and performed simulations for eccentricity values up to 0.1. For larger eccentricities, high-order terms ($O(e^4)$) must be taken into account since Equation 2.2 is accurate until the second eccentricity order (Renaud et al., 2021). We assumed that the moon has zero obliquity, close to Io's

Table 2.2: Interior parameters – Outputs.

Parameter	Symbol
Asthenosphere melt fraction	ϕ_α
Asthenosphere thickness	h_α
Asthenosphere viscosity	η_α
Asthenosphere shear modulus	μ_α
Mantle viscosity	η_m
Mantle temperature	T_m

(Baland et al., 2012), and thus we did not take it into account in the calculation of the total amount of tidal heat generated.

The imaginary part of the k_2 Love number, $\text{Im}(k_2)$ describes the deformation of the moon's gravity field due to the tidal interactions with the planet. It depends on the interior structure, properties, rheology of the moon, and the moon's orbital period (Segatz et al., 1988). Efforts to obtain $\text{Im}(k_2)$ for Io (Lainey et al., 2009) with astrometric observations constrained it at 0.015 ± 0.003 .

Equation 2.2 demonstrates how the tidally generated heat flux of a moon depends on the orbital properties of the satellite. Self-luminous exomoons closer to the host planet and with higher orbital eccentricity would produce higher tidal heat fluxes, which is favorable to their observability.

Different approaches to $\text{Im}(k_2)$ calculation

A simplistic approach to calculate the imaginary k_2 Love number assumes that $\text{Im}(k_2) = \frac{k_2}{Q} = \text{constant}$, where Q (tidal quality factor) quantifies the fraction of the orbital energy that is dissipated per orbit due to friction. This parameter is not well constrained, however rocky bodies are expected to have values from 10 to 500 (Goldreich & Soter, 1966). Such an approach, does not take into account the feedback between the thermal state of a planet and its response to tidal forces. In addition, it does not consider the tidal quality factor's dependency on the orbital period of the satellite (Renaud & Henning, 2018). It has also been found to underestimate tidal heat production (see eg. Meyer & Wisdom (2007); Dobos & Turner (2015)).

Another approach, which has been widely used for Solar System moons (Fischer & Spohn, 1990; Hussmann & Spohn, 2004), is to model tidal dissipation using the viscoelastic theory for self-gravitating bodies (Peltier, 1974; Sabadini R., 2016), where a rheological law is needed to couple stress and strain. This method allows for the incorporation of the material properties' temperature dependence (eg. Karato & Wu (1993)). The most simple viscoelastic model is the Maxwell model. The value of $\text{Im}(k_2)$ is closely related to the Maxwell time ($\frac{\eta}{\mu}$). When the tidal period is close to this value, tidal dissipation reaches its maximum. For periods longer than what corresponds to the Maxwell time, the moon responds as a viscous fluid and for shorter tidal periods, as an elastic body. This approach has also been implemented for the study of exoplanet tidal responses (Shoji & Kurita, 2014; Henning et al., 2009; Barr et al., 2018).

A viscoelastic approach to describe tidal heating in exomoons was used for the first time by Dobos & Turner (2015). They implemented the Maxwell viscoelastic model, which, however, does not accurately describe the laboratory behavior of olivine (Jackson & Faul, 2010) and does not take into account the anelastic transient creep response over timescales shorter than the Maxwell time. The transient creep is described as a regime where the strain rate is a function of time. On the contrary, the (more) advanced Andrade rheological model (Andrade, 1910) adopts this behavior and is more realistic. The Andrade model has been used in studies of Solar System bodies (Castillo-Rogez et al., 2011; Bierson & Nimmo, 2016) and exoplanets (Renaud & Henning, 2018; Walterová & Běhouňková, 2020). Renaud & Henning (2018) found significantly higher tidal heating when assuming Andrade rheology for Io-like moons, thus the incorporation of it – instead of the Maxwell one – has implications on THEM detectability.

Calculation of $\text{Im}(k_2)$

We used the viscoelastic theory for self-gravitating bodies and incorporated the Andrade model to calculate $\text{Im}(k_2)$. The tidal response of the moon can be obtained by solving the equations of motion for the deformation of each layer in the Fourier domain, via the correspondence principle (Peltier, 1974). The latter results in a set of differential equations that describe the deformation of each layer.

To solve the differential equations and obtain the gravitational potential at the surface, we used the propagator matrix technique (Jara-Oru  & Vermeersen, 2011; Sabadini R., 2016) and the Andrade rheological law. For more details on how we solved the propagator matrix technique, see Appendix A of Rovira-Navarro et al. (2021). The viscoelastic response of the material in each layer depends on the shear modulus μ and viscosity η . The Fourier transformed shear modulus $\tilde{\mu}$ is related to the creep function $\tilde{J}$, which for the Andrade law is (Efroimsky, 2012):

$$\tilde{\mu} = \tilde{J}^{-1}, \quad (2.3)$$

$$\tilde{J} = \frac{1}{\mu} - \frac{i}{\eta n} + \frac{\mu^{\alpha-1}}{(i\zeta\eta n)^\alpha} \alpha! \quad (2.4)$$

The transient creep response is modeled in the last term of equation 2.4 and is described by two parameters ζ and α . We assumed that $\zeta = 1$ for the rest of our work. For assumptions on α , see Section 2.4.2.

2.2.3 Thermal equilibrium

The tidal model describes the heat that is generated through tidal interactions, and the heat transfer model simulates how this energy is transferred through the different layers of the interior. The two models are not independent but interact with each other through feedback (Figure 2.1, upper part). An $\text{Im}(k_2)$ value corresponds to a particular interior structure but also affects the amount of tidal dissipation that is produced (Equation 2.2)). For high values of tidal dissipation, the interior temperature increases, and consequently

the interior properties, layers, and melt fraction change. This means that the interior structure is modified, affecting the $\text{Im}(k_2)$.

Therefore, equilibrium is reached once the amount of heat emitted from the moon's surface into space is equal to the amount of heat that is generated (Figure 2.1, lower part). Henning et al. (2009) showed that significantly tidally active planetary bodies achieve thermal equilibrium in a few million years. The overall thermal equilibrium equation that we solve for is:

$$\dot{Q}_{tid} - \dot{Q}_s = 0, \quad (2.5)$$

where $\dot{Q}_s$ is the surface heat flow and $\dot{Q}_{tid}$ is the internal heat production. The value of $\dot{Q}_s$ was computed via the equations for melt segregation presented in Moore (2003) and $\dot{Q}_{tid}$ via Equation 5.5.

In thermal equilibrium, the average surface temperature T_{surf} can be calculated by Stefan-Boltzmann law:

$$T_{surf}^4 = \frac{q_s + \frac{(1-A)S}{4}}{\sigma}, \quad (2.6)$$

where σ is the Stefan-Boltzmann constant, q_s is the equilibrium surface heat flux (where $q_s = \dot{Q}_s/(4\pi R^2)$), A is the moon's bond albedo (assumed equal to Io's), and S is the stellar irradiation. For ϵ Eridani, this corresponds to $0.34 \times L_{Sun}$ (Saumon et al., 1996), where L_{Sun} is the solar luminosity. The second term of Equation 2.6 describes the heat flux that is not reflected by the moon's surface and is thus taken into account in the thermal budget.

Thermal equilibrium points were defined as the intersections of the tidal heat and the transferred heat (i.e., the heat generated and the heat advected to the surface of the moon). These points can be stable or non-stable (Moore, 2003), as shown in Figure 2.4. At a stable equilibrium point, a temperature increase would lead to a higher heat advection rate compared to the heat generation one. The moon, thus, tends to restore its equilibrium. The reversed scenario is described by a $\frac{d\dot{Q}_s}{dT_m} < \frac{d\dot{Q}_{tid}}{dT_m}$. In this case, a slight increase in the interior mantle temperature would drive the moon out of equilibrium since the heat production would exceed the advection capabilities of the moon, warming up the interior (Figure 2.4). High temperatures coming from formation would potentially make the moon approach Figure 2.4 from the right side of the graph. This is a favorable condition for the moon to reach the higher stable equilibrium states first, such as the warmer stable equilibrium point.

In this work, we present results for the stable equilibrium points that correspond to higher temperatures. Scenarios where the moon would reach the lower stable equilibrium point exist (e.g., going out and in a mean motion resonance – see Fuller et al. (2016)); however, studying these cases was beyond the scope of this work, which is mainly focused on assessing whether and for what interior and orbital properties putative THEMs could reach temperatures that allow for observations and under what assumptions we can place constraints on their properties.

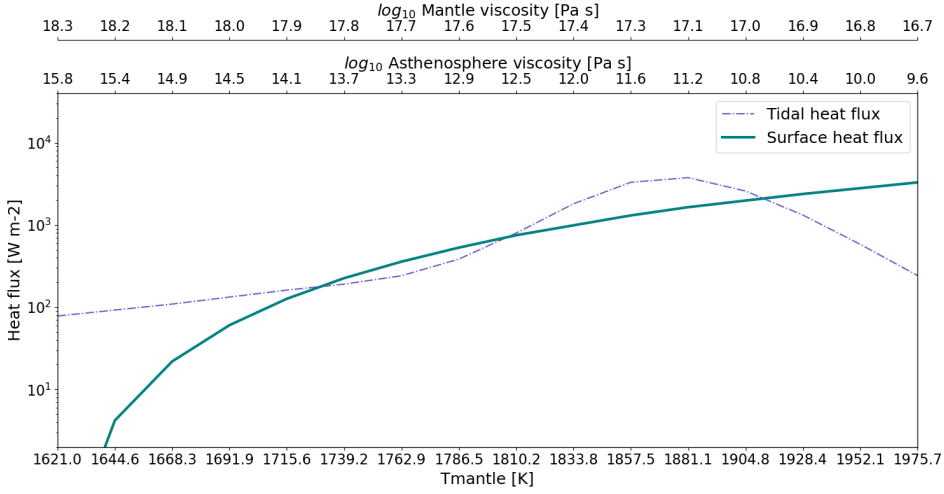


Figure 2.4: Generated tidal heat flux as a function of the mantle temperature (T_m) and the log of the asthenosphere's (η_a) and mantle viscosity (η_m). Stable and non-stable equilibria points are shown as black and gray dots, correspondingly. At a non-stable equilibrium point, a deviation in the mantle temperature drives the moon out of equilibrium, whereas a body at a stable thermal equilibrium state tends to restore its equilibrium. The tidal heat flux was calculated for a moon with a semi-major axis of $a = 6.59$ Roche radii, $e = 0.02$, $\alpha = 0.5$, and $B = 30$ with the rest of the sensitivity parameters set to their nominal values (Table 2.3)

2.3 Observability

In this section, we define what we consider to be an observable moon around ϵ Eridani b. Figure 2.5 shows the expected star, planet, and moon fluxes in this system. The exoplanet ϵ Eridani b was indirectly detected through radial velocity with a mass of $\approx 0.65 M_J$ (Rosenthal et al., 2021; Llop-Sayson et al., 2021). The planet's spectrum was approximated via the models for young gas giants of Spiegel & Burrows (2012), assuming no clouds, 500 Myr age, $1 M_J$, and solar metallicity (ϵ Eridani b: -0.04 dex; Rosenthal et al., 2021). The star's SED is shown as a black body of temperature 5084 K (Kovtyukh, V. V. et al., 2003). In some wavelength regions, the flux of the THEM surpasses that of the planet – for a 270K exomoon, these regions are at 3.6 and 6 microns, and widen significantly at higher exomoon temperatures.

The instrument MIRI is equipped with four coronagraphs: one Lyot and three four-quadrant phase masks (4QPMs; Boccaletti et al., 2022). Of these, the 4QPMs have the smallest achievable inner working angles (IWAs), between 0.33 and 0.49 arcseconds (Boccaletti et al., 2015). For a semi-major axis of 3.5 AU (Llop-Sayson et al., 2021), the planet has a separation of ≈ 1.09 arcseconds from its host star, which is outside of the inner working angle of the 4QPM coronagraphs. Boccaletti et al. (2022) measured the on-sky performance of MIRI's coronagraphs and concluded that post-processing techniques

can bring the final contrast down to the background and detector limited noise floor at separations larger than one arcsecond. Future instruments, like METIS (Brandl et al., 2021), are expected to reach even smaller contrast ratios.

We therefore define a "detectable exomoon" as the coldest exomoon that reaches the 10σ point source detection limit for MIRI in a 10,000 second integration at ϵ Eridani's distance of 3.2 parsecs (MacGregor et al., 2015). The average moon surface temperature in our model is calculated through Equation 2.6 and represents the theoretical total thermal output of the moon, assuming no localized variations due to volcanic activity or hotspots on the surface. Figure 2.5 shows that this limit is reached for an average surface temperature of 270 K for a $2R_{Io}$ exomoon orbiting ϵ Eridani b. Moons of the same size with a higher effective temperature are also considered detectable.

The moon's thermal flux could be constrained from observed excess of heat flux at different wavelengths where the planet is not expected to be bright, for example, at water or methane absorption bands. It is beyond the scope of this work to disentangle the moon's signal from the planet's in specific observational bands. Rather, our goal is to assess the detectability and orbital-interior configurations that can lead to observations. The use of different planetary atmosphere models could also potentially affect the combined planet-moon flux measured. We ignored any effect the latter would have in disentangling the putative detected flux in its planet and moon components.

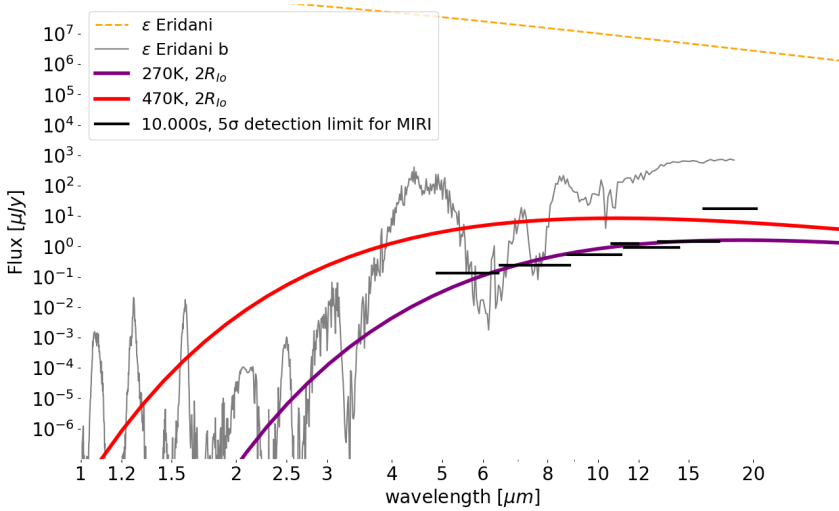


Figure 2.5: Fluxes of hypothetical $2R_{Io}$ moons around ϵ Eridani b. The black lines are the 10σ and 10,000 second detection limits for MIRI (Glasse et al., 2015). The planet model (Spiegel & Burrows, 2012) is shown in gray. The red and purple lines correspond to the black bodies of a 270 and 470 K $2 \times R_{Io}$ exomoon, and the yellow dashed line corresponds to the black body of the star.

2.4 Results

In this section, we explore how interior and orbital parameters could be constrained if the thermal heat flux of a THEM was known. We first explore how this could be known if our model was perfect and all the free parameters were well determined. Thus, the first subsection refers to results obtained assuming the nominal values of Table 2.3. We then take into account modeling parameter uncertainties to explore how constraints can be placed, as shown in Section 2.4.2.

2.4.1 Interior structure dependence on orbital properties

Figure 2.6 shows the resulting surface temperatures using the models from Section 2.2 for a $2R_{Io}$ exo-Io in a stable thermal equilibrium state as a function of the moon's semi-major axis a and orbital eccentricity e . For moons with the same density as Io, this corresponds to $8M_{Io}$. Satellite formation theories indicate an upper limit of $M_{moon}/M_{planet} \approx 10^{-4}$ (Canup & Ward, 2006). According to this limit, exomoons of such mass could be found around $1.1 M_J$ planets or higher. This is compatible with the ϵ Eridani b minimum mass between 0.65 and $1.55 M_J$ (Rosenthal et al., 2021; Hatzes et al., 2000). We focused our analysis on exomoons of the same size because the moon's radius needs to be constrained in order to derive any interior and orbital conclusions with our method. The way to constrain the moon's radius, as well as the implications it has on the interpretation of our results, is further discussed in Sections 2.5.2 and 2.5.3.

Tidal interactions between a host exoplanet and the modeled exomoons could heat their surface temperature up to the order of 600K for the shown ranges of orbital parameters (Figure 2.6). Moons experiencing such an amount of tidal heating would be in a magma ocean regime (see below). The values of a and e that would make a Super-Io reach MIRI's detection limit (Section 2.3) are demonstrated with the 270 K isotherm, which divides Figure 2.6 into two areas: "detectable" and "non-detectable" moons. For example, a THEM orbiting epsilon Eridani b at 5.5 Roche radii would need to maintain an eccentricity higher than 0.009 to be detectable with MIRI. This value is of comparable magnitude to Solar System moons in mean motion resonance (MMR).

Figure 2.6 can thus be used to predict surface equilibrium temperatures of THEMs under the assumptions of our model (see Tables 2.1, 2.3). The dark red area defines the area of the parameter space for which the melt fraction of the mantle exceeds 0.45 (Moore, 2003). When this excess occurs, the asthenosphere behavior resembles a magma ocean. We note that tidal dissipation in such a regime is largely unstudied and depends on poorly constrained parameters. Super-Ios with orbital characteristics that fall within this area produce higher tidal heat rates than what their interiors can advect, either through convection or heat piping. As a result, they are in a "magma ocean" state where they reach the limits of our models since liquid tides Tyler (2011) or poroviscoelasticity Rovira-Navarro et al. (2022) would need to be considered. Nevertheless, such moons would be detectable (under our assumptions) since their surface would reach higher temperatures than those with lower asthenosphere melt. Because all moons with asthenosphere properties on the boundary of a magma ocean are detectable, moons with a magma ocean would be as well. Such moons could reach warmer thermal equilibrium states with a more efficient heat

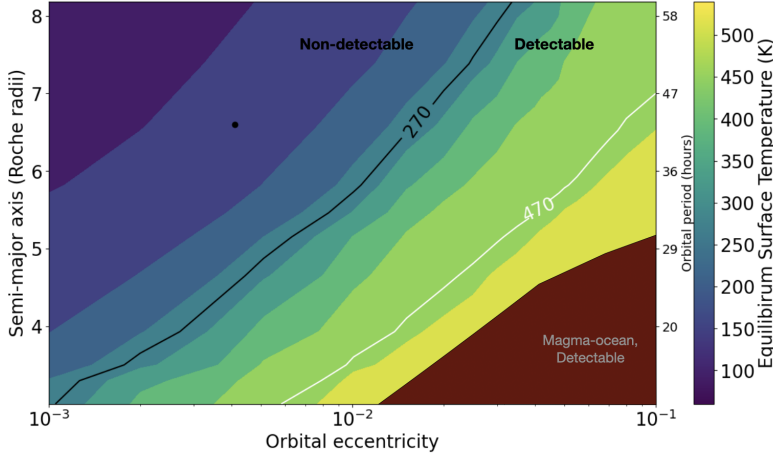


Figure 2.6: Surface equilibrium temperature of a $2R_{Io}$ THEM as a function of its orbital eccentricity (e) and semi-major axis (a). The black dot indicates Io's current orbital parameters. The nominal values of the interior parameters that we used are presented in Table 2.3. The 270K isotherm divides the parameter space into detectable and non-detectable exomoons.

transport mechanism (convection in low viscous layer; (Solomatov, 2007)). They could also still be approaching thermal equilibrium at the moment of detection, radiating excess heat (e.g., from formation).

In Figure 2.11a and b, the surface temperature and $\text{Im}(k_2)$, respectively, of a Super-Io orbiting its host star at 4.65 Roche radii are plotted as a function of its orbital eccentricity. An assumption of a constant $\text{Im}(k_2)$ would lead to significantly different results compared to the correspondence principle technique. Calculating $\text{Im}(k_2)$ via the correspondence principle technique, as is done in this work, can affect our interpretation of whether an exomoon is detectable or not. For example, for the studied moon and a semi-major axis of 4.65 Roche radii the equilibrium, $\text{Im}(k_2)$ can change by a factor of ten, depending on the eccentricity (See Figure 2.11b, blue line). From Equation 2.6, this difference would correspond to a calculated temperature that is off by 500 K, a temperature difference that, as seen in Section 2.3, can define whether a moon is observable.

The value of $\text{Im}(k_2)$ provides a direct link between an exomoon observation with its interior structure and could be used to draw conclusions on the interior properties shown in Table 2.2. Figure 2.7 shows two different equilibrium interior structures that correspond to eccentricities of 0.004 and 0.02 and a semi-major axis of 4.65 Roche radii. The two different eccentricities have equilibrium surface temperatures of 270K and 470K, respectively. The $\text{Im}(k_2)$ of the 470K exo-Io is approximately twice as high as the 270K exomoon, for a semi-major axis of 4.65 Roche radii.

Given that moons would reach stable thermal equilibrium at different tidal heat rates for each pair of a and e , figures similar to Figure 2.6 can be produced for every inte-

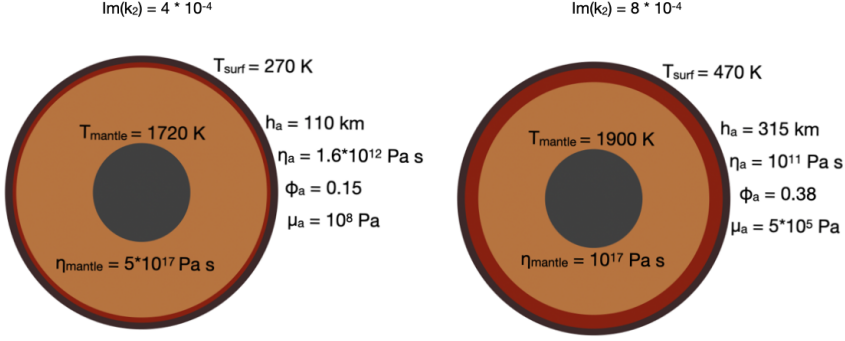


Figure 2.7: Two different equilibrium interior structures for $a = 4.65$ Roche radii. The one on the left ($e = 0.004$) has a thinner asthenosphere compared to the one on the right ($e = 0.02$), resulting in a smaller $\text{Im}(k_2)$. The parameter symbols are explained in Table 2.2.

rior property in Table 2.2. Figure 2.8 shows how the melt fraction of the asthenosphere changes with varying semi-major axis and eccentricity. Jäger & Szabó (2021) modeled THEMs with one hotspot, assuming a non-homogeneous heat flux distributed among their surface. Such hotspots enhance detectability in thermal wavelengths. While our model does not take this into account, we highlight that the various hotspots of a THEM could be used to place constraints on its orbital period, based on the variability of the signal that the hotspots would induce in direct imaging observations.

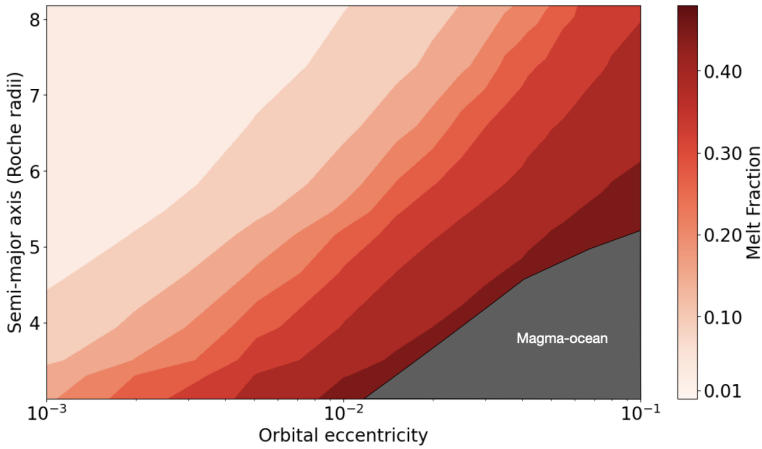


Figure 2.8: Asthenosphere melt fraction (ϕ_α) of stable thermal equilibrium states of exo-Ios as a function of their orbital eccentricity and semi-major axis.

If the surface temperature and semi-major axis are known, the moon's eccentricity (Figure 2.6) and interior properties (Figure 2.8) can be inferred because a surface temperature value corresponds to one stable equilibrium $Im(k_2)$ value for a given eccentricity. In other words, the surface temperature of a putative exomoon with a given semi-major axis and interior structure would be a function of the orbital eccentricity. The blue lines in Figure 2.11 show how for a semi-major axis of 4.65 Roche radii the inferred surface temperature (Figure 2.11a) and the interior properties (Figure 2.11b,c,d,e,f) change with the orbital eccentricity. Since some interior properties exhibit uncertainties, we performed a sensitivity analysis to assess whether and to what extent constraints on the orbital eccentricity and interior can be placed with a putative heat flux observation.

2.4.2 Orbital and interior constraints from observations

To summarize Section 2.4, our coupled tidal-thermal analysis can relate the surface heat flux of putative exo-Ios with the corresponding equilibrium $Im(k_2)$ values for a given moon's semi-major axis. This also means that constraints on the interior equilibrium states could possibly be deduced. Given a semi-major axis, a single solution for the orbital eccentricity exists when assuming the nominal values of Table 2.3. However, the values of the parameters in Table 2.3 are not known exactly, and thus their uncertainty needs to be incorporated in the conclusions that can be drawn with our model.

In this section, we present the results of this analysis when varying the parameters presented in Table 2.3 for the shown number of points and ranges. We obtained surface equilibrium temperatures as well as the corresponding interior parameters in Table 2.2 with the goal to assess i) how a surface temperature alone can constrain the moon semi-major axis and eccentricity; ii) the fraction of simulations for a given eccentricity and semi-major axis that lead to an observable exo-Io; and iii) the constraints in the interior properties and the orbital eccentricity if the surface temperature and the semi-major axis are known.

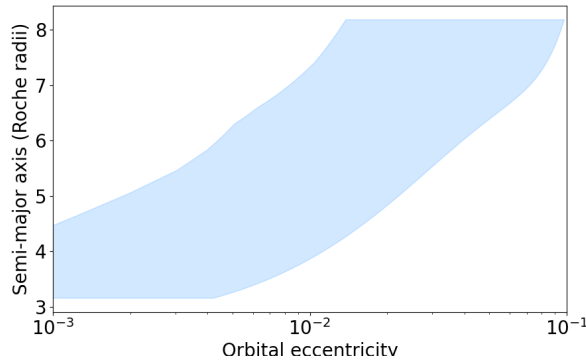
For all three purposes, we varied the mantle shear modulus from 2×10^9 (Steinke et al. (2020)) to $6.5 \times 10^{10} Pa$, which corresponds to the end case of a mantle shear modulus equal to the lithospheric one, assuming no melt (Segatz et al., 1988; Peale et al., 1979). The Andrade parameter α can take values from 0.1 - 0.5 for olivine (Gibb & Cooper, 1998), while the melt fraction coefficient can take values from 10 - 40 (Henning et al., 2009). Finally, we varied the parameters that control the magma advection between typical values (η : 2 - 3 (Moore, 2003), γ : 10^{-6} - 10^{-5} Katz (2008)). Because the mantle solidus viscosity is highly uncertain, we varied it by a factor of ten from the commonly used value of $10^{16} Pa \cdot s$ (Renaud & Henning, 2018; Moore, 2003; Fischer & Spohn, 1990). We note that higher values of $\eta_{s,m}$ would need to be considered for internal structures with an asthenosphere melt fraction larger than the threshold melt fraction defined in Section 2.2 (Kervazo et al., 2022). Each set of the sensitivity parameters led to different stable thermal equilibrium states and thus surface temperatures. The sensitivity parameters were varied altogether along the discussed ranges. Ultimately, each a and e pair could result in 720 different equilibrium states.

The influence of the sensitivity analysis on the final equilibrium temperature is demonstrated in Figure 2.9, where the a and e values that can lead to 270 K (observable with

Table 2.3: Parameters and their ranges used for the sensitivity analysis.

Parameter	Description	Nominal value (Section 5)	Range (Section 6)	Number of points
α	Andrade parameter	0.3	0.1 - 0.5	5
B	Melt fraction coefficient	20	10 - 40	4
μ_{mantle}	Deep mantle shear modulus	6.5×10^{10} Pa	$2 \times 10^9 - 6.5 \times 10^{10}$ Pa	3
γ	Melt scale velocity	10^{-5}	$10^{-6} - 10^{-5}$	2
η	Permeability exponent	2	2-3	2
$\eta_{s,m}$	Mantle solidus viscosity	10^{16} Pa s	$10^{15} - 10^{17}$ Pa s	3

MIRI; Section 2.3) are shown. This already puts constraints on the orbital properties that a particular heat flux observation would correspond to. For example, an exo-Io with an eccentricity of 0.01 and a surface temperature observation of 270 K could be within ≈ 4 -7.2 Roche radii away from the host planet in thermal equilibrium.

Figure 2.9: Range of exo-Io orbital properties that are compatible with a surface temperature of 270K and a radius of $2R_{Io}$ as a result of the sensitivity analysis.

To assess the fraction of simulations that result in an observable moon, we calculated the equilibrium surface temperature for the sensitivity parameters' ranges shown in Table 2.3. Each set of parameters led to a different equilibrium state for the same pair of a, e . If the resulting surface temperature was higher than 270K, we considered the moon observable (Section 2.3). We then calculated the fraction of the 720 simulated exo-Ios that are observable for each pair of semi-major axis and eccentricity, and the results are presented in Figure 2.10. For an eccentricity of 0.02, an exo-Io around ϵ Eridani b would need to have a semi-major axis of ≈ 4 Roche radii for 100% of the simulations to produce an observable moon. We note that this eccentricity is about five times higher than that of Io, and the semi-major axis is around 1.6 times smaller than Io's semi-major axis.

Incorporating the uncertainties of the sensitivity parameters places more realistic constraints on the orbital eccentricity and interior properties for a theoretical T_{surf} and a detection. Figure 2.11 shows the possible solutions for the interior properties of an exo-Io orbiting ϵ Eridani b at 4.65 Roche radii as a function of the orbital eccentricity (light blue shading). The blue lines in the figure panels correspond to the nominal values analysis of Section 2.4. For an observation of 270K (black dotted lines) only exo-Ios with e smaller

than 0.022 would be in thermal equilibrium. This constraint is looser for higher temperatures. For 470K (red dotted lines) the corresponding range would be 0.01 - 0.1. Moreover, the constraints on the interior properties become stricter for higher temperatures. For example, only bodies with melt fractions larger than 0.1 can explain an observation of 470K for the given semi-major axis.

As the eccentricity increases the equilibrium surface temperature increases since the moon experiences more tidal heating. As we approached larger eccentricities, the range of possible surface temperatures (and the other interior parameters) tightened. This is because the equilibrium $\text{Im}(k_2)$ experiences larger variations close to the Maxwell time (see Figure 2.11b) for the considered range of parameters. The peak of the curve, which corresponds to the Maxwell time, can be seen for lower eccentricities of the shown semi-major axis. In the nominal values analysis, the equilibrium structure with viscosity and shear modulus tuned close to the Maxwell time for $a = 4.65$ Roche radii forms for an eccentricity of 0.015.

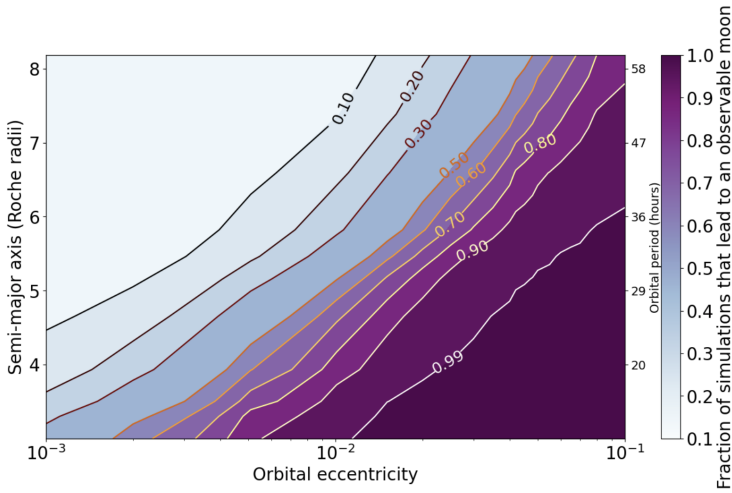


Figure 2.10: Fraction of simulations that lead to an observable moon (warmer than 270K; Section 2.3) as a function of the moon's orbital semi-major axis and eccentricity.

2.5 Discussion

The direct detection of THEMs around exoplanets relies on disentangling the different fluxes (star, planet, moon) in a system at a given separation. The flux of the moon needs to be comparable to (if not higher than) the planet's flux at a selected wavelength band, and contrast limitations with the star must also be taken into account. In this work, we focus on modeling the moon's expected thermal flux, which depends on the amount of tidal heating that is produced in the moon interior, which is in turn a function of the interior structure and orbit of the moon.

The expected tidal heat of THEMs was modeled following a more simplistic approach regarding tidal interactions and interior modeling by Limbach & Turner (2013). For the first time, Dobos & Turner (2015) took into account the viscoelastic behavior that describes the tidal response of the material making up the interior of planetary bodies. In their work, Dobos & Turner (2015) included the Maxwell viscoelastic approach commonly used to model the response of Solar System planetary bodies (Shoji et al., 2013) as well as in exoplanet science (Barr et al., 2018). They assumed a two-layered body and convection as the main heat transfer mechanism in the mantle. In our analysis, we used a coupled thermal-tidal model combined with viscoelastic Andrade rheology, and we assumed magma advection as the main heat transfer mechanism in a partially molten sub-layer. The effect of changing the classical Maxwell approach to the Andrade one has been studied for planetary bodies (Renaud & Henning, 2018; Walterová & Běhouňková, 2017). In general, Andrade rheology produces higher tidal heating rates, due to the transient creep mechanism. This is aligned with our results when compared with Dobos & Turner (2015), who for a $2R_{Io}$ moon at Io's orbital period and an eccentricity of 0.1 found 273 K. We found an equilibrium temperature above 400K for the same orbital properties.

Tides provide a direct link between the interior and the orbital properties of a planetary body. Observations that can constrain the amount of tidal heat in the interior (e.g., thermal flux) combined with accurate modeling of the interior and potentially the orbit can be helpful for drawing inferences regarding the system properties of exoplanets and/or exomoons. Direct observations of THEMs are (the only) direct method of probing the tidally heated surface. Our analysis shows the effect of tidal heating on the surface temperature of THEMs. We found regimes of orbital properties where the moon has to be in a magma ocean state to be able to dissipate the tidally generated heat. As seen in Figure 2.11, we also found that we can place constraints on interior properties and eccentricity depending on the (observed) temperature when given a semi-major axis and a moon radius. Several approaches to exomoon detection have been proposed in which the exomoon mass (Kenworthy & Mamajek, 2015; Sartoretti & Schneider, 1999; Vanderburg et al., 2018; Teachey & Kipping, 2018), radius and semi-major axis (Teachey & Kipping, 2018), and atmospheric properties (Agol et al., 2015; Oza et al., 2019) could be constrained. Our work provides a way to infer system properties, such as the orbital eccentricity, and compatible interior structures. Finally a THEM detection would indicate the likely existence of at least a second moon in resonance since tides would circularize an isolated moon's orbit.

In the following sections, we explore some observational and modeling challenges. These include discussions on longevity, semi-major axis and radius constraints, and more massive moons that could potentially host an atmosphere. Finally, we explore how our results could be potentially validated via other observational methods.

2.5.1 Longevity and mean motion resonance

The ϵ Eridani system is a relatively young system (400-800 Myr; Mamajek & Hillenbrand, 2008; Janson, Markus et al., 2015), and such systems have a potential disadvantage for the direct detection of THEMs, as any planet in them is expected to be warm from formation. Since the planet-moon contrast also plays a significant role in THEM

observability, this could (possibly) hinder a detection.

On the other hand, the system's young age could offer an observational advantage compared to older systems. In an isolated moon-planet system, tides quickly circularize the moon's orbit, and close moons can migrate outward quite fast (Rovira-Navarro et al., 2021), which limits the observability window. A second moon in resonance can boost the eccentricity of the first moon and maintain the surface temperature high enough for detection via tidal heating. In both Jupiter's and Saturn's satellite systems, there are currently MMRs that likely originated with the outward migration of inner satellites, capturing the outer ones in MMRs (Yoder & Peale, 1981; Dermott et al., 1988). Even though the MMRs in the Solar System indicate that they are likely prevalent in older systems as well, it is reasonable to assume that MMRs are common in relatively young systems since moons can be captured in MMRs during their formation (Peale & Lee, 2002; Ogihara & Ida, 2012).

The lifetime of an MMR depends on the mass ratio of the moons, among other parameters, and a short-lived resonance could last <200 Myr (Tokadjian & Piro, 2022). Rovira-Navarro et al. (2021) calculated that an exo-Io with $2R_{Io}$ could have a temperature higher than 400K for 10 Myrs (during the early stages of an MMR). This would make such a moon detectable for 10 Myrs. Thus, if one considers the expected timescale of MMRs, young systems could potentially serve as good targets for THEM observations.

2.5.2 Combination with other exomoon detection methods: Constraining the moon radius and semi-major axis

As discussed in Figure 2.11, which describes the possible constraints we can place on the orbital eccentricity and the interior properties of the moon, we assumed a fixed semi-major axis and satellite radius. This means that tidal heating can provide constraints on the interior properties and eccentricity if the orbital period and the size of the satellite are known. Therefore, the question of how can we constrain these two parameters (and to what accuracy) in a direct imaging observation appears.

Even though both Llop-Sayson et al. (2021) and Mawet et al. (2019) find inclinations closer to an edge-on orbit of 78.8 and 89.0, respectively (with large uncertainties), there is no consensus yet of ϵ Eridani b's inclination. Nevertheless, we explored possible ways of constraining the properties in scenarios where a system is closer to being edge-on and face-on. Since a moon in such a system would not be spatially resolved from the planet it orbits, its semi-major axis cannot be constrained in the same way the semi-major axis of a planet is measured in exoplanet direct imaging observations (e.g., Bohn et al., 2019). However, with time series observations of the same target, plausible constraints on the moon's orbital period could be derived. If the system is edge-on (assuming the planet's and moon's orbits are coplanar), the moon would transit the planet, so the task of deriving the moon's orbital period would be straightforward. For systems close to a face-on orbit, one could constrain a moon's orbital period via the periodicity of the signal coming from patterns on its surface, as hotspots are expected to be present on the surfaces of THEM. Time series observations of an edge-on system can also be used to infer the satellite's radius (Cabrera, J. & Schneider, J., 2007).

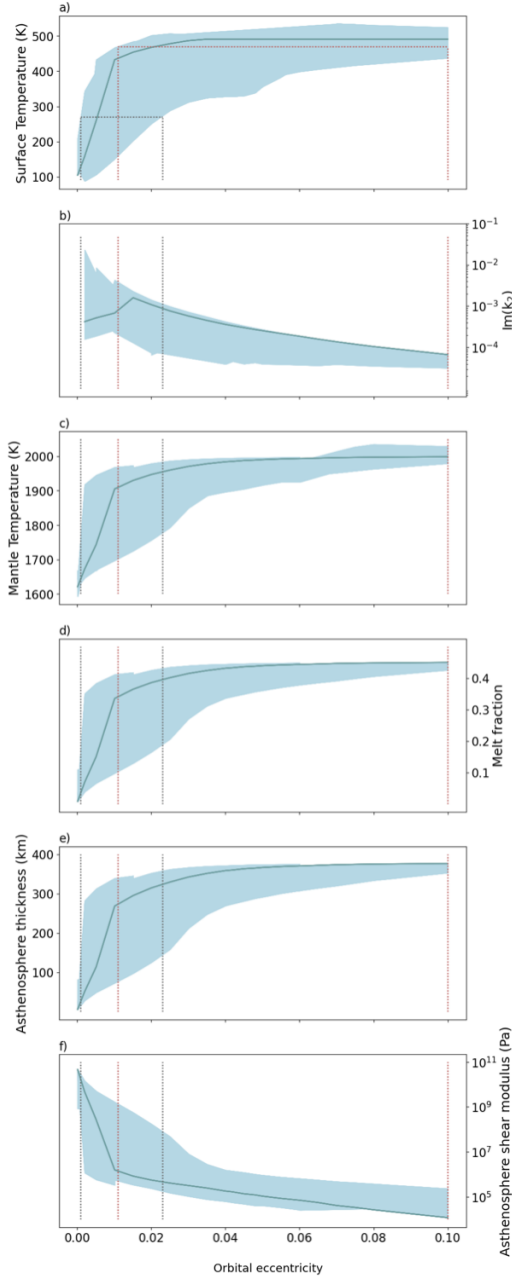


Figure 2.11: Computed ranges for the model’s output parameters (Table 2.2) that lead to exo-Ios with $a = 4.65$ Roche radii and a radius of $2 \times R_{Io}$ in a stable thermal equilibrium. The blue line corresponds to the nominal values analysis (Section 5). The gray and red dotted lines respectively show the limits of a 270 K and 470 K surface temperature observation.

2.5.3 Larger moons

Though exomoons can be of various sizes and some are even more massive than the ones seen in our Solar System (Canup & Ward, 2006), the discussed results in this work refer only to $2R_{Io}$ exomoons. Since tidal dissipation depends on the moon's radius, we would expect larger satellites to reach warmer thermal equilibrium states, especially in interior regimes with more efficient heat transport than heat piping. However, larger satellites could be massive enough to sustain a substantial atmosphere (Lammer et al., 2014). In this case, direct detection of the thermal emission would be hindered, since the outer atmospheric layer would be relatively colder and detection via spectroscopic signatures would be more promising (Oza et al., 2019). Nonetheless, we point out that a substantial atmosphere would redistribute the tidal energy, making the SED resemble a black body when hotspots on the surface shift the SED to bluer wavelengths (Limbach & Turner, 2013).

2.5.4 Future model validation

In this work we applied models previously used to reproduce Io's averaged heat flux (Moore, 2003; Rovira-Navarro et al., 2021) in order to investigate the parameter space, the resulting mean surface temperatures, and the possible detection of THEMs via direct imaging. These models have not been yet validated for bodies larger than Io; thus, we explore possible observations and complementary models that could validate the applicability of our results to the analysis of observations in the future.

The observables that we propose are mostly for quantities that are related to tidally induced active volcanism. One notable option is the spectral signatures from volcanic outgassing or hotspots. Oza et al. (2019) introduced a proxy between the amount of outgassed material, the size, and the tidal heating rate of the body. This means that we can constrain the tidal heating rate by quantifying volcanically related gases (e.g., sodium, potassium) with spectroscopy, when given the size of the body. This measurement could serve as an independent way to deduce the tidal heating rate and, thus, the $\text{Im}(k_2)$ of the moon via Equation 2.2.

Hotspots induced by tidal heating in THEMs could also serve as a way to observe surface inhomogeneities. This has already been applied in exoplanets via single band photometry (Cowan & Fujii, 2018; Majeau et al., 2012). Since different regions of the moon's surface would be visible at different orbital phases, spatial inhomogeneities on the surface could be inferred. These variations depend on interior properties in tidally active bodies (Steinke et al., 2020). Thus, one could determine whether possible inferred inhomogeneities are compatible with the amount of tidal heating induced and the interior properties assumed. In addition, the presence of hotspots would be a possible way to constrain the moon's orbit period (see Section 2.5.2).

Another possible consideration would be validating the calculated $\text{Im}(k_2)$ through orbital constraints, in other words, quantifying whether the $\text{Im}(k_2)$ is compatible with the orbital properties of the putative detection. The orbital circularization timescale depends on the $\text{Im}(k_2)$ of the moon (Rovira-Navarro et al., 2021). The eccentricity constraints that our analysis provides and the calculated $\text{Im}(k_2)$ should be compatible with the system's

age. Such an analysis would require different scenarios to be evaluated, including the possibility for a resonance lock (Fuller et al., 2016) with the planet’s interior, as is likely in the case for Saturn’s satellite system (Lainey et al., 2020).

Finally, these considerations are not limited to moons but can also be explored in exoplanets, serving as a way to better understand the mechanism of tidal heating in rocky bodies (Henning et al., 2009; Renaud & Henning, 2018). Applying the discussed model to exoplanets and validating the results would offer a bigger observational sample to test the model’s limits.

2.6 Conclusions

We used tidal and thermal models that describe Io’s observed surface heat flux (Rovira-Navarro et al., 2021) to investigate the observability of tidally heated exomoons (THEMs) around ϵ Eridani b. We conclude that for orbital properties of the same order, such as Solar System satellites (semi-major axis of 5.5 Roche radii and eccentricity of 0.009), a $2R_{Io}$ THEM is detectable around ϵ Eridani b with MIRI. When we took into account uncertainties in the interior properties, approximately 40% of such simulated THEMs reached a surface temperature high enough to be detectable. However, 100% of our simulations led to an observable Super-Io for a moon eccentricity of 0.02 and a semi-major axis of approximately 4 Roche radii. If no significant atmosphere is present, a larger moon would experience more intense tidal heating, and thus it would also be detectable.

With a successful thermal flux detection, the models we present could place constraints on orbital parameters, with the assumption that the satellites are in thermal equilibrium. If the satellite’s semi-major axis and radius are inferred (e.g., via exomoon transits), we can place stricter constraints on the orbital eccentricity and infer interior properties, such as melt fraction and thickness of the asthenosphere (see also Table 2.2) or whether the moon is in a magma ocean state. For instance, for detection of a THEM with a surface temperature of 270K and a semi-major axis of 4.65 Roche radii, the exo-Io would need to have an eccentricity smaller than 0.022 to be in thermal equilibrium. This constraint is looser for higher surface temperatures. In addition, only bodies with melt fractions larger than 0.1 can explain an observation of 470K for this semi-major axis. A number of complementary observations of exomoons and their environments, such as hotspot properties, volcanic outgassing, and orbital configuration, could be used to test the applicability of our models after the detection of a THEM.

Bibliography

- Agol, E., Jansen, T., Lacy, B., Robinson, T. D., & Meadows, V. 2015, *The Astrophysical Journal*, 812, 5, doi: [10.1088/0004-637x/812/1/5](https://doi.org/10.1088/0004-637x/812/1/5)
- Anderson, J. D., Sjogren, W. L., & Schubert, G. 1996, *Science*, 272, 709, doi: [10.1126/science.272.5262.709](https://doi.org/10.1126/science.272.5262.709)
- Andrade, E. N. D. C. 1910, *Proceedings of the Royal Society of London Series A*, 84, 1
- Baland, R.-M., Yseboodt, M., & van Hoolst, T. 2012, *Icarus*, 220, 435, doi: [10.1016/j.icarus.2012.05.020](https://doi.org/10.1016/j.icarus.2012.05.020)
- Barr, A. C., Dobos, V., & Kiss, L. L. 2018, *A&A*, 613, A37, doi: [10.1051/0004-6361/201731992](https://doi.org/10.1051/0004-6361/201731992)
- Benisty, M., Bae, J., Facchini, S., et al. 2021, *The Astrophysical Journal Letters*, 916, L2, doi: [10.3847/2041-8213/ac0f83](https://doi.org/10.3847/2041-8213/ac0f83)
- Bierson, C. J., & Nimmo, F. 2016, *Journal of Geophysical Research: Planets*, 121, 2211, doi: <https://doi.org/10.1002/2016JE005005>
- Boccaletti, A., Lagage, P.-O., Baudoz, P., et al. 2015, *Publications of the Astronomical Society of the Pacific*, 127, 633, doi: [10.1086/682256](https://doi.org/10.1086/682256)
- Boccaletti, A., Cossou, C., Baudoz, P., et al. 2022, doi: [10.48550/ARXIV.2207.11080](https://doi.org/10.48550/ARXIV.2207.11080)
- Bohn, A. J., Kenworthy, M. A., Ginski, C., et al. 2019, *Monthly Notices of the Royal Astronomical Society*, 492, 431, doi: [10.1093/mnras/stz3462](https://doi.org/10.1093/mnras/stz3462)
- Brandl, B., Bettonvil, F., Van Boekel, R., et al. 2021, *Published in The Messenger* vol. 182, pp. 22-26, March 2021., doi: [10.18727/0722-6691/5218](https://doi.org/10.18727/0722-6691/5218)
- Cabrera, J., & Schneider, J. 2007, *A&A*, 464, 1133, doi: [10.1051/0004-6361:20066111](https://doi.org/10.1051/0004-6361:20066111)
- Canup, R. M., & Ward, W. R. 2006, *Nature*, 441, 834–839, doi: [10.1038/nature04860](https://doi.org/10.1038/nature04860)
- Castillo-Rogez, J. C., Efroimsky, M., & Lainey, V. 2011, *Journal of Geophysical Research (Planets)*, 116, E09008, doi: [10.1029/2010JE003664](https://doi.org/10.1029/2010JE003664)
- Cowan, N. B., & Fujii, Y. 2018, *Mapping Exoplanets*, ed. H. J. Deeg & J. A. Belmonte (Cham: Springer International Publishing), 1469–1484, doi: [10.1007/978-3-319-55333-7_147](https://doi.org/10.1007/978-3-319-55333-7_147)
- Dermott, S. F., Malhotra, R., & Murray, C. D. 1988, *Icarus*, 76, 295, doi: [10.1016/0019-1035\(88\)90074-7](https://doi.org/10.1016/0019-1035(88)90074-7)
- Dobos, V., Charnoz, S., Pál, A., Roque-Bernard, A., & Szabó, G. M. 2021, 133, 094401, doi: [10.1088/1538-3873/abfe04](https://doi.org/10.1088/1538-3873/abfe04)
- Dobos, V., & Turner, E. L. 2015, *The Astrophysical Journal*, 804, 41, doi: [10.1088/0004-637x/804/1/41](https://doi.org/10.1088/0004-637x/804/1/41)
- Efroimsky, M. 2012, *The Astrophysical Journal*, 746, 150, doi: [10.1088/0004-637x/746/2/150](https://doi.org/10.1088/0004-637x/746/2/150)
- Fischer, H.-J., & Spohn, T. 1990, *Icarus*, 83, 39, doi: [https://doi.org/10.1016/0019-1035\(90\)90005-T](https://doi.org/10.1016/0019-1035(90)90005-T)
- Fuller, J., Luan, J., & Quataert, E. 2016, *Monthly Notices of the Royal Astronomical Society*, 458, 3867, doi: [10.1093/mnras/stw609](https://doi.org/10.1093/mnras/stw609)
- Glasse, A., Rieke, G. H., Bauwens, E., et al. 2015, *Publications of the Astronomical Society of the Pacific*, 127, 686, doi: [10.1086/682259](https://doi.org/10.1086/682259)
- Goldreich, P., & Soter, S. 1966, *Icarus*, 5, 375, doi: [https://doi.org/10.1016/0019-1035\(66\)90051-0](https://doi.org/10.1016/0019-1035(66)90051-0)
- Gribb, T. T., & Cooper, R. F. 1998, *Journal of Geophysical Research: Solid Earth*, 103, 27267, doi: <https://doi.org/10.1029/98JB02786>
- Hatzes, A. P., Cochran, W. D., McArthur, B., et al. 2000, *ApJ*, 544, L145, doi: [10.1086/317319](https://doi.org/10.1086/317319)
- Heller, R. 2014, *ApJ*, 787, 14, doi: [10.1088/0004-637x/787/1/14](https://doi.org/10.1088/0004-637x/787/1/14)
- Heller, R. 2017, *Handbook of Exoplanets*

- Heller, R., Hippke, M., Placek, B., Angerhausen, D., & Agol, E. 2016, *Astronomy & Astrophysics*, 591, A67, doi: [10.1051/0004-6361/201628573](https://doi.org/10.1051/0004-6361/201628573)
- Henning, W. G., O'Connell, R. J., & Sasselov, D. D. 2009, 707, 1000, doi: [10.1088/0004-637x/707/2/1000](https://doi.org/10.1088/0004-637x/707/2/1000)
- Hussmann, H., & Spohn, T. 2004, *Icarus*, 171, 391, doi: [10.1016/j.icarus.2004.05.020](https://doi.org/10.1016/j.icarus.2004.05.020)
- Jackson, I., & Faul, U. H. 2010, *Physics of the Earth and Planetary Interiors*, 183, 151, doi: <https://doi.org/10.1016/j.pepi.2010.09.005>
- Janson, Markus, Quanz, Sascha P., Carson, Joseph C., et al. 2015, *A&A*, 574, A120, doi: [10.1051/0004-6361/201424944](https://doi.org/10.1051/0004-6361/201424944)
- Jara-Orué, H. M., & Vermeersen, B. L. 2011, *Icarus*, 215, 417, doi: <https://doi.org/10.1016/j.icarus.2011.05.034>
- Jäger, Zoltán, J., & Szabó, G. M. 2021, *Monthly Notices of the Royal Astronomical Society*, 508, 5524, doi: [10.1093/mnras/stab2955](https://doi.org/10.1093/mnras/stab2955)
- Karato, S.-I., & Wu, P. 1993, *Science*, 260, 771, doi: [10.1126/science.260.5109.771](https://doi.org/10.1126/science.260.5109.771)
- Katz, R. F. 2008, *Journal of Petrology*, 49, 2099, doi: [10.1093/petrology/egn058](https://doi.org/10.1093/petrology/egn058)
- Kenworthy, M. A., & Mamajek, E. E. 2015, *The Astrophysical Journal*, 800, 126, doi: [10.1088/0004-637x/800/2/126](https://doi.org/10.1088/0004-637x/800/2/126)
- Kervazo, M., Tobie, G., Choblet, G., Dumoulin, C., & Běhouňková, M. 2022, *Icarus*, 373, 114737, doi: <https://doi.org/10.1016/j.icarus.2021.114737>
- Kipping, D., Bryson, S., Burke, C., et al. 2022, *Nature Astronomy*, 6, 367, doi: [10.1038/s41550-021-01539-1](https://doi.org/10.1038/s41550-021-01539-1)
- Kipping, D. M. 2009, *Monthly Notices of the Royal Astronomical Society*, 396, 1797, doi: <https://doi.org/10.1111/j.1365-2966.2009.14869.x>
- Kipping, D. M., Bakos, G. Á., Buchhave, L., Nesvorný, D., & Schmitt, A. 2012, 750, 115, doi: [10.1088/0004-637x/750/2/115](https://doi.org/10.1088/0004-637x/750/2/115)
- Kovtyukh, V. V., Soubiran, C., Belik, S. I., & Gorlova, N. I. 2003, *A&A*, 411, 559, doi: [10.1051/0004-6361:20031378](https://doi.org/10.1051/0004-6361:20031378)
- Lainey, V., Arlot, J.-E., Karatekin, O., & Van Hoolst, T. 2009, *Nature*, 459, 957—959, doi: [10.1038/nature08108](https://doi.org/10.1038/nature08108)
- Lainey, V., Casajus, L. G., Fuller, J., et al. 2020, *Nature Astronomy*, 4, 1053
- Lammer, H., Schiefer, S.-C., Juvan, I., et al. 2014, *Origins of Life and Evolution of Biospheres*, 44, 239, doi: [10.1007/s11084-014-9377-2](https://doi.org/10.1007/s11084-014-9377-2)
- Lazzoni, C., Desidera, S., Gratton, R., et al. 2022, *Monthly Notices of the Royal Astronomical Society*, 516, 391, doi: [10.1093/mnras/stac2081](https://doi.org/10.1093/mnras/stac2081)
- Limbach, M. A., & Turner, E. L. 2013, *The Astrophysical Journal*, 769, 98, doi: [10.1088/0004-637X/769/2/98](https://doi.org/10.1088/0004-637X/769/2/98)
- Llop-Sayson, J., Wang, J. J., Ruffio, J.-B., et al. 2021, *AJ*, 162, 181, doi: [10.3847/1538-3881/ac134a](https://doi.org/10.3847/1538-3881/ac134a)
- MacGregor, M. A., Wilner, D. J., Andrews, S. M., Lestrade, J.-F., & Maddison, S. 2015, *The Astrophysical Journal*, 809, 47, doi: [10.1088/0004-637x/809/1/47](https://doi.org/10.1088/0004-637x/809/1/47)
- Majeau, C., Agol, E., & Cowan, N. B. 2012, *ApJ*, 747, L20, doi: [10.1088/2041-8205/747/2/L20](https://doi.org/10.1088/2041-8205/747/2/L20)
- Makarov, V. V., & Efroimsky, M. 2014, *The Astrophysical Journal*, 795, 7, doi: [10.1088/0004-637X/795/1/7](https://doi.org/10.1088/0004-637X/795/1/7)
- Mamajek, E. E., & Hillenbrand, L. A. 2008, *The Astrophysical Journal*, 687, 1264, doi: [10.1086/591785](https://doi.org/10.1086/591785)
- Mawet, D., Hirsch, L., Lee, E. J., et al. 2019, *AJ*, 157, 33, doi: [10.3847/1538-3881/aaef8a](https://doi.org/10.3847/1538-3881/aaef8a)
- Mei, S., Bai, W., Hiraga, T., & Kohlstedt, D. 2002, *Earth and Planetary Science Letters*, 201, 491, doi: [https://doi.org/10.1016/S0012-821X\(02\)00745-8](https://doi.org/10.1016/S0012-821X(02)00745-8)

- Meyer, J., & Wisdom, J. 2007, *Icarus*, 188, 535, doi: <https://doi.org/10.1016/j.icarus.2007.03.001>
- Moore, W. B. 2001, *Icarus*, 154, 548, doi: <https://doi.org/10.1006/icar.2001.6739>
- . 2003, *Journal of Geophysical Research: Planets*, 108, doi: <https://doi.org/10.1029/2002JE001943>
- Ogihara, M., & Ida, S. 2012, *The Astrophysical Journal*, 753, 60, doi: [10.1088/0004-637X/753/1/60](https://doi.org/10.1088/0004-637X/753/1/60)
- Oza, A. V., Johnson, R. E., Lellouch, E., et al. 2019, *The Astrophysical Journal*, 885, 168, doi: [10.3847/1538-4357/ab40cc](https://doi.org/10.3847/1538-4357/ab40cc)
- Peale, S. J., Cassen, P., & Reynolds, R. T. 1979, *Science*, 203, 892, doi: [10.1126/science.203.4383.892](https://doi.org/10.1126/science.203.4383.892)
- Peale, S. J., & Lee, M. H. 2002, *Science*, 298, 593, doi: [10.1126/science.1076557](https://doi.org/10.1126/science.1076557)
- Peltier, W. R. 1974, *Reviews of Geophysics*, 12, 649, doi: <https://doi.org/10.1029/RG012i004p00649>
- Reese, C., Solomatov, V., & Moresi, L.-N. 1999, *Icarus*, 139, 67, doi: <https://doi.org/10.1006/icar.1999.6088>
- Renaud, J. P., & Henning, W. G. 2018, *The Astrophysical Journal*, 857, 98, doi: [10.3847/1538-4357/aab784](https://doi.org/10.3847/1538-4357/aab784)
- Renaud, J. P., Henning, W. G., Saxena, P., et al. 2021, *The Planetary Science Journal*, 2, 4, doi: [10.3847/psj/abc0f3](https://doi.org/10.3847/psj/abc0f3)
- Reynolds, R. T., McKay, C. P., & Kasting, J. F. 1987, *Advances in Space Research*, 7, 125, doi: [https://doi.org/10.1016/0273-1177\(87\)90364-4](https://doi.org/10.1016/0273-1177(87)90364-4)
- Rosenthal, L. J., Fulton, B. J., Hirsch, L. A., et al. 2021, *ApJS*, 255, 8, doi: [10.3847/1538-4365/abe23c](https://doi.org/10.3847/1538-4365/abe23c)
- Rovira-Navarro, M., Katz, R. F., Liao, Y., van der Wal, W., & Nimmo, F. 2022, *Journal of Geophysical Research: Planets*, 127, doi: <https://doi.org/10.1029/2021JE007117>
- Rovira-Navarro, M., van der Wal, W., Steinke, T., & Dirkx, D. 2021, 2, 119, doi: [10.3847/psj/abf6cb](https://doi.org/10.3847/psj/abf6cb)
- Ruffio, J.-B., Horstman, K., Mawet, D., et al. 2023, *The Astronomical Journal*, 165, 113, doi: [10.3847/1538-3881/acb34a](https://doi.org/10.3847/1538-3881/acb34a)
- Sabadini R., Vermeersen B., . C. G. 2016, *Global Dynamics of the Earth: Applications of Viscoelastic Relaxation Theory to Solid-Earth and Planetary Geophysics* (2nd ed.; Berlin: Springer)
- Sartoretti, P., & Schneider, J. 1999, *A&AS*, 134, 553, doi: [10.1051/aas:1999148](https://doi.org/10.1051/aas:1999148)
- Saumon, D., Hubbard, W. B., Burrows, A., et al. 1996, *The Astrophysical Journal*, 460, 993, doi: [10.1086/177027](https://doi.org/10.1086/177027)
- Schubert, G., Cassen, P., & Young, R. 1979, *Icarus*, 38, 192, doi: [https://doi.org/10.1016/0019-1035\(79\)90178-7](https://doi.org/10.1016/0019-1035(79)90178-7)
- Segatz, M., Spohn, T., Ross, M. N., & Schubert, G. 1988, *Icarus*, 75, 187, doi: [10.1016/0019-1035\(88\)90001-2](https://doi.org/10.1016/0019-1035(88)90001-2)
- Shoji, D., Hussmann, H., Kurita, K., & Sohl, F. 2013, *Icarus*, 226, 10, doi: <https://doi.org/10.1016/j.icarus.2013.05.004>
- Shoji, D., & Kurita, K. 2014, *ApJ*, 789, 3, doi: [10.1088/0004-637X/789/1/3](https://doi.org/10.1088/0004-637X/789/1/3)
- Simon, A., Sztatmáry, K., & Szabó, Gy. M. 2007, *A&A*, 470, 727, doi: [10.1051/0004-6361:20066560](https://doi.org/10.1051/0004-6361:20066560)
- Solomatov, V. 2007, in *Treatise on Geophysics* (Amsterdam: Elsevier), 91
- Spencer, J. R., Rathbun, J. A., Travis, L. D., et al. 2000, *Science*, 288, 1198, doi: [10.1126/science.288.5469.1198](https://doi.org/10.1126/science.288.5469.1198)
- Spiegel, D. S., & Burrows, A. 2012, *The Astrophysical Journal*, 745, 174, doi: [10.1088/0004-637x/745/2/174](https://doi.org/10.1088/0004-637x/745/2/174)

- Steinke, T., Hu, H., Höning, D., van der Wal, W., & Vermeersen, B. 2020, *Icarus*, 335, 113299, doi: <https://doi.org/10.1016/j.icarus.2019.05.001>
- Teachey, A., & Kipping, D. M. 2018, *Science Advances*, 4, eaav1784, doi: 10.1126/sciadv.aav1784
- Tokadjian, A., & Piro, A. L. 2022, doi: 10.48550/ARXIV.2206.11368
- Trani, A. A., Hamers, A. S., Geller, A., & Spera, M. 2020, *Monthly Notices of the Royal Astronomical Society*, 499, 4195, doi: 10.1093/mnras/staa3098
- Tyler, R. 2011, *Icarus*, 211, 770, doi: <https://doi.org/10.1016/j.icarus.2010.10.007>
- Vanderburg, A., Rappaport, S. A., & Mayo, A. W. 2018, 156, 184, doi: 10.3847/1538-3881/aaf0fc
- Veeder, G. J., Matson, D. L., Johnson, T. V., Blaney, D. L., & Goguen, J. D. 1994, *Journal of Geophysical Research: Planets*, 99, 17095, doi: <https://doi.org/10.1029/94JE00637>
- Walterová, M., & Běhouňková, M. 2020, 900, 24, doi: 10.3847/1538-4357/aba8a5
- Walterová, M., & Běhouňková, M. 2017, *Celestial Mechanics and Dynamical Astronomy*, 129, 235, doi: 10.1007/s10569-017-9772-x
- Yoder, C. F., & Peale, S. J. 1981, *Icarus*, 47, 1, doi: [https://doi.org/10.1016/0019-1035\(81\)90088-9](https://doi.org/10.1016/0019-1035(81)90088-9)

3 | The spectroastrometric detectability of nearby Solar System-like exomoons

Adapted from

Q. B. van Woerkom, E. Kleisioti
Astronomy & Astrophysics, 684, A72 (2024)

Context. Though efforts to detect them have been made with a variety of methods, no technique can claim a successful, confirmed detection of a moon outside the Solar System yet. Moon detection methods are restricted in capability to detecting moons of masses beyond what formation models would suggest, or they require surface temperatures exceeding what tidal heating simulations allow.

Aims. We expand upon spectroastrometry, a method that makes use of the variation of the centre of light with wavelength as the result of an unresolved companion, which has previously been shown to be capable of detecting Earth-analogue moons around nearby exo-Jupiters, with the aim to place bounds on the types of moons detectable using this method.

Methods. We derived a general, analytic expression for the spectroastrometric signal of a moon in any closed Keplerian orbit, as well as a new set of estimates on the noise due to photon noise, pointing inaccuracies, background and instrument noise, and a pixelated detector. This framework was consequently used to derive bounds on the temperature required for Solar System-like moons to be observable around super-Jupiters in nearby systems, with ϵ Indi Ab as an archetype.

Results. We show that such a detection is possible with the ELT for Solar System-like moons of moderate temperatures (150–300 K) in line with existing literature on tidal heating, and that the detection of large (Mars-sized or greater) icy moons of temperatures such as those observed in our Solar System in the very nearest systems may be feasible.

3.1 Introduction

The Solar System hosts a variety of large moons, presenting environments as diverse and scientifically interesting as its planets. As the count of exoplanets found so far is in the thousands, it is natural to ask whether these extrasolar planets hide an equal number of extrasolar moons. Secondary or population-level effects of such moons have already been found (e.g. Kenworthy & Mamajek 2015; Hippke 2015; Teachey et al. 2018; Oza et al. 2019; Saillenfest et al. 2023), and so the question is not whether these moons exist, but rather what they look like, and in what systems and around which planets can they be found.

The detection and characterisation of such satellites accompanying extrasolar planets holds the potential to further our understanding of planet formation, evolution, and habitability. Different moon and planet formation scenarios and their outcomes have been linked to predictions of or requirements on, for example, the time of formation of the satellites (Cilibrasi et al., 2018), their size and mass relative to their host (Nakajima et al., 2022; Canup & Ward, 2006; Hansen, 2019), circumplanetary disc (CPD) composition (Batygin & Morbidelli, 2020; Oberg et al., 2023), host magnetosphere (Canup & Ward, 2006), host mass (Oberg et al., 2023), instellation or host migration history (Heller & Pudritz, 2015a,b), and orbital properties (Li et al., 2020). While the Solar System is host to a large number of moons, the limited scenario we are presented with cannot conclusively bear witness to any of these analyses: validation of these formation studies would require the detection and characterisation of satellites of planets outside the Solar System.

Moreover, moons with the mass of Mars or greater (which are not found in the Solar System) are promising targets for habitability studies (Lammer et al., 2014; Williams et al., 1997; Dobos et al., 2022; Forgan & Dobos, 2016), and the observationally confirmed existence of subsurface oceans on Titan (Beuthe, 2015; Bills & Nimmo, 2011; Baland et al., 2011), Enceladus (Beuthe, 2016), among others, and the likely current or past existence of such oceans on Triton (Nimmo & Spencer, 2015; Schenk et al., 2021; McKinnon & Kirk, 2014; Gaeman et al., 2012) and other Solar System bodies (e.g. Hussmann et al. 2006; Burnett & Hayne 2023; Rovira-Navarro et al. 2023; Nimmo et al. 2016; Bagheri et al. 2022; Bierson & Nimmo 2022; Nimmo & Pappalardo 2016) hold promise for the potential habitability of such worlds, even at sizes observed in the Solar System. This makes Solar System-like satellites objects of interest concerning habitability in their own right, not just as extensions of the population of small icy and rocky planets orbiting stars directly.

Current searches for exomoons are limited primarily to those using transit timing variations (TTVs) and transit duration variations (TDVs), which can yield orbital and mass information on the moon (Kipping, 2009a,b; Heller et al., 2014; Teachey et al., 2018, 2020; Fox & Wiegert, 2021; Kipping & Yahalomi, 2022; Kipping et al., 2022). For this method, unfortunately, the effects of even large moons are degenerate with those produced by other, potentially unobserved planets in the system (Fox & Wiegert, 2021; Kipping & Teachey, 2020). Consequently, candidate moons are met with skepticism (Teachey et al., 2020; Fox & Wiegert, 2021; Kipping, 2020; Tokadjian & Piro, 2022), especially as they have thus far required invoking eccentric formation scenarios (Hamers & Portegies Zwart, 2018; Hansen, 2019; Kipping et al., 2022). Other detection and characterisa-

tion methods have been proposed, from those directly analogous to those used in planet detection such as radial velocity measurements of the host planet (Ruffio et al., 2023; Vanderburg et al., 2018) or transit spectroscopy (Kaltenegger, 2010; Limbach et al., 2021) to the detection of thermal excesses in direct imaging data (Limbach & Turner, 2013; Kleisioti et al., 2021, 2023) or microlensing (Han & Han, 2002; Han, 2008; Hwang et al., 2018). These also face major limitations, however. The first two methods, with current instrumentation, can unfortunately only detect binary-like satellites in terms of size and mass (Lazzoni et al., 2022), whereas the third requires exceptional tidal heating rates. Microlensing detections are isolated events, and therefore are difficult to confirm and cannot be followed up on.

In this analysis, we build upon previous work by Cabrera & Schneider (2007), who discussed the possibility of detecting extrasolar satellites by astrometry of the planet or photometric phenomena induced by mutually eclipsing and dimming events, and Agol et al. (2015), who put these two together and discussed the possibility of detecting extrasolar satellites by use of a method called spectroastrometry, in which one measures the differential on-sky position between the light originating from a system in different filters. A shift in the centre of light between two filters cannot be the result of a point-source or symmetric object (e.g. rings), and so explanation of such a shift in a planet signal requires the presence of a (potentially unresolved) second object. This method has previously found use in characterisation of close-separation stellar binaries and active galactic nuclei at scales well below the diffraction limit, as the centroid can be measured to precision better than the diffraction or seeing limits (Bailey, 1998a,b; Porter et al., 2004; Whelan & Garcia, 2008).

Bailey (1998b) already predicted that ‘... a large telescope using low-order adaptive optics to achieve image sizes of ~ 0.1 arc second in the IR should be able to use spectroastrometry to make measurements to ~ 100 micro-arcsec’, which is roughly equivalent to the separations of Solar System-like moons at distances of the order of tens of parsecs. We derive improved estimates of the signal and noise for spectroastrometry of photometric points, and we show that the upcoming class of extremely large telescopes (ELTs), with the European ELT as archetype, will indeed be capable of detecting and characterising nearby mild-to-warm tidally heated exomoons (THEMs) of sizes and separations such as those found in our Solar System and compatible with moon formation theory, with relatively little regard for inclination or orientation of the satellite orbit.

In contrast, satellites with the expected mass ratios of $\sim 10^{-4}$ compared to their host predicted by Canup & Ward (2006) at medium-to-wide planet-moon separations will remain elusive even with future instrumentation for most other methods (Ruffio et al., 2023; Lazzoni et al., 2022). Additionally, those other methods impose a restrictive orientation of the orbit of the satellite (for planet-transiting moons or radial velocity detections; Lazzoni et al. 2022) or require a fortuitous transiting orientation of the host planet with respect to its star (Kipping, 2009a,b). We show that spectroastrometry only imposes a weak orientation preference on observations that is complementary to that required for the radial velocity and planet-transit methods.

We structure the analysis as follows: we begin by presenting the spectroastrometric signal, noise, and some their basic and derived properties in Sections 3.2.1 to 3.2.5, followed by a description of our benchmark scenario in Section 3.2.6. The results for this

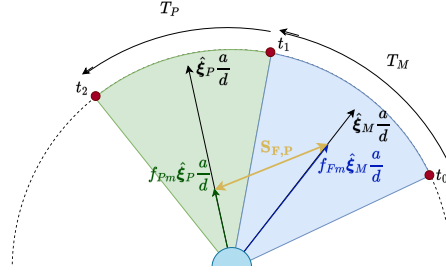


Figure 3.1: Illustration of the geometry underlying the calculation of the spectroastrometric signal in the face-on case ($p = 1$).

benchmark scenario are presented in Section 5.3, and the limitations of our analysis, the repercussions with respect to current-generation telescopes, and a comparison with other moon detection and characterisation methods are presented in Section 3.4. We conclude matters in Section 3.5.

3

3.2 Methods

In the following, we present the framework upon which our analysis is based. It is structured as follows: in Sections 3.2.1 and 3.2.2 we introduce the spectroastrometric signal and some of its basic properties, followed by a discussion on the contaminating noise sources in Section 3.2.3 and the consequences on observation design in Section 3.2.4. We then derive an expression for the minimum flux a moon must have to be detectable at a given signal-to-noise ratio given any instrument specifications in Section 3.2.5, and introduce the model scenario used to evaluate the efficacy of spectroastrometry in detecting Solar System-like moons in Section 3.2.6.

3.2.1 The centroid and the spectroastrometric signal

In defining the spectroastrometric signal, we take an approach that differs from that taken by Agol et al. (2015); this framework allows us to compute several additional error estimates. Motivated by the idealised mathematical limit of the photon-count averaged centre of light on a detector D for ever smaller pixels, we shall define the centroid for an observation over a time interval T_F through a filter F , $\mathbf{c}_F$, as the photon count-weighted integral over all positions $\mathbf{c}$ over the course of an observation O , during which a total of N_F photons are counted as follows:

$$\mathbf{c}_F = \frac{1}{N_F} \int_{O,D} \mathbf{c} N_F(\mathbf{c}). \quad (3.1)$$

The differential photon count hitting the detector for each position $\mathbf{c}$, $N_F(\mathbf{c})$, can be rewritten, accounting for the fact that the incoming photon rate is a function of the detector location it hits and of time, t . We choose to ignore the effect of the photon path through the instrument, such that we can then write $N_F(\mathbf{c}) = I_F(\mathbf{c}, t) \Omega t S$ with I_F the photon intensity through the filter F originating from the point $\mathbf{c}$ on the celestial sphere at time t , Ω the

infinitesimal area on the detector that the photons hit (expressed as solid angle on the celestial sphere), and S the infinitesimal area of the telescope aperture that the photon field passes through. If we furthermore assume that the total photon flux originating from the part of the sky we observe through the filter F , $F_F = \int_D I_F(\mathbf{c}, t) \Omega$, is constant throughout the observation such that $N_F = F_F T_F S$, we obtain:

$$\mathbf{c}_F = \frac{1}{T} \int_T \left(\frac{1}{F_F} \int_D \mathbf{c} I_F(\mathbf{c}, t) \Omega \right) t \quad (3.2)$$

where S was taken outside the integral as we had assumed the photon flux on the detector to be independent of the photon path through the instrument. The outermost integral is ostensibly a time-average, while

$$\mathbf{c}_F(t) = \frac{1}{F_F} \int_D \mathbf{c} I_F(\mathbf{c}, t) \Omega \quad (3.3)$$

is the photon flux-averaged centre of light at time t . We have thus shown that the centroid as measured from an observation is the time-averaged value of the instantaneous centroid $\mathbf{c}_F(t)$ over the duration of that observation: $\mathbf{c}_F = \langle \mathbf{c}_F(t) \rangle_T$.

We note that for an $I_F(\mathbf{c}, t)$ that is point-symmetric about some point $\mathbf{c}_0(t)$ we have $\mathbf{c}_F(t) = \mathbf{c}_0(t)$: motivated by this observation, we shall now assume that we are observing a planet-moon system (we note, however, that computation of the centroid of an observation according to Eq. 3.1 does not require this assumption), such that we can decompose the intensity originating from any given on-sky location into that originating from the planet (denoted by the subscript p) and that originating from the moon (with the corresponding subscript m). Then, by linearity of the integral:

$$\mathbf{c}_F = \frac{F_{Fp}}{F_F} \langle \mathbf{c}_{Fp}(t) \rangle_{T_F} + \frac{F_{Fm}}{F_F} \langle \mathbf{c}_{Fm}(t) \rangle_{T_F} \quad (3.4)$$

where F_{Fp} (respectively F_{Fm}) is the flux in the filter F due to the planet (respectively moon). We observe that so long as the point-spread function (PSF) for our telescope is point-symmetric, we have that the components $I_{Fp}(\mathbf{c}, t)$ and $I_{Fm}(\mathbf{c}, t)$ of our intensity are respectively point-symmetric about the on-sky position of the planet and moon, which we shall denote $\mathbf{c}_p$ and $\mathbf{c}_m$, such that finally:

$$\mathbf{c}_F = \langle \mathbf{c}_p(t) \rangle_{T_F} + \frac{F_{Fm}}{F_F} \langle \mathbf{c}_m(t) - \mathbf{c}_p(t) \rangle_{T_F}, \quad (3.5)$$

analogous to Eq. 4 in Agol et al. (2015). We must note, though, that here we have shown that filter fluxes must be expressed in photon fluxes, not energy fluxes, for this relation to hold. For notational brevity, we shall henceforth write $\mathbf{c}_m(t) - \mathbf{c}_p(t) = \mathbf{c}_{mp}(t)$ for the on-sky projected angular separation of the two bodies. In imitation of the approach Agol et al. (2015) take to forego the necessity of a reference position, we then define the spectroastrometric signal $S_{M,P}$ as the absolute difference between the centroid location in a filter M in which we expect to observe the moon (the ‘moon filter’; not to be confused with the notation for absolute magnitude used in other literature) and another filter P in which we

expect the planet to be dominant (the ‘planet filter’); we remark that we also differentiate between the periods over which the two observations were made, T_M and T_P respectively:

$$\begin{aligned} S_{M,P} &= \mathbf{c}_M - \mathbf{c}_P \\ &= \frac{F_{Mm}}{F_M} \langle \mathbf{c}_{mp}(t) \rangle_{T_M} - \frac{F_{Pm}}{F_P} \langle \mathbf{c}_{mp}(t) \rangle_{T_P} \end{aligned} \quad (3.6)$$

where we have assumed that the time-averaged position of the planet over both the periods T_M and T_P is identical. As we shall encounter these quantities more often, let us denote the fraction of the flux in the band M (respectively P) due to the moon, $\frac{F_{Mm}}{F_M}$ (respectively $\frac{F_{Pm}}{F_P}$), as f_{Mm} (respectively f_{Pm}).

3.2.2 The spectroastrometric signal for closed Keplerian orbits

For $\langle \mathbf{c}_{mp}(t) \rangle$ an analytic solution exists in terms of known quantities from orbital mechanics for all closed Keplerian orbits. One can then show that the expected value of the signal for a given observation of a moon with unconstrained inclination i and ω (i.e. a flat prior on both i and ω) is given by:

$$S_{M,P} = \frac{\gamma a f_{Mm}}{d} \hat{\xi}_F - \frac{f_{Pm}}{f_{Mm}} \hat{\xi}_P \quad (3.7)$$

with γ a parameter describing our knowledge of the inclination i and orientation (through ω) of the moon; if i and ω are unconstrained (i.e. uniformly distributed), we have $p \approx 0.842$ if instead the moon is positioned in the worst possible orientation (edge-on i.e. $i = \pi/2$), we have $p = 2/\pi$; in the best possible orientation (face-on i.e. $i = 0$) we have $p = 1$. $\hat{\xi}_M$ (respectively $\hat{\xi}_P$) is the non-dimensionalised time-averaged in-orbit position over the time period T_M (respectively T_P) of the moon, and d is the system-observer distance. An illustration of the geometry involved is given in Fig. 3.1.

It will suffice for now to know that it can be shown that the time-averaged in-orbit position depends on the orbital properties of the moon according to Eq. 3.8:

$$\hat{\xi} = \frac{P}{2\pi T} \left(\frac{(1 - \frac{e^2}{2}) \sin E - \frac{e}{4} \sin 2E}{(1 - e^2)^{1/2} (\frac{e}{4} \cos 2E - \cos E)} \right) \Big|_{E_0}^{E_1} - \left(\frac{\frac{3e}{2}}{0} \right) \quad (3.8)$$

where P (not to be confused with the filter P , which only appears in subscripts) and e are the period and eccentricity of the orbit of the moon, T is the timespan over which we observe in the filter of interest, and E_0 and E_1 are the eccentric anomaly at the start and end of the observation in that same filter, respectively. For a given time since periapsis, E_0 and E_1 can be calculated by solving Kepler’s equation, for which a variety of solution methods exist; we employ the non-iterative method described by Markley (1995).

3.2.3 Sources of spectroastrometric noise

There are, however, several sources of noise that will contaminate the signal. In the following, we shall describe relevant noise sources and their corresponding expressions,

as follows: (1) photon shot noise, (2) pixel noise, (3) background and instrument flux noise and (4) pointing noise. We (will) note that each of these noise sources acts upon each of the measured centroids individually (that is, per filter) and independently. We will therefore consider in the following the noise that each of these sources imparts upon the measured centroid in a filter, noting that these noise sources are present in both the filter M and the filter P . We can then combine the two into the resulting total noise for the spectroastrometric signal in Sec. 3.2.3.

Photon noise

The PSF of the telescope is not just the reason by which we cannot resolve the moon and planet directly on the exposure; the resulting spread in photon arrival locations causes an inherent and unavoidable variance in the measured centroid, given that we can only ever take a finite sample of the PSF. Under the condition of point symmetry of the PSF we have for the photon noise σ_{PN} :

$$\sigma_{PN} = \frac{\sigma_{PSF}}{\sqrt{N}} \quad (3.9)$$

where σ_{PSF} is the standard deviation of the PSF for a single sample (i.e. a single photon) and N is the number of photons observed in the filter. For a diffraction-limited telescope, the Gaussian approximation of the Airy disc used by Agol et al. (2015), where $\sigma_{PSF} = 0.45\lambda_c/D$ (with λ_c the central wavelength of the observation filter and D the telescope diameter), gives a useful general expression, but where available an estimate from PSF shape models would of course be preferred. As we use the ELT as archetype for the full class of extremely large telescopes (for which PSF models are not yet available), we will use the expression by Agol et al. (2015) in our simulations, but prefer to retain σ_{PSF} in expressions.

Pixel noise

Another source of noise derives from the fact that we are not probing the actual on-sky intensity distribution, but a pixelated version thereof. The finite size of the pixels on our detectors means that we lose some information about each detected photon. An upper bound for the noise that this introduces is given by

$$\sigma_{px} = \frac{\alpha}{\sqrt{2N}} \quad (3.10)$$

with α the pixel width, and N again the total number of photons observed in the filter.

Background and instrument flux noise

The noise in background and instrument flux will also give rise to noise in the measured centroid. An upper bound for this contribution is given by

$$\sigma_n = \sqrt{\frac{6}{5}} \left(\frac{1}{6} \left[\frac{6\sigma_{PSF}}{\alpha} \right] \right) \frac{\alpha}{\sqrt{N}} \quad (3.11)$$

under the assumptions that the planet detection in the flux is $\geq 5\sigma$, that we sample the centroid from the detector region encompassing the 3σ -region of the PSF (which contains $> 97\%$ of the incoming flux) and that the noise is uncorrelated between pixels.

Pointing noise

The imperfect pointing accuracy of the telescope will also impact the extracted centroid; we can account for this by assuming that each observed photon has a further random offset dictated by the pointing accuracy of the telescope. In that case, the mathematical framework works out precisely as for the PSF, so long as the timescale on which the telescope pointing is affected by inaccuracies is significantly lower than the total time of the exposure, such that photons can be assumed to be independently affected. In the case of the ELT, the uncompensatable random errors vary on subsecond timescales (Rodeghiero et al., 2021), such that we deem this a reasonable assumption. METIS will achieve fine-guiding accuracies below $0.02\lambda/D$ (Brandl et al., 2021), which translates to a worst-case pointing offset below $\sigma_{PO} \approx 1$ mas, such that we can expect the pointing inaccuracy σ_p to be at the very greatest

$$\sigma_p = \frac{\sigma_{PO}}{\sqrt{N}}. \quad (3.12)$$

This term is negligible for the ELT, but may be important or even limiting for space telescopes in particular.

This treatment then accounts for random pointing noise; systematic pointing offsets can be removed by referencing against the reference objects used. If possible with the given coronagraphic system, the central star or another bright co-moving object would be a suitable candidate. Otherwise, a background object can be used. As such objects are in general far brighter than the planet, the corresponding spectroastrometric noise is likely to be negligible. If the telescope reacquisition pointing accuracy between different filters allows for it, referencing against other objects may even become unnecessary. This may introduce systematic bias if there is an unknown offset between filters (e.g. due to imperfect adaptive optics), however, and so this should be carefully accounted for.

Total noise

The fact that all noise sources go as $N^{-1/2}$ motivates us to combine them into one term, such that we can describe the total noise in a filter as $\sigma_{tot} = \sigma N^{-1/2}$. We can consider the noise σ to be an ‘effective noise per photon’, and under the assumption that all noise sources are independent we can calculate σ to be

$$\begin{aligned} \sigma &= \sqrt{N}\sigma_{tot} = \sqrt{\sigma_{PN}^2 + \sigma_{px}^2 + \sigma_n^2 + \sigma_p^2} \\ &= \sqrt{\sigma_{PSF}^2 + \sigma_{PO}^2 + \left(\frac{1}{2} + \frac{1}{30} \left[\frac{6\sigma_{PSF}}{\alpha} \right]^2\right) \alpha^2}. \end{aligned} \quad (3.13)$$

It is instructive to remark that σ for the both filters, σ_M and σ_P , is a property inherent to a given filter on a given telescope, but it does not depend on the object to be observed.

The combined noise σ affects the measured centroids of both of the filters in question. Assuming that these two measured centroids are statistically independent, the total noise in the measured spectroastrometric signal, σ_S , is then:

$$\begin{aligned}\sigma_S &= \sqrt{\sigma_{tot,M}^2 + \sigma_{tot,P}^2} = \sqrt{\frac{\sigma_M^2}{N_M} + \frac{\sigma_P^2}{N_P}} \\ &= \frac{1}{\sqrt{S_{eff}\varepsilon}} \sqrt{\frac{\sigma_M^2(1-f_{Mm})}{F_{Mp}T_M} + \frac{\sigma_P^2(1-f_{Pm})}{F_{Pp}T_P}}\end{aligned}\quad (3.14)$$

with ε being the achromatic efficiency of the telescope and S_{eff} its effective surface area, where we have used that $N_M = S_{eff}\varepsilon T_M F_{Mp}/(1-f_{Mm})$ (an analogous expression of course holds for N_P).

Note that it follows directly from Eq. 3.14 that the best planet filter P to observe in so as to minimise the noise is the one in which F_{Pp}/σ_P^2 is maximised; the same conclusion holds for the moon filter F , so long as the moon is expected to be sufficiently luminous in this filter, too.

3.2.4 Consequences for the observation time allocation

From Sec. 3.2.3 we can conclude an important guideline for observations: namely, one can show that given a fixed total observation time $T = T_M + T_P$, there exists an allocation between T_M and T_P such that σ_S as given by Eq. 3.14 is optimised. This time allocation can be shown to satisfy the relation

$$\frac{T_M}{T_P} = \frac{\sigma_M}{\sigma_P} \sqrt{\frac{F_{Pp}}{F_{Mp}}} \sqrt{\frac{1-f_{Mm}}{1-f_{Pm}}} \approx \frac{\sigma_M}{\sigma_P} \sqrt{\frac{F_{Pp}}{F_{Mp}}}.\quad (3.15)$$

The approximation is justified by noting that for a suitable planet filter P we ought to expect that $f_{Pm} \approx 0$, and if the moon does not fully dominate in M , $\sqrt{1-f_{Mm}} \approx 1$ is also reasonable. As this approximated optimal time allocation requires no a priori knowledge of any tentative moon, we find it most representative to perform our evaluation of the method using this time allocation. We wish to note that this optimal time allocation is equally valid for the noise estimate used by Agol et al. (2015), though they do not appear to have taken note of it.

3.2.5 Minimum required moon flux

In general, unfortunately, we have no a priori knowledge of the expected flux of moons. Moreover, we are interested not in the signal-to-noise ratio produced by a specific moon, but rather we would like to answer the converse question: the luminosity a moon ought to have such that it is detectable with at least a given signal-to-noise ratio S/N . One can take Eqs. 3.7 and 3.14 to arrive, after some manipulation, at a criterion for detectability:

$$\begin{aligned}\hat{\xi}_M^2 f_{Mm}^2 + (C_M - 2f_{Pm}\hat{\xi}_M \cdot \hat{\xi}_P) f_{Mm} \geq \\ C_M + C_P - f_{Pm}^2 \hat{\xi}_P^2,\end{aligned}\quad (3.16)$$

where

$$C_M = \left(\frac{S/Nd\sigma_M}{a\gamma} \right)^2 \frac{1}{\epsilon S_{eff} F_{Mp} T_M}, \quad (3.17)$$

$$C_P = \left(\frac{S/Nd\sigma_P}{a\gamma} \right)^2 \frac{1 - f_{Pm}}{\epsilon S_{eff} F_{Pp} T_P}. \quad (3.18)$$

This is a quadratic form in f_{Fm} , whence one can derive the following minimum flux requirement for detectability at the specified signal-to-noise ratio:

$$\frac{F_{Mm}}{F_{Mp}} \geq \frac{A + \sqrt{B}}{D} \quad (3.19)$$

with

$$A = \frac{C_M}{2} + C_P + f_{Pm} \hat{\xi}_M \cdot \hat{\xi}_P - f_{Pm}^2 \hat{\xi}_P^2 \quad (3.20)$$

$$B = \left(\frac{C_M}{2} - f_{Pm} \hat{\xi}_M \cdot \hat{\xi}_P \right)^2 - \hat{\xi}_M^2 \left(f_{Pm}^2 \hat{\xi}_P^2 - C_M - C_P \right) \quad (3.21)$$

$$D = \left(\hat{\xi}_M - f_{Pm} \hat{\xi}_P \right)^2 - C_P. \quad (3.22)$$

This, should be stressed, holds for all closed Keplerian orbits, given the expression for $\hat{\xi}$ in the form of Eq. 3.8, so long as $D > 0$. This latter constraint follows when writing Eq. 3.16 as a form that is quadratic in F_{Mm}/F_{Mp} , and it is satisfied roughly when $C_P \lesssim 1$ such that

$$\frac{S/N\sigma_P}{\sqrt{\epsilon S_{eff} F_{Pp} T_P}} \lesssim \frac{a\gamma}{d}. \quad (3.23)$$

Note that the moon fluxes in either band are, of course, both unknown quantities; as f_{Pm} is relatively low (close to zero) if a suitable planet filter P was chosen, it is more informative (and receptive to implicit computation) to put constraints on F_{Mm} as a function of f_{Pm} than the other way around. If one can relate f_{Mm} and f_{Pm} to a set of defining parameters (say, for example, the surface temperature and radius of a moon), it is then possible to solve the constraint posed by Eq. 3.19 implicitly, given a set of orbital and observation parameters.

3.2.6 Model scenario

To assess the limits of what types of Solar System-like moons may be detectable in nearby systems in the near-future using ELT-class telescopes, we explore a benchmark scenario. We take METIS as reference instrument, given that its capability to detect Earth-sized planets around nearby stars in thermal emission has been well-established (Brandl et al., 2021); it should therefore not be problematic to reach a 5σ detection (in flux) of a giant planet, so as to satisfy the assumptions required for Eq. 3.11. The telescope model parameters are summarised in Table 3.1. For the moon filter M , we take the $N2$ -filter as it is the longest-wavelength continuum filter on METIS, which will therefore be best-suited

Table 3.1: Telescope and system model parameters used in the benchmark scenario.

Quantity	Value	Reference
METIS/ELT properties		
Planet filter P	M'	-
Moon filter M	$N2$	-
Diameter [m]	37	C20
System throughput [-]	0.36	C20
Atmospheric transmission [-]	0.8	J13, N12
σ_{PSF} in P [mas]	12.0	-
σ_{PSF} in M [mas]	28.1	-
Model system properties		
Reference distance [pc]	3.6481	P16, V23
Planet mass [M_{Jup}]	3.25	F19
Age [Gyr]	> 3.0	F19

C20: Carlomagno et al. (2020); J13: Jones et al. (2013); N12: Noll et al. (2012); P16: Prusti et al. (2016); V23: Vallenari et al. (2023); F19: Feng et al. (2019). Brandl et al. (2021) give an overview of the METIS optical system and pixel sizes.

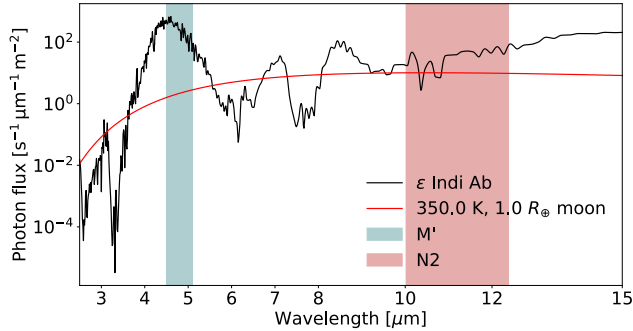


Figure 3.2: Spectrum for ϵ Indi Ab, generated from *ATMO2020* assuming a $3.25 M_{Jup}$, 3 Gyr planet, and equilibrium chemistry; the chosen M' and $N2$ bands are marked. Also shown is the extreme scenario of a 350 K, Earth-sized blackbody moon, for which it is clear that the planet still dominates by ~ 2 orders of magnitude in M' , while the moon contributes an appreciable fraction of the flux in $N2$, such that a spectroastrometric signal may be observed between the two filters. We note that the region from $5.5\text{--}7.5 \mu\text{m}$, though it has promising absorption regions, is inaccessible from the ground.

to capture low-temperature (< 300 K) thermal emission. For the planet filter P , by contrast, we choose the near-infrared filter M' , which captures a region in which giant planets such as Jupiter, Saturn (Roman, 2023) and higher-mass exoplanets (Phillips et al., 2020) are luminous, while remaining stiff to the types of temperatures expected globally for tidally heated moons (see e.g. Dobos & Turner 2015). As an example, the used spectrum for ε Indi Ab (which we shall justify shortly) is shown with a 350 K, Earth-sized moon (representing an upper bound on the hottest, largest plausible moons) for comparison in Fig 3.2: it is clear that the planet still dominates wholly in M' , while the moon has an appreciable contribution in $N2$. METIS requirements mandate that its optical system is diffraction-limited (Brandl et al., 2021), which we will therefore take as an assumption on the PSF-width. Atmospheric transmission is set to an achromatic 80%, based on a representative scenario simulated using ESO's *SkyCalc* (Jones et al., 2013; Noll et al., 2012). We set an observation time of 6 hours, representing a length of night that can be reasonably expected to occur regularly at the ELT site (Lombardi et al., 2009), though we note that with a scaling of the noise with $T^{-1/2}$, our results are relatively stiff to the total observation time.

We model a reference moon-planet system based on ε Indi Ab, the nearest Jupiter analogue known imageable by JWST (and thus, presumably, ELT), and its nominal parameters as determined by Feng et al. (2019). The parameters necessary for this analysis are given in Table 3.1; based on this planet mass and age, a spectrum is interpolated from the chemical equilibrium atmosphere-spectra in the publically available atmosphere library *ATMO2020* by Phillips et al. (2020). As their simulated atmospheres only provide data for planets of this mass up to ages of ~ 3 Gyr, we cannot take an age in the age range of 3.7 – 4.3 provided by Feng et al. (2019), though we note that preliminary results using *ATMO2020* show that in this case the spectroastrometric signal-to-noise ratio is increasing with age of the planet (i.e. with decreasing temperature): this makes an age of 3 Gyr conservative.

In imitation of Solar System moons (with the notable exception of Titan), we assume the moon to be an airless icy or rocky body. In such a case, the observed brightness temperature in the infrared agree relatively well with the surface temperature (to within a couple ~ 10 K), regardless of surface material (see e.g. Hu et al. 2012; Whittaker et al. 2022); integrated brightness temperatures of Jupiter's icy moons Ganymede and Callisto agree relatively well with their expected surface temperatures (Squyres, 1980). We therefore choose to model the moon as a black body, such that the only free parameters that remain to explore are (1) its size (but notably not directly its mass), (2) its surface temperature and (3) its orbital properties. Each of these we vary over ranges made plausible by a combination of observed Solar System moons and moon formation theory, so as to explore the signal-to-noise ratio of the spectroastrometric signal. In particular, we vary the size between an Io-radius and an Earth-radius, which, allowing the satellite to be either icy or rocky, covers the full range of expected moon masses of $10^{-5} - 10^{-3}$ host masses for large satellites proposed in literature (e.g. Canup & Ward 2006; Cilibrasi et al. 2018; Moraes et al. 2018). We vary the semi-major axis over the range seen for the Galilean satellites.

While analysis of time-series observations of the system under the assumption of a moon on a Keplerian orbit may allow one to produce higher-significance detections (see

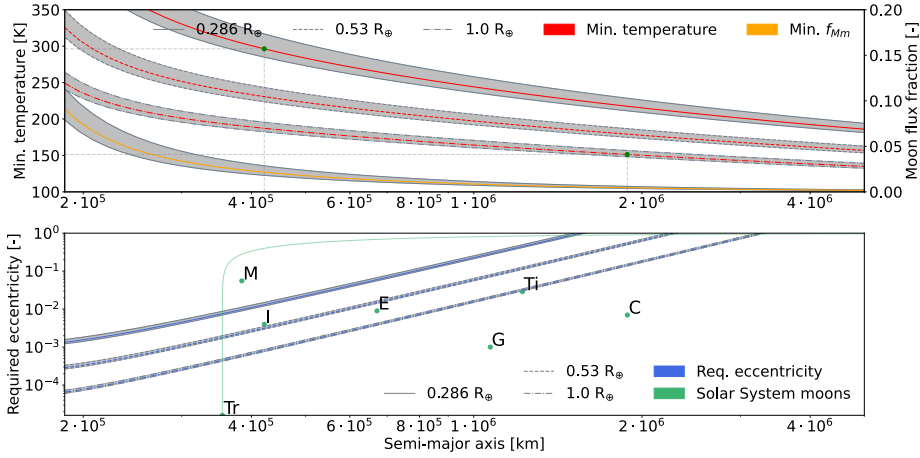


Figure 3.3: Minimum blackbody temperature and corresponding moon flux fraction in M for a total observation time of 6 hours on ELT/METIS as a function of semi-major axis for 5σ detectability of a moon around ε Indi Ab for an Io-sized, Mars-sized, and Earth-sized moon (top), with a corresponding first-order estimate of the required eccentricity (bottom). The grey region delineates the area bounded by the edge-on and face-on cases ($p = 2/\pi$ and $p = 1$); the red and blue lines correspond to the inclination-averaged case ($p \approx 0.842$). Semi-major axes and eccentricities of the seven largest Solar System moons Ganymede, Titan, Callisto, Io, the Moon, Europa and Triton are marked by their first letter(s). The post-capture migration path of Triton assuming conservation of angular momentum (such as in Ross & Schubert 1990) is also marked to illustrate the observational potential of captured moons. The moons used for further analysis in Secs. 3.3.2 and 3.3.3 are marked in green in the top plot. For all three moons over all explored semi-major axes, the minimum 5σ -detectable temperature corresponds to a spectroastrometric signal of roughly 0.013 mas.

Sec. 4.2.2 in Agol et al. (2015) for an example), we prefer to analyse solely the spectroastrometric signal in one observation, as it requires no assumptions on the nature of the signal. A high-significance detection of a spectroastrometric signal would therefore provide incontrovertible evidence of a signal of astrophysical origin, regardless of whether it is a moon or not; further analysis and conclusions on the nature of this signal can then follow.

3.3 Results

We structure our results as follows; we examine the minimum temperature required for detectability in circular orbits as a function of semi-major axis in Sec. 3.3.1, and perform a first-order analysis of the required eccentricities for these temperatures under the assumption that the detectability is only marginally affected by low eccentricities. We

validate this assumption in Sec. 3.3.2, and finally perform an analysis of the attainable signal-to-noise ratios as a function of moon blackbody temperature and distance for two sample moons of given size and semi-major axis in Sec. 3.3.3.

3.3.1 Minimum moon temperature for detectability

Fig. 3.3 shows the minimum required blackbody temperature of a moon for various sizes (corresponding to Io, Mars and the Earth) to be detectable at 5σ in a circular orbit around ε Indi Ab, assuming a total of 6 hours of observation time. Also shown is a first-order estimate of the eccentricities required for each of the various size bodies at each semi-major axis to reach the given minimum temperature by assuming radiative equilibrium of a blackbody moon experiencing viscoelastic dissipation as given by Segatz et al. (1988) and using the value of $-\text{Im}(k_2)$ given for Io by Lainey (2016). For comparison, the semi-major axes and eccentricities of the seven largest Solar System moons are marked; as Triton currently has a circular orbit but is known to have migrated to its current position after capture over a timespan of ~ 1 Gyr (Ross & Schubert, 1990; McKinnon & Kirk, 2014), its constant-angular momentum post-capture evolution as described by Ross & Schubert (1990) is also drawn. The value of f_{Mm} corresponding to these minimum temperatures is also shown; over the explored semi-major axis values, f_{pm} for the minimum detectable temperatures is negligible, and so the required values of f_{Mm} coincide. For this same reason, the spectroastrometric noise is nearly constant across all semi-major axes at ~ 0.0026 mas, corresponding to a minimum detectable spectroastrometric signal of ~ 0.013 mas.

3.3.2 Eccentricity effects

Fig. 3.4 shows the minimum moon blackbody temperature for two sample moons (that will be explored and justified in further detail in Sec. 3.3.3) at an ε Indi Ab-like system-observer distance at a variety of eccentricities and orbital phases covering all possibilities for the inclination-averaged case ($p \approx 0.842$). The green and blue lines, indicating the minimum required temperature for $e = 0$ and ± 10 K deviations from that contour, show that the required temperature for moons with Solar System-like eccentricities ($e \lesssim 0.1$) is in general well-approximated by the required temperature for the circular case throughout the orbit; additionally, the required temperature for detectability is in fact in all cases lower than for the circular case over $> 50\%$ of the orbit.

3.3.3 Applicability to distant systems

The results presented in Secs. 3.3.1 and 3.3.2 suggest that there is a set of nearby systems in which planet-like moons of directly imageable giant planets can be detected. This motivates us to explore the extent of this viable detection space for two scenarios, representing the end-points of what Lazzoni et al. (2022) deem the class of planet-like satellites (namely those formed by core accretion in the CPD, analogous to most Solar System satellites): (1) an Io-sized moon at Io-like separation from its host and (2) an Earth-sized moon at a Callisto-like separation from its host. The first requires the least number of assumptions, as it is a type of moon observed in the Solar System, and tidal

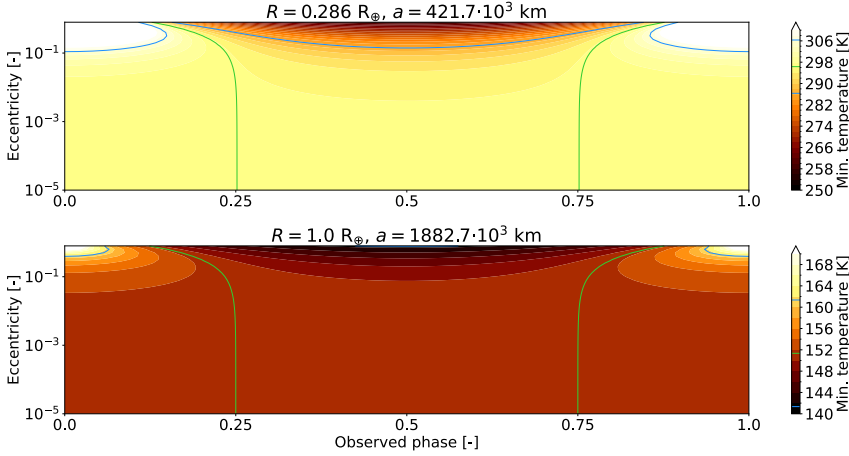


Figure 3.4: Minimum temperature for 5σ detectability as a function of the observed orbital phase and eccentricity for an Io-like moon with an Io-like semi-major axis (top) and for an Earth-like moon with a Callisto-like semi-major axis (bottom). The green and blue contours indicate the contour corresponding to the nominal (zero-eccentricity) required temperature (as marked on the top plot in Fig. 3.3), and the 10 K deviations from this temperature, respectively; in both cases, these are also marked on the colourbar. We note that in all non-zero eccentricity cases the temperature required for observability is in fact lower than for the circular case over $> 50\%$ of the orbit.

heating-mechanisms through which it might reach temperatures to be luminous in the IR over observable timescales are well-established (e.g. Dobos & Turner 2015; Rovira-Navarro et al. 2021). The second would be on the larger end of what one expects to see around a host like ϵ Indi Ab according to moon formation studies such as Canup & Ward (2006), though more recently Cilibrasi et al. (2018) produced results that seem to suggest such masses may be attainable. Additionally, where fixed-Q tidal theory would predict that such a far-out moon should be unlikely to experience significant tidal interactions, the recently proposed paradigm of resonance locking would allow such far-out moons to experience tidal interactions still (Fuller et al., 2016; Lainey et al., 2020). These two cases should therefore in principle bracket the full range of plausible planet-like moons that might be expected to be luminous in the IR; the signal-to-noise ratio as a function of blackbody temperature and system-observer distance for these two cases are illustrated in Fig. 3.5.

3.4 Discussion

Figs. 3.3 and 3.5 indicate that spectroastrometry may be able to provide detections of large icy moons (with surface temperatures as low as $T_s \lesssim 150 \text{ K}$) or even smaller, hot rocky moons (with surface temperatures as low as $T_s \lesssim 300 \text{ K}$) in nearby systems; such

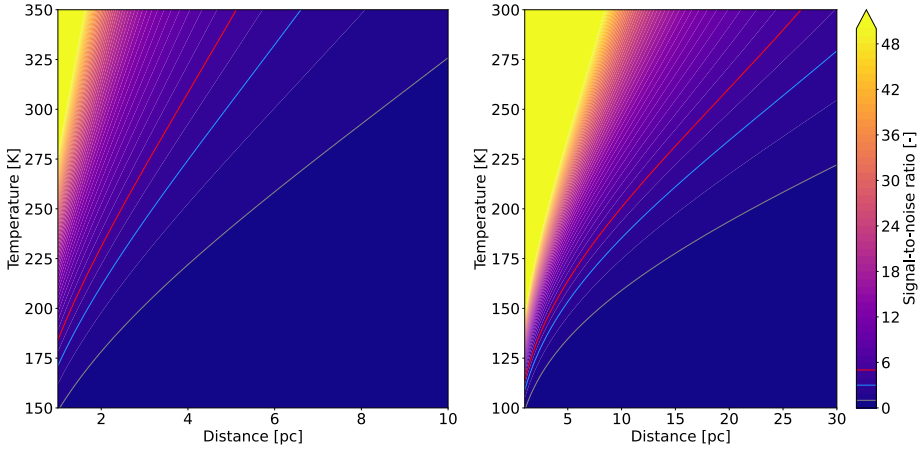


Figure 3.5: Signal-to-noise ratio for an Io-sized moon on an Io-like orbit (left) and an Earth-sized moon on a Callisto-like orbit (right) around an ε Indi Ab-like planet as a function of blackbody temperature and system-observer distance (we note that the axis scale and datum differ between the two moons). The grey, blue, and red lines mark the 1σ , 3σ , and 5σ boundaries, respectively.

temperatures are plausible for tidally heated moons on orbits comparable to modern-day Solar System moons (e.g. Dobos & Turner 2015; Forgan & Dobos 2016; Rovira-Navarro et al. 2021) and easily exceeded by conditions as have been presumed to exist in the early Solar System (e.g. Ross & Schubert 1990), potentially over Gyr timescales (McKinnon & Benner, 1990; Lunine & Nolan, 1992). The possibility of observing large icy moons at low temperatures is interesting, as the large icy moons Ganymede and Callisto in our Solar System have (and are stable at) surface (and brightness) temperatures of order ~ 150 K (Squyres, 1980) (though a large part of this is contributed by solar flux), and the largest and most massive moons are thought to form at or beyond the ice line of their CPD (Heller & Pudritz, 2015b), therefore being icy. The results for smaller hot moons are also of interest, as Rovira-Navarro et al. (2021) have shown that plausible scenarios may arise in which such temperatures are maintained for timescales $\gtrsim 1$ Gyr.

We will discuss these results in several contexts: in Sec. 3.4.1, we compare our framework against that in previous literature, and we discuss several caveats to our new formulation in Sec. 3.4.2. One may also wonder if perhaps current-generation infrared telescopes may be able to detect objects in this manner, too: we discuss what this would take in Sec. 3.4.3, and follow this up with a discussion on the applicability of spectroastrometry to moon-planet systems other than the ones we have studied in this paper in Sec. 3.4.4. Finally, we make a comparison of spectroastrometry against other methods in Sec. 3.4.5 and discuss what combinations with other methods may possibly allow unambiguous detection, characterisation and confirmation of moon candidates in Sec. 3.4.6.

3.4.1 Comparison to previous work

While we have expanded the framework provided by Agol et al. (2015) to work for closed Keplerian orbits in general (Sec. 3.2.2) and to include additional noise bounds (Sec. 3.2.3), a great deal of conclusions in their work still hold. In particular, the scaling of the signal-to-noise ratio as $S/N \propto (\epsilon T)^{1/2} d^{-2}$ remains generally applicable, and under the assumptions that the detector pixel size is designed to sample the PSF well (i.e. $\alpha \propto \sigma_{PSF}$), that the pointing stability noise is negligible and that the telescope is diffraction-limited we also recover the telescope-diameter proportionality $S/N \propto D^2$. Additionally, while Agol et al. (2015) do not appear to explicitly have taken note of this, (1) in their formulation the noise is a function of the spectral properties of the moon, but not of its orbit (excepting transits), (2) the spectroastrometric signal-to-noise ratio of a single observation can be straightforwardly calculated for a given observation without requiring any a priori knowledge on the nature of the observed system and (3) there exists an optimal time allocation that minimises the noise of an observation that can be well-approximated by quantities that can be known or estimated a priori (Sec. 3.2.4). Each of these conclusions still hold in our expanded formulation.

There are several additions we have gained over this previous work, however. We have shown that the viability of spectroastrometry is relatively insensitive to the orbital parameters of an exomoon with the exception of its semi-major axis and particularly high eccentricities (well exceeding those found in the Solar System). We found an expression for the best-case and worst-case inclinations as well as the expected spectroastrometric signal for a flat prior on moon inclinations. Additionally, one can show from Eq. 3.8 that in the limit of large T/P , $\hat{\xi} \rightarrow -[3e/2, 0]^T$, such that circular or small-eccentricity orbits become invisible. Further analysis of Eq. 3.8 shows that this already occurs for $T/P \gtrsim 1$. Hence, we should not expect to be able to observe moons with periods on the order of or shorter than our observation time in the relevant filter, both because their semi-major axis and the resulting orbital motion is small, which was already apparent from the work by Agol et al. (2015), but also because their signal is washed out by this time-averaging effect for $T/P \gtrsim 1$. Conversely, highly eccentric moons on short-period orbits may instead become visible precisely *because* of this time-averaging effect. While for ground-based telescopes observation times are unlikely to exceed orbital periods, this is a plausible scenario for space-based observations, which would require far longer observation time to reach a performance similar to large-diameter ground telescopes.

Additionally, we have shown that while background and instrument noise in centroid measurements for a significant ($> 5\sigma$) detection of the planet is likely to be of similar magnitude to the photon noise, the noise due to a pixelated detector (for a well-sampled PSF) and pointing stability of the telescope in question are unlikely to provide major contributions to the centroid noise, and therefore to the spectroastrometric noise.

3.4.2 Limitations on this formulation

A major limitation of the method as developed in this manner is the lack of an expression for speckle noise, which ostensibly does not satisfy the assumption of independence between pixels required for Eq. 3.11. Until this effect can be quantified, these results

should be taken only as representative for moons of far-out or free-floating planets, where speckle noise is negligible, though fortunately the majority of large exomoons are expected to occur around wide-orbit planets (Dobos et al., 2021; Heller & Pudritz, 2015a), beyond the snowline (Inderbitzi et al., 2020). If an expression or estimate for speckle noise in spectroastrometry can be found, we might be able to push spectroastrometry to find moons of close-in planets in reflected light, too, such as the case of an Earth-Moon analogue studied by Agol et al. (2015), though this would require a different (augmented) model of the moons' spectral energy distribution incorporating reflected light.

A second limitation for close-in planets is the lack of inclusion of the planet-moon barycentre movement over the observations in our formulation. While the movement thereof between observations can be accounted for if the orbital properties of the planet about its host are known, the movement throughout the observation will likely have an effect that is worth quantifying in future studies: using the orbital parameters given by Feng et al. (2023), the worst-case angular velocity (i.e. for a face-on orbit at pericentre) for ϵ Indi Ab is on the order of 0.1 mas/hr, which is of the same order as spectroastrometric effects. For wide-separation planets or edge-on planets observed at their most distant apparent separation, this effect is negligible, however. As our neglect of speckle noise means that wide-separation planets should be preferred to start with, for this effect to become strong will most likely require that speckle noise be dealt with, first.

Another matter that needs mentioning is the fact that there are objects that cannot immediately be distinguished from moons; background objects may, per chance, induce a spectroastrometric signal. Follow-up observations will, however, reject such candidates without issue, given the rapid motion expected of moons about their host that such background objects will not display. Additionally, thermal emission from asymmetric ring systems around planets will cause a signal that may mimic thermal emission from a hot moon; one could foresee such asymmetric rings arising in a miniature version of the scenario invoked by András & Rieke (2020) for the debris cloud formerly identified with Formalhaut b, for example, though notably Formalhaut b was not detectable in the infrared. As such asymmetries on a Keplerian orbit should be expected to dissipate over the order of several orbits, a signal due to such occurrences should not be expected to remain stable over observational timescales; additionally, the presence of rings (asymmetric or not) may be excluded altogether by the method proposed by Lazzoni et al. (2020), for example.

Spots or asymmetric patterns on the planet may produce an astrometric signal, too: we note that the Great Red Spot on Jupiter is dim in the infrared (Ge et al., 2019), and so we should by analogy expect any such effects to stem from larger-scale variability. For Jupiter, such rotational variability is on the order of 1% in flux around the $10.5 \mu\text{m}$ region, whereas in the $5 \mu\text{m}$ region this is roughly 20% (Ge et al., 2019). For the moon filter we can thus safely disregard this variability: the planet filter does warrant a small calculation. In the worst-case scenario of a pole-on planet with all this variability concentrated on a single spot at the equator, and with a Jupiter-like radius and rotation period of 10 hours, the resultant astrometric signal will be on the order of 10^{-2} mas. As the 20% variability on Jupiter is the result of large-scale variability, not spot-like localised variability (Ge et al., 2019), we expect that this effect will be significantly smaller in practice. Additionally, higher-mass planets are expected to have a lower rotational period (Snellen et al., 2014),

which will dampen the signal strongly if the rotational period becomes of the same order as the observation time in a filter. Nonetheless, these variability effects may thus, in the worst case, be present at an order of magnitude that will contaminate the most sensitive of our results: follow-up observations in different planet-bands (perhaps with lower variability) will then provide a conclusive result on the presence or absence of a moon.

It is thus possible to exclude background objects, (asymmetric) ring systems, or planet variability either immediately or after follow-up observations. Consequently, we expect that moons are the only objects or phenomena that can be responsible for long-term spectroastrometric signals, though any putative signal will need follow-up observations for confirmation.

3.4.3 Spectroastrometric capabilities of current-generation telescopes

As these results show that observing tidally heated exomoons on future IR telescopes is plausible, one might wonder whether current-generation IR telescopes have the capabilities required to observe tidally heated moons in nearby systems. The prime candidate here, of course, is JWST; unfortunately, the scaling of the signal-to-noise ratio with D^2 suggests that the observation time required would be on the order of days. JWST would thus only be sensitive to hot moons around nearby directly imageable planets that are less luminous than ϵ Indi Ab, none of which are currently known.

Additionally, while the fine-guidance pointing stability of JWST is of an order similar to that of ELT, target reacquisition (which would be required when switching between filters) only has accuracies on the order of mas (Hartig & Lallo, 2022), which introduces systematic error. This may be remedied if one uses astrometric observations (i.e. using a single filter) of the moon throughout its orbit instead, but in that case it still remains to be shown that the measured effect is due to motion of a moon rather than due to a third object disturbing the Keplerian motion of the planet. In fortuitous circumstances, one might also be able to use sufficiently bright background objects (that can be astrometrically positioned to the required accuracy) to reference the observations in the two filters against each other, but this requires that such objects be available and fixed. We leave it to future work to determine the viability of each of these methods to perform spectroastrometric measurements using JWST.

3.4.4 Detectability of other moon-planet systems

In this analysis, we have considered Solar System-like moons around a planet analogous to ϵ Indi Ab, as it is the nearest known Jupiter analogue that is directly imageable. However, such a system need not be optimal in terms of detectability of any moons; moreover, it is likely that with JWST operational many more directly imageable planets will be discovered in nearby system that had previously eluded detection. It is thus productive to consider what other planets might be found, or perhaps what types of moons might be detectable around them.

One such category is lower-mass planets; exploratory results using the code in this paper suggest that even lower-temperature moons will be observable around lower-mass

planets, as the relative flux of the moon then increases appreciable in the moon filter. If located in a suitable nearby system (such that stellar contamination is not a problem), this may thus allow the detection of true Solar System-analogues: that is to say, Solar System-analogue planets accompanied by Solar System-size and Solar System-temperature moons. Down to Saturn-masses this is hardly problematic, but for lower-mass planets (transitioning into the ice giant-regime) the spectral feature at $5\ \mu\text{m}$ starts to become muted (Roman, 2023; Linder et al., 2019), such that the planet will no longer outshine its moon in that band; another planet filter than M' (which was selected in a fairly ad hoc fashion) is required for ice giants. Detection of moons around such planets would thus require a more robust filter selection procedure than we have followed in our analysis of ϵ Indi Ab. Hence, we propose that in anticipation of the detection of directly imageable low-mass giant planets in nearby systems by JWST further research is done on filter performance over a wide variety of planet masses and ages.

A second category of systems does not concern the type of planet, but rather the type of moon; while we have for the purposes of our analysis explicitly remained in the familiar realm of Solar System-like moons, current exomoon candidates are ostensibly unlike the moons seen in our Solar System. The candidates put forward by Teachey et al. (2018), Teachey & Kipping (2018), Lazzoni et al. (2020) and Kipping et al. (2022) are perhaps rather thought of as binary objects; this poses unique challenges for spectroastrometry in that the spectra of two gas giant planets in a mutual orbit are likely to possess similar features qualitatively over a broad range of wavelengths. As both objects are, without requiring tidal heating, likely to be relatively bright, however, their spectroastrometric signal may still be detectable, and if so, perhaps at system distances further away than Solar System-like moons. Given the importance of such objects in informing moon formation theory (e.g. Hamers & Portegies Zwart 2018; Hansen 2019; Moraes & Neto 2020), it is worth exploring whether any filter combination might be able to detect or rule out the presence of any such moons; perhaps, even, whether a filter combination may be able to detect both Solar System-like moons and binary-like objects.

3.4.5 Comparing against other moon detection methods

Over other methods, spectroastrometry provides an additional boon in the fact that, if the barycentre motion discussed in Sec. 3.4.2 is accounted for, the astrometry produced is of a sufficient level to potentially detect the orbital motion of nearby exoplanets over a single observation; even in the absence of a moon detection, the data is therefore still useful in novel ways. Another major advantage that spectroastrometry has over the current suite of standard exomoon detection efforts is the lack of degeneracies (if observed over multiple epochs), such as those induced by unseen second planets in the case of the methods proposed for transiting planets (Fox & Wiegert, 2021; Kipping & Teachey, 2020); as one measures explicitly the movement of the moon about its planet, these third-object effects are unambiguously removed. Finally, spectroastrometry provides the possibility of repeatable observations of nearby moons as small and nearly as cold as those observed in the Solar System, far below temperatures required for other direct imaging methods for tidally heated moons (e.g. Kleisioti et al. 2023), while being relatively insensitive to the inclination or orientation of the moon or its planet.

3.4.6 Synergies with other methods

Further modelling of the moon or its orbit can further enhance the significance of results and produce predictions or constraints on quantities such as the semi-major axis, period, size, host planet mass and flux distribution between satellite and host (Agol et al., 2015) and consequently even interior properties of the satellite (e.g. Kleisioti et al. 2023) that can be (independently) verified with other methods, such as radial velocity or astrometric measurements of the planet or such as TTVs/TDVs, auxiliary stellar transits or moon-transits of the planet, if the system is fortuitously oriented. Especially noteworthy is the fact that at satellite inclinations where spectroastrometry fares poorest (near edge-on), transits of their host and radial velocity measurements become viable, which makes spectroastrometry a useful complement to those methods. Finally, mutual events (Cabrera & Schneider, 2007) observed in the infrared might provide information on the composition of the planet and moon as well as provide independent constraints on the moon orbit (Schneider et al., 2015).

Another detail of particular interest is the fact that spectroastrometry provides an independent constraint on moon and planet fluxes as well as the moon orbit that may be combined with those derivable from moon-planet models such as discussed in Kleisioti et al. (2023), which can be produced from the same direct imaging data that spectroastrometry can be performed on. In combination with the results derivable from other methods, it is therefore possible to come to a near-full characterisation of the moon in question in terms of its orbit, composition, size and surface conditions.

We would therefore like to emphasise the possible capabilities of simultaneous use of spectroastrometry over multiple epochs, photometric modelling, astrometry and transit observations of moon-transits of the planet, as all of these should in principle be possible with the same series of direct-imaging observations. Given the set of mutually independent estimates for similar parameters available between the set of these, self-consistency of any candidate can be straightforwardly checked. We therefore strongly recommend that the viability of this combination is evaluated in future studies.

3.5 Conclusion

Spectroastrometry has previously been shown to be a promising method for detection of Earth-Moon-like systems or Earth-like moons orbiting Jovians by Agol et al. (2015). We have shown that there is a further class of satellites, tidally heated moons analogous to those in the Solar System, that are observable in nearby systems using this method with next-generation ground telescopes. Illustrated by two example systems motivated by moons observed in our current-day Solar System, we see that for nearby systems even large icy bodies or hot bodies comparable in size to those seen in our Solar System may be observable.

In showing this, we have derived an expression for the spectroastrometric signal that covers all closed Keplerian orbits, along with the orbital motion of the moon throughout the observation, which shows that the efficacy of spectroastrometry is only weakly dependent on the orbital properties of an exomoon, except for moons with periods equal to or lower than the observation time, which are unlikely to be detected. Moreover, we

have derived additional conservative noise estimates for noise due to (1) background and instrument noise, (2) a pixelated detector and (3) pointing inaccuracies. This now allows evaluation of spectroastrometry as a method on telescopes other than the ideal photon-noise limited space telescopes assumed in previous research and without requiring a priori any assumptions on the orbit or nature of any potential moon.

Bibliography

- Agol, E., Jansen, T., Lacy, B., Robinson, T. D., & Meadows, V. 2015, *The Astrophysical Journal*, 812, 5, doi: [10.1088/0004-637X/812/1/5](https://doi.org/10.1088/0004-637X/812/1/5)
- András, G., & Rieke, G. H. 2020, *Proceedings of the National Academy of Sciences*, 117, 9712, doi: [10.1073/pnas.1912506117/-/DCSupplemental.y](https://doi.org/10.1073/pnas.1912506117/-/DCSupplemental.y)
- Bagheri, A., Khan, A., Deschamps, F., et al. 2022, *Icarus*, 376, doi: [10.1016/j.icarus.2021.114871](https://doi.org/10.1016/j.icarus.2021.114871)
- Bailey, J. 1998a, *Monthly Notices of the Royal Astronomical Society*, 301, 161, doi: [10.1046/j.1365-8711.1998.02010.x](https://doi.org/10.1046/j.1365-8711.1998.02010.x)
- Bailey, J. A. 1998b, in *Optical Astronomical Instrumentation*, Vol. 3355 (SPIE), 932–939, doi: [10.1117/12.316802](https://doi.org/10.1117/12.316802)
- Baland, R. M., Van Hoolst, T., Yseboodt, M., & Karatekin, Ö. 2011, *Astronomy and Astrophysics*, 530, doi: [10.1051/0004-6361/201116578](https://doi.org/10.1051/0004-6361/201116578)
- Batygin, K., & Morbidelli, A. 2020, *The Astrophysical Journal*, 894, 143, doi: [10.3847/1538-4357/ab8937](https://doi.org/10.3847/1538-4357/ab8937)
- Beuthe, M. 2015, *Icarus*, 258, 239, doi: [10.1016/j.icarus.2015.06.008](https://doi.org/10.1016/j.icarus.2015.06.008)
- . 2016, *Icarus*, 280, 278, doi: [10.1016/j.icarus.2016.08.009](https://doi.org/10.1016/j.icarus.2016.08.009)
- Bierson, C. J., & Nimmo, F. 2022, *Icarus*, 373, doi: [10.1016/j.icarus.2021.114776](https://doi.org/10.1016/j.icarus.2021.114776)
- Bills, B. G., & Nimmo, F. 2011, *Icarus*, 214, 351, doi: [10.1016/j.icarus.2011.04.028](https://doi.org/10.1016/j.icarus.2011.04.028)
- Brandl, B., Bettonvil, F., Van Boekel, R., et al. 2021, *The Messenger*, 182, 22, doi: <http://doi.org/10.18727/0722-6691/5218>
- Burnett, E., & Hayne, P. 2023. <http://arxiv.org/abs/2302.13226>
- Cabrera, J., & Schneider, J. 2007, *Astronomy and Astrophysics*, 464, 1133, doi: [10.1051/0004-6361:20066111](https://doi.org/10.1051/0004-6361:20066111)
- Canup, R. M., & Ward, W. R. 2006, *Nature*, 441, doi: [10.1038/nature04860](https://doi.org/10.1038/nature04860)
- Carlomagno, B., Delacroix, C., Absil, O., et al. 2020, *Journal of Astronomical Telescopes, Instruments, and Systems*, 6, doi: [10.1117/1.jatis.6.3.035005](https://doi.org/10.1117/1.jatis.6.3.035005)
- Cilibrasi, M., Szulágyi, J., Mayer, L., et al. 2018, *Monthly Notices of the Royal Astronomical Society*, 480, 4355, doi: [10.1093/mnras/sty2163](https://doi.org/10.1093/mnras/sty2163)
- Dobos, V., Charnoz, S., Pál, A., Roque-Bernard, A., & Szabó, G. M. 2021, *Publications of the Astronomical Society of the Pacific*, 133, doi: [10.1088/1538-3873/abfe04](https://doi.org/10.1088/1538-3873/abfe04)
- Dobos, V., Haris, A., Kamp, I. E. E., & van der Tak, F. F. S. 2022, *Monthly Notices of the Royal Astronomical Society*, 513, 5290, doi: [10.1093/mnras/stac1180](https://doi.org/10.1093/mnras/stac1180)
- Dobos, V., & Turner, E. L. 2015, *Astrophysical Journal*, 804, doi: [10.1088/0004-637X/804/1/41](https://doi.org/10.1088/0004-637X/804/1/41)
- Feng, F., Anglada-Escudé, G., Tuomi, M., et al. 2019, *Monthly Notices of the Royal Astronomical Society*, 490, 5002, doi: [10.1093/mnras/stz2912](https://doi.org/10.1093/mnras/stz2912)
- Feng, F., Butler, R. P., Vogt, S. S., Holden, B., & Rui, Y. 2023, *Monthly Notices of the Royal Astronomical Society*, 525, 607, doi: [10.1093/mnras/stad2297](https://doi.org/10.1093/mnras/stad2297)
- Forgan, D., & Dobos, V. 2016, *MNRAS*, 457, 1233, doi: [10.1093/mnras/stw024](https://doi.org/10.1093/mnras/stw024)
- Fox, C., & Wiegert, P. 2021, *Monthly Notices of the Royal Astronomical Society*, 501, 2378, doi: [10.1093/mnras/staa3743](https://doi.org/10.1093/mnras/staa3743)
- Fuller, J., Luan, J., & Quataert, E. 2016, *Monthly Notices of the Royal Astronomical Society*, 458, 3867, doi: [10.1093/mnras/stw609](https://doi.org/10.1093/mnras/stw609)
- Gaeman, J., Hier-Majumder, S., & Roberts, J. H. 2012, *Icarus*, 220, 339, doi: [10.1016/j.icarus.2012.05.006](https://doi.org/10.1016/j.icarus.2012.05.006)
- Ge, H., Zhang, X., Fletcher, L. N., et al. 2019, *The Astronomical Journal*, 157, 89, doi: [10.3847/1538-3881/aafba7](https://doi.org/10.3847/1538-3881/aafba7)

- Hamers, A. S., & Portegies Zwart, S. F. 2018, *The Astrophysical Journal*, 869, L27, doi: 10.3847/2041-8213/aaf3a7
- Han, C. 2008, *The Astrophysical Journal*, 684, 684
- Han, C., & Han, W. 2002, *The Astrophysical Journal*, 580, 490. <http://exoplanets.org>.
- Hansen, B. M. S. 2019, *Science Advances*, 5. <https://www.science.org>
- Hartig, G., & Lallo, M. 2022, JWST Line-of-Sight Jitter Measurement during Commissioning, Tech. rep., STScI. <https://soccer.stsci.edu>
- Heller, R., & Pudritz, R. 2015a, *Astronomy and Astrophysics*, 578, doi: 10.1051/0004-6361/201425487
- . 2015b, *Astrophysical Journal*, 806, doi: 10.1088/0004-637X/806/2/181
- Heller, R., Williams, D., Kipping, D., et al. 2014, Formation, habitability, and detection of extrasolar moons, Mary Ann Liebert Inc., doi: 10.1089/ast.2014.1147
- Hippke, M. 2015, *Astrophysical Journal*, 806, doi: 10.1088/0004-637X/806/1/51
- Hu, R., Ehlmann, B. L., & Seager, S. 2012, *Astrophysical Journal*, 752, doi: 10.1088/0004-637X/752/1/7
- Hussmann, H., Sohl, F., & Spohn, T. 2006, *Icarus*, 185, 258, doi: 10.1016/j.icarus.2006.06.005
- Hwang, K.-H., Udalski, A., Bond, I. A., et al. 2018, *The Astronomical Journal*, 155, 259, doi: 10.3847/1538-3881/aac2cb
- Inderbitzi, C., Szulágyi, J., Cilibrasi, M., & Mayer, L. 2020, *Monthly Notices of the Royal Astronomical Society*, 499, 1023, doi: 10.1093/mnras/staa2796
- Jones, A., Noll, S., Kausch, W., Szyszka, C., & Kimeswenger, S. 2013, *Astronomy and Astrophysics*, 560, doi: 10.1051/0004-6361/201322433
- Kaltenegger, L. 2010, *The Astrophysical Journal Letters*, 712, 125, doi: 10.1088/2041-8205/712/2/L125
- Kenworthy, M. A., & Mamajek, E. E. 2015, *Astrophysical Journal*, 800, doi: 10.1088/0004-637X/800/2/126
- Kipping, D. 2020, *The Astrophysical Journal*, 900, L44, doi: 10.3847/2041-8213/abafa9
- Kipping, D., & Teachey, A. 2020, *Serbian Astronomical Journal*, 25, doi: 10.2298/SAJ2001025K
- Kipping, D., & Yahalomi, D. A. 2022, *Monthly Notices of the Royal Astronomical Society*, 518, 3482, doi: 10.1093/mnras/stac3360
- Kipping, D., Bryson, S., Burke, C., et al. 2022, *Nature Astronomy*, 6, 367, doi: 10.1038/s41550-021-01539-1
- Kipping, D. M. 2009a, *Monthly Notices of the Royal Astronomical Society*, 392, 181, doi: 10.1111/j.1365-2966.2008.13999.x
- . 2009b, *Monthly Notices of the Royal Astronomical Society*, 396, 1797, doi: 10.1111/j.1365-2966.2009.14869.x
- Kleisioti, E., Dirkx, D., Rovira Navarro, M., & Kenworthy, M. 2021, in *Proceedings of the Europlanet Science Congress 2021*, doi: 10.5194/epsc2021-546
- Kleisioti, E., Dirkx, D., Rovira-Navarro, M., & Kenworthy, M. A. 2023, *Astronomy & Astrophysics*. <http://arxiv.org/abs/2305.03410>
- Lainey, V. 2016, *Celestial Mechanics and Dynamical Astronomy*, 126, 145, doi: 10.1007/s10569-016-9695-y
- Lainey, V., Casajus, L. G., Fuller, J., et al. 2020, *Nature Astronomy*, 4, 1053, doi: 10.1038/s41550-020-1120-5
- Lammer, H., Schiefer, S. C., Juvan, I., et al. 2014, *Origins of Life and Evolution of Biospheres*, 44, 239, doi: 10.1007/s11084-014-9377-2
- Lazzoni, C., Desidera, S., Gratton, R., et al. 2022, *Monthly Notices of the Royal Astronomical Society*, 516, 391, doi: 10.1093/mnras/stac2081

- Lazzoni, C., Zurlo, A., Desidera, S., et al. 2020, *Astronomy and Astrophysics*, 641, doi: 10.1051/0004-6361/201937290
- Li, D., Johansen, A., Mustill, A. J., Davies, M. B., & Christou, A. A. 2020, *Astronomy and Astrophysics*, 638, doi: 10.1051/0004-6361/201936672
- Limbach, M. A., & Turner, E. L. 2013, *Astrophysical Journal*, 769, doi: 10.1088/0004-637X/769/2/98
- Limbach, M. A., Vos, J. M., Winn, J. N., et al. 2021, *The Astrophysical Journal Letters*, 918, L25, doi: 10.3847/2041-8213/ac1e2d
- Linder, E. F., Mordasini, C., Mollière, P., et al. 2019, *Astronomy and Astrophysics*, 623, doi: 10.1051/0004-6361/201833873
- Lombardi, G., Zitelli, V., & Ortolani, S. 2009, *Monthly Notices of the Royal Astronomical Society*, 399, 783, doi: 10.1111/j.1365-2966.2009.15309.x
- Lunine, J. I., & Nolan, M. C. 1992, *Icarus*, 100, 221
- Markley, F. L. 1995, *Celestial Mechanics and Dynamical Astronomy*, 63, 101
- McKinnon, W. B., & Benner, L. A. M. 1990, in *Abstracts of the Lunar and Planetary Science Conference*, Vol. 21, 777–778
- McKinnon, W. B., & Kirk, R. L. 2014, in *Encyclopedia of the Solar System* (Elsevier), 861–881, doi: 10.1016/b978-0-12-415845-0.00040-2
- Moraes, R., & Neto, E. V. 2020, *Monthly Notices of the Royal Astronomical Society*, 495, 3763, doi: 10.1093/mnras/staa1441
- Moraes, R. A., Kley, W., & Vieira Neto, E. 2018, *Monthly Notices of the Royal Astronomical Society*, 475, 1347, doi: 10.1093/mnras/stx3268
- Nakajima, M., Genda, H., Asphaug, E., & Ida, S. 2022, *Nature Communications*, 13, doi: 10.1038/s41467-022-28063-8
- Nimmo, F., & Pappalardo, R. T. 2016, *Journal of Geophysical Research: Planets*, 121, 1378, doi: 10.1002/2016JE005081
- Nimmo, F., & Spencer, J. R. 2015, *Icarus*, 246, 2, doi: 10.1016/j.icarus.2014.01.044
- Nimmo, F., Hamilton, D. P., McKinnon, W. B., et al. 2016, *Nature*, 540, 94, doi: 10.1038/nature20148
- Noll, S., Kausch, W., Barden, M., et al. 2012, *Astronomy and Astrophysics*, 543, doi: 10.1051/0004-6361/201219040
- Oberg, N., Cazaux, S., Kamp, I., et al. 2023, *Astronomy & Astrophysics*, 672, A142. <http://arxiv.org/abs/2302.14425>
- Oza, A. V., Johnson, R. E., Lellouch, E., et al. 2019, *The Astrophysical Journal*, 885, 168, doi: 10.3847/1538-4357/ab40cc
- Phillips, M. W., Tremblin, P., Baraffe, I., et al. 2020, *Astronomy and Astrophysics*, 637, doi: 10.1051/0004-6361/201937381
- Porter, J. M., Oudmaijer, R. D., & Baines, D. 2004, *Astronomy and Astrophysics*, 428, 327, doi: 10.1051/0004-6361:20035686
- Prusti, T., De Bruijne, J. H., Brown, A. G., et al. 2016, *Astronomy and Astrophysics*, 595, doi: 10.1051/0004-6361/201629272
- Rodeghiero, G., Arcidicono, C., Pott, J.-U., et al. 2021, *J. Astron. Telesc. Instrum. Syst.*, 7, <https://www.spiedigitallibrary.org/journals/Journal-of-Astronomical-Telescopes,-Instruments,-and-Systems>
- Roman, M. T. 2023, *Remote Sensing*, 15, 1811, doi: 10.3390/rs15071811
- Ross, M. N., & Schubert, G. 1990, *Geophysical Research Letters*, 17, 1749, doi: 10.1029/GL017i010p01749
- Rovira-Navarro, M., Matsuyama, I., & Hay, H. C. F. C. 2023, *The Planetary Science Journal*, 4, 23, doi: 10.3847/psj/acae9a

- Rovira-Navarro, M., Van Der Wal, W., Steinke, T., & Dirkx, D. 2021, *The Planetary Science Journal*, 2, 119, doi: [10.3847/PSJ/abf6cb](https://doi.org/10.3847/PSJ/abf6cb)
- Ruffio, J.-B., Horstman, K., Mawet, D., et al. 2023, *The Astronomical Journal*, 165, 113. <http://arxiv.org/abs/2301.04206>
- Saillenfest, M., Sulis, S., Charpentier, P., & Santerne, A. 2023, *Astronomy & Astrophysics*, 675, A174. <http://arxiv.org/abs/2306.07348>
- Schenk, P. M., Beddingfield, C. B., Bertrand, T., et al. 2021, *Remote Sensing*, 13, doi: [10.3390/rs13173476](https://doi.org/10.3390/rs13173476)
- Schneider, J., Lainey, V., & Cabrera, J. 2015, *International Journal of Astrobiology*, 14, 191, doi: [10.1017/S1473550414000299](https://doi.org/10.1017/S1473550414000299)
- Segatz, M., Spohn, T., Ross, M. N., & Schubert, G. 1988, *ICARUS*, 75, 187
- Snellen, I. A., Brandl, B. R., De Kok, R. J., et al. 2014, *Nature*, 508, 63, doi: [10.1038/nature13253](https://doi.org/10.1038/nature13253)
- Squyres, S. W. 1980, *ICARUS*, 44, 502
- Teachey, A., Kipping, D., Burke, C. J., Angus, R., & Howard, A. W. 2020, *The Astronomical Journal*, 159, 142, doi: [10.3847/1538-3881/ab7001](https://doi.org/10.3847/1538-3881/ab7001)
- Teachey, A., & Kipping, D. M. 2018, *Science Advances*, 4, eaav1784. <https://www.science.org>
- Teachey, A., Kipping, D. M., & Schmitt, A. R. 2018, *The Astronomical Journal*, 155, 36, doi: [10.3847/1538-3881/aa93f2](https://doi.org/10.3847/1538-3881/aa93f2)
- Tokadjian, A., & Piro, A. L. 2022, *The Astrophysical Journal Letters*, 929, L2, doi: [10.3847/2041-8213/ac61e8](https://doi.org/10.3847/2041-8213/ac61e8)
- Vallenari, A., Brown, A. G. A., Prusti, T., et al. 2023, *Astronomy & Astrophysics*, 674, A1, doi: [10.1051/0004-6361/202243940](https://doi.org/10.1051/0004-6361/202243940)
- Vanderburg, A., Rappaport, S. A., & Mayo, A. W. 2018, *The Astronomical Journal*, 156, 184, doi: [10.3847/1538-3881/aae0fc](https://doi.org/10.3847/1538-3881/aae0fc)
- Whelan, E., & Garcia, P. 2008, *Spectro-astrometry: The method, its limitations, and applications*, doi: [10.1007/978-3-540-68032-1_6](https://doi.org/10.1007/978-3-540-68032-1_6)
- Whittaker, E. A., Malik, M., Ih, J., et al. 2022, *The Astronomical Journal*, 164, 258, doi: [10.3847/1538-3881/ac9ab3](https://doi.org/10.3847/1538-3881/ac9ab3)
- Williams, D. M., Kasting, J. F., & Wade, R. A. 1997, *Nature*, 385, 234

4 | Direct detectability of tidally heated exomoons by photometric orbital modulation

Adapted from

E. Kleisioti, D. Dirkx, X. Tan and M. A. Kenworthy

Astronomy & Astrophysics, 687, A125 (2024)

Aims. We investigate whether volcanic exomoons can be detected in thermal wavelength light curves due to their phase variability along their orbit. The method we use is based on the photometric signal variability that volcanic features or hotspots would cause in infrared (IR) wavelengths, when they are inhomogeneously distributed on the surface of a tidally heated exomoon (THEM).

Methods. We simulated satellites of various sizes around an isolated planet and modeled the system's variability in two IR wavelengths, taking into account photon shot noise. The moon's periodic signal as it orbits the planet introduces a peak in the frequency space of the system's time-variable flux. We investigated the THEM and system properties that would make a moon stand out in the frequency space of its host's variable flux.

Results. The moon's signal can produce a prominent feature in its host's flux periodogram at shorter IR wavelengths for hotspots with temperatures similar to the ones seen on the Jovian moon, Io, while the same moon would not be identifiable in longer IR wavelengths. By comparing observations at two different wavelengths, we are able to disentangle the signal of an exomoon with transiting and non-transiting orbital inclinations from the planet's signal in the frequency domain for system distances up to 10 pc for Mars-sized exomoons and even further for Earth-sized ones.

Conclusions. This method enlarges the parameter space of detectable exomoons around isolated planetary mass objects and directly imaged exoplanets, as it is sensitive to Io- to Earth-sized exomoons with hot volcanic features for a wide range of non-transiting orbital inclinations. Exomoon transits and the detection of outgassed volcanic molecules can subsequently confirm a putative detection.

4.1 Introduction

Solar System planets host a large number of moons, with great diversity; from the gas giants' icy satellites, to the volcanic moon, Io, and the only moon with a substantial atmosphere, Titan. In the Solar System, moons present a wide variety of geological and orbital properties; however, their detection around exoplanets still remains to be confirmed. Given the large number of discovered exoplanets, their detection is ever more likely.

Searches for extrasolar satellites are unveiling upper limits on exomoon properties from a non-detection (Vanderburg & Rodriguez, 2021; Ruffio et al., 2023) or effects that are associated with the existence of a moon, such as the detection of volcanic species and gaps in ring systems (Oza et al., 2019; Kenworthy & Mamajek, 2015). Candidate exomoons have been proposed (Teachey & Kipping, 2018; Fox & Wiegert, 2020; Kipping et al., 2022); however, their detection has been put into question (Rodenbeck et al., 2018; Heller et al., 2019; Kipping, 2020; Heller & Hippke, 2023).

Several exomoon detection methods around close-in planets have been suggested, following the success of the exoplanet transit method. Transit timing (Sartoretti & Schneider, 1999; Simon et al., 2007) and transit duration variations (Kipping, 2009) are based on the effects that an exomoon has on planetary transits due to gravitational interactions. Furthermore, Heller (2014) suggested detection via statistical analysis of the stellar photometric transit signal. Exomoon atmospheres can also be detected via transit spectroscopy (Kaltenegger, 2010). However, these methods are only applicable to close-in planets, which according to orbital evolution models are less likely to host satellites (Trani et al., 2020; Dobos et al., 2021).

Directly imaged (DI) exoplanets, on the other hand, are further away from their parent star due to the challenges brought by star-light suppression at small angular distances. The formation pathways of DI exoplanets are still unclear (e.g., Bohn et al., 2021), and could be better constrained with a satellite detection around them. Exomoon detection methods around DI exoplanets include direct imaging of an unresolved satellite, planet radial velocity measurements, planet astrometry, and transits (Cabrera & Schneider (2007); Agol et al. (2015); Vanderburg et al. (2018); van Woerkom & Kleisioti (2024)). With current instrumentation, these methods are limited to detecting binary-like satellites (Lazzoni et al., 2022). Such techniques can also be applied to brown dwarfs (BDs) or isolated planetary-mass objects (IPMOs) (Limbach et al., 2021), since high-contrast imaging is not necessary to subtract the stellar light.

Direct detection via thermal excess of tidally heated exomoons (THEMs), heated by tidal interactions along an eccentric, short-period orbit has also been proposed (Limbach & Turner, 2013). The latter requires tidal heating to take place in the interior of the moon. Tidal heating is present in Solar System bodies, the most prominent example being that of Io (e.g., Moore, 2003; Běhouňková et al., 2021; Rovira-Navarro et al., 2022). Most studies on the direct detection of THEMs have considered a uniform temperature distribution over the moon's surface to evaluate the temperatures that can be reached by tidal interactions and assess potential detections of thermal excess (Dobos & Turner, 2015; Rovira-Navarro et al., 2021; Kleisioti et al., 2023). However, the latter assumption does not take into account the temperature inhomogeneity on the surface of our only known example of a THEM, Io (de Pater et al., 2017; de Kleer et al., 2019). For example, Loki Patera,

one of the largest and most persistent hotspots on Io's surface, with a surface area equal to 21500 km², or 0.05 % of its surface (Davies et al., 2015), is responsible for 10 percent of Io's heat flow (Veeder et al., 1994).

Jäger & Szabó (2021) suggest that the temperature distribution in a THEM will be uneven. The authors claim that this uneven temperature distribution can enhance the direct detectability of exomoons. Motivated by the latter, we argue that such a hotspot distribution would produce a periodic signal in thermal infrared (IR) light curves of BDs, DI exoplanets, and IPMOs, and we explore the conditions under which this periodicity is detectable. The detection of extrasolar bodies via thermal periodicity has previously been suggested for the detection of rocky asteroids (Lin & Loeb, 2014) and exoplanets around white dwarfs (WDs) (Limbach et al., 2022). The authors considered detection by measuring amplitude variations in WD light curves from rocky bodies' phase curves due to the thermal emission differences between the dayside and the nightside. In addition, Forgan (2017) suggested that moons could be detected via periodicity detection in exoplanetary transit phase curves. Thermal phase curves have been used for the characterization of rocky exoplanets around main-sequence stars (Demory et al., 2016; Zieba et al., 2022; Gillon et al., 2023). To quantify the feasibility of our proposed method, we simulated phase curves of THEMs with hotspots, adding realistic host variable signals. We show that the thermal output of hotspots can produce detectable signals with MIRI in their hosts' IR light curves by extracting the signal of the moon from the host's periodogram.

This work is organized as follows: in Section 4.2, we present our models for exomoon and host signal variability. Section 4.3 discusses our method of extracting the exomoon signal from the host's periodogram. In Section 4.4, we present our results, firstly for a system at 3 pc and later on for THEMs with different properties at several distances. Finally, in Section 4.5, we discuss possible synergies of our method with other exomoon detection methods and ways to confirm a detection.

4.2 Photometric signal variability

In this section we present the models that we use for the photometric variability over time of a volcanic moon and its host. We then compute the combined light curve of the system by adding the two light curves.

4.2.1 Exo-Io modeled photometric light curves

Volcanic activity on Io is the result of tidally induced heating in the interior of the moon. Over the years, Io's volcanic activity has been monitored (*e.g.*, de Pater et al., 2017; Cantrall et al., 2018; de Kleer et al., 2019; Tate et al., 2023) and the spatial distribution of volcanoes (Bartolić et al., 2021) has been used to infer tidal heating parameters in the interior (Davies et al., 2024). Measured hotspot temperatures on Io reach up to ≈ 2000 K (McEwen et al., 1998). A larger concentration of hotspots was found by Zambon et al. (2023) in the polar regions of Io; however, recently Davies et al. (2024) concluded that Io's polar volcanoes are about the same in number per unit area but are less energetic than those at lower latitudes.

de Kleer & de Pater (2016) divided Io’s hotspots into two main categories depending on their temporal behavior and temperature. “Sudden brightening events” are characterized by a sudden high thermal output, which steadily decays over a timescale of ≈ 1 month. On the other hand, “persistent hotspots” are active for more than ≈ 1 year and show low temporal variability with typically lower thermal outputs. Loki Patera, one of the most persistent hotspots on Io’s surface (de Kleer et al., 2019), presents characteristics of both categories, showing both stability over time and eruption events, with temperatures of up to ≈ 540 K (de Pater et al., 2017).

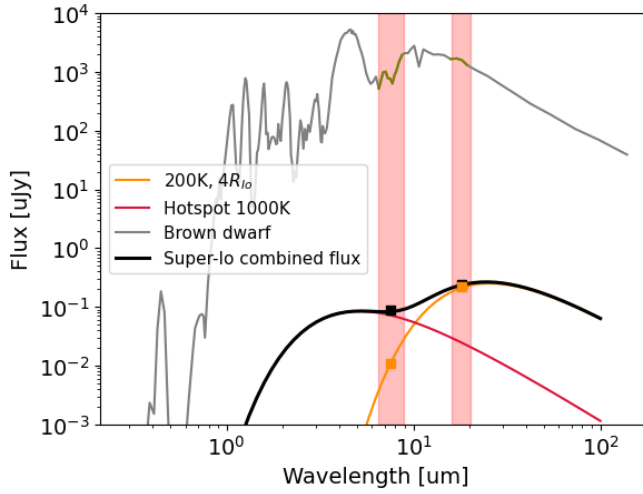


Figure 4.1: Brown dwarf spectrum with $T_{eff} = 600$ K and a THEM’s spectrum with $T_m = 200$ K, $T_h = 1000$ K, and $R_m = R_{Earth}$ at 3 pc. The two red rectangles show the wavelength ranges of MIRI filters F770W and F1800W. The black and orange points correspond to the integrated flux coming from a moon when the volcano is in and out of our line of sight, respectively. The difference between the two configurations is larger in filter F770W, as is shown by the orange and black points.

We modeled THEM light curves, assuming moons that are tidally locked to their host, with different radii, R_m , varying from Io-sized bodies to Earth-sized ones, with a surface temperature baseline of T_m . We generated a spherical harmonics map with *starry* (Luger et al., 2019) to model the nonhomogenous surface of THEMs. We added the expansion of one and three top hat function(s) on the map to simulate one or three circular spots, respectively, with radius R_h and temperature T_h . We chose a spherical harmonics degree = 30, as we modeled small features on the moon’s surface, due to the small R_h/R_m ratio.

Figure 4.1 shows the spectral energy distribution of a moon with $T_m = 200$ K and $T_h = 1000$ K. The resulting flux variability of a rotating moon would differ from longer wavelength filters to shorter wavelength ones; the flux difference induced by the visibility of the volcano is larger in the JWST/MIRI filter F770W than in F1800W, as is shown by the black and orange points, respectively. Panels b and c in Figure 4.2 show the moon’s temporal light curve with Io’s orbital period and in an edge-on orbit, at a distance of 3 pc.

When modeling moons larger in size than Io, we kept the ratio, $\frac{R_h}{R_m} = \frac{R_{LokiPatera}}{R_{Io}} = 4.54 \cdot 10^{-2}$, constant, assuming Loki Patera's surface area to be equal to 21500 km^2 , as it was measured to be by (Davies et al., 2015).

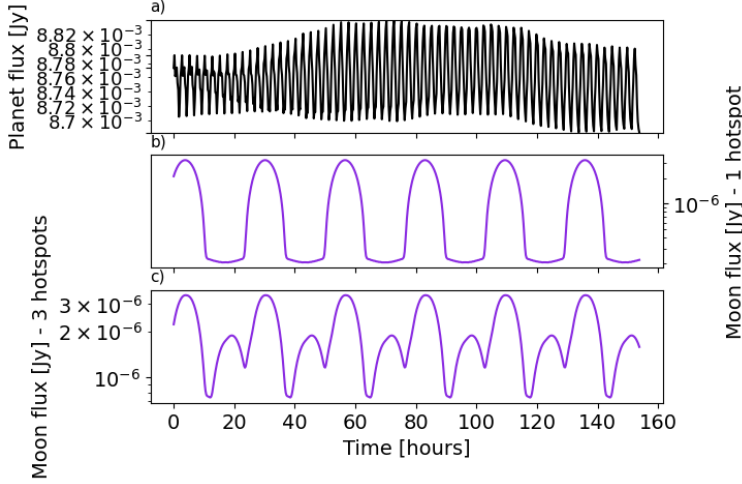


Figure 4.2: Modeled F770W flux variabilities of (a) the host and an Earth-sized, $T_m = 200 \text{ K}$, $T_h = 1000 \text{ K}$ moon with (b) one or (c) three hotspots at 90 degrees inclination at 3 pc. The overall observation time (including both filters) assumed in this work is 140h.

4.2.2 Host modeled photometric light curves

Exoplanets and BDs are expected to present variability due to atmospheric inhomogeneities (e.g., clouds) combined with their rotational modulation. Several surveys have demonstrated that this variability is common among BDs (Metchev et al., 2015; Vos et al., 2022) and is often well described by a semi-periodic signal or a combination of several sine functions for observations in one epoch (Biller, 2017; Apai et al., 2017; Artigau, 2018). Some observed light curves also evolve in time (Artigau et al., 2009; Yang et al., 2016; Karalidi et al., 2016). Recent surveys of young, low-mass BDs measure a variability between 2 and ≈ 35 hours with a median of 12 hours (Vos et al., 2022). Simulated normalized light curves of such bodies have amplitudes from 0.5 percent to a few percent, which is consistent with observations (Radigan, 2014; Vos et al., 2019). Using atmospheric general circulation models (GCMs) of BDs, Tan & Showman (2021a) found that faster rotators typically present smaller variability amplitudes. Finally, lower-mass BDs are likely more variable than their more massive counterparts (Vos et al., 2019). BDs and DI exoplanets share color and magnitude similarities (Faherty et al., 2016) and from the perspective of planetary atmospheric dynamics they are in the same self-luminous dynamical regime (Showman et al., 2020).

Most IR light curve datasets of BDs or IMPOs are measured continuously for short timescales (e.g., 5-20 hours Vos et al. (2019); Esplin et al. (2016)) or with lower cadences

(e.g., days or weeks (Brooks et al., 2023)). Thus, any long-term evolution is not accurately measured in such systems, with the exception of Apai et al. (2021). Longer datasets are needed for the detection of moons, which can have orbital periods much larger than available datasets. In this work, we use GCMs to simulate IPMOs' bolometric light curves and model their long-term evolution. The IPMO circulation model in this work has been updated from that in Tan & Showman (2021a) and Tan & Showman (2021b) by using a more realistic non-gray radiative transfer and assuming equilibrium chemistry and a solar atmospheric composition (Tan et al. in prep). We also computed spectroscopic light curves to estimate the variability at different MIRI filters by post-processing the 3D temperature and cloud IMPO circulation model fields with PICASO (Batalha et al., 2019; Adams et al., 2022; Robbins-Blanch et al., 2022, see Appendix A). The IMPO circulation model and PICASO have the same opacity source and method of computing radiative transfer, which ensures the accurate spectroscopic post-processing of the circulation.

For our spectroscopic light curves, we substituted the amplitude of the calculated bolometric flux with the characteristic amplitude from the spectroscopic light curve within a given bandpass. This assumes that the light curve periodicity at wavelengths between 6-20 μ m is similar to that of the bolometric light curve, a behavior that has been observed in measured spectroscopic light curves (Apai et al., 2017; Esplin et al., 2016; Yang et al., 2016).

Figure 4.2a shows the calculated F770W/MIRI variability of a 2.5 h variable host, with an effective temperature of $T_{eff} = 600$ K and a surface gravity of $g = 100$ m/s². Our goal is to demonstrate that we can distinguish the signal of a volcanic companion in a realistic IPMO light curve. When simulating light curves of systems viewed near edge-on, we take into account only the intrinsic variability of the IPMO and companion signals, without considering any transits or secondary eclipses, as we expect them to enhance the periodicity of the signal, and thus the detectability compared to a non-transiting moon. We present results of simulations using the modeled IMPO as a host and argue that the same method can be used to find companions around lower-mass IMPOs and DI planets. When referring to the companion of DI exoplanets and IPMOs, the term "exomoon" can be used; however, it should be noted that there is a blurred line between exoplanets, IPMOs, and BDs (Teachey, 2024). When this method is used to find companions around isolated and more massive BDs, the term "volcanic companion" is more accurate.

4.3 Detectable moon signals in hosts' periodograms

To assess whether an exomoon would produce a detectable signal peak when taking time-series observations of a host, we firstly added the time-variable flux of moons with different T_h , R_h , R_m , and T_m to the flux of the 2.5 h variable host in two MIRI filters. It should be noted that for a T_h range between 300 and 2000K the optimal filter choice would change, since the blackbody peak changes. We then integrated over 0.5h observations, alternating between each filter after every integration, and added shot noise to the combined system flux.

Panels a and b of Figure 4.3 show the Lomb-scargle periodogram of the combined fluxes in filters F770W and F1800W, respectively. The black curves demonstrate the

periodogram of the host's light curve, whereas the purple (one hotspot) and blue (three hotspots) are the result of the combined system flux with an Earth-sized moon that has $T_h = 1000\text{K}$ at a 26.4h orbital period. There are several peaks on the planet's periodogram, with the most prominent one being equal to the planet's intrinsic variability at 2.5 h. The planet's periodogram (black) also exhibits several smaller peaks at larger periods that can hinder the moon signal (Apai et al., 2021). This is expected to affect the detectability of moons with different orbital periods, which we explore in Section 4.4.1.

In the combined periodogram (purple) in filter F770W there is a clear peak at ≈ 26.4 hours that is not present in the host's periodogram (black). The same moon produces a much smaller signal in the F1800W filter, since it does not capture the high temperature profile of the hotspot, as is seen in Figure 4.1. The latter discrepancy between the two filters enables the moon's signal to be disentangled from the planet's one.

To better assess the differences between the two filters and the detectability of moons, we also defined a quantity, A , as follows:

$$A = P_{F770W} - P_{F1800W}, \quad (4.1)$$

where P is the periodogram's power for the two different filters. Figure 4.3c shows A^2 as a function of the moon's orbital period, where the peak due to the input orbital period (26.4h) is the most prominent feature. The vertical black lines correspond to false alarm probabilities (FAPs), calculated according to the null hypothesis of non-varying data with Gaussian noise.

Since photon noise is a stochastic process, Figure 4.3 shows only one of the possible instances that we might expect from such a system. Figure 4.4 shows the same system with $T_h = 600\text{K}$ at two different instances of shot noise, one where the moon's peak is the most prominent one (gray) and one where the shot noise interferes with the signal, resulting in a spurious feature (red). To assess the effect of the photon noise on the observability of the exomoon signal, we performed the same calculation 10^3 times (see Appendix B) and defined a true positive rate as the ratio of the instances in which the most prominent peak is caused by the moon over the total number of instances. The relationship between the FAP and the true positive rate is shown in Appendix C.

The signals of THEMs would appear between periods that can theoretically be constrained by taking into account their orbital stability. In a THEM search via photometric orbital modulation, moon peaks would appear in periods larger than the Roche limit of a particular system. In the following simulations, we took the smaller period limit at which a moon's signal can appear in the planet's periodogram, which is equal to the Roche limit for the modeled IPMO with radius $R = 1.006R_J$ and mass $M = 4M_J$.

4.4 Results

In this section we present our results, firstly for the modeled 2.5 h variable planet at 3 pc presented in Section 4.2.2. We then expand on the potential detectability of THEMs for some typical systems.

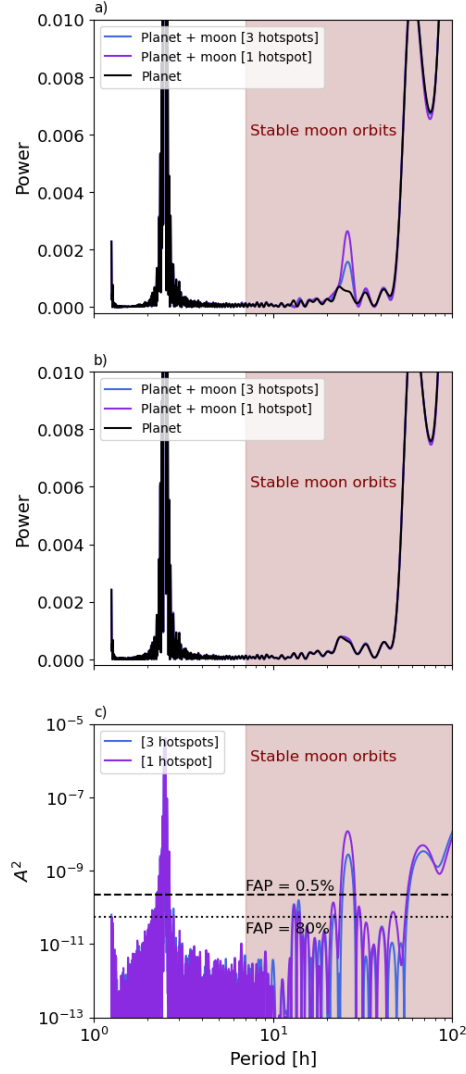


Figure 4.3: (a) Lomb-scargle periodogram for MIRI filter F770W. (b) Lomb-scargle periodogram for MIRI filter F1800W. The THEM signal is diluted in longer thermal wavelengths. (c) A^2 as a function of the moon's orbital period for the 2.5 h variable IPMO and an Earth-sized exomoon with $T_h = 1000$ K at an edge-on orbit at 3 pc. The dashed and dotted black lines denote $FAP = 0.5\%$ and $FAP = 80\%$. The red area shows the stable moon orbit region, between the host's Roche limit and the Hill sphere.

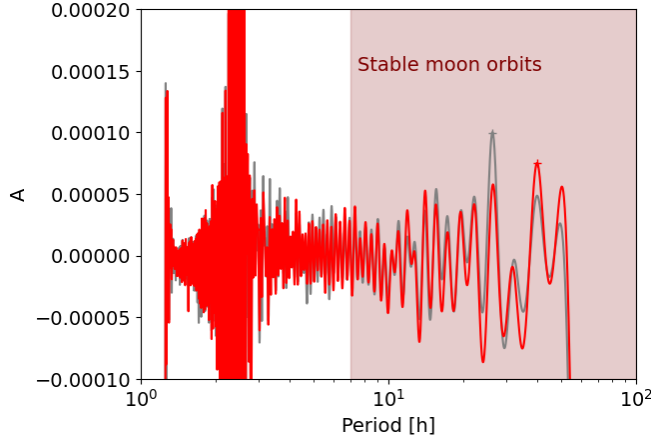


Figure 4.4: Two instances of A , which is subject to shot noise, for the 2.5 h variable planet and a THEM with $T_h = 600$ K, at 3 pc, and 90 degrees inclination. The instance shown with a gray line correctly identifies the input moon orbital period (26.4 h), in contrast to the instance represented by a red line. The red area shows the stable moon orbit region, between the host's Roche limit and the Hill sphere.

4.4.1 Tidally heated exomoons around a 2.5 h variable planet at 3 parsecs

Figure 4.5a shows the true positive ratio of an Earth-sized moon as a function of its orbital period and hotspot temperature (T_h) at a 90° inclination. A black line is overplotted for a true positive ratio = 50 %. For the majority of orbital periods, an Earth-sized moon's signal has a true positive rate of 50% for $T_h = 550$ K. We note that F770W is not the optimal filter for the detection of bodies with T_h in the entire shown parameter space; however, such an analysis is out of the scope of this work.

There are some dark regions in Figure 4.5 that represent a true positive rate equal to zero. These correspond to periods where the intrinsic variability of the host interferes with the moon's signal. Moons with orbital periods within this range would not produce a detectable peak in the host's periodogram regardless of their hotspot properties. The periods at which this occurs cannot be predicted a priori; however, observations at a longer IR wavelength (F1800W) can constrain them, assuming that there is a similarity between the host's variability periods in the two bands (Appendix A).

As is seen in Figure 4.5b, a smaller inclination (30°) does not significantly affect the observable range of moon orbital periods. However, the hotspot temperatures that produce detectable moon peaks are larger: ≈ 600 K for an Earth-sized moon with $T_m = 200$ K.

4.4.2 Applicability to systems at larger distances

To evaluate the limits of this method in terms of system distance, as well as the moon and hotspot parameter spaces that lead to detectable signatures, we calculated the T_h that

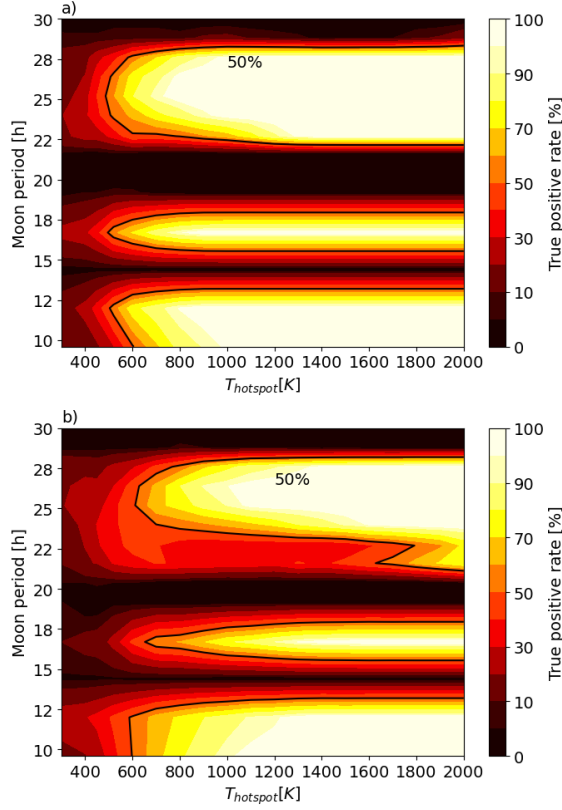


Figure 4.5: True-positive ratio for an Earth-sized moon around the 2.5 h variable planet as a function of the moon's orbital period and T_h . The system is assumed to be at 3 pc for an (a) edge-on and (b) 30° inclined orbit.

results in a true positive rate = 50% ($T_{h,50}$) for a range of R_m, T_m, R_h (Figure 4.6). For a system distance of <5 pc, exo-Ios as small as $R_m = R_{Io}$ can be detected for high hotspot temperatures (>1400K) in 140 h observations. For larger moons between 2 and 4 R_{Io} , a signal can be detected even for moderate T_h (≈ 900 -1500 and 500-700K, respectively).

4.5 Discussion

A THEM with hotspot temperatures similar to the ones seen on Io can produce a detectable signature in JWST time-series data of IPMOs. We discuss whether a detection can be justified from such a signal in putative exomoon hosts' periodograms, which other sources can produce such signatures, and factors that need to be taken into account when extending the results in different systems.

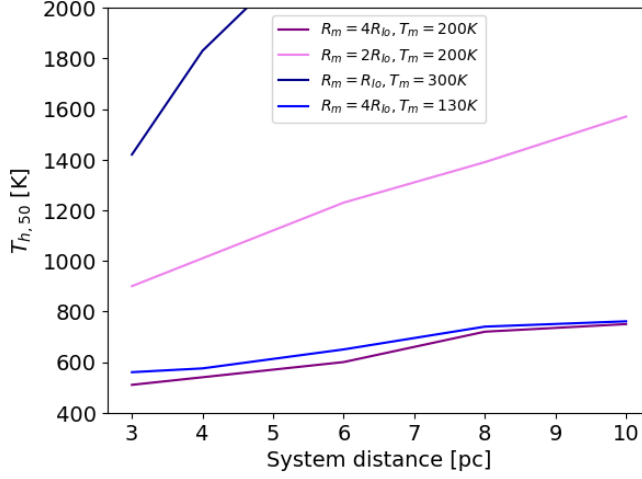


Figure 4.6: $T_{h,50}$ as a function of the system’s distance for the modeled 2.5 h variable planet with a 600 K effective temperature and different moon properties (orbital period = 27 h). For moon sizes between 2-4 R_{Io} , a moon can be detected even for moderate T_h and T_m in 140 h observations. For very nearby systems, an exo-Io ($R_m = R_{Io}$) can be detected for high T_h (>1400 K)

4.5.1 Other sources of such signals and synergies with other exomoon detection methods

This paper focuses on the possibility of THEM signatures being present in MIRI/JWST light curves. Assessing the probability that a particular peak within the stable moon orbital period range is from a putative exomoon is out of the scope of this work. The latter would depend, among other confounding effects, on the planet’s intrinsic variability itself, which cannot be assumed a priori. However, there are strategies that can be used to follow up on candidate exomoon signals.

Firstly, additional observations over long periods or within a period of time would allow for the planet’s variability to change over time. In contrast, the exomoon signal would always appear at the same period, its orbital period, even if the location and intensity of the hotspots change. A factor that might affect the interpretation of a signal is the integration time of each observation or the sampling frequency, as it can introduce false-positive signals. Repeating an observation with a different sampling frequency can bypass these false positives, and allow the exomoon signal to persist.

Other exomoon detection methods can serve as confirmation of the existence of a THEM or vice versa. If a THEM is large enough and the orbital inclination is within the range of transiting inclinations, it can produce detectable transits in the photometric light curves of BDs or IPMOs (Limbach et al., 2022). However, the presented hotspot variability method is sensitive to exomoon detections in a much wider range of inclinations compared to the exomoon transit method. Detection via IR excess (Limbach & Turner, 2013; Kleisioti et al., 2023), the detection of alkalines (Oza et al., 2019), or radio sig-

nals induced by planet-moon interactions (Narang et al., 2022) can also contribute to constraining the existence of a moon around a BD or DI exoplanet. Finally, the method of spectroastrometry can also contribute to the confirmation of a THEM detection, as it will be sensitive to similar, temperately warm moons with the upcoming Extremely Large Telescope (ELT) (van Woerkom & Kleisioti, 2024). Radial velocity measurements of the planet with current instrumentation are sensitive to binary-like moons (Lazzoni et al., 2022) or to mass ratios much larger than the ones seen in the Solar System gas giants and their satellites (Ruffio et al., 2023).

4.5.2 Hotspot time variability and spatial distribution on Io and exo-Ios

This method is subject to the frequency of eruptions on a putative THEM. Persistent volcanoes, like those seen on Io, are more likely to be present on a THEM's surface, since they are stable for more than ≈ 1 year; however, they have lower thermal fluxes. "Sudden brightening events," with higher temperatures, fade over a timescale of ≈ 1 month, which is much smaller than the observation time assumed in this work (140h), and thus also likely to be detectable.

The spatial distribution of volcanoes needs to allow enough variability in a moon's phase curve and can boost or hinder a moon's signal. A homogeneous distribution along the surface of hotspots with similar properties would produce a flat moon phase curve. On the other hand, two hotspots on the same hemisphere (even if they are smaller than the modeled sizes) would enhance the moon's periodicity amplitude.

4.5.3 Possibility of hotspot detection around cooler planets

Our current models assume a host planet temperature of 600 K. We note, however, that if the host planet is colder than this, then cooler and smaller moons will be detectable too, since the fraction, $\frac{F_m}{F_p}$, will be similar for colder volcanoes. Ultimately, the increased fractional photon shot noise from the smaller fluxes from the host and exomoon will require longer integrations to detect the moon at a similar significance.

In the case of host exoplanets with low effective temperatures, the possibility exists that the planet itself is not detectable at all, while the hotspots on the warm end of the hotspot parameter space can exceed NIRCam's sensitivity at small distances from the Earth (see Figure 4.7b).

4.6 Conclusions

We modeled the IR variability of a 600 K isolated planet and added phase curves of THEMs with different hotspot, physical, and orbital properties. We conclude that a THEM with hotspot temperatures similar to the ones seen on the Jovian moon, Io, can produce detectable signatures in the host's IR periodograms for a wide range of orbital inclinations. For some exomoon orbital periods, which would depend on the planet's intrinsic variability and cannot be known a priori, a detection is not possible independently of the

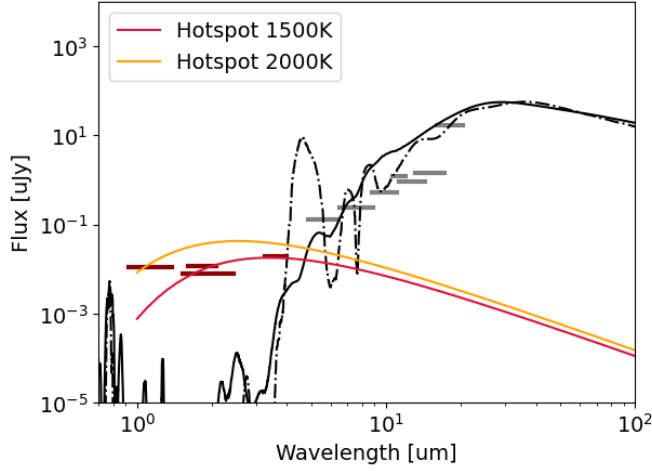


Figure 4.7: Hotspots with radii of $R_h = R_{LokiPatera}$ at 3 pc, around a cold undetectable host of 150 K with (dashed line) or without (continuous line) clouds (Morley et al., 2014). The vertical red and black lines correspond to the 10σ , 10000 s detection limits of NIRCams (Rieke et al., 2023) and MIRI (Glasse et al., 2015), respectively.

hotspot properties. Synergies with other methods, such as exomoon transits and spectral signatures due to volcanism, can contribute to confirming the presence of an exomoon. When taking into account shot noise, this method can detect Io-sized satellites with volcanic temperatures >1400 K for distances <5 pc, and Mars to Earth-sized moons further away for moderate volcanic temperatures around a 600 K planet. The latter detection limits can be looser for moons around colder hosts. If a host is cold enough, direct detection of a volcano is possible with NIRCams at 3 pc.

Bibliography

- Adams, D. J., Kataria, T., Batalha, N. E., Gao, P., & Knutson, H. A. 2022, *ApJ*, 926, 157, doi: 10.3847/1538-4357/ac3d32
- Agol, E., Jansen, T., Lacy, B., Robinson, T. D., & Meadows, V. 2015, *The Astrophysical Journal*, 812, 5, doi: 10.1088/0004-637x/812/1/5
- Apai, D., Nardiello, D., & Bedin, L. R. 2021, *The Astrophysical Journal*, 906, 64, doi: 10.3847/1538-4357/abcb97
- Apai, D., Karalidi, T., Marley, M. S., et al. 2017, *Science*, 357, 683, doi: 10.1126/science.aam9848
- Artigau, Bouchard, Doyon, & Lafrenière. 2009, *The Astrophysical Journal*, 701, 1534, doi: 10.1088/0004-637X/701/2/1534
- Artigau, É. 2018, *Variability of Brown Dwarfs*, ed. H. J. Deeg & J. A. Belmonte (Cham: Springer International Publishing), 555–573, doi: 10.1007/978-3-319-55333-7_94
- Bartolić, F., Luger, R., Foreman-Mackey, D., Howell, R. R., & Rathbun, J. A. 2021, *Occultation mapping of Io's surface in the near-infrared I: Inferring static maps*. <https://arxiv.org/abs/2103.03758>
- . 2022, *The Planetary Science Journal*, 3, 67, doi: 10.3847/PSJ/ac2a3e
- Batalha, N. E., Marley, M. S., Lewis, N. K., & Fortney, J. J. 2019, *ApJ*, 878, 70, doi: 10.3847/1538-4357/ab1b51
- Biller, B. 2017, *Astronomical Review*, 13, 1, doi: 10.1080/21672857.2017.1303105
- Bohn, Ginski, Christian, Kenworthy, Matthew A., et al. 2021, *A&A*, 648, A73, doi: 10.1051/0004-6361/202140508
- Brooks, H., Kirkpatrick, J. D., Meisner, A. M., et al. 2023, *The Astronomical Journal*, 165, 232, doi: 10.3847/1538-3881/acccf7
- Běhounková, M., Tobie, G., Choblet, G., et al. 2021, *Geophysical Research Letters*, 48, e2020GL090077, doi: <https://doi.org/10.1029/2020GL090077>
- Cabrera, & Schneider. 2007, *A&A*, 464, 1133, doi: 10.1051/0004-6361:20066111
- Cantrall, C., de Kleer, K., de Pater, I., et al. 2018, *Icarus*, 312, 267, doi: <https://doi.org/10.1016/j.icarus.2018.04.007>
- Davies, A. G., Perry, J. E., Williams, D. A., & Nelson, D. M. 2023, *Nature Astronomy*, doi: 10.1038/s41550-023-02123-5
- Davies, A. G., Perry, J. E., Williams, D. A., & Nelson, D. M. 2023, *Nature Astronomy*, doi: 10.1038/s41550-023-02123-5
- Davies, A. G., Perry, J. E., Williams, D. A., & Nelson, D. M. 2024, *Nature Astronomy*, 8, 94, doi: 10.1038/s41550-023-02123-5
- Davies, A. G., Veeder, G. J., Matson, D. L., & Johnson, T. V. 2015, *Icarus*, 262, 67, doi: <https://doi.org/10.1016/j.icarus.2015.08.003>
- de Kleer, K., & de Pater, I. 2016, *Icarus*, 280, 378, doi: <https://doi.org/10.1016/j.icarus.2016.06.019>
- de Kleer, K., de Pater, I., Davies, A. G., & Ádámkovics, M. 2014, *Icarus*, 242, 352, doi: <https://doi.org/10.1016/j.icarus.2014.06.006>
- de Kleer, K., Nimmo, F., & Kite, E. 2019, *Geophys. Res. Lett.*, 46, 6327, doi: 10.1029/2019GL082691
- de Kleer, K., de Pater, I., Molter, E. M., et al. 2019, *The Astronomical Journal*, 158, 29, doi: 10.3847/1538-3881/ab2380
- de Pater, I., de Kleer, K., Davies, A. G., & Ádámkovics, M. 2017, *Icarus*, 297, 265, doi: <https://doi.org/10.1016/j.icarus.2017.03.016>

- Demory, B.-O., Gillon, M., de Wit, J., et al. 2016, *Nature*, 532, 207–209, doi: 10.1038/nature17169
- Dobos, V., Charnoz, S., Pál, A., Roque-Bernard, A., & Szabó, G. M. 2021, 133, 094401, doi: 10.1088/1538-3873/abfe04
- Dobos, V., & Turner, E. L. 2015, *The Astrophysical Journal*, 804, 41, doi: 10.1088/0004-637x/804/1/41
- Esplin, T. L., Luhman, K. L., Cushing, M. C., et al. 2016, *ApJ*, 832, 58, doi: 10.3847/0004-637x/832/1/58
- Faherty, J. K., Riedel, A. R., Cruz, K. L., et al. 2016, *ApJS*, 225, 10, doi: 10.3847/0067-0049/225/1/10
- Forgan, D. H. 2017, *MNRAS*, 470, 416, doi: 10.1093/mnras/stx1217
- Fox, C., & Wiegert, P. 2020, *Monthly Notices of the Royal Astronomical Society*, 501, 2378, doi: 10.1093/mnras/staa3743
- Gillon, M., Ducrot, E., Agol, E., et al. 2023, TRAPPIST-1 Planets: Atmospheres Or Not?, JWST Proposal. Cycle 2, ID. #3077
- Glasse, A., Rieke, G. H., Bauwens, E., et al. 2015, *PASP*, 127, 686, doi: 10.1086/682259
- Heller, Rodenbeck, & Bruno. 2019, *A&A*, 624, A95, doi: 10.1051/0004-6361/201834913
- Heller, R. 2014, *ApJ*, 787, 14, doi: 10.1088/0004-637x/787/1/14
- Heller, R., & Hippke, M. 2023, *Nature Astronomy*, 8, 193–206, doi: 10.1038/s41550-023-02148-w
- Henning, W. G., Renaud, J. P., Saxena, P., et al. 2018, Highly Volcanic Exoplanets, Lava Worlds, and Magma Ocean Worlds: An Emerging Class of Dynamic Exoplanets of Significant Scientific Priority. <https://arxiv.org/abs/1804.05110>
- Herrick, R. R., & Hensley, S. 2023, *Science*, 379, 1205, doi: 10.1126/science.abm7735
- Jäger, Zoltán, J., & Szabó, G. M. 2021, *Monthly Notices of the Royal Astronomical Society*, 508, 5524, doi: 10.1093/mnras/stab2955
- Kaltenegger, L. 2010, *The Astrophysical Journal Letters*, 712, L125, doi: 10.1088/2041-8205/712/2/L125
- Karalidi, T., Apai, D., Marley, M. S., & Buenzli, E. 2016, *The Astrophysical Journal*, 825, 90, doi: 10.3847/0004-637x/825/2/90
- Kenworthy, M. A., & Mamajek, E. E. 2015, *The Astrophysical Journal*, 800, 126, doi: 10.1088/0004-637x/800/2/126
- Kipping, D. 2020, *The Astrophysical Journal Letters*, 900, L44, doi: 10.3847/2041-8213/abafa9
- Kipping, D., Bryson, S., Burke, C., et al. 2022, *Nature Astronomy*, 6, 367, doi: 10.1038/s41550-021-01539-1
- Kipping, D. M. 2009, *Monthly Notices of the Royal Astronomical Society*, 396, 1797, doi: <https://doi.org/10.1111/j.1365-2966.2009.14869.x>
- Kleisioti, E., Dirkx, D., Rovira-Navarro, M., & Kenworthy, M. A. 2023, *A*, 675, A57, doi: 10.1051/0004-6361/202346082
- Lazzoni, C., Desidera, S., Gratton, R., et al. 2022, *Monthly Notices of the Royal Astronomical Society*, 516, 391, doi: 10.1093/mnras/stac2081
- Limbach, M. A., & Turner, E. L. 2013, *The Astrophysical Journal*, 769, 98, doi: 10.1088/0004-637x/769/2/98
- Limbach, M. A., Vanderburg, A., Stevenson, K. B., et al. 2022, *Monthly Notices of the Royal Astronomical Society*, 517, 2622, doi: 10.1093/mnras/stac2823
- Limbach, M. A., Vos, J. M., Winn, J. N., et al. 2021, *The Astrophysical Journal Letters*, 918, L25, doi: 10.3847/2041-8213/ac1e2d
- Lin, H. W., & Loeb, A. 2014, *The Astrophysical Journal*, 793, L43, doi: 10.1088/2041-8205/

- 793/2/143
- Luger, R., Agol, E., Foreman-Mackey, D., et al. 2019, *AJ*, 157, 64, doi: [10.3847/1538-3881/aae8e5](https://doi.org/10.3847/1538-3881/aae8e5)
- McEwen, A. S., Keszthelyi, L., Spencer, J. R., et al. 1998, *Science*, 281, 87, doi: [10.1126/science.281.5373.87](https://doi.org/10.1126/science.281.5373.87)
- Metchev, S. A., Heinze, A., Apai, D., et al. 2015, *The Astrophysical Journal*, 799, 154, doi: [10.1088/0004-637X/799/2/154](https://doi.org/10.1088/0004-637X/799/2/154)
- Moore, W. B. 2003, *Journal of Geophysical Research: Planets*, 108, doi: <https://doi.org/10.1029/2002JE001943>
- Morley, C. V., Marley, M. S., Fortney, J. J., et al. 2014, *The Astrophysical Journal*, 787, 78, doi: [10.1088/0004-637X/787/1/78](https://doi.org/10.1088/0004-637X/787/1/78)
- Narang, M., Oza, A. V., Hakim, K., et al. 2022, *The Astronomical Journal*, 165, 1, doi: [10.3847/1538-3881/ac9eb8](https://doi.org/10.3847/1538-3881/ac9eb8)
- Oza, A. V., Johnson, R. E., Lellouch, E., et al. 2019, *The Astrophysical Journal*, 885, 168, doi: [10.3847/1538-4357/ab40cc](https://doi.org/10.3847/1538-4357/ab40cc)
- Quick, L. C., Roberge, A., Mlinar, A. B., & Hedman, M. M. 2020, *Publications of the Astronomical Society of the Pacific*, 132, 084402, doi: [10.1088/1538-3873/ab9504](https://doi.org/10.1088/1538-3873/ab9504)
- Radigan, J. 2014, *The Astrophysical Journal*, 797, 120, doi: [10.1088/0004-637X/797/2/120](https://doi.org/10.1088/0004-637X/797/2/120)
- Rieke, M. J., Kelly, D. M., Misselt, K., et al. 2023, *Publications of the Astronomical Society of the Pacific*, 135, 028001, doi: [10.1088/1538-3873/acac53](https://doi.org/10.1088/1538-3873/acac53)
- Robbins-Blanch, N., Kataria, T., Batalha, N. E., & Adams, D. J. 2022, *The Astrophysical Journal*, 930, 93, doi: [10.3847/1538-4357/ac658c](https://doi.org/10.3847/1538-4357/ac658c)
- Rodenbeck, Heller, Hippke, & Gizon. 2018, *A&A*, 617, A49, doi: [10.1051/0004-6361/201833085](https://doi.org/10.1051/0004-6361/201833085)
- Rovira-Navarro, M., Katz, R. F., Liao, Y., van der Wal, W., & Nimmo, F. 2022, *Journal of Geophysical Research: Planets*, 127, e2021JE007117, doi: <https://doi.org/10.1029/2021JE007117>
- Rovira-Navarro, M., Van der Wal, W., Steinke, T., & Dirkx, D. 2021, *Planetary Science Journal*, 2, doi: [10.3847/PSJ/abf6cb](https://doi.org/10.3847/PSJ/abf6cb)
- Ruffio, J.-B., Horstman, K., Mawet, D., et al. 2023, *The Astronomical Journal*, 165, 113, doi: [10.3847/1538-3881/acb34a](https://doi.org/10.3847/1538-3881/acb34a)
- Sartoretti, P., & Schneider, J. 1999, *A&AS*, 134, 553, doi: [10.1051/aas:1999148](https://doi.org/10.1051/aas:1999148)
- Showman, A. P., Tan, X., & Parmentier, V. 2020, *Space Science Reviews*, 216, doi: [10.1007/s11214-020-00758-8](https://doi.org/10.1007/s11214-020-00758-8)
- Simon, Szatmáry, & Szabó. 2007, *A&A*, 470, 727, doi: [10.1051/0004-6361:20066560](https://doi.org/10.1051/0004-6361:20066560)
- Simon, Rowe, Gaulme, et al. 2016, *ApJ*, 817, 162, doi: [10.3847/0004-637X/817/2/162](https://doi.org/10.3847/0004-637X/817/2/162)
- Sinton, W., Lindwall, D., Cheigh, F., & Tittlemore, W. 1983, *Icarus*, 54, 133, doi: [https://doi.org/10.1016/0019-1035\(83\)90074-X](https://doi.org/10.1016/0019-1035(83)90074-X)
- Tan, X., & Showman, A. P. 2021a, *MNRAS*, 502, 2198, doi: [10.1093/mnras/stab097](https://doi.org/10.1093/mnras/stab097)
- . 2021b, *MNRAS*, 502, 678, doi: [10.1093/mnras/stab060](https://doi.org/10.1093/mnras/stab060)
- . 2021c, *MNRAS*, 502, 2198, doi: [10.1093/mnras/stab097](https://doi.org/10.1093/mnras/stab097)
- Tate, C. D., Rathbun, J. A., Hayes, A. G., Lopes, R. M. C., & Pettine, M. 2023, *Spatiotemporal patterns of Io's bright transient eruptions, 1978-2022*. <https://arxiv.org/abs/2309.15231>
- Teachey, A. 2024, *Detecting and Characterizing Exomoons and Exorings (Handbook of Exoplanets, 2nd Edition)*. <https://arxiv.org/abs/2401.13293>
- Teachey, A., & Kipping, D. M. 2018, *Science Advances*, 4, eaav1784, doi: [10.1126/sciadv.aav1784](https://doi.org/10.1126/sciadv.aav1784)
- Teachey, A., Kipping, D. M., & Schmitt, A. R. 2017, *The Astronomical Journal*, 155, 36, doi: [10.3847/1538-3881/aa93f2](https://doi.org/10.3847/1538-3881/aa93f2)

- Trani, A. A., Hamers, A. S., Geller, A., & Spera, M. 2020, *Monthly Notices of the Royal Astronomical Society*, 499, 4195, doi: [10.1093/mnras/staa3098](https://doi.org/10.1093/mnras/staa3098)
- van Woerkom, Q. B., & Kleisioti, E. 2024, *A&A*, 684, A72, doi: [10.1051/0004-6361/202348604](https://doi.org/10.1051/0004-6361/202348604)
- Vanderburg, A., Rappaport, S. A., & Mayo, A. W. 2018, 156, 184, doi: [10.3847/1538-3881/aae0fc](https://doi.org/10.3847/1538-3881/aae0fc)
- Vanderburg, A., & Rodriguez, J. E. 2021, *The Astrophysical Journal Letters*, 922, L2, doi: [10.3847/2041-8213/ac33b4](https://doi.org/10.3847/2041-8213/ac33b4)
- Veeder, G. J., Matson, D. L., Johnson, T. V., Blaney, D. L., & Goguen, J. D. 1994, *Journal of Geophysical Research: Planets*, 99, 17095, doi: <https://doi.org/10.1029/94JE00637>
- Vos, J. M., Faherty, J. K., Gagné, J., et al. 2022, *The Astrophysical Journal*, 924, 68, doi: [10.3847/1538-4357/ac4502](https://doi.org/10.3847/1538-4357/ac4502)
- Vos, J. M., Biller, B. A., Bonavita, M., et al. 2019, *MNRAS*, 483, 480, doi: [10.1093/mnras/sty3123](https://doi.org/10.1093/mnras/sty3123)
- Yang, H., Apai, D., Marley, M. S., et al. 2016, *The Astrophysical Journal*, 826, 8, doi: [10.3847/0004-637X/826/1/8](https://doi.org/10.3847/0004-637X/826/1/8)
- Zambon, F., Mura, A., Lopes, R. M. C., et al. 2023, *Geophysical Research Letters*, 50, e2022GL100597, doi: <https://doi.org/10.1029/2022GL100597>
- Zieba, S., Zilinskas, M., Kreidberg, L., et al. 2022, *A&A*, 664, A79, doi: [10.1051/0004-6361/202142912](https://doi.org/10.1051/0004-6361/202142912)

A. Planet spectral variability

Figures 4.8 and 4.9 show the normalized flux variations with time, calculated by the IPMO circulation model for an edge-on and a 30 deg inclined orbit.

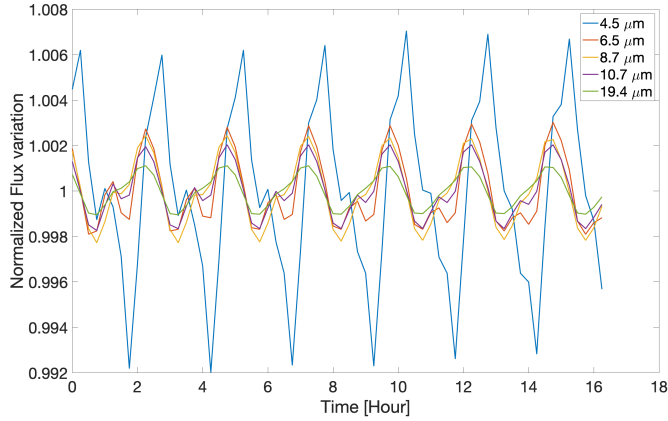


Figure 4.8: Host spectroscopic variability for an edge-on view. The period of variability remains the same, while the amplitude of variability changes as a function of wavelength.

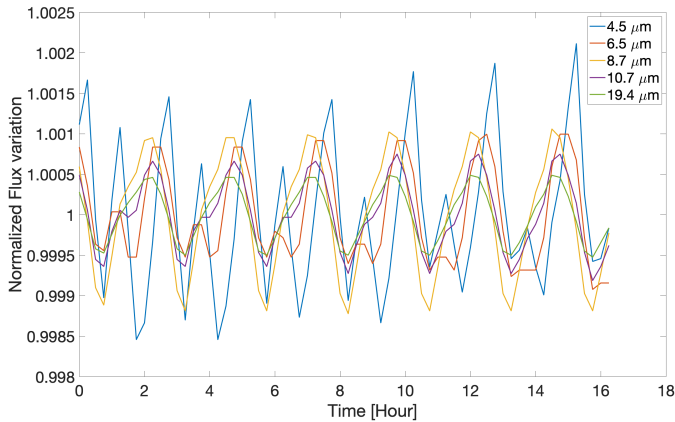


Figure 4.9: Host spectroscopic variability (30° inclined). The period of variability remains the same, while the amplitude of variability changes as a function of wavelength.

B. True positive rate as a function of number of instances

Figure 4.10 shows the true positive rate as a function of the number of shot noise instances (iterations). We chose 10^3 iterations as the number of iterations for the simulations shown in Figures 4.5 and 4.6.

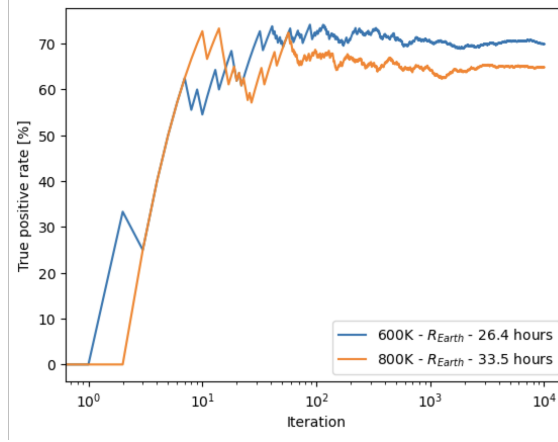


Figure 4.10: True positive rate as a function of the number of shot noise instances for an Earth-sized moon with $T_h = 600$ K, an orbital period of 26.4 h (blue line) and $T_h = 800$ K, and an orbital period of 33.5 h (orange line).

C. False alarm probabilities as a function of the true positive rate

This section refers to the FAP calculations that are presented in Section 4.3 and shown in Figure 4.3. We calculated the FAPs and confidence intervals using a Gamma distribution with a scale parameter equal to the variance of the 95th percentile of the time-domain data and a shape parameter equal to one, as the square magnitude of each frequency coefficient for time domain data with Gaussian noise approximates a Gamma distribution. Figure 4.11 shows the percentage of correctly identified moon peaks that are detected with FAPs smaller than 10% and 50 % as a function of the true positive rate.

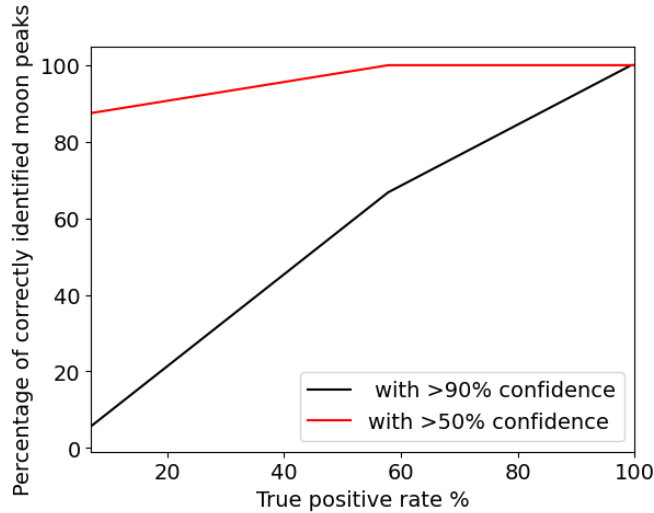


Figure 4.11: Percentage of correctly identified moon peaks with > 90% confidence (black line) and > 50% confidence (red line) as a function of the true positive rates, for Earth-sized moons with an orbital period of 26.4 hours.

5 | Modeling the interiors of Trappist-1f, g, h: Tidal Heating, Subsurface Oceans, and Cryovolcanic Activity

Submitted to Astronomy & Astrophysics

E. Kleisioti, D. Dirkx, A. Louca, M. Rovira-Navarro, M. A. Kenworthy

Aims. We model the interior of the Trappist-1f,g,h exoplanets with contributions from tidal and radiogenic heating. We constrain the thickness of heat-producing layers that can maintain equilibrium with a given thickness of the outer shell, and, thus, we identify interior structures that are in thermal equilibrium, consistent with the most recent observed mass and radius of the planets. We estimate the total internal heat and assess whether it is sufficient to drive detectable cryovolcanic activity.

Methods. We use an interior model that considers a spherical and radially symmetric planet with an icy shell covering a subsurface ocean and a thermal model, that takes into account tidal heat, as well as radiogenic heat produced from the radioactive elements accumulated in the mantle. We approximate the rate of volcanic outgassing by scaling with the Earth's volcanic outgassing, driven primarily by radiogenic sources. We use radiative transfer to create synthetic transmission spectra of a water exosphere. We generate synthetic NIRISS/JWST data for a configuration where the outgassing is evenly distributed over the surface, and one where the outgassing is concentrated at the planet's limb.

Results. We find that for all three planets the tidal heat in the mantle is negligible compared to both the tidal heating in the high pressure ice layer and the expected radiogenic heat. Trappist-1f and g are in thermal equilibrium for outer shell thicknesses between ≈ 4 and 10 km, with a water subsurface ocean with thicknesses between ≈ 90 and 120 km. In agreement with previous work, Trappist-1f produces the highest values of water column densities. The maximum water column density at $1.1 \times 10^{18} \frac{\text{mol}}{\text{m}^2}$ is not detectable with NIRISS. Detecting cryovolcanic outgassing at the level of $\sim 15 \times \dot{M}_{\text{volc,Earth}}$ (that is, 15 times the volcanic mass outgassing rate of Earth) would require approximately 450 transits. This corresponds to a scenario in which nearly 90% of the planet's available interior heat is converted into volatile outgassing, representing a theoretical upper limit, well above Earth's estimated values.

Conclusions. The interior structures of Trappist-1f and g would be, under the assumptions of our model, in thermal equilibrium only in cases where the outer ice I shell is relatively thin, and thus, a subsurface ocean would be likely in direct contact with the surface through cryovolcanism, in agreement with previous work. Trappist-1 h would be in thermal equilibrium for thicker ice-shells. The most optimistic configuration of cryovolcanic outgassing for Trappist-1f would require over a decade long campaign with the JWST. Future efforts to detect cryovolcanism may benefit from targeting exoplanets with higher orbital eccentricities, where increased tidal dissipation could lead to larger rates of water outgassing.

5.1 Introduction

Since the discovery of the Trappist-1 planet system (Gillon et al., 2017), the system has provided an intriguing opportunity to the exoplanet community for observational and theoretical studies (see e.g. Krissansen-Totton & Fortney, 2022; Zieba et al., 2023; Pichierrì et al., 2024; Schoonenberg, Djoeké et al., 2019)). Trappist-1 hosts seven known, transiting exoplanets in orbital resonance, and in almost edge-on orbits (Teyssandier et al., 2022; Agol et al., 2021). It is the first known system of potentially rocky, terrestrial exoplanets with incident fluxes in the range of the Solar System rocky planets, three of which are located within the star's habitable zone.

The small radius of the star aids the planets' characterisation. Agol et al. (2021) performed an analysis of transit timing variations (TTVs) that includes all transit data from Spitzer since the discovery of the system, and provided precise mass, and radius measurements for the planets. In addition, they observed a slight downward trend of density with orbital distance. One possible explanation is different volatile/water content for the seven planets. If confirmed, the three outer planets, f, g, and h, might have between 4.5 and 6.4 wt% water assuming an Earth-like core (Agol et al., 2021). The latter, together with their low equilibrium temperatures, makes them good candidates for “cold ocean planets” (Quick et al., 2020).

Cold ocean planets are “ocean-bearing worlds with ice covered surfaces” (Quick et al., 2020). Their interior structure and properties are expected to be similar to those of the Solar System icy moons (Ehrenreich et al., 2006). As such, they might harbor subsurface oceans fueled by tidal or radiogenic heating, underneath an icy shell (Nimmo & Papalardo, 2016). Cold ocean planets might be in abundance in the galaxy (Zeng et al., 2019), and are significant targets for habitability and astrobiology studies. Several candidate worlds of this nature have been proposed. For example, Quick et al. (2023) identified 17 planet candidates that might be icy, including Trappist-1, f, g, h, according to their measured densities and equilibrium temperatures. Another planet, whose properties are compatible with a water-rich planet covered in an icy surface is LHS 1140 b (Quick et al., 2020, 2023; Cadieux et al., 2024).

Several studies have characterized the possible water-bearing interior of Trappist-1 g, f, h planets (see e.g. Barr et al., 2018; Dobos et al., 2019). Acuña et al. (2021) studied their putative hydrospheres by modelling their pressure-temperature profiles, and concluded that water on the planets would be in solid phases. The planets' non zero orbital eccentricity and short orbital periods suggest that tidal heating might be significant in their thermal budget (Luger et al., 2017). Barr et al. (2018) studied tidal heating in the Trappist-1 system, and indicated that the interior of the outer planets could have similar geodynamics as Solar System icy moons.

If the outer Trappist-1 planets indeed have similar internal structures and geological features to icy moons, they might also exhibit cryovolcanism. Cryovolcanism has been detected on Enceladus (Porco et al., 2006), Europa (Fagents et al., 2000; Fagents, 2003; Roth et al., 2014; Jia et al., 2018), Triton (Croft et al., 1995), and other icy bodies in the Solar System (Fagents et al., 2022) and is a source of water outgassing, contributing into the formation of exospheres. In the Solar System, some icy moons exhibit tenuous exospheres or outgassing activity, such as Europa, which has an oxygen dominated exosphere (Smyth

&Marconi, 2006; Oza et al., 2019a), and Enceladus, which possesses water vapor plumes that feed a diffuse torus around the moon (Villanueva et al., 2023; Porco et al., 2006). Our knowledge on the atmospheres of the Trappist-1 planets is limited, including whether or not they possess atmospheres in the first place. The extended Pre-Main-Sequence (PMS) phase of M-dwarf stars, like Trappist-1, makes the planets subject to atmospheric loss, due to their stars' prolonged high luminosity and intense XUV emission (Luger & Barnes, 2015). However, some efforts have been conducted for the observational characterization of the Trappist-1 atmospheres; de Wit et al. (2018) ruled out cloudless, hydrogen dominated atmospheres for planets d, e and f. In addition, Zieba et al. (2023) found evidence of either tenuous or no atmosphere for planet c, and the photometric secondary eclipse observations of Greene et al. (2023) hint that planet b is most probably a bare rock.

Tidal models of varying complexity have been applied to study bodies and moons within the Solar System (Rovira-Navarro et al., 2022; Bierson & Steinbrügge, 2021) and exoplanet systems (Henning & Hurford, 2014; Shoji & Kurita, 2014; van Woerkom & Kleisioti, 2024). They range from models that assume tidal parameters that are independent of the orbital period and interior structure (constant-Q approach), and more complicated multi-layered approaches, which take into account the viscoelastic behavior of each layer material properties (Kleisioti et al., 2023; Rovira-Navarro et al., 2021). Since the discovery of the Trappist planets, several authors have attempted to constrain their interior structure and potential dynamics assuming that the outer planets Trappist-1 f, g, and h, are “cold ocean worlds”. Quick et al. (2023) obtained ice shell thicknesses, tidal heating rates and cryovolcanic column densities. They used the constant-Q approach to assess tidal heating, which does not take into account the dependency of tidal parameters on the rheological and orbital parameters of the planets, and has been found to underestimate tidal heat production (Ross & Schubert, 1989). Barr et al. (2018) also modeled tidal heating in the system, however they did not use the updated mass and radius constraints of Agol et al. (2021), resulting in significantly higher predicted water contents.

In this work, we examine the interior structure compatible with the updated density estimates using a multilayer, viscoelastic approach and examine the potential for cryovolcanism and its remote detection. By constraining the heat generated within each layer, we can determine the range of internal structures compatible with a given ice shell thickness and assess the total internal heat budget. We focus on the possibility that the outer planets Trappist-1 f, g, and h contain water and do not possess thick atmospheres, with the goal to assess possible thermal equilibrium states, and whether exospheres can be detectable with JWST. We model fully differentiated planets with an icy shell, subsurface ocean, high pressure ice layer (HPI), mantle, and a core, and obtain interior structures in thermal equilibrium. We study the possible thermal states of an icy shell and a subsurface ocean on Trappist-1f,g,h, using thermal models that have been applied to Solar System icy satellites. To do so, we use the planet masses and radii of Agol et al. (2021), together with a tidal model that captures the behavior of material properties as a function of the orbital period. In Section 5.2 we describe our thermal, tidal, and volcanic outgassing models. In Section 5.3 we present the interior constraints for Trappist-1f, and cryovolcanic detectability results. Section 5.4 compares our results to previous work, and discusses whether thermal equilibrium interior structures can generate cryovolcanic signatures detectable with JWST.

5.2 Methods

We assume a fully differentiated body, with radially homogeneous layer properties that consist of an iron core, a silicate mantle, a high pressure ice (HPI) layer that accounts for the possible presence of the water ice polymorphs II through VII (e.g. Jaccard (1976)), a liquid, subsurface ocean and an ice I shell with densities ρ_c , ρ_m , ρ_{HPI} , ρ_{ocean} , and $\rho_{ice,I}$ (Dobos et al., 2019; Barr et al., 2018). For our work, we require a model to determine feasible interior structures of the planets that are compatible with the mass and radius values (see Table 5.2), under the assumption of thermal equilibrium. Here we describe the thermal model (Section 5.2.1) used to calculate the equilibrium states of the ice I shell, and the tidal model (Section 5.2.2) to determine the heating in the dissipative layers of the planets' interior. We describe the planets' thermal equilibrium model in Section 5.2.3.

5.2.1 Heat transfer model

For the heat transfer model of the ice I shell, we follow the approach of Sohl et al. (2003a), who modelled the thermal structure of Titan's ice shell. The ice I shell is divided into a conductive outer layer and a convective sub-layer, as is typically modeled for Solar System icy moons (see e.g. Hussmann et al., 2002; Green et al., 2021). The heat that is transported through the conductive stagnant lid layer is:

$$\frac{Q_{cond}}{4\pi R_p^2} = k \frac{(T_{top} - T_s)}{D_{cond}} \quad (5.1)$$

Where R_p is the planet's radius, D_{cond} is the thickness of the conductive layer, T_s and T_{top} are the surface and top temperature of the convective layer and k is the thermal conductivity coefficient, assumed to be equal to $3.3 \text{ W m}^{-1} \text{ K}^{-1}$ (Spohn & Schubert, 2003).

The equation for heat transport in the convective, sublayer is:

$$\frac{Q_{conv}}{4\pi(R_p - D_{cond})^2} = k \frac{(T_m - T_{top})}{D_{conv}} \left(\frac{Ra}{Ra_c} \right)^\beta \quad (5.2)$$

Where D_{conv} is the thickness of the convective layer, T_m is the melting temperature of the ice I, and Ra and Ra_c are the Rayleigh and the critical Rayleigh number (in the order of 10^3 (Schubert et al., 1979)). The Rayleigh number is given by Equation 5.3. Convection becomes a significant mechanism for heat transport in the ice shell when $Ra \geq Ra_c$. If $Ra \leq Ra_c$ we assume that the ice shell is purely conductive (Equation 5.1).

$$Ra = \frac{\alpha \rho_{ice,I} g_p (T_m - T_{top}) D_{conv}^3}{\kappa \eta(T_{int})} \quad (5.3)$$

Where α and κ are the ice I thermal expansion coefficient and thermal diffusivity equal to $1.6 \times 10^{-4} \text{ K}^{-1}$ and $1.47 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ respectively (Sohl et al., 2003a). g_p is the surface gravity of each planet and $\eta(T_{int})$ is the viscosity of the convective layer's mean temperature (T_{int}).

In thermal equilibrium, the heat flux (Q_{eq}) that is transferred through the conductive layer is equal to the flux convected through the sublayer:

$$Q_{cond} = Q_{conv} = Q_{eq} \quad (5.4)$$

To obtain the thermal equilibrium state of the ice I shell, we solve Equations 5.1, 5.2, 5.3 and 5.4 iteratively for the layer thicknesses (D_{stag} , D_{conv}) and the equilibrium heat flux Q_{eq} for different values of total ice I layer thickness (D_{ice}). To do so, we firstly assume a value for D_{ice} , which is the free parameter in our interior models. This sets the pressure, and thus, the melting temperature at the bottom of the convective layer (T_m), at the depth $R_{ice,I}$, as seen in Figure 5.1. The melting temperature is calculated as a function of pressure, as shown in Figure 5.8 for an ammonia containing ocean of 5 wt.% (Grasset et al., 2000). These concentrations are consistent with those inferred for icy Solar System bodies, like Titan, where ammonia acts as an antifreeze facilitating the existence of subsurface oceans under cold conditions (Sohl et al., 2003b). Furthermore, formation beyond the water ice line of Trappist-1f,g,h (see Section 5.4.3) would promote the accretion of volatile compounds, including ammonia. With the assumption that the ocean is isothermal we calculate the pressure at the bottom of the ocean, and thus the thickness of the ocean, and the radius R_{HPI} . This process is visualized in the red segment of Figure 5.2. For more details on the iterative method, we refer the reader to Sohl et al. (2003a).

5.2.2 Tidal response model

The amount of tidal heat dissipated in the interior of a planet is given by Equation 5.5 (eg. Segatz et al., 1988).

$$\dot{E} = -\frac{21}{2} \text{Im}(k_2) \frac{(nR)^5}{G} e^2 \quad (5.5)$$

Where n is the planet's mean motion, e the orbital eccentricity of the planet, and G the universal gravitational constant. We are assuming that the planets are rotating synchronously (Lobo et al., 2023; Turbet, Martin et al., 2018). In addition, we assume that the planets have zero obliquity, and therefore have zero obliquity tides.

$\text{Im}(k_2)$ is the imaginary part of the k_2 Love number, which describes the deformation of the planet's gravity field due to the tidal interactions with the host star. $\text{Im}(k_2)$ depends on the interior structure (and hence the mass of the dissipative layers), properties, rheology of the planet and its orbital period (Segatz et al., 1988; Renaud & Henning, 2018; Shoji & Kurita, 2014). We computed the tidal dissipation using the viscoelastic theory for self gravitating bodies (see e.g. Peltier, 1974; Sabadini R., 2016) with the Maxwell rheological law, which connects stress and strain, and has already been applied to study Solar System moons (Husmann & Spohn, 2004; Fischer & Spohn, 1990; Tobie, G. et al., 2019; Roberts & Nimmo, 2008; Rovira-Navarro et al., 2022) and exoplanet systems (Rovira-Navarro et al., 2021; Dobos & Turner, 2015; Hay & Matsuyama, 2019). By solving the equations of motion for the deformation of each layer in the Fourier domain via the correspondence principle (Peltier, 1974), we obtain the gravitational potential at the surface and thus, the Love number. We use the method described by Rovira-Navarro et al. (2024) for spherically symmetric bodies, and use the LOV3D software package (Rovira Navarro & Matsuyama, 2024) to compute the tidal dissipation in each layer for a given planetary structure.

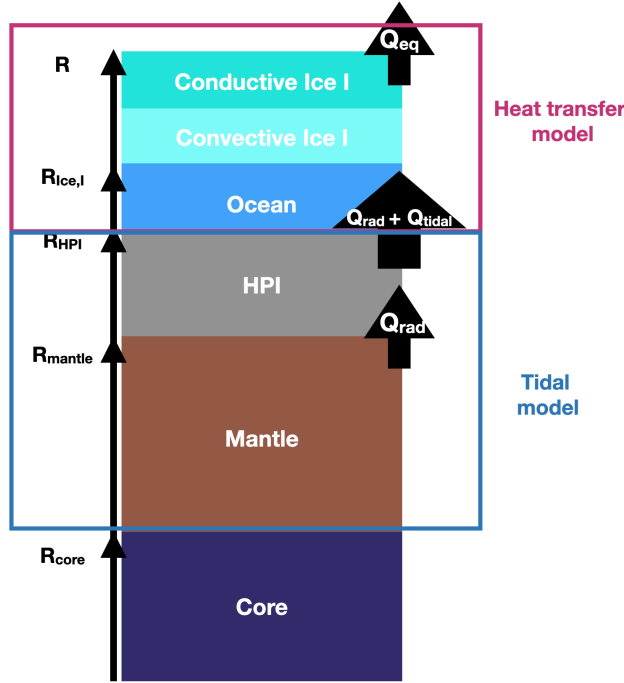


Figure 5.1: Schematic overview of the interior model of Trappist-1f,g,h. The ice I layer is divided into a conductive and a convective sublayer. The thermal model determines the thickness of the conductive and convective layers, $R_{ice,I}$, R_{HPI} , and Q_{eq} . The tidal model computes the tidal heating rates in the HPI, and the mantle. The layer boundaries are not to scale. Note that the convective layer is only present for a sufficiently high ($\gtrsim 10^3$) Rayleigh number

5

The rheological and physical properties that were used for the thermal and tidal models are presented in Table 5.1, while the orbital properties of each planet are shown in Table 5.2. We evaluate the tidal dissipation occurring in the HPI, mantle and ice I layers.

5.2.3 Interior heat balance and structure calculation

The heat transfer model described in Section 5.2.1 provides the heat flux for a given value of the ice I layer thickness (D_{ice}), and the associated thermal equilibrium heat output (Q_{eq}). In this manner, Q_{eq} is a function of D_{ice} . For the entire planet to exist in equilibrium, Q_{eq} should be equal to the amount of heat that is produced in the interior. Our aim is to determine the mass and thickness of each interior layer - the core (m_c), mantle (m_m), and high-pressure ice (HPI) layer (m_{HPI}) - for a range of ice shell thicknesses (D_{ice}), such that the total internal heat production is consistent with Q_{eq} and measured planetary mass and radius.

We focus on two dominant sources of interior heat: tidal heating in the HPI layer

Table 5.1: Physical and rheological properties of the interior model layers.

Parameter + Symbol	Value	Reference
HPI Viscosity (η_{HPI})	10^{14} Pa s	(Barr et al., 2018)
Mantle Viscosity (η_m)	10^{20} Pa s	(Lau et al., 2016)
Ice I Viscosity (η_{iceI})	10^{14} Pa s	(Barr et al., 2018)
HPI shear modulus (μ_{HPI})	3.5×10^{10} Pa	(Barr et al., 2018)
Mantle shear modulus (μ_m)	7×10^{10} Pa	(Segatz et al., 1988)
Ice I shear modulus (μ_{iceI})	3.3×10^9 Pa	(Hussmann et al., 2002)
HPI density (ρ_{HPI})	1310 kg m^{-3}	(Sohl et al., 2003a)
Mantle density (ρ_m)	5000 kg m^{-3}	(Barr et al., 2018)
Ice I density ($\rho_{ice,1}$)	917 kg m^{-3}	(Sohl et al., 2003a)
Ocean density (ρ_{ocean})	950 kg m^{-3}	(Sohl et al., 2003a)
Core density (ρ_{core})	12050 kg m^{-3}	(Barr et al., 2018)

Table 5.2: Planet parameters used in the model.

Parameter	Symbol	Trappist-1f	Trappist-1g	Trappist-1h
Planet mass [$M_\oplus$]	M_p	1.039 ± 0.031	1.321 ± 0.038	0.326 ± 0.020
Planet radius [$R_\oplus$]	R_p	$1.045^{+0.013}_{-0.012}$	$1.129^{+0.015}_{-0.013}$	0.775 ± 0.014
Equilibrium temperature [K]	T_{eq}	192	174	151
Orbital period [days]	P	9.20	12.35	18.77
Orbital eccentricity	e	0.01007	0.00208	0.00567

Note. The planet as well as the star parameters that were used in order to calculate the planets' equilibrium temperatures are taken from Agol et al. (2021). For the calculation of T_{eq} we assumed $A = 0.4$ to account for possible surface contamination and the lower reflectivity of ice at near-infrared wavelengths, where M-dwarf spectra peak (Shields et al., 2013). Eccentricity values are taken from Grimm et al. (2018).

and radiogenic heating in the silicate mantle, and assume that the heat flux through the ice shell (Q_{eq}) must equal the sum of the radioactive decay (Q_{rad}) that is produced by the accumulation of radioactive elements in the silicate mantle, and the tidal heat that is produced in the high pressure ice layer ($Q_{tidal,HPI}$)(see Eq. 5.6). We validate the latter assumption later in this Section.

$$Q_{eq} = Q_{tidal,HPI} + Q_{rad} \quad (5.6)$$

For the calculation of Q_{rad} , we follow the approach of Schubert et al. (1986), and use Equation (1) from Hussmann & Spohn (2004), which expresses the radiogenic heat production as a function of mantle mass (m_m). We assume a mantle with chondritic composition and a system age of 7.6 Gyr (Burgasser & Mamajek, 2017). We estimate the tidal heat produced in the high-pressure ice layer, $Q_{tid,HPI}$, from the total tidal dissipation rate given by Equation 5.5. The value of $Q_{tid,HPI}$ depends on the mass and thickness of the HPI layer, through their influence on the layer's rheology and the overall viscoelastic response of the planet.

To constrain the full interior structure, we can apply the following constraints, which describe the mass conservation (Equation 5.7), and the geometry of the system (Equation 5.8), solving for the radius of the HPI layer (R_{HPI}).

$$M_p = m_c + m_m + m_{ocean} + m_{ice,I} + m_{HPI} \quad (5.7)$$

$$R_{HPI} = \left(\frac{3}{4\pi} \right)^{\frac{1}{3}} \left(\frac{m_{HPI}}{\rho_{HPI}} + \frac{m_m}{\rho_m} + \frac{m_c}{\rho_{core}} \right)^{\frac{1}{3}} \quad (5.8)$$

Where $m_{ice,I}$ is the mass of the ice I shell. The rest of parameters in Equations 5.7, 5.8 are described in Table 5.1.

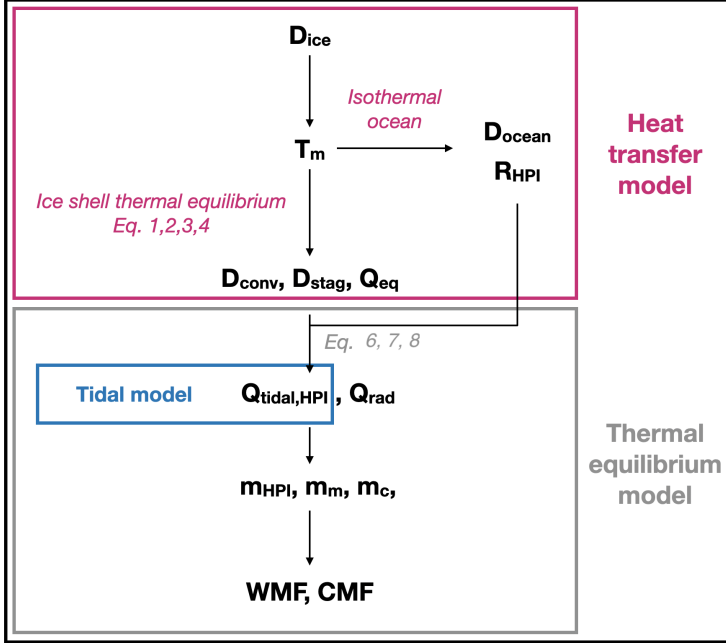


Figure 5.2: Schematic of the parameter calculation process. The red segment visualizes the heat transfer model in the outer ice shell, which is described in Section 5.2.1. The grey segment describes the process of calculating the thermal equilibrium in the entire planet (Section 5.2.3). The latter thermal equilibrium dictates that $Q_{eq} = Q_{tidal,HPI} + Q_{rad}$

Since $Q_{tid,HPI}$ is a function of m_{HPI} (see Section 5.2.2) and Q_{rad} is a function of m_m , we solve the system of equations 5.6, 5.7, 5.8 for m_m , m_{HPI} , and m_c for a range of D_{ice} . Thus, we calculate m_c , m_m , m_{HPI} , Q_{rad} , and $Q_{tidal,HPI}$ as a function of D_{ice} . This allows us to derive the corresponding Core Mass Fractions (CMF) and Water Mass Fractions (WMF) values as a function of D_{ice} . The gray boxed region of Figure 5.2 visualises the calculation process described in this Section.

We finally assess whether the assumption made in Equation 5.6 is valid. We recompute the expected tidal heating rates in the different layers, as seen in Figure 5.3 for the computed interior structures with varying HPI, mantle, and core masses. In all cases, we conclude that the tidal heating rate in the mantle ($Q_{tidal,m}$) is at least one order of magnitude lower than both the tidal heating in the HPI and the expected radiogenic heat (see

Figure 5.3), while the tidal heat in the ice I shell ($Q_{\text{tidal,iceI}}$) is typically four orders of magnitude smaller than the total heat generated in the interior (see Figure 5.9), validating our initial assumption of neglecting $Q_{\text{tidal,m}}$ and $Q_{\text{tidal,iceI}}$ in Equation 5.6.

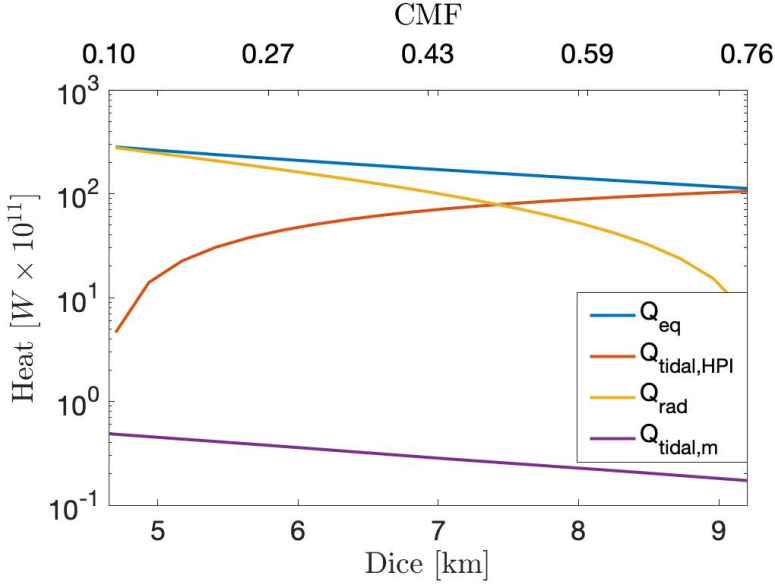


Figure 5.3: Comparison of heat contribution from several sources for Trappist-1f as a function of ice shell thickness. Tidal heat in the mantle is negligible in the entire parameter space, while radiogenic heat and tidal heat in the ice shell both contribute significantly to the ice sheet equilibrium heat. Trappist-1f due to its size and eccentricity has the highest tidal heat of the three planets.

5.2.4 Modelling observations of cryovolcanic activity

Cryovolcanic activity has been observed on Saturn's moon, Enceladus (Villanueva et al., 2023; Spencer et al., 2018), and is also suspected on Jupiter's moon, Europa, based on multiple detections (Roth et al., 2014; Sparks et al., 2017; Paganini et al., 2020). However, the detection reported by Sparks et al. (2017) remains controversial (Giono et al., 2020). In the case of Enceladus, a subsurface ocean is located ≤ 10 km beneath the south polar surface (Iess et al., 2014), and is estimated to thin to less than 5 km in this region (Čadek et al., 2016). This makes the cryovolcanic plume likely to originate directly from the ocean (Manga & Wang, 2007). Cryovolcanic activity on Enceladus is thought to be regular and has been found to be correlated with the orbital period (Ingersoll et al., 2020) and tidal stresses (Hedman et al., 2013; Souček et al., 2024). On the other hand, cryovolcanic eruptions on Europa are sporadic (Sparks et al., 2017). In particular, Paganini et al. (2020); Phillips et al. (2000) show that large cryovolcanic eruptions are likely rare, and

Fagents et al. (2000) suggest that smaller eruptions are likely to occur more frequently. Given an ice shell of $\approx 25\text{--}30$ km (Quick & Marsh, 2015), cryovolcanic activity on Europa is thought to originate from water pockets that are located within the ice shell (Fagents, 2003; Manga & Wang, 2007).

Similar geological features, including volcanism and cryovolcanism, may be present on exoplanet systems (Kleisioti et al., 2024; Quick et al., 2023, 2020; Oza et al., 2019b; Meyer zu Westram et al., 2024; Guenther & Kislyakova, 2019). However, predicting cryovolcanic outgassing on cold ocean exoplanets is challenging because it can be influenced by poorly constrained parameters and interior processes, including the total internal heat production, possibly the fraction of that heat generated by tidal dissipation, and the thickness of the outer ice shell. While surface fractures, like Enceladus' tiger stripes, may form solely due to tidal stretching and compression, radiogenic heating can also contribute to maintaining subsurface liquid reservoirs (Leone et al., 2021). If tidal dissipation is sufficient to create cracks, radiogenic heat may further sustain or enhance internal melting, and together these heat sources can maintain subsurface oceans that enable cryovolcanic activity (Ingersoll et al., 2020; Neveu & Rhoden, 2019).

To approximate the cryovolcanic outgassing we use the analogy of Oza et al. (2019a); Quick et al. (2023) which relates outgassing rates of Solar System icy moons to tidal heat production. However, since radiogenic heating dominates over tidal heating in the Trappist-1 planets by several orders of magnitude, we compare their total outgassing to the Earth's volcanic outgassing. This comparison serves as a scaling relation between total internal heat production and outgassing rate, using Earth as a reference point for linking radiogenic heating to outgassing (Equation 5.9).

$$\dot{M}_{\text{Volc}} \approx \left(\frac{\dot{E}_{\text{Total}}}{\dot{E}_{\text{Total,Earth}}} \right) \dot{M}_{\text{Volc,Earth}} \quad (5.9)$$

Where $\dot{E}_{\text{Total}}$ is the planet's total interior heat, equal to the sum of the tidal and the radiogenic heat. $\dot{E}_{\text{Total,Earth}} = 47 \times 10^{12} \text{ W}$ is the Earth's surface heat flow (Davies & Davies, 2010). $\dot{M}_{\text{VolcEarth}} = 10.7 \times 10^3 \text{ kg/s}$ is the Earth's estimated volcanic outgassing rate of water vapor, assuming a molar fraction of 60% H_2O and 40% CO_2 (Sigurdsson et al., 1999), and a global CO_2 mass rate of 0.54 Gt/year, corresponding to a total volcanic gas mass rate of ≈ 1.3 Gt/year (Burton et al., 2013). The total volcanic outgassing $\dot{M}_{\text{volc}}$ that is promoted by $\dot{E}_{\text{Total}}$ can also be expressed in terms of the gravitational binding energy of a water molecule to the planet (U):

$$\dot{M}_{\text{Volc}} \approx \eta m_{\text{H}_2\text{O}} \frac{\dot{E}_{\text{Total}}}{U} \quad (5.10)$$

Where η is an efficiency factor describing how efficiently the internal energy is used to power volcanic outgassing (Oza et al., 2019b), $m_{\text{H}_2\text{O}}$ is the mass of one water molecule. An efficiency factor of $\eta = 1$ would represent the theoretical upper limit, where all the available energy is used for the outgassing of water. In reality, this value is much lower. For Earth, when substituting the total outgassing and $\dot{E}_{\text{Total,Earth}}$ into Equation 5.10, η is ≈ 0.04 . The gravitational binding energy U is equal to $\frac{GM_p m_{\text{H}_2\text{O}}}{R_p}$ (Johnson et al., 2015).

We calculated the column density of H_2O , N_{volc} , that is ejected based on the relation (Oza et al., 2019a; Quick et al., 2023):

$$N_{Volc} = \left(\frac{\sqrt{H}}{5.7 \pi m_{H_2O} R_P^2 \sqrt{g_P}} \right) \dot{M}_{Volc} \quad (5.11)$$

Where H is the atmospheric scale height. N_{volc} can be used to calculate the density profile of water within the atmosphere. The total surface pressure is the sum of all partial pressures, also known as *Dalton's law of partial pressure*, $P_{tot} = P_1 + P_2 + \dots + P_n$, with n species in the atmosphere. Assuming the atmosphere is only composed of outgassed water, the total surface pressure is simply the partial surface pressure of water:

$$P_{tot} = P_{Volc} = N_{Volc} m_{H_2O} g_P \quad (5.12)$$

where P_{Volc} is the partial surface pressure of the outgassed water. Assuming an exponential decay model for the density of the planet's atmosphere, we get a density profile of the outgassed water. This density profile assumes an isothermal atmospheric profile. We set the temperature equal to the equilibrium temperatures T_{eq} , shown in Table 5.2. We then forward this density and isothermal profile to a radiative transfer code, *petitRADTRANS* (Mollière et al. 2019; 2020; Alei et al. 2022), to calculate the transmission spectrum. We make use of the POKAZATEL linelist (Polyansky et al. 2018) for the water opacities. We model the spectrum from 0.2 to 2.5 micron, covering several water features. Finally, we forward these synthetic transmission spectra to the *PandExo* Exposure Time Calculator (Batalha et al. 2017) to generate mock JWST data points using the NIRISS Substrip 256 instrument. We make use of the Phoenix models for the stellar spectrum of Trappist-1.

Given their relatively close-in orbits and the active nature of TRAPPIST-1, exospheres may form not only through outgassing from cryovolcanic activity, but also via the mass loss through thermal escape caused by XUV activity (Wordsworth et al., 2018; Luger & Barnes, 2015)(see also Section 5.4.3). Quick et al. (2023) modeled this latter phenomenon by calculating the water mass loss rate under the XUV flux of Trappist-1, and translating it into column densities produced by the XUV-driven escape. We account for this contribution in our final column density by adding the values of the XUV produced water column densities from their Table 5 to our calculated N_{volc} .

We consider two distinct configurations for the spatial distribution of cryovolcanic outgassing on each planet. The first represents a worst-case scenario for detectability, where the outgassing material is uniformly distributed across the planet's surface. This scenario assumes that geyser-like plumes are globally distributed over the planet's surface, and results in a homogeneous volcanic density N_{volc} over the planet's three-dimensional sphere. In contrast, the second configuration represents a best-case scenario, where outgassing is localized at one pole of the planet. The latter case resembles the case of Enceladus, where cryovolcanic activity is focused at the south pole in the tiger stripes region. By exploring these two extreme scenarios, we aim to assess the feasibility of observing cryovolcanic activity on Trappist-1f, g, and h.

5.3 Results

We first present our results by exploring the possible interior structures that achieve thermal equilibrium. Next, we examine the resulting water column densities these structures can produce and infer their potential impact on observations.

5.3.1 Possible interior structures of the planets Trappist 1 - f,g,h

In Figure 5.4a, we present the interior structure of Trappist-1f (R_{core} , R_{mantle} , R_{HPI}) as a function of D_{ice} (see Section 5.2.3). Figures 5.10, 5.11 present the corresponding Figures for Trappist-1,g and h. A given D_{ice} thickness can transport an amount of heat equal to the radiogenic heat generated in the mantle and the tidal heat produced in the HPI layer. Thicker ice I layers can transport smaller amounts of heat. The latter translates to a structure with higher $\frac{M_{HPI}}{M_{Mantle}}$ ratios, as seen in Figure 5.3. Thus, as D_{ice} increases, the ratio $\frac{M_{HPI}}{M_{Mantle}}$ also increases (Figure 5.4). The various interior structures are consistent with the observed densities of the planets. As a result, the calculated range for ice shell thickness is limited; thicker ice shells reach thermal equilibrium at lower Q_{eq} values. Achieving such equilibrium requires a larger core, since a smaller mantle reduces radiogenic heating. This, in turn, prevents the total internal heat (radiogenic from the mantle and tidal from the high-pressure ice (HPI) layer) from exceeding the heat transfer capacity of the ice shell. Thus, the high-pressure ice (HPI) layer expands rapidly with D_{ice} , compensating for the increased core size.

The right horizontal-axis limit of Figure 5.4 corresponds to the case of a planet without a mantle layer, meaning that the iron core would be in direct contact with the HPI (CMF = 0.75). The left horizontal-axis limit is consistent with an interior structure that lacks a HPI layer. Such an interior structure corresponds to the minimum WMF. Smaller WMF's would not be compatible with Trappist-1f,g,h having an icy shell with a subsurface liquid ocean under the assumptions of our model. Although modifying the physical and rheological parameters shown in Table 5.1 would change the exact numerical results, the overall trends and magnitudes remain representative of a body with the layered internal structure we consider. Without an HPI layer, the subsurface ocean would be in direct contact with the mantle, a configuration particularly important for astrobiological and habitability studies, since it allows for the potential exchange of essential elements between the rocky interior and the ocean, as is believed to occur on Europa (Hand et al., 2022).

Figure 5.4b shows the thickness of the stagnant lid, convective layer, and ocean layer, as a function of D_{ice} . If Trappist-1f has a CMF of 0.5 and an ice shell in thermal equilibrium, the ocean, approximately 100 km thick, would lie about 6 km beneath an almost entirely conductive ice shell. The extremely thin convective shell thickness supports the assumption of a conducting ice I layer made in this work (Section 5.2.2), in contrast to the convective, thicker ice shells observed on icy moons within the Solar System (see e.g. Hussmann et al., 2002).

We present the thermal equilibrium interior structure parameters for Trappist-1f,g,h in Tables 5.3, 5.4, 5.5 respectively for CMF=0.18, 0.32, and 0.5 assuming that the planets have not been exposed to events that could have stripped away their mantle, such as mantle

evaporation (Cameron, 1985). For the planets Trappist-1f and g, even in the case of a large CMF equal to 0.5, a subsurface ocean would exist below an ice shell of thickness $\lesssim 10$ km. Such a thin ice I shell hints that the ocean is more likely to be in direct contact with the surface through fractures in the icy crust. As a result, a plume would likely be composed of material originating directly from the subsurface ocean, similarly to the cryovolcanic mechanism on Enceladus (Quick et al., 2023; Postberg et al., 2018; Porco et al., 2014). Trappist-1h, the least massive of the three planets, exhibits equilibrium interior structures with an ice layer thickness $\gtrsim 10$ km. This raises the possibility that any cryovolcanism on Trappist-1h could resemble that of Europa, coming from water-pockets in the ice (see Section 5.2.4) (Quick et al., 2023).

In the following section we discuss whether cryovolcanism could be observed with spectroscopic observations on Trappist-1f,g,h.

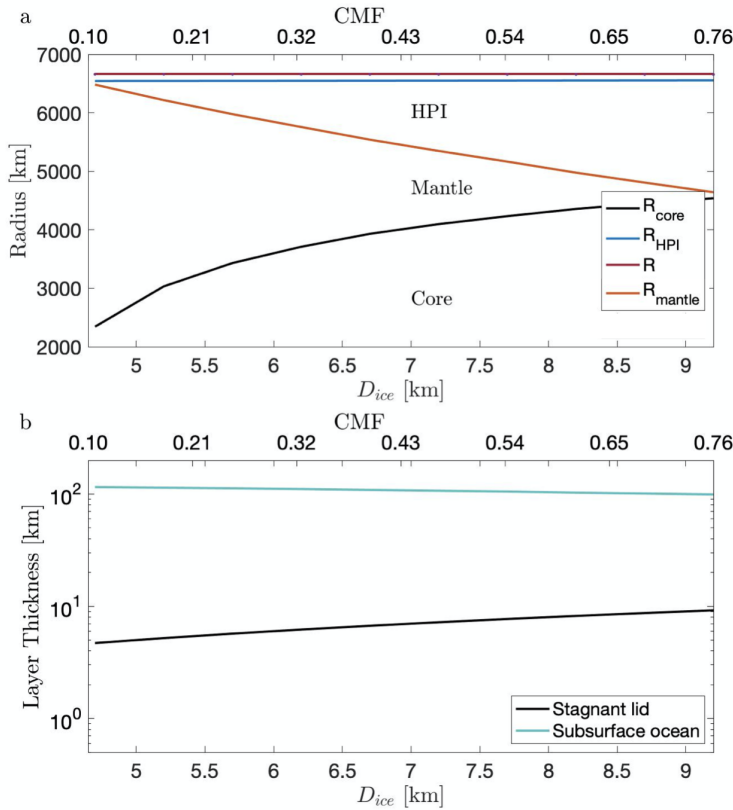


Figure 5.4: a. Interior structure as a function of D_{ice} for the planet Trappist-1f. b. Thickness of the stagnant lid, convective and ocean layers as a function of D_{ice} .

Table 5.3: Interior and thermal parameters of Trappist-1f in thermal equilibrium for different values of CMF.

Parameter	Symbol	CMF = 0.11 (min)	CMF = 0.18	CMF = 0.32	CMF = 0.50
Thickness of ice I layer [km]	$D_{ice,I}$	4.7	4.9	5.6	6.8
Ocean thickness [km]	D_{ocean}	117.4	117.1	115.4	111.5
Water mass fraction	WMF	0.019	0.038	0.085	0.14
Water column density					
- Favorable configuration [mol/m^2]	N_{volc}	1.1×10^{18}	1.0×10^{18}	9.4×10^{17}	8.2×10^{17}

Table 5.4: Interior and thermal parameters of Trappist-1g in thermal equilibrium for different values of CMF

Parameter	Symbol	CMF = 0.09 (min)	CMF = 0.18	CMF = 0.32	CMF = 0.50
Thickness of ice I layer [km]	$D_{ice,I}$	5.2	5.9	7.2	9.2
Ocean thickness [km]	D_{ocean}	112.5	110.0	104.4	95.6
Water mass fraction	WMF	0.011	0.030	0.059	0.080
Water column density					
- Favorable configuration [mol/m^2]	N_{volc}	9.9×10^{17}	9.6×10^{18}	8.4×10^{17}	6.6×10^{17}

5.3.2 Observations of cryovolcanic activity

Figure 5.5a shows N_{volc} as calculated from Equation 5.11 as a function of the planet's CMF and $\text{Im}(k_2)$, for Trappist-1f, the planet with the highest water column density (see Tables 5.3, 5.4, 5.5). N_{volc} is shown both for (1) cryovolcanism where outgassing is concentrated on one pole of the planet (blue line), and (2) cryovolcanism where outgassing is globally distributed over the planet's entire surface (black line). Any other distribution of outgassing on the surface is anticipated to produce a signal that falls between these two cases. Smaller CMF values are linked higher N_{volc} values, which can be explained by the fact that larger CMFs correspond to greater ice layer thicknesses D_{ice} (see Section 5.3.1), resulting in lower equilibrium heat Q_{eq} . If cryovolcanic outgassing depends primarily on the amount of generated tidal heat, N_{volc} would increase with CMF, because a higher CMF is associated with a thicker HPI layer, which would generate more tidal heat. Therefore, depending on whether cryovolcanism is driven by Q_{eq} or Q_{tid} , interior structures with lower or higher CMF values may be more observable. Figure 5.5b presents N_{volc} for the homogeneous (black) and favorable (blue) configuration as a function of $\dot{M}_{volc}$.

Figure 5.6 presents the spectrum of a bounded water exosphere on Trappist-1f for two different values of N_{volc} . These figures were created using a radiative transfer code and exposure time calculator following the methods in section 5.2.4. With a water column density of $N_{volc} = 6.3 \times 10^{17}$ molecules/ m^2 , the surface pressure becomes $P_{surf} = 1.76 \cdot 10^{-6}$ bar (see section 5.2.4 for methodology). The top plot illustrates that the errorbars from the synthetic JWST data are larger than the water features for this surface pressure of water, and, therefore, will not be detectable with NIRISS. However, if JWST observes every transit of Trappist-1f ($P = 9.2$ days) for 12 years, amounting to approximately 450 transits, an N_{volc} of 1.9×10^{19} molecules/ m^2 becomes detectable (bottom plot). The water feature at 1.4 micron is, in this case, larger than the errorbars of the synthetic JWST data. Even in this extreme scenario, the resulting volcanic density corresponds to an outgassing rate of approximately 25 $\times$ the maximum $\dot{M}_{volc}$ generated for Trappist-1f in our model

Table 5.5: Interior and thermal parameters of Trappist-1h in thermal equilibrium for different values of CMF

Parameter	Symbol	CMF = 0.02 (min)	CMF = 0.18	CMF = 0.32	CMF = 0.50
Thickness of ice I layer [km]	$D_{ice,I}$	9.4	11.5	13.7	18.0
Ocean thickness [km]	D_{ocean}	111.0	108.4	103.5	92.0
Water mass fraction	WMF	0.080	0.095	0.118	0.150
Water column density					
- Favorable configuration [mol/m^2]	N_{Volc}	9.2×10^{17}	8.7×10^{17}	7.5×10^{17}	5.8×10^{17}

(represented by the black dashed vertical line in Figure 5.5b).

5.4 Discussion

In this section, we first compare our modeling results with previous studies. Next, we explore the detectability of cryovolcanic activity on Trappist-1f, g, and h, and discuss potential interior constraints that could be determined through spectroscopic observations of water column densities.

5.4.1 Column density comparison with previous work

Quick et al. (2023) identified 17 exoplanets that are potentially icy, by inferring their equilibrium surface temperatures and their mean densities. They also discussed the potential of observing cryovolcanic activity on these planets, which include Trappist-1f,g,h. To do so, they calculated tidal dissipation in the planets' interior with Equation 5.5, assuming a constant $\text{Im}(k_2)$ value, equal to 0.003, for all three planets. This value is consistent with $\text{Im}(k_2)$ values for Solar System icy satellites (Zhang & Zhang, 2004), and with studies of tidal dissipation in terrestrial planets (Henning & Hurford, 2014; Goldreich & Soter, 1966). Nevertheless, this approach does not take into account the $\text{Im}(k_2)$ dependency on the orbital period and interior properties (Renaud & Henning, 2018). We show that depending on the interior properties, the value of $\text{Im}(k_2)$ for Trappist-1f changes between $\approx 10^{-6} - 10^{-3}$ (see Figure 5.5a). This affects the calculated tidal heating rates and, consequently, the observability of cryovolcanic activity on those planets. Since Quick et al. (2023) calculated cryovolcanic densities averaged over the 3D sphere of the planets, we can compare our results only in the scenario of a homogeneous distribution of cryovolcanic material. In this case, our model predicts lower tidal heating rates, and, smaller water column densities compared to Quick et al. (2023), who calculate a water column density of 3.7×10^{17} molecules/ m^2 for Trappist-1f. It is important to note that our results are scaled to Earth, whereas their calculations are referenced to Europa in Equation 5.9, which may partially account for the observed discrepancy.

In addition, their approach considers only tidally induced heating when scaling to Europa. However, other heat sources (e.g. radiogenic heating) can promote cryovolcanic activity via the melting of the icy layer and the cycling of water between the interior and the surface (see e.g. Quick & Marsh, 2016). Since radiogenic heating is the dominant heating mechanism for the range of feasible interior structures of Trappist-1f,g,h (see Figure 5.3), volcanically produced water column densities can be significantly higher for

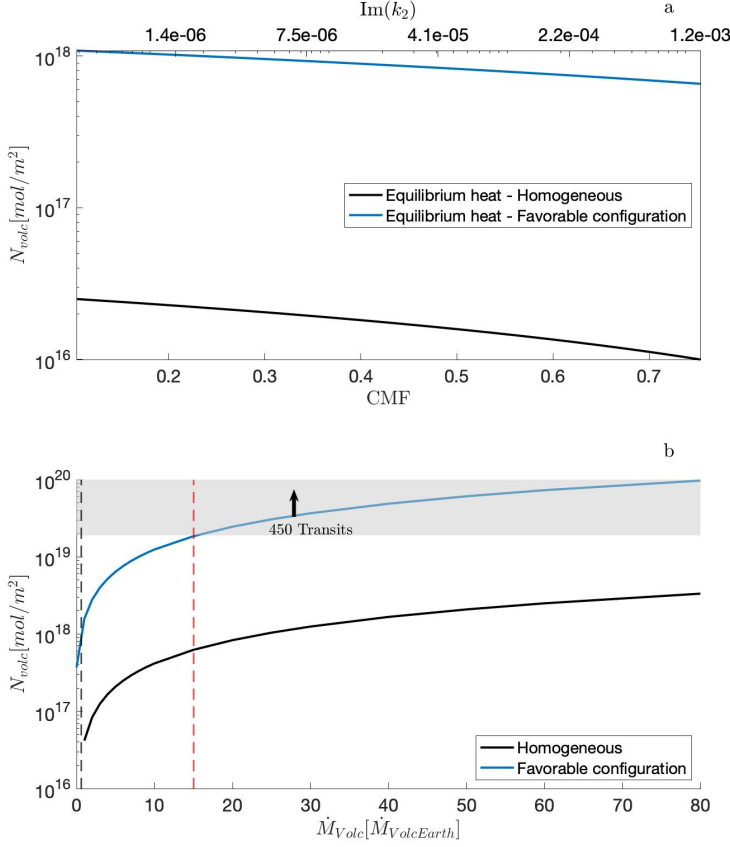


Figure 5.5: (a) N_{volc} as a function of CMF and Im_{k_2} for Trappist-1f. Interior constraints can be placed with an observation of N_{volc} . (b) N_{volc} as a function of $\dot{M}_{volc}$. The blue and black continuous lines show N_{volc} for the favorable configuration of cryovolcanism when geyser-like plumes are situated on one pole of the planet, and when plumes are globally distributed over the planet's entire surface, respectively. The vertical red dashed line represents $\approx 25\times$ the maximum $\dot{M}_{volc}$ generated for Trappist-1f by our model (vertical black dashed line). In order for N_{volc} to be observable the outgassing mass rate would need to be $\approx 25\times$ higher than what our model produces. This value corresponds to an efficiency factor $\eta \approx 0.9$, with 90% of the generated energy in the interior being used for the outgassing of water.

all three planets, when radiogenic heating is considered (Figure 5.5). As seen in Tables 5.3, 5.4, 5.5, Trappist-1 g,h are expected to produce smaller N_{volc} , making Trappist-1f the best candidate for observing cryovolcanic activity among the three planets, which is in agreement with the results of Quick et al. (2023). However, it would take 450 transits for NIRISS to observe a cryovolcanic atmosphere produced by a cryovolcanic outgassing

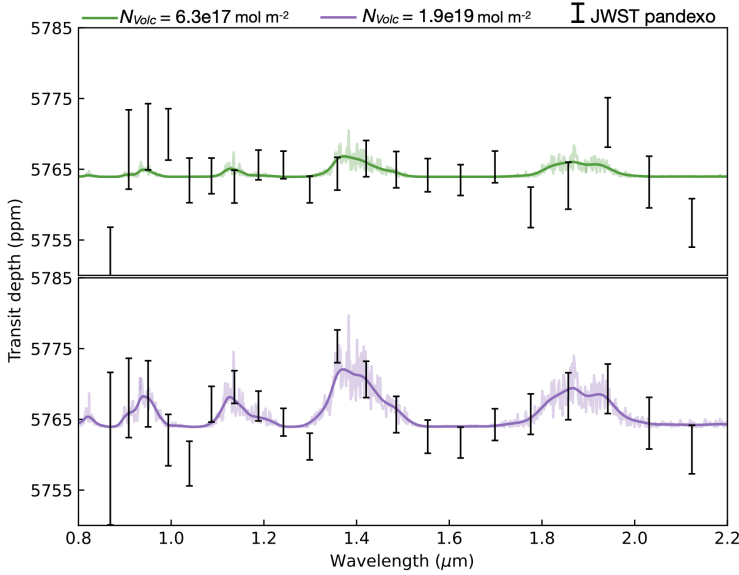


Figure 5.6: The spectrum of a bounded exosphere consisting only of water produced by cryovolcanism and volatile loss from XUV irradiation where the upper panel is produced using a volcanic column density of $N_{volc} = 6.3 \cdot 10^{17} \text{ molecules/m}^2$, and the lower panel is produced using a volcanic column density of $N_{volc} = 1.9 \cdot 10^{19} \text{ molecules/m}^2$. The colored lines are produced using the radiative transfer code *petitRADTRANS*, and the black data points are created using the ETC calculator *PandExo* for the NIRISS instrument. All mock JWST datapoints have been created using 450 transits and a binned spectral resolution of 12.

rate $\approx 25\times$ higher than the maximum of what our model predicts. Further modelling would investigate the detectability from the upcoming class of extremely large telescopes (ELTs).

5.4.2 Water Mass Fraction comparison with previous work

In addition to refining the mass/radius measurements for the Trappist-1 planets, Agol et al. (2021) theorized over their possible interior structures and water content. They estimated their WMFs assuming a condensed water layer of 300 K at 1 bar. Acuña et al. (2021) also modelled the interior and hydrospheres of the Trappist-1 planets, taking into account Equations of State (EOS) for different phases of water, including water vapor and high pressure ice phases. In Figure 5.7, we show the calculated WMFs for CMF = 0.25 from our model, taking into account the mass and radius uncertainties (Table 5.2), and we compare them to those derived by Agol et al. (2021); Acuña et al. (2021). We compare our results solely with the latter two studies, as previous work (Barr et al., 2018; Dorn et al., 2018) on the interior structures of the system have not used the updated

values for mass and radius. In particular, they have modelled the interior of the Trappist-1 planets using the mass and radius measurements, constrained by Delrez et al. (2018); Grimm et al. (2018). Our results (Figure 5.7) are mostly within the uncertainties of Acuña et al. (2021), and there is a larger discrepancy with Agol et al. (2021), whose results are significantly lower (for planets f and h). This discrepancy can be explained by our different modelling strategies. In order to reach the given density constraints, dictated by the mass and radius measurements, Agol et al. (2021) used a condensed water layer, without taking into account any equation of state for different phases, thus assuming lower density for the water layer. The agreement of our results with Acuña et al. (2021) is to be expected, as we included similar phases for water (high pressure ice polymorphs). Our results can be interpreted as one out of the multiple interior structures that Acuña et al. (2021) predict, since their error-bars are calculated for CMF values that span between 0.2 and 0.3, and we only show the interior structure for CMF = 0.25.

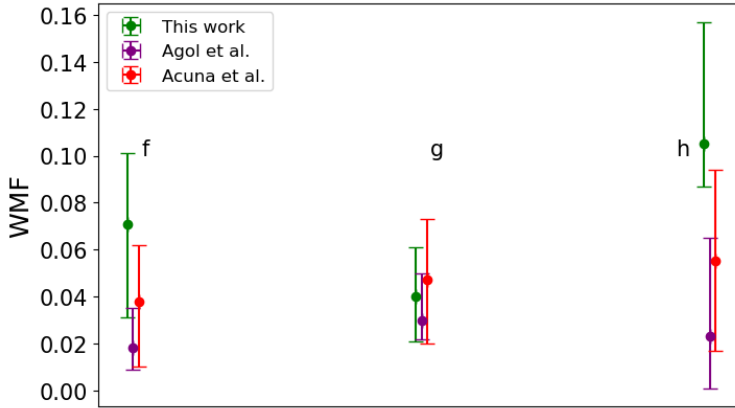


Figure 5.7: Estimated WMF together with their uncertainties for Trappist-1 f,g,h with our model (green), Agol et al. (2021, purple), and Acuña et al. (2021, red).

5.4.3 Water content in the Trappist-1 system and other possible interior structures

The extended Pre-Main-Sequence (PMS) phase of M-dwarf stars, like Trappist-1, can drive substantial atmospheric and water loss due to the increased luminosity and XUV activity (see e.g. Wordsworth et al., 2018; Luger & Barnes, 2015). The magnitude of this mass loss depends on the planet's orbital distance, making close-in planets more prone to volatile escape (Bolmont et al., 2017). Gialluca et al. (2024) quantified the water loss rates for the Trappist-1 planets, and studied their implications on recent observations (Zieba et al., 2023; Greene et al., 2023), which imply a tenuous oxygen atmosphere or no atmosphere for planets c and b. According to Gialluca et al. (2024), however, the loss of atmospheres on the inner planets does not preclude the retention of substantial water inventories on the outer planets, where lower stellar irradiation could allow water to persist.

As seen from Figure 5.5, tidal heating rates and, thus N_{volc} is highly dependant on the CMF that is assumed for the planets. We explore the range of probable CMFs for the planets that are compatible with their formation mechanism. The most favored scenario for the Trappist-1 planets is formation in a protoplanetary disk, possibly beyond the water ice line, with a subsequent inward migration, which is supported by the resonant chain and compactness of the system (Teyssandier et al., 2022). Planet formation within a protoplanetary disk results in planets with similar ratios of relative refractory elements, meaning similar CMFs, for fully differentiated bodies (Bond et al., 2010; Elser et al., 2012), but with different volatile element content (Öberg & Bergin, 2016). Thus, the WMF of the planets also depends on their formation mechanism. If the Trappist-1 planets are best described by the CMF of the most dense planet (planet c with 22% – 31% CMF), their densities can be fitted with different light-element content or water, according to Dorn et al. (2018). With our model, the latter CMF ratios would mean WMF values of $\approx 4 - 8 \times 10^{-2}$, $3 - 6 \times 10^{-2}$, and $1 - 11 \times 10^{-2}$ for Trappist-1f, g and h respectively.

Varying the WMF in order to obtain the observed densities is compatible with the results of Agol et al. (2021, Figure 5.7), who found that all Trappist-1 planets fall within one compositional line that is less dense than Solar System terrestrial planets. Other possible compositions for the Trappist-1 planets include either an interior with less iron compared to the terrestrial content, or oxidized iron in the mantle (Agol et al., 2021).

5.4.4 Future work

A first question to address in the future would be how to confirm that an observation of water comes from cryovolcanism. Exogenic sources of water are expected to remain constant over time (Paganini et al., 2020), whereas endogenic cryovolcanism may vary depending on the balance of interior processes such as tidal heating and radiogenic heat generation. Repeated observations could potentially contribute to the confirmation of the origin of water. The relationship between cryovolcanism and the different interior heat sources remains an open question, with significant implications for interpreting observations of cryovolcanic activity.

A second point of discussion would be a possible connection of observations of cryovolcanic activity to interior constraints. If tidal heating is the dominant driver of cryovolcanism, planets with low CMF values are more likely to exhibit detectable cryovolcanic signatures due to enhanced tidal dissipation. Conversely, if the total internal heat budget is dominated by radiogenic sources, planets with higher CMF values might exhibit stronger cryovolcanic activity.

Further investigation is needed to determine feasible interior models for a particular water column density observation. A more detailed analysis would need to consider uncertainties in interior parameters and ice rheology, the temperature dependence of rheological properties and the identification of secondary equilibrium states in mantle dynamics, as in Kleisioti et al. (2023). While our study outlines the potential sources of cryovolcanism and their implications, the detailed uncertainties inherent to interior modeling and observational constraints fall outside the scope of this work. Future research is needed to refine these models and better constrain the interplay between planetary structure, heat generation, and cryovolcanic activity.

5.5 Conclusions

In this work we used thermal and tidal heat models, that have been applied to Solar System icy moons, to assess the possible interior structures compatible with a subsurface ocean for the planets Trappist-1f,g and h. We firstly find that for all three planets the tidal heat in the mantle is negligible compared to tidal heating in the high pressure ice layer and the expected radiogenic heat.

In addition, we constrain the ice I and subsurface ocean layer thicknesses for all three planets. The interior structures of the inner two planets, Trappist-1f and g, would be in thermal equilibrium only in cases where the outer ice I shell is relatively thin, between ≈ 4 and 10 km, under the assumptions of our model. Such thin ice shells would make the possibility that a subsurface ocean - if any- would outgas material directly to a putative exosphere. We also calculated the corresponding WMFs and CMFs that are compatible with such interior structures. We find that for an Earth-like CMF (0.32) Trappist-1f,g,h, would possess a subsurface ocean in thermal equilibrium for a WMF of 8.5×10^{-2} , 5.9×10^{-2} and 11.8×10^{-1} .

Finally, we assessed the possibility of detection of cryovolcanism via transmission spectroscopy with JWST/NIRCam. We performed this analysis only for Trappist-1f, firstly because of the expected higher volcanic column densities, and secondly because of its smaller orbital period, which would aid observations. If any cryovolcanic activity is present, it would require 450 transits and the best-case configuration, for a volcanic outgassing rate $\approx 15 \times \dot{M}_{volc,Earth}$, which if any cryovolcanic activity is present, would have highest chances of being observed on Trappist-1f. This would require 450 transits, for a volcanic outgassing rate $\approx 15 \times \dot{M}_{volc,Earth}$, which is $25 \times$ the maximum $\dot{M}_{volc}$ generated for Trappist-1f in our model. Since a transit of Trappist-1f lasts for 1 hour, it would take approximately 450 hours of observations to detect a putative cryovolcanic signal on the planet. We encourage the community to target exoplanets with higher orbital eccentricities, where increased tidal dissipation could lead to larger rates of cryovolcanic outgassing.

Bibliography

- Acuña, Deleuil, Magali, Mousis, Olivier, et al. 2021, *AI&A*, 647, A53, doi: [10.1051/0004-6361/202039885](https://doi.org/10.1051/0004-6361/202039885)
- Agol, E., Dorn, C., Grimm, S. L., et al. 2021, *The Planetary Science Journal*, 2, 1, doi: [10.3847/PSJ/abd022](https://doi.org/10.3847/PSJ/abd022)
- Alei, E., Konrad, B. S., Angerhausen, D., et al. 2022, *A&A*, 665, A106, doi: [10.1051/0004-6361/202243760](https://doi.org/10.1051/0004-6361/202243760)
- Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, *A&A*, 558, A33, doi: [10.1051/0004-6361/201322068](https://doi.org/10.1051/0004-6361/201322068)
- Barr, A. C., Dobos, V., & Kiss, L. L. 2018, *Astronomy I& Astrophysics*, 613, A37, doi: [10.1051/0004-6361/201731992](https://doi.org/10.1051/0004-6361/201731992)
- Batalha, N. E., Mandell, A., Pontoppidan, K., et al. 2017, *PASP*, 129, 064501, doi: [10.1088/1538-3873/aa65b0](https://doi.org/10.1088/1538-3873/aa65b0)
- Bierson, C. J., & Steinbrügge, G. 2021, *The Planetary Science Journal*, 2, 89, doi: [10.3847/PSJ/abf48d](https://doi.org/10.3847/PSJ/abf48d)
- Bolmont, E., Selsis, F., Owen, J. E., et al. 2017, *MNRAS*, 464, 3728, doi: [10.1093/mnras/stw2578](https://doi.org/10.1093/mnras/stw2578)
- Bond, J. C., O'Brien, D. P., & Lauretta, D. S. 2010, *The Astrophysical Journal*, 715, 1050, doi: [10.1088/0004-637X/715/2/1050](https://doi.org/10.1088/0004-637X/715/2/1050)
- Bradák, B., Ákos Kereszturi, & Gomez, C. 2023, *Advances in Space Research*, 72, 4064, doi: <https://doi.org/10.1016/j.asr.2023.07.062>
- Burgasser, A. J., & Mamajek, E. E. 2017, *The Astrophysical Journal*, 845, 110, doi: [10.3847/1538-4357/aa7fea](https://doi.org/10.3847/1538-4357/aa7fea)
- Burton, M. R., Sawyer, G. M., & Granieri, D. 2013, *Reviews in Mineralogy and Geochemistry*, 75, 323, doi: [10.2138/rmg.2013.75.11](https://doi.org/10.2138/rmg.2013.75.11)
- Cadieux, C., Doyon, R., MacDonald, R. J., et al. 2024, *The Astrophysical Journal Letters*, 970, L2, doi: [10.3847/2041-8213/ad5afa](https://doi.org/10.3847/2041-8213/ad5afa)
- Cameron, A. 1985, *Icarus*, 64, 285, doi: [https://doi.org/10.1016/0019-1035\(85\)90091-0](https://doi.org/10.1016/0019-1035(85)90091-0)
- Croft, S. K., Kargel, J. S., Kirk, R. L., et al. 1995, in *Neptune and Triton*, ed. D. P. Cruikshank, M. S. Matthews, & A. M. Schumann, 879–947
- Davies, J. H., & Davies, D. R. 2010, *Solid Earth*, 1, 5, doi: [10.5194/se-1-5-2010](https://doi.org/10.5194/se-1-5-2010)
- de Wit, J., Wakeford, H. R., Lewis, N. K., et al. 2018, *Nature Astronomy*, 2, 214–219, doi: [10.1038/s41550-017-0374-z](https://doi.org/10.1038/s41550-017-0374-z)
- Delrez, L., Gillon, M., Triaud, A. H. M. J., et al. 2018, *Monthly Notices of the Royal Astronomical Society*, 475, 3577, doi: [10.1093/mnras/sty051](https://doi.org/10.1093/mnras/sty051)
- Dobos, Barr, Amy C., & Kiss, László L. 2019, *AI&A*, 624, A2, doi: [10.1051/0004-6361/201834254](https://doi.org/10.1051/0004-6361/201834254)
- Dobos, V., & Turner, E. L. 2015, *The Astrophysical Journal*, 804, 41, doi: [10.1088/0004-637X/804/1/41](https://doi.org/10.1088/0004-637X/804/1/41)
- Dorn, C., Mosegaard, K., Grimm, S. L., & Alibert, Y. 2018, *The Astrophysical Journal*, 865, 20, doi: [10.3847/1538-4357/aad95d](https://doi.org/10.3847/1538-4357/aad95d)
- Ehrenreich, D., des Etangs, A. L., Beaulieu, J.-P., & Grasset, O. 2006, *The Astrophysical Journal*, 651, 535, doi: [10.1086/507577](https://doi.org/10.1086/507577)
- Elser, S., Meyer, M., & Moore, B. 2012, *Icarus*, 221, 859, doi: <https://doi.org/10.1016/j.icarus.2012.09.016>
- Fagents, S. A. 2003, *Journal of Geophysical Research: Planets*, 108, doi: <https://doi.org/10.1029/2003JE002128>

- Fagents, S. A., Greeley, R., Sullivan, R. J., et al. 2000, *Icarus*, 144, 54, doi: <https://doi.org/10.1006/icar.1999.6254>
- Fagents, S. A., Lopes, R. M., Quick, L. C., & Gregg, T. K. 2022, in *Comparative Planetology*, Vol. 1, Planetary Volcanism across the Solar System, ed. T. K. Gregg, R. M. Lopes, & S. A. Fagents (Elsevier), 161–234, doi: <https://doi.org/10.1016/B978-0-12-813987-5.00005-5>
- Fischer, H.-J., & Spohn, T. 1990, *Icarus*, 83, 39, doi: [https://doi.org/10.1016/0019-1035\(90\)90005-T](https://doi.org/10.1016/0019-1035(90)90005-T)
- Gialluca, M. T., Barnes, R., Meadows, V. S., et al. 2024, The Implications of Thermal Hydrodynamic Atmospheric Escape on the TRAPPIST-1 Planets. <https://arxiv.org/abs/2405.02401>
- Gillon, M., Triaud, A. H. M. J., Demory, B.-O., et al. 2017, *Nature*, 542, 456, doi: [10.1038/nature21360](https://doi.org/10.1038/nature21360)
- Giono, G., Roth, L., Ivchenko, N., et al. 2020, *The Astronomical Journal*, 159, 155, doi: [10.3847/1538-3881/ab7454](https://doi.org/10.3847/1538-3881/ab7454)
- Goldreich, P., & Soter, S. 1966, *Icarus*, 5, 375, doi: [10.1016/0019-1035\(66\)90051-0](https://doi.org/10.1016/0019-1035(66)90051-0)
- Grasset, O., Sotin, C., & Deschamps, F. 2000, *Planetary and Space Science*, 48, 617, doi: [https://doi.org/10.1016/S0032-0633\(00\)00039-8](https://doi.org/10.1016/S0032-0633(00)00039-8)
- Green, A. P., Montesi, L. G. J., & Cooper, C. M. 2021, *Journal of Geophysical Research: Planets*, 126, e2020JE006677, doi: <https://doi.org/10.1029/2020JE006677>
- Greene, T. P., Bell, T. J., Ducrot, E., et al. 2023, *Nature*, 618, 39–42, doi: [10.1038/s41586-023-05951-7](https://doi.org/10.1038/s41586-023-05951-7)
- Grimm, Demory, Brice-Olivier, Gillon, Michaël, et al. 2018, *A&A*, 613, A68, doi: [10.1051/0004-6361/201732233](https://doi.org/10.1051/0004-6361/201732233)
- Guenther, E. W., & Kislyakova, K. G. 2019, *Monthly Notices of the Royal Astronomical Society*, 491, 3974, doi: [10.1093/mnras/stz3288](https://doi.org/10.1093/mnras/stz3288)
- Hammond, N. P., Parmentier, E. M., & Barr, A. C. 2018, *Journal of Geophysical Research: Planets*, 123, 3105, doi: <https://doi.org/10.1029/2018JE005781>
- Hand, K. P., Phillips, C. B., Murray, A., et al. 2022, *The Planetary Science Journal*, 3, 22, doi: [10.3847/PSJ/ac4493](https://doi.org/10.3847/PSJ/ac4493)
- Hay, H. C. F. C., & Matsuyama, I. 2019, *The Astrophysical Journal*, 875, 22, doi: [10.3847/1538-4357/ab0c21](https://doi.org/10.3847/1538-4357/ab0c21)
- Hedman, M., Gosmeyer, C., Nicholson, P., et al. 2013, *Nature*, 500, 182, doi: [10.1038/nature12371](https://doi.org/10.1038/nature12371)
- Henning, W. G., & Hurford, T. 2014, *The Astrophysical Journal*, 789, 30, doi: [10.1088/0004-637X/789/1/30](https://doi.org/10.1088/0004-637X/789/1/30)
- Hofgartner, J. D., Birch, S. P., Castillo, J., et al. 2022, *Icarus*, 375, 114835, doi: <https://doi.org/10.1016/j.icarus.2021.114835>
- Hunter, J. D. 2007, *Computing In Science & Engineering*, 9, 90, doi: [10.1109/MCSE.2007.55](https://doi.org/10.1109/MCSE.2007.55)
- Husmann, H., & Spohn, T. 2004, *Icarus*, 171, 391, doi: <https://doi.org/10.1016/j.icarus.2004.05.020>
- Husmann, H., Spohn, T., & Wiczerkowski, K. 2002, *Icarus*, 156, 143, doi: <https://doi.org/10.1006/icar.2001.6776>
- Iess, L., Stevenson, D. J., Parisi, M., et al. 2014, *Science*, 344, 78, doi: [10.1126/science.1250551](https://doi.org/10.1126/science.1250551)
- Ingersoll, A. P., Ewald, S. P., & Trumbo, S. K. 2020, *Icarus*, 344, 113345, doi: <https://doi.org/10.1016/j.icarus.2019.06.006>
- Jaccard, C. 1976, *Journal of Glaciology*, 17, 155–156, doi: [10.3189/S0022143000030847](https://doi.org/10.3189/S0022143000030847)
- Jia, X., Kivelson, M. G., Khurana, K. K., & Provan, G. T. 2018, *Nature Astronomy*, 2, 459, doi: [10.1038/s41550-018-0450-z](https://doi.org/10.1038/s41550-018-0450-z)

- Johnson, R. E., Oza, A., Young, L. A., Volkov, A. N., & Schmidt, C. 2015, *ApJ*, 809, 43, doi: 10.1088/0004-637X/809/1/43
- Kleisioti, Dirkx, D., Rovira-Navarro, M., & Kenworthy, M. A. 2023, *A&A*, 675, A57, doi: 10.1051/0004-6361/202346082
- Kleisioti, Dirkx, D., Tan, X., & Kenworthy, M. A. 2024, *A&A*, 687, A125, doi: 10.1051/0004-6361/202449428
- Krissansen-Totton, J., & Fortney, J. J. 2022, *The Astrophysical Journal*, 933, 115, doi: 10.3847/1538-4357/ac69cb
- Lau, H. C. P., Mitrovia, J. X., Austermann, J., et al. 2016, *Journal of Geophysical Research: Solid Earth*, 121, 6991, doi: <https://doi.org/10.1002/2016JB013043>
- Leone, G., Bieger, K., & Soto, M. 2021, , 2, 29, doi: 10.3847/PSJ/abdb33
- Lesage, E., Massol, H., & Schmidt, F. 2020, *Icarus*, 335, 113369, doi: <https://doi.org/10.1016/j.icarus.2019.07.003>
- Lobo, A. H., Shields, A. L., Palubski, I. Z., & Wolf, E. 2023, *The Astrophysical Journal*, 945, 161, doi: 10.3847/1538-4357/aca970
- Luger, R., & Barnes, R. 2015, *Astrobiology*, 15, 119, doi: 10.1089/ast.2014.1231
- Luger, R., Sestovic, M., Kruse, E., et al. 2017, *Nature Astronomy*, 1, 0129, doi: 10.1038/s41550-017-0129
- Luo, H., O'Rourke, J. G., & Deng, J. 2024, *Science Advances*, 10, eado7603, doi: 10.1126/sciadv.ado7603
- Manga, M., & Wang, C.-Y. 2007, *Geophysical Research Letters*, 34, doi: <https://doi.org/10.1029/2007GL029297>
- Meyer zu Westram, M., Oza, A. V., & Galli, A. 2024, *Journal of Geophysical Research: Planets*, 129, e2023JE007935, doi: <https://doi.org/10.1029/2023JE007935>
- Mollière, P., Wardenier, J. P., van Boekel, R., et al. 2019, *A&A*, 627, A67, doi: 10.1051/0004-6361/201935470
- Mollière, P., Stolker, T., Lacour, S., et al. 2020, *A&A*, 640, A131, doi: 10.1051/0004-6361/202038325
- Neveu, M., & Rhoden, A. R. 2019, *Nature Astronomy*, 3, 543, doi: 10.1038/s41550-019-0726-y
- Nimmo, F., & Pappalardo, R. T. 2016, *Journal of Geophysical Research: Planets*, 121, 1378, doi: <https://doi.org/10.1002/2016JE005081>
- Ojha, L., Troncone, B., Buffo, J., Journaux, B., & McDonald, G. 2022, *Nature Communications*, 13, doi: 10.1038/s41467-022-35187-4
- Oza, A. V., Leblanc, F., Johnson, R. E., et al. 2019a, *Planetary and Space Science*, 167, 23, doi: <https://doi.org/10.1016/j.pss.2019.01.006>
- Oza, A. V., Johnson, R. E., Lellouch, E., et al. 2019b, *The Astrophysical Journal*, 885, 168, doi: 10.3847/1538-4357/ab40cc
- Paganini, L., Villanueva, G. L., Roth, L., et al. 2020, *Nature Astronomy*, 4, 266, doi: 10.1038/s41550-019-0933-6
- Peltier, W. R. 1974, *Reviews of Geophysics*, 12, 649, doi: <https://doi.org/10.1029/RG012i004p00649>
- Phillips, C. B., McEwen, A. S., Hoppa, G. V., et al. 2000, *Journal of Geophysical Research: Planets*, 105, 22579, doi: <https://doi.org/10.1029/1999JE001139>
- Pichierri, G., Morbidelli, A., Batygin, K., et al. 2024, *Nature Astronomy*, 8, 1408, doi: 10.1038/s41550-024-02342-4
- Polyansky, O. L., Kyuberis, A. A., Zobov, N. F., et al. 2018, *MNRAS*, 480, 2597, doi: 10.1093/mnras/sty1877
- Porco, C., DiNino, D., & Nimmo, F. 2014, *The Astronomical Journal*, 148, 45, doi: 10.1088/

- 0004-6256/148/3/45
- Porco, C. C., Helfenstein, P., Thomas, P. C., et al. 2006, *Science*, 311, 1393, doi: 10.1126/science.1123013
- Postberg, F., Khawaja, N., Abel, B., et al. 2018, *Nature*, 558, 564, doi: 10.1038/s41586-018-0246-4
- Quick, L. C., & Marsh, B. D. 2015, *Icarus*, 253, 16, doi: <https://doi.org/10.1016/j.icarus.2015.02.016>
- . 2016, *Journal of Volcanology and Geothermal Research*, 319, 66, doi: <https://doi.org/10.1016/j.jvolgeores.2016.03.018>
- Quick, L. C., Roberge, A., Mendoza, G. T., Quintana, E. V., & Youngblood, A. A. 2023, *The Astrophysical Journal*, 956, 29, doi: 10.3847/1538-4357/ace9b6
- Quick, L. C., Roberge, A., Mlinar, A. B., & Hedman, M. M. 2020, *Publications of the Astronomical Society of the Pacific*, 132, 084402, doi: 10.1088/1538-3873/ab9504
- Renaud, J. P., & Henning, W. G. 2018, *The Astrophysical Journal*, 857, 98, doi: 10.3847/1538-4357/aab784
- Roberts, J. H., & Nimmo, F. 2008, *Icarus*, 194, 675, doi: <https://doi.org/10.1016/j.icarus.2007.11.010>
- Ross, M., & Schubert, G. 1989, *Icarus*, 78, 90, doi: [https://doi.org/10.1016/0019-1035\(89\)90071-7](https://doi.org/10.1016/0019-1035(89)90071-7)
- Rossum, G. 1995, *Python Reference Manual*, Tech. rep., Centrum voor Wiskunde en Informatica (CWI), Amsterdam, The Netherlands, The Netherlands
- Roth, L., Saur, J., Retherford, K. D., et al. 2014, *Science*, 343, 171, doi: 10.1126/science.1247051
- Rovira-Navarro, M., Katz, R. F., Liao, Y., van der Wal, W., & Nimmo, F. 2022, *Journal of Geophysical Research: Planets*, 127, e2021JE007117, doi: <https://doi.org/10.1029/2021JE007117>
- Rovira-Navarro, M., & Matsuyama, I. 2024, *LOV3D: A Spectral Method to Compute the Tides of Laterally Heterogeneous Bodies (v1.0)*, 1, 4TU.ResearchData, doi: 10.4121/5511f97f-04b9-479f-9e87-41dc6095a86c.v1
- Rovira-Navarro, M., Matsuyama, I., & Berne, A. 2024, *The Planetary Science Journal*, 5, 129, doi: 10.3847/PSJ/ad381f
- Rovira-Navarro, M., van der Wal, W., Steinke, T., & Dirkx, D. 2021, *The Planetary Science Journal*, 2, 119, doi: 10.3847/PSJ/abf6cb
- Sabadini R., Vermeersen B., . C. G. 2016, *Global Dynamics of the Earth: Applications of Viscoelastic Relaxation Theory to Solid-Earth and Planetary Geophysics (2nd ed.; Berlin: Springer)*
- Schneeberger, A., Mousis, O., Deleuil, M., & Lunine, J. I. 2024, *A&A*, 682, L10, doi: 10.1051/0004-6361/202348309
- Schoonenberg, Djoeke, Liu, Beibei, Ormel, Chris W., & Dorn, Caroline. 2019, *A&A*, 627, A149, doi: 10.1051/0004-6361/201935607
- Schubert, G., Cassen, P., & Young, R. 1979, *Icarus*, 38, 192, doi: [https://doi.org/10.1016/0019-1035\(79\)90178-7](https://doi.org/10.1016/0019-1035(79)90178-7)
- Schubert, G., Spohn, T., & Reynolds, R. T. 1986, in *IAU Colloq. 77: Some Background about Satellites*, ed. J. A. Burns & M. S. Matthews (University of Arizona Press), 224–292
- Segatz, M., Spohn, T., Ross, M. N., & Schubert, G. 1988, *Icarus*, 75, 187, doi: 10.1016/0019-1035(88)90001-2
- Shields, A. L., Meadows, V. S., Bitz, C. M., et al. 2013, *Astrobiology*, 13, 715, doi: 10.1089/ast.2012.0961
- Shoji, D., & Kurita, K. 2014, *The Astrophysical Journal*, 789, 3, doi: 10.1088/0004-637X/789/1/3

- Sigurdsson, H., Houghton, B., Rymer, H., Stix, J., & McNutt, S. 1999, *Encyclopedia of Volcanoes*, 1st edn. (Academic Press)
- Smyth, W. H., & Marconi, M. L. 2006, *Icarus*, 181, 510, doi: <https://doi.org/10.1016/j.icarus.2005.10.019>
- Sohl, F., Hussmann, H., Schwentker, B., Spohn, T., & Lorenz, R. D. 2003a, *Journal of Geophysical Research: Planets*, 108, doi: <https://doi.org/10.1029/2003JE002044>
- . 2003b, *Journal of Geophysical Research: Planets*, 108, doi: <https://doi.org/10.1029/2003JE002044>
- Souček, O., Běhounková, M., Lanzendörfer, M., et al. 2024, *Nature Communications*, 15, 7405, doi: [10.1038/s41467-024-51677-z](https://doi.org/10.1038/s41467-024-51677-z)
- Sparks, W. B., Schmidt, B. E., McGrath, M. A., et al. 2017, *The Astrophysical Journal Letters*, 839, L18, doi: [10.3847/2041-8213/aa67f8](https://doi.org/10.3847/2041-8213/aa67f8)
- Spencer, J. R., Nimmo, F., Ingersoll, A. P., et al. 2018, in *Enceladus and the Icy Moons of Saturn*, ed. P. M. Schenk, R. N. Clark, C. J. A. Howett, A. J. Verbiscer, & J. H. Waite (University of Arizona Press), 163, doi: [10.2458/azu_uapress_9780816537075-ch008](https://doi.org/10.2458/azu_uapress_9780816537075-ch008)
- Spohn, T., & Schubert, G. 2003, *Icarus*, 161, 456, doi: [https://doi.org/10.1016/S0019-1035\(02\)00048-9](https://doi.org/10.1016/S0019-1035(02)00048-9)
- Teyssandier, Libert, A.-S., & Agol, E. 2022, *A&A*, 658, A170, doi: [10.1051/0004-6361/202142377](https://doi.org/10.1051/0004-6361/202142377)
- Tjoa, J. N. K. Y., Mueller, M., & van der Tak, F. F. S. 2020, *AI&A*, 636, A50, doi: [10.1051/0004-6361/201937035](https://doi.org/10.1051/0004-6361/201937035)
- Tobie, G., Mocquet, A., & Sotin, C. 2005, *Icarus*, 177, 534, doi: <https://doi.org/10.1016/j.icarus.2005.04.006>
- Tobie, G., Grasset, O., Dumoulin, C., & Mocquet, A. 2019, *A&A*, 630, A70, doi: [10.1051/0004-6361/201935297](https://doi.org/10.1051/0004-6361/201935297)
- Turbet, Martin, Bolmont, Emeline, Leconte, Jeremy, et al. 2018, *A&A*, 612, A86, doi: [10.1051/0004-6361/201731620](https://doi.org/10.1051/0004-6361/201731620)
- van der Walt, S., Colbert, S. C., & Varoquaux, G. 2011, *Computing in Science & Engineering*, 13, 22
- van Woerkom, Q. B., & Kleisioti, E. 2024, *AA*, 684, A72, doi: [10.1051/0004-6361/202348604](https://doi.org/10.1051/0004-6361/202348604)
- Villanueva, G. L., Hammel, H. B., Milam, S. N., et al. 2023, *Nature Astronomy*, 7, 1056, doi: [10.1038/s41550-023-02009-6](https://doi.org/10.1038/s41550-023-02009-6)
- Wordsworth, R. D., Schaefer, L. K., & Fischer, R. A. 2018, *The Astronomical Journal*, 155, 195, doi: [10.3847/1538-3881/aab608](https://doi.org/10.3847/1538-3881/aab608)
- Zeng, L., Jacobsen, S. B., Sasselov, D. D., et al. 2019, *Proceedings of the National Academy of Sciences*, 116, 9723, doi: [10.1073/pnas.1812905116](https://doi.org/10.1073/pnas.1812905116)
- Zhang, H., & Zhang, C.-Z. 2004, *Chinese Journal of Astronomy and Astrophysics*, 4, 499, doi: [10.1088/1009-9271/4/5/499](https://doi.org/10.1088/1009-9271/4/5/499)
- Zieba, S., Kreidberg, L., Ducrot, E., et al. 2023, *Nature*, 620, 746–749, doi: [10.1038/s41586-023-06232-z](https://doi.org/10.1038/s41586-023-06232-z)
- Öberg, K. I., & Bergin, E. A. 2016, *The Astrophysical Journal Letters*, 831, L19, doi: [10.3847/2041-8205/831/2/L19](https://doi.org/10.3847/2041-8205/831/2/L19)
- Čadež, O., Tobie, G., Van Hoolst, T., et al. 2016, *Geophysical Research Letters*, 43, 5653, doi: <https://doi.org/10.1002/2016GL068634>

A. Melting temperature as a function of pressure

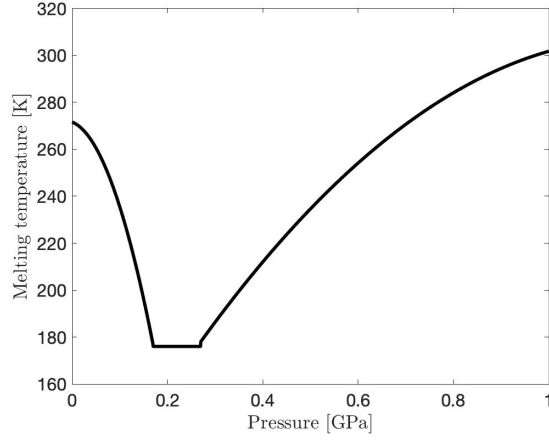


Figure 5.8: Melting temperature as a function of pressure for an ammonia containing ocean of 5 wt.% (Grasset et al., 2000; Sohl et al., 2003a)

B. Tidal heat generated in the Ice I outer shell

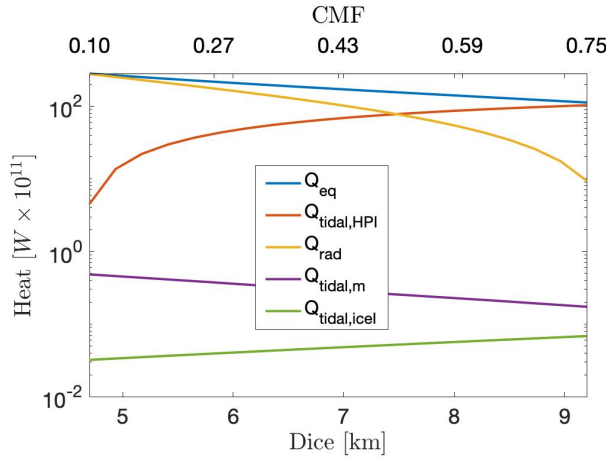


Figure 5.9: Heat source distribution in the interior of Trappist-1f. $Q_{tidal,HPI}$, $Q_{tidal,m}$, and $Q_{tidal,iceI}$ is the tidal heat generated in the HPI layer, mantle and ice I shell respectively. Q_{rad} is the radiogenic heat produced in the mantle. $Q_{tidal,iceI}$ is at least 4 orders of magnitude smaller than the total heat generated in the interior (Q_{eq}).

C. Interior structures as a function of D_{ice} for the planets Trappist-1g,h

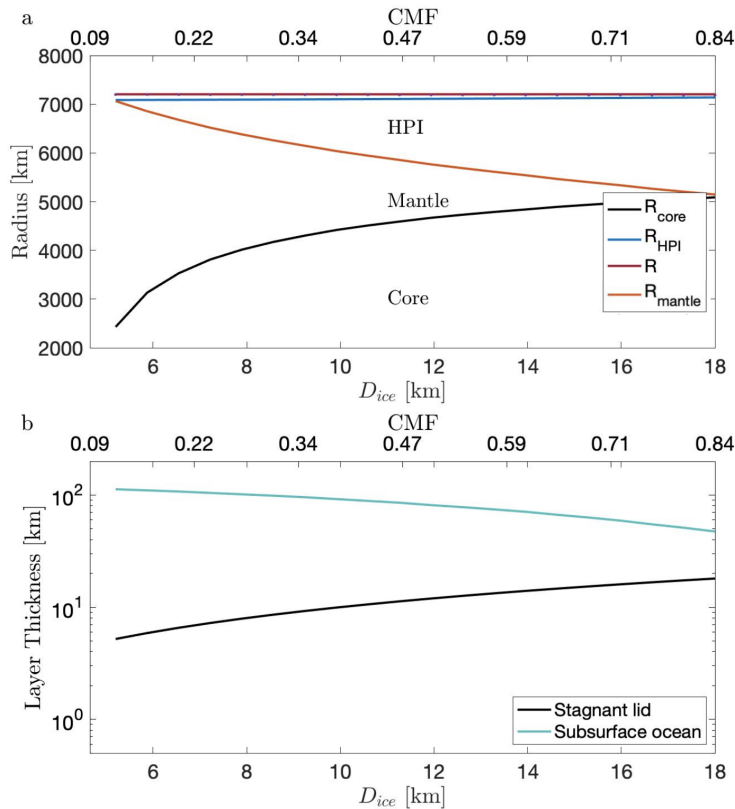


Figure 5.10: a. Interior structure as a function of D_{ice} for the planet Trappist-1g.

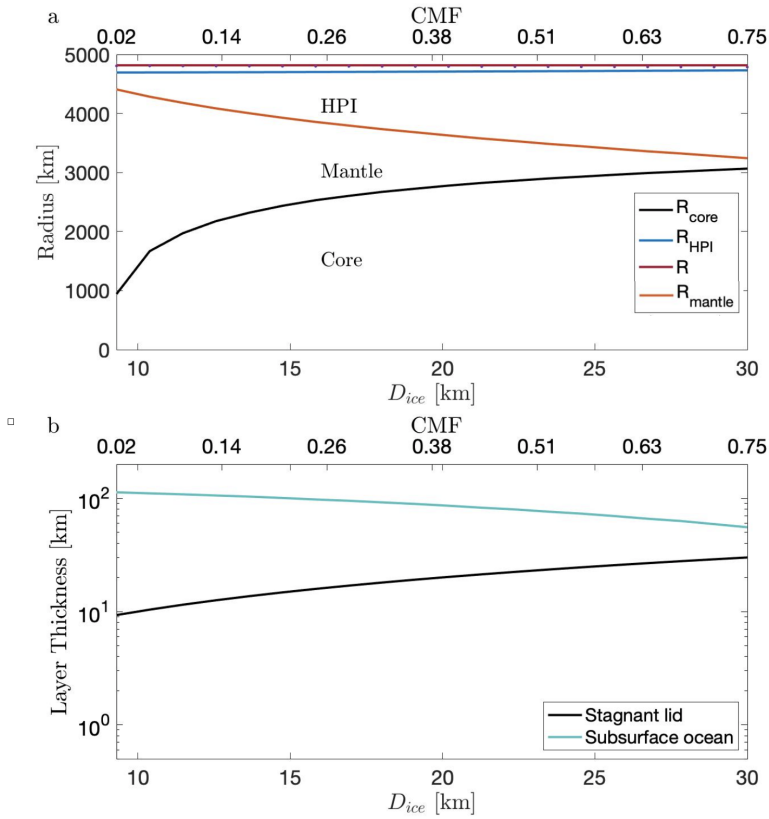


Figure 5.11: (a) Interior structure as a function of D_{ice} for the planet Trappist-1h.

English summary

Are we alone? The search for life elsewhere 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 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 influenced 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 incorporating 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 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.

Nederlandstalige samenvatting

Zijn we alleen? De zoektocht naar leven elders in het heelal is een langgekoesterde vraag van de mensheid. We kunnen nu op zoek gaan naar tekenen van leven op andere objecten in ons zonnestelsel: op het oppervlak van Mars en in de verborgen, ondergrondse oceanen van manen van planeten in het zonnestelsel, zoals die van Jupiter en Saturnus.

Manen in het zonnestelsel vertonen een grote diversiteit in hun fysische en baankenmerken, en sommige vallen op door hun geologische activiteit. Io, de binnenste maan van Jupiter, is het meest vulkanisch actieve object in het zonnestelsel, met honderden hotspots over het oppervlak. Enceladus, een ijzige maan van Saturnus, bezit oppervlaktrescheuren, actieve pluimen van waterdamp en een wereldwijde ondergrondse oceaan. Een gemeenschappelijke drijvende kracht achter deze verschijnselen is getijdenverwarming: wanneer een maan in een excentrische baan rond een planeet draait, zorgen wisselende zwaartekrachtskrachten ervoor dat het lichaam buigt en interne warmte genereert. Op lange tijdschalen kan dit proces water onder een ijzige korst vloeibaar houden en vulkanisme in stand houden. Door vloeibaar water en geologische activiteit te onderhouden, kunnen dergelijke processen de ingrediënten en energiebronnen leveren die nodig zijn voor bewoonbaarheid. Terwijl ons zonnestelsel nabijegelegen proefgevallen biedt, kan de zoektocht naar leven ook worden uitgebreid naar exoplaneetstelsels rond andere sterren.

Buiten het zonnestelsel markeerden de ontdekking van planeten rond de pulsar PSR 1257+12 en, kort daarna, 51 Pegasi b, een reuzenplaneet met een omlooptijd van slechts enkele dagen, een keerpunt voor het vakgebied. Sindsdien is het aantal exoplaneetontdekkingen snel toegenomen, met tegenwoordig duizenden bekende exoplaneten. Veel daarvan lijken in niets op de planeten in ons eigen zonnestelsel: “hete Jupiters” zijn Jupiter-achtige planeten die erg dicht bij hun ster staan. “Superaardes” (planeten met een grootte tussen die van de Aarde en Neptunus) zijn veelvoorkomend, terwijl exoplaneten ter grootte van de Aarde zeldzamer zijn. Afhankelijk van hoe ver hun banen van hun sterren liggen, kunnen sommige van deze planeten zelfs lijken op de ijzige manen in ons zonnestelsel, met koude oppervlakken en mogelijke interne oceanen.

Gezien het belang van manen in ons eigen zonnestelsel is het logisch te vragen of exoplaneten ook manen hebben, en of die eveneens leven kunnen herbergen. Omdat elke gasreus in het zonnestelsel natuurlijke satellieten heeft, ligt het voor de hand te verwachten dat veel gasreus-exoplaneten die we hebben gevonden ook door manen (exomanen) worden omgeven. Toch is tot op heden geen enkele exomaan ondubbelzinnig bevestigd. Een van de belangrijkste redenen is dat de signalen van manen zwak zijn vergeleken met die van hun grotere moederplaneten. Nu exoplaneetontdekkingen een breed parametergebied beslaan, moeten we bepalen welke moederplaneten de beste kansen op detectie bieden, welke technieken het meest effectief zijn, en welke maaneigenschappen waarneembaar zijn.

De transitmethode, die tot nu toe verantwoordelijk is voor de meeste exoplaneetontdekkingen, detecteert planeten wanneer ze voor hun ster langs bewegen en een kleine, periodieke afname in de helderheid veroorzaken. De planeten zelf zijn niet direct zichtbaar, maar hun schaduwen(transits) wel. Deze techniek is gevoelig voor planeten die dicht

bij hun ster staan, omdat de kans op een uitlijning waarbij wij een transit zien dan groter is. Dat kan nadelen hebben voor de zoektocht naar exomanen: manen van planeten op nauwe banen kunnen onstabiel zijn omdat de zwaartekracht van de ster weinig ruimte laat voor stabiele omloopbanen. Bovendien vereisen exomaanzoektochten rond transiterende exoplaneten een gunstige geometrie: planeet en maan moeten precies goed uitgelijnd zijn met onze gezichtslijn zodat hun overgangen zichtbaar zijn. Ten slotte zijn lange waarnemingsreeksen nodig om meerdere transits te vangen. Dit motiveert een focus op direct waargenomen exoplaneten, waarvan de banen verder van hun sterren liggen. Op deze grotere afstanden kunnen we het sterlicht onderdrukken en het licht van de planeet zelf opvangen.

Het waarnemen van het licht van de planeet en het detecteren van zwakke satellieten zoals manen brengt eigen uitdagingen met zich mee, omdat de overweldigende helderheid van de moederster onderdrukt moet worden, en zelfs dan kan de planeet haar manen overstralen. Toch kan in infrarode golflengten, waar warmtestraling belangrijk wordt, een bijzondere klasse van objecten opvallen: getijdenverhitte exomanen (THEMs). Deze zijn analoog aan Jupiters vulkanisch actieve maan Io en bieden een unieke kans: aangedreven door getijdenkrachten kunnen deze manen hoge oppervlaktetemperaturen bereiken en in bepaalde infrarode banden even helder of zelfs helderder zijn dan hun moederplaneet. In tegenstelling tot transitwaarnemingen is directe thermische detectie niet afhankelijk van een specifieke baanfase of herhaalde gebeurtenissen. Dit opent een mogelijkheid tot het detecteren van manen rond reuzenplaneten die op grote afstanden van hun ster cirkelen, waar andere exoplaneetdetectiemethoden moeite hebben.

De hoeveelheid getijdenverwarming die een wereld ondergaat, wordt onder meer beïnvloed door zijn baan en door de manier waarop materialen in het binnenste vervormen en energie dissiperen. Omdat getijdenverwarming afhangt van de interne eigenschappen van een lichaam, is het bestuderen van THEM's niet alleen een manier om manen te detecteren, maar ook een instrument om hun interne structuur en eigenschappen te onderzoeken. Vergelijkbare benaderingen zijn in ons eigen zonnestelsel toegepast: zo heeft Io's vulkanisme lang vragen opgeroepen over de aanwezigheid van een wereldwijde magma-oceaan of een gedeeltelijk gesmolten mantel, en metingen van Io's vervorming onder getijdenkrachten zijn cruciaal geweest om deze scenario's te toetsen. Deze redenering doortrekken naar exoplaneten en hun manen betekent dat getijdenverwarming ons niet alleen helpt ze te identificeren, maar ook om hun interne eigenschappen en de mechanismen van warmte-transport in hun binnenste af te leiden. Deze processen zijn belangrijk voor de astrobiologie en maken getijdenverhitte werelden tot interessante doelwitten voor studies naar bewoonbaarheid, aangezien hun interne energiebronnen leefbare omgevingen kunnen ondersteunen, ongeacht of ze direct sterlicht ontvangen.

Dit proefschrift richt zich op de detecteerbaarheid van THEM's via verschillende methoden en onderzoekt tegelijk de interne en orbitale eigenschappen die ze waarneembaar maken. Het zet stappen richting het vinden van zulke manen en verkent wanneer getijden hen voldoende kunnen verhitten om in het infrarood te gloeien, en of hun helderheid of de variatie daarin met huidige en komende telescopen kan worden gemeten. Door mogelijke waarnemingen te combineren met modellen van getijdenverwarming, verkent het proefschrift verder welke eigenschappen van het binnenste van planeten en manen kunnen worden afgeleid. Modellen van getijdenverwarming worden ten slotte gebruikt om

de inwendige opbouw te bestuderen van ijzige exoplaneten die vermoedelijk lijken op de ijzige manen van ons zonnestelsel. Hier ligt de focus op Trappist-1 f, g en h: kan interne warmte ondergrondse oceanen in stand houden, en zijn tekenen van vulkanische activiteit detecteerbaar? Gezamenlijk benadrukken deze studies de rol van getijdenverwarming als zowel een detectieroute als een venster op interne processen van extrasolaire werelden.

Hoofdstuk 2. De detecteerbaarheid en eigenschappen van THEMs rond de exoplaneet Eridani b

In dit hoofdstuk onderzoeken we of getijdenverhitte exomanen (THEMs) in infrarood-golflengten helder genoeg kunnen zijn om met de James Webb-ruimtetelescoop te worden gedetecteerd rond nabije reuzenplaneten. We gebruiken de planeet Eridani b als testgeval. We zetten modellen in die de baan en fysische eigenschappen van een maan koppelen aan de getijdenwarmte die binnenin wordt opgewekt en aan hoe die warmte door haar lagen wordt getransporteerd, totdat er een evenwicht ontstaat tussen geproduceerde en afgevoerde warmte. We testen vele mogelijke maanscenario's, waarbij we hun grootte en baan variëren en onzekerheden in materiaaleigenschappen meenemen. Onze resultaten laten zien dat een maan van ongeveer tweemaal de grootte van Io, die de nabije planeet Eridani b omcirkelt, detecteerbaar kan zijn als zij haar planeet op afstanden en met baanexcentriciteiten omloopt die vergelijkbaar zijn met die van manen in het zonnestelsel. Cruciaal laten we zien dat, als de grootte en baanafstand van een maan al bekend zijn uit een andere methode, zoals de transitmethode, haar infraroodhelderheid kan worden gebruikt om grenzen te stellen aan haar baanexcentriciteit en interne eigenschappen—bijvoorbeeld of zij lagen van gesmolten gesteente bevat. Dit betekent dat een succesvolle detectie van een getijdenverhitte exomaan (THEM) directe informatie over haar binnenste kan opleveren, waardoor THEMs krachtige proefobjecten zijn om te begrijpen hoe interieurs en banen op elkaar inwerken.

Hoofdstuk 3. Spectro-astrometrie: een veelbelovende methode om exomanen te vinden

Hoewel het vorige hoofdstuk laat zien dat THEMs in principe detecteerbaar kunnen zijn, zijn de huidige methoden nog niet gevoelig genoeg om manen te vinden zoals we die in het zonnestelsel kennen. De objecten die momenteel de detectielimieten benaderen, zijn ofwel groter, heter, of beide. Om dit probleem van “te groot of te heet” te omzeilen, hebben we een methode onderzocht die spectro-astrometrie heet. Deze techniek speurt naar minuscule verschuivingen in de schijnbare positie van het licht van een planeet bij verschillende kleuren (golflengten), veroorzaakt wanneer een onzichtbare maan bijdraagt aan het signaal van het systeem. We ontwikkelden een wiskundige beschrijving van het spectro-astrometrische signaal dat door een maan in een baan wordt opgewekt en schatten verschillende ruisbronnen die zo'n signaal kunnen beïnvloeden, waaronder onnauwkeurigheid in het richten van de telescoop, achtergrondruis en beperkingen van de detector. Vervolgens pasten we dit raamwerk toe op nabije reuzenplaneten, met ϵ Indi Ab als voorbeeld, om te bepalen welke typen manen detecteerbaar zijn. Onze resultaten laten zien dat detectie mogelijk is met telescopen van de volgende generatie, zoals

de Extremely Large Telescope, voor manen die qua grootte vergelijkbaar zijn met die in ons zonnestelsel. In het bijzonder vinden we dat manen zoals in ons eigen zonnestelsel met gematigde oppervlaktetemperaturen detecteerbaar zijn, waardoor de detectielimieten—vergeleken met het vorige hoofdstuk—dichter in de buurt komen van de manen die we kennen. We laten ook zien dat grote, ijzige manen, ter grootte van Mars of groter, zelfs in de dichtstbijzijnde planetenstelsels waarneembaar zouden kunnen zijn.

Hoofdstuk 4. Hotspots toevoegen: een nieuwe manier om THEMs te vinden

In dit hoofdstuk onderzoeken we of vulkanische exomanen, met hete oppervlakkige hotspots, kunnen worden ontdekt door te volgen hoe hun helderheid verandert terwijl ze rond hun planeet bewegen. Het idee is dat een THEM actieve vulkanen of verspreide hotspots over het oppervlak kan hebben, zoals bij Io. Deze zorgen ervoor dat de infrarode helderheid verandert wanneer verschillende gebieden in en uit zicht roteren. Om dit te testen simuleren we manen van verschillende groottes die een geïsoleerde planeet omcirkelen en onderzoeken we hoe zij de infrarode helderheid van het systeem beïnvloeden. Vervolgens bekijken we of deze zich herhalende veranderingen in de gegevens als duidelijke signalen te onderscheiden zijn. We vinden dat vulkanische manen met hotspottemperaturen zoals gemeten op Io een detecteerbare signatuur kunnen achterlaten bij kortere infrarode golflengten. Bij langere infrarode golflengten verzwakt het signaal, maar door waarnemingen op twee verschillende golflengten te vergelijken, kunnen we de bijdrage van een maan scheiden van die van haar planeet. Onze resultaten wijzen erop dat deze methode vulkanische manen met de grootte van Mars binnen ongeveer 10 parsec kan vinden, en manen die net zo groot zijn als de Aarde zelfs op grotere afstanden. Deze aanpak vergroot de mogelijkheden om naar exomanen te zoeken, vooral rond direct waargenomen of geïsoleerde planeten, omdat zij ook manen kan detecteren wanneer hun banen niet met onze gezichtslijn zijn uitgelijnd en dus geen transits laten zien.

Hoofdstuk 5. Modelleren van de inwendige structuren en cryovulkanische activiteit van de exoplaneten Trappist-1 f, g en h

In dit hoofdstuk verkennen we de inwendige opbouw van drie exoplaneten in het Trappist-1-stelsel—de planeten f, g en h—waarvan de oppervlaktetemperaturen en dichtheden suggereren dat ze op de ijzige manen van ons zonnestelsel kunnen lijken. Ons doel is te bepalen onder welke omstandigheden interne verwarming ondergrondse oceanen in stand kan houden en zelfs ijsvulkanen (cryovulkanen) kan aandrijven. We modelleren hoe warmte in deze planeten wordt opgewekt uit twee hoofdbronnen: getijdenverwarming en radiogene verwarming, afkomstig van het verval van radioactieve elementen. Door deze warmtebronnen te koppelen aan de dikte van ijskorsten en oceanen bepalen we welke interne structuren warmteproductie en -verlies in balans kunnen houden. Onze resultaten laten zien dat voor Trappist-1f en -1g thermisch evenwicht alleen mogelijk is als hun buitenste ijskorsten relatief dun zijn—ongeveer 4 tot 10 kilometer—met daaronder oceanen van circa 90 tot 120 kilometer dik. Trappist-1h daarentegen zou een dikkere ijskorst nodig hebben om in evenwicht te blijven. We hebben ook onderzocht of vulkanische uitgassing van water met de James Webb-ruimtetelescoop detecteerbaar is. Zelfs onder de

meest optimistische aannames zou detectie een campagne van meer dan een decennium vergen. Dat maakt detectie met de huidige instrumenten zeer onwaarschijnlijk. Toekomstige pogingen maken meer kans door zich te richten op exoplaneten met excentrischere banen, waar sterkere getijdenverwarming de wateruitgassing tot detecteerbare niveaus kan opkrikken.

Ελληνική περίληψη

Είμαστε μόνοι; Η αναζήτηση ζωής αλλού στο σύμπαν είναι ένα διαχρονικό ερώτημα της ανθρωπότητας. Σήμερα μπορούμε να αναζητήσουμε σημάδια ζωής σε άλλα σώματα του ηλιακού μας συστήματος, όπως στην επιφάνεια του Άρη και στους κρυμμένους, υπόγειους ωκεανούς δορυφόρων πλανητών, για παράδειγμα στους δορυφόρους του Δία και του Κρόνου.

Οι δορυφόροι του ηλιακού μας συστήματος παρουσιάζουν μεγάλη ποικιλία στα φυσικά και τροχιακά τους χαρακτηριστικά, και μερικοί ξεχωρίζουν για τη γεωλογική τους δραστηριότητα. Η Ιώ, ο εσώτερος δορυφόρος του Δία, είναι το πιο ηφαιστειακά ενεργό σώμα στο ηλιακό σύστημα, με εκατοντάδες εστίες θερμότητας στην επιφάνειά της. Ο Εγκέλαδος, ένας παγωμένος δορυφόρος του Κρόνου, διαθέτει επιφανειακές ρωγμές, ενεργούς πίδακες υδρατμών και έναν υπόγειο ωκεανό. Ένας βασικός μηχανισμός πίσω από αυτή την ποικιλία φαινομένων είναι η παλιρροϊκή θερμότητα: καθώς ένας δορυφόρος κινείται σε ελλειπτική τροχιά γύρω από τον πλανήτη του, οι μεταβαλλόμενες βαρυτικές δυνάμεις τον παραμορφώνουν και παράγουν εσωτερική θερμότητα. Σε μεγάλες χρονικές κλίμακες, αυτή η διαδικασία μπορεί να διατηρήσει το νερό σε υγρή μορφή κάτω από μια παγωμένη επιφάνεια και να συμβάλλει στην εκδήλωση ηφαιστειακής δραστηριότητας. Η ύπαρξη υγρού νερού και γεωλογικής δραστηριότητας μπορεί να προσφέρει τα συστατικά και τις πηγές ενέργειας που είναι απαραίτητες για την ανάπτυξη ζωής, κάνοντας το φαινόμενο της παλιρροϊκής θερμότητας να παίζει καθοριστικό ρόλο για την αναζήτησή της. Το ηλιακό μας σύστημα μας δίνει την ευκαιρία να μελετήσουμε κοντινούς κόσμους, αλλά η αναζήτηση ζωής φτάνει πολύ πιο μακριά, έως τα εξωπλανητικά συστήματα άλλων άστρων.

Πέρα από το ηλιακό σύστημα, η ανακάλυψη πλανητών που περιφέρονται γύρω από τον πάσσαρ PSR 1257+12 και, λίγο αργότερα, του 51 Pegasi b, ενός πλανήτη γίγαντα με τροχιακή περίοδο μόλις λίγων ημερών, αποτέλεσε ορόσημο. Έκτοτε, οι ανακαλύψεις εξωπλανητών αυξήθηκαν ραγδαία, με αποτέλεσμα σήμερα να είναι γνωστοί χιλιάδες εξωπλανήτες. Πολλοί από αυτούς δεν μοιάζουν με τους πλανήτες του δικού μας συστήματος. Για παράδειγμα, οι «καυτοί Δίες - Hot Jupiters» είναι γιγαντιαίοι πλανήτες σε πολύ μικρές τροχιές. Οι «υπεργαίες - Super Earths» (πλανήτες με μέγεθος ανάμεσα στη Γη και τον Ποσειδώνα) απαντώνται πολύ συχνά στον γαλαξία μας, ενώ οι εξωπλανήτες στο μέγεθος της Γης είναι πιο σπάνιοι. Ανάλογα με την απόστασή τους από το άστρο τους, μερικοί από αυτούς μπορεί να μοιάζουν με τους παγωμένους δορυφόρους του ηλιακού μας συστήματος, με ψυχρές επιφάνειες από πάγο και πιθανόν εσωτερικούς ωκεανούς.

Δεδομένης της σημασίας των δορυφόρων στο ηλιακό μας σύστημα, είναι φυσικό να αναρωτηθούμε αν και οι εξωπλανήτες έχουν δορυφόρους και αν αυτοί θα μπορούσαν να φιλοξενούν ζωή. Εφόσον όλοι οι αέριοι γίγαντες στο ηλιακό μας σύστημα έχουν φυσικούς δορυφόρους, είναι λογικό πολλοί από τους εξωπλανήτες-γίγαντες που έχουμε βρει να διαθέτουν επίσης δορυφόρους (εξωδορυφόρους). Ωστόσο, μέχρι σήμερα, δεν έχει επιβεβαιωθεί η ανίχνευση κανενός εξωδορυφόρου. Ένας βασικός λόγος είναι ότι τα σήματα των δορυφόρων είναι αμυδρά σε σύγκριση με εκείνα των μεγάλων πλανητών τους. Καθώς οι εξωπλανήτες που έχουν βρεθεί μέχρι σήμερα

είναι διαφορετικοί μεταξύ τους είναι αναγκαίο να καθοριστεί ποιοι απο αυτούς προσφέρουν τις μεγαλύτερες πιθανότητες ανίχνευσης εξωδορυφόρων, ποιες τεχνικές αποδεικνύονται πιο αποτελεσματικές και ποια χαρακτηριστικά δορυφόρων μπορούν να παρατηρηθούν.

Για να απαντήσουμε τα παραπάνω, θα πρέπει πρώτα να κατανοήσουμε βασικές έννοιες σχετικά με τις τεχνικές ανίχνευσης εξωπλανητών. Η μέθοδος η οποία έχει αποδώσει περισσότερες ανακαλύψεις εξωπλανητών μέχρι σήμερα, είναι η μέθοδος της διέλευσης. Σύμφωνα με την μέθοδο αυτή γίνεται παρατήρηση των πλανητών όταν περνούν μπροστά από τα άστρα τους, οπότε προκαλούν μία μικρή περιοδική μείωση στη φωτεινότητά τους. Οι ίδιοι οι πλανήτες δεν είναι άμεσα ορατοί, είναι όμως οι διελεύσεις τους. Η τεχνική είναι πιο ευαίσθητη σε πλανήτες που κινούνται πολύ κοντά στα άστρα τους, επειδή η μικρή απόσταση από το άστρο αυξάνει την πιθανότητα διέλευσης. Αυτό όμως δυσκολεύει την ανίχνευση εξωδορυφόρων: σε πλανήτες που κινούνται πολύ κοντά στα άστρα τους, οι δορυφόροι μπορεί να μην επιβιώνουν για πολύ, αφού η ισχυρή βαρυτική έλξη του άστρου δεν επιτρέπει εύκολα σταθερές τροχιές. Επιπλέον, οι αναζητήσεις εξωδορυφόρων με τη μέθοδο της διέλευσης απαιτούν ευνοϊκή γεωμετρία, δηλαδή ο πλανήτης και ο δορυφόρος του να ευθυγραμμίζονται με τη δική μας οπτική γωνία ώστε να είναι ορατές οι διελεύσεις τους. Τέλος, για μια επιβεβαιωμένη ανίχνευση εξωδορυφόρου χρειάζονται μακροχρόνιες παρατηρήσεις για να καταγραφούν πολλαπλές διελεύσεις. Αυτό καθιστά ελκυστικούς στόχους τους εξωπλανήτες που έχουν ανιχνευθεί μέσω άμεσης απεικόνισης, καθώς βρίσκονται σε σχετικά μεγάλες αποστάσεις από τα άστρα τους. Σε αυτές τις αποστάσεις μπορούμε να καταστείλουμε το φως του άστρου, επιτρέποντας την απευθείας μελέτη της ακτινοβολίας του πλανήτη.

Η παρατήρηση του φωτός ενός πλανήτη και η ανίχνευση αμυδρών σημάτων από τους δορυφόρους του, παρουσιάζουν επίσης σημαντικές δυσκολίες, καθώς η εκτυφλωτική λάμψη του άστρου πρέπει πρώτα να περιοριστεί. Ακόμη και όταν αυτό επιτευχθεί, το ίδιο το φως του πλανήτη μπορεί να υπερκαλύπτει εκείνο των δορυφόρων του. Ωστόσο, στο υπέρυθρο φάσμα, όπου η θερμική ακτινοβολία του ίδιου του αντικειμένου αποτελεί την κύρια πηγή εκπομπής, αναδυσκνείται μια ιδιαίτερη κατηγορία σωμάτων, οι παλιρροϊκά θερμαινόμενοι εξωδορυφόροι (Tidally Heated Exomoons, THEMs). Αυτοί είναι ανάλογοι με την Ιώ, τον ηφαιστειακά ενεργό δορυφόρο του Δία, και προσφέρουν μια μοναδική ευκαιρία: κινούμενοι από έντονες παλιρροϊκές δυνάμεις, μπορούν να φτάσουν σε πολύ υψηλές επιφανειακές θερμοκρασίες, και σε ορισμένα υπέρυθρα μήκη κύματος, να ξεπερνούν σε φωτεινότητα τον πλανήτη τους. Σε αντίθεση με τις διελεύσεις, η άμεση θερμική απεικόνιση δεν εξαρτάται από μια συγκεκριμένη φάση της τροχιάς του πλανήτη. Με τον τρόπο αυτό δημιουργείται μια νέα δυνατότητα για την ανίχνευση δορυφόρων γύρω από γιγάντιους πλανήτες σε μεγάλες αποστάσεις από τα άστρα τους, περιοχές όπου οι υπόλοιπες μέθοδοι ανίχνευσης εξωπλανητών παρουσιάζουν περιορισμούς.

Η ποσότητα παλιρροϊκής θερμότητας που παράγεται στο εσωτερικό ενός δορυφόρου επηρεάζεται, μεταξύ άλλων, από την τροχιά του και τον τρόπο με τον οποίο τα υλικά στο εσωτερικό του παραμορφώνονται και διαχέουν ενέργεια. Επειδή λοιπόν η παλιρροϊκή θερμότητα συνδέεται άμεσα με τις εσωτερικές ιδιότητες ενός σώματος, η μελέτη των THEMs προσφέρει όχι μόνο μια μέθοδο ανίχνευσης δορυφόρων, αλλά

και ένα πολύτιμο εργαλείο για την εξερεύνηση της εσωτερικής τους δομής και των φυσικών τους ιδιοτήτων. Παρόμοιες προσεγγίσεις έχουν χρησιμοποιηθεί και στο δικό μας ηλιακό σύστημα. Για παράδειγμα, η ηφαιστειακή δραστηριότητα της Ιούς εγείρει εδώ και δεκαετίες ερωτήματα για το αν διαθέτει έναν παγκόσμιο ωκεανό μάγματος ή ένα μερικώς λωμένο μανδύα. Οι μετρήσεις της παραμόρφωσής της από τις παλιρροϊκές δυνάμεις υπήρξαν καθοριστικές για τη διερεύνηση της πιθανότητας των δύο σεναρίων. Επεκτείνοντας αυτό το σκεπτικό σε εξωπλανήτες και τους δορυφόρους τους, η παλιρροϊκή θερμότητα μπορεί να μας βοηθήσει να αντλήσουμε πληροφορίες για τις εσωτερικές τους ιδιότητες και τους μηχανισμούς μεταφοράς θερμότητας στο εσωτερικό τους. Αυτές οι διεργασίες είναι σημαντικές για την αστροβιολογία και καθιστούν την μελέτη των παλιρροϊκά θερμαινόμενων κόσμων ιδιαίτερα πολύτιμη για την αναζήτηση ζωής στο σύμπαν.

Η παρούσα διατριβή κάνει βήματα στην αναζήτηση εξωδορυφόρων και επικεντρώνεται στην ανιχνευσιμότητα των THEMs μέσω ποικίλων μεθόδων, ενώ εξετάζει τις εσωτερικές και τροχιακές ιδιότητες που τα καθιστούν παρατηρήσιμα. Παράλληλα, διερευνάται κατά πόσο η φωτεινότητά των THEMs ή οι διακυμάνσεις της μπορούν να μετρηθούν με τα τρέχοντα και τα μελλοντικά τηλεσκόπια. Συνδυάζοντας υποθετικές παρατηρήσεις με μοντέλα παλιρροϊκής θερμότητας, η διατριβή διερευνά περαιτέρω τους περιορισμούς που μπορούν να τεθούν στις εσωτερικές δομές πλανητών και δορυφόρων. Τα μοντέλα παλιρροϊκής θερμότητας αξιοποιούνται, επίσης, για τη μελέτη του εσωτερικού παγωμένων εξωπλανητών, οι οποίοι θεωρείται ότι παρουσιάζουν αναλογίες με τους παγωμένους δορυφόρους του ηλιακού μας συστήματος. Ειδικότερα, εξετάζεται κατά πόσο η θερμότητα θα μπορούσε να διατηρήσει υπόγειους ωκεανούς, καθώς και αν ενδείξεις ηφαιστειακής δραστηριότητας θα ήταν δυνατόν να ανιχνευθούν στο πλανητικό σύστημα Trappist-1. Συνολικά, οι μελέτες αυτές αναδεικνύουν τον ρόλο της παλιρροϊκής θερμότητας τόσο ως μέσο ανίχνευσης όσο και ως εργαλείο κατανόησης των εσωτερικών διεργασιών σε εξωπλανητικά συστήματα.

Κεφάλαιο 2. Διερευνώντας την ανιχνευσιμότητα και τις ιδιότητες των THEMs γύρω από τον εξωπλανήτη ϵ Eridani b

Σε αυτό το κεφάλαιο διερευνούμε αν οι παλιρροϊκά θερμαινόμενοι εξωδορυφόροι μπορούν να είναι αρκετά φωτεινοί στο υπέρυθρο ώστε να ανιχνευθούν με το διαστημικό τηλεσκόπιο James Webb Space Telescope (JWST) γύρω από κοντινούς γίγαντες πλανήτες. Χρησιμοποιούμε τον πλανήτη Eridani b σαν case study. Αναπτύσσουμε μοντέλα που συνδέουν την τροχιά και τις φυσικές ιδιότητες ενός δορυφόρου με τη θερμότητα που παράγεται στο εσωτερικό του μέσω παλιρροϊκών δυνάμεων. Επιπλέον, μοντελοποιούμε τον τρόπο με τον οποίο η θερμότητα μεταφέρεται στα εσωτερικά στρώματα του δορυφόρου, μέχρι να επιτευχθεί ισορροπία μεταξύ παραγωγής και απώλειας θερμότητας. Εξετάζουμε πολλά πιθανά σενάρια δορυφόρων, μεταβάλλοντας το μέγεθος, την τροχιά τους και ενσωματώνοντας αβεβαιότητες στις ιδιότητες των υλικών τους. Τα αποτελέσματά μας δείχνουν ότι ένας δορυφόρος περίπου διπλάσιος σε μέγεθος από την Ιώ, που περιφέρεται γύρω από τον ϵ Eridani b, μπορεί να είναι ανιχνεύσιμος αν έχει τροχιακές ιδιότητες παρόμοιες με αυτές των δορυφόρων του ηλιακού μας συστήματος. Ένα από τα βασικά συμπεράσματα του κεφαλαίου

είναι ότι, εφόσον το μέγεθος και η τροχιακή απόσταση ενός δορυφόρου ήταν ήδη γνωστά από άλλη μέθοδο, όπως η μέθοδος της διέλευσης, η υπέρυθρη φωτεινότητά του θα μπορούσε να αξιοποιηθεί για τον προσδιορισμό της εκκεντρότητας της τροχιάς και των εσωτερικών ιδιοτήτων και χαρακτηριστικών, όπως για παράδειγμα την παρουσία στρωμάτων λιωμένων πετρωμάτων. Αυτό σημαίνει ότι μια επιτυχής ανίχνευση δορυφόρου στο υπέρθυρο γύρω από τον ϵ Eridani b θα μπορούσε να μας δώσει άμεσες πληροφορίες για το εσωτερικό του, καθιστώντας τα THEMs πολύτιμα πεδία μελέτης για την κατανόηση της αλληλεπίδρασης εσωτερικού και τροχιάς.

Κεφάλαιο 3. Σπεκτροαστρομετρία: μια υποσχόμενη μέθοδος για την ανίχνευση εξωδορυφόρων

Αν και το προηγούμενο κεφάλαιο έδειξε ότι τα THEMs (διπλάσια σε μέγεθος από την Ιώ) μπορούν να ανιχνευθούν στην υπέρυθρη ακτινοβολία, οι τρέχουσες μέθοδοι δεν είναι ακόμη αρκετά ευαίσθητες για να βρουν δορυφόρους σαν αυτούς που γνωρίζουμε στο ηλιακό μας σύστημα. Οι δορυφόροι που βρίσκονται σήμερα στα όρια ανίχνευσης των μεθόδων είναι είτε μεγαλύτεροι, είτε θερμότεροι, είτε και τα δύο. Για να ξεπεράσουμε αυτό το πρόβλημα, εξερευνήσαμε μια μέθοδο που ονομάζεται σπεκτροαστρομετρία. Η τεχνική αυτή μετράει μικρές μετατοπίσεις στη φαινομενική θέση ενός πλανήτη σε διαφορετικά μήκη κύματος. Οι μετατοπίσεις αυτές προκαλούνται όταν ένας δορυφόρος, το φως του οποίου δεν μπορεί να ανιχνευθεί από μόνο του, συνεισφέρει στο συνολικό σήμα. Αναπτύσσουμε μια μαθηματική περιγραφή του σπεκτροαστρομετρικού σήματος που παράγει ένας δορυφόρος σε τροχιά, και εκτιμάμε τις πηγές θορύβου που μπορούν να επηρεάσουν μία τέτοια μέτρηση, όπως μικρές αποκλίσεις στη στόχευση του τηλεσκοπίου, τον θόρυβο υποβάθρου και λειτουργικούς περιορισμούς του ανιχνευτή. Εφαρμόζουμε τα παραπάνω μοντέλα σε υποθετικούς δορυφόρους γύρω από κοντινούς γίγαντες πλανήτες, με παράδειγμα τον ϵ Indi Ab, για να δούμε τι είδους δορυφόροι μπορούν να ανιχνευθούν με τη μέθοδο της σπεκτροαστρομετρίας. Τα αποτελέσματά μας δείχνουν ότι η ανίχνευση είναι δυνατή με τα τηλεσκόπια νέας γενιάς όπως το ELT, για δορυφόρους παρόμοιους σε μέγεθος με εκείνους του ηλιακού μας συστήματος. Κατ' αυτόν τον τρόπο, τα όρια ανίχνευσης έρχονται πιο κοντά σε εκείνα των ήδη γνωστών δορυφόρων. Τέλος, δείχνουμε ότι μεγάλοι παγωμένοι δορυφόροι, σε μέγεθος συγκρίσιμο με τον Άρη, θα μπορούσαν να ανιχνευθούν στα πλησιέστερα πλανητικά συστήματα.

Κεφάλαιο 4. Προσθέτοντας θερμές εστίες και ηφαίστεια: μια νέα μέθοδος για την ανίχνευση THEMs

Σε αυτό το κεφάλαιο εξετάζουμε αν δορυφόροι, με θερμές εστίες και ηφαίστεια στην επιφάνειά τους, μπορούν να ανιχνευθούν μέσω αλλαγών στη φωτεινότητά τους καθώς κινούνται γύρω από τους πλανήτες τους. Αν ένα THEM έχει ενεργά ηφαίστεια ή θερμές περιοχές διάσπαρτες στην επιφάνειά του, όπως η Ιώ, τότε η υπέρυθρη φωτεινότητά του θα μεταβάλλεται καθώς διαφορετικές περιοχές στρέφονται προς ή μακριά από εμάς. Για να το δοκιμάσουμε αυτό, προσομοιώνουμε δορυφόρους διαφορετικών μεγεθών γύρω από έναν μεμονωμένο πλανήτη και μελετούμε πώς αλλάζουν

την υπέρυθρη φωτεινότητα του συστήματος. Στη συνέχεια εξετάζουμε αν αυτές οι περιοδικές αλλαγές είναι ευδιάκριτες στα δεδομένα. Βρίσκουμε ότι ηφαιστειακοί δορυφόροι με θερμές περιοχές σε θερμοκρασίες παρόμοιες με εκείνες της Ιούς μπορούν να αφήσουν ανιχνεύσιμο αποτύπωμα σε μικρότερα υπέρυθρα μήκη κύματος. Σε μεγαλύτερα μήκη κύματος το σήμα εξασθενεί, αλλά συγκρίνοντας παρατηρήσεις σε δύο διαφορετικά μήκη κύματος μπορούμε να ξεχωρίσουμε τη συνεισφορά του δορυφόρου από εκείνη του πλανήτη. Τα αποτελέσματα δείχνουν ότι αυτή η μέθοδος μπορεί να εντοπίσει δορυφόρους με το μέγεθος του Άρη σε αποστάσεις έως 10 parsecs, και μεγέθους Γης σε πιο απομακρυσμένα συστήματα. Η προσέγγιση αυτή διευρύνει τις δυνατότητες αναζήτησης εξωδορυφόρων, ιδιαίτερα γύρω από μεμονωμένους πλανήτες ή πλανήτες που έχουν απεικονιστεί άμεσα, καθώς μπορεί να ανιχνεύσει δορυφόρους ακόμη και αν οι τροχιές τους δεν ευθυγραμμίζονται ώστε να παραρητηθούν διελεύσεις.

Κεφάλαιο 5. Μοντελοποίηση των εσωτερικών και της κρυοηφαιστειακής δραστηριότητας των εξωπλανητών Trappist-1 f, g, h

Σε αυτό το κεφάλαιο εξερευνούμε τα εσωτερικά τριών εξωπλανητών στο σύστημα Trappist-1, των πλανητών f, g, h, των οποίων οι θερμοκρασίες και οι πυκνότητες δείχνουν ότι μπορεί να μοιάζουν με τους παγωμένους δορυφόρους του ηλιακού μας συστήματος. Στόχος μας είναι να δούμε αν η εσωτερική θερμότητά του μπορεί να επιτρέψει την ύπαρξη υπόγειων ωκεανών και να τροφοδοτήσει παγωμένα ηφαίστεια, γνωστά ως κρυοηφαίστεια. Μοντελοποιούμε πώς παράγεται θερμότητα στο εσωτερικό αυτών των πλανητών από δύο κύριες πηγές: την παλιρροϊκή και τη ραδιογενή θερμότητα από τη διάσπαση ραδιενεργών στοιχείων στο εσωτερικό του. Συνδέοντας αυτές τις πηγές θερμότητας με εσωτερικές ιδιότητες των πλανητών, όπως το πάχος των ωκεανών, εντοπίζουμε ποιες εσωτερικές δομές μπορούν να διατηρήσουν ισορροπία παραγωγής και απώλειας θερμότητας. Τα αποτελέσματά μας δείχνουν ότι για τους Trappist-1 f, g η ισορροπία αυτή είναι δυνατή μόνο αν το εξωτερικό παγωμένο κέλυφος είναι σχετικά λεπτό, περίπου 4–10 χιλιομέτρων, με υπόγειους ωκεανούς πάχους 90–120 χιλιομέτρων. Σε αυτές τις περιπτώσεις, οι υπόγειοι ωκεανοί θα μπορούσαν να συνδέονται άμεσα με την επιφάνεια. Ο Trappist-1 h αντίθετα, θα χρειαζόταν παχύτερο κέλυφος για να διατηρηθεί σε θερμική ισορροπία. Δοκιμάσαμε επίσης αν η κρυοηφαιστειακή εκπομπή νερού, από πίδακες ατμών θα μπορούσε να ανιχνευθεί με το διαστημικό τηλεσκόπιο JWST. Ακόμη και στα πιο αισιόδοξα σενάρια, η ανίχνευση θα απαιτούσε καμπάνια άνω της δεκαετίας, κάτι που καθιστά απίθανη την παρατήρηση με σημερινά όργανα. Μελλοντικές προσπάθειες μπορεί να έχουν περισσότερες πιθανότητες εστιάζοντας σε εξωπλανήτες με πιο ελλειπτικές τροχιές, όπου η μεγαλύτερα παλιρροϊκή θερμότητα μπορεί να αυξήσει τους ρυθμούς εκπομπής νερού σε ανιχνεύσιμα επίπεδα.

List of publications

Refereed publications

1. *Tidally heated exomoons around ϵ Eridani b: Observability and prospects for characterization*
E. Kleisioti, D. Dirkx, M. Rovira-Navarro, and M. A. Kenworthy
Astronomy and Astrophysics, 675, A57 (2023)
2. *The spectroastrometric detectability of nearby Solar System-like exomoons*
Q. B. van Woerkom and E. Kleisioti
Astronomy and Astrophysics, 684, A72 (2024)
3. *Direct detectability of tidally heated exomoons by photometric orbital modulation*
E. Kleisioti, D. Dirkx, X. Tan, and M. A. Kenworthy
Astronomy and Astrophysics, 687, A125 (2024)
4. *The MIRI Exoplanets Orbiting White dwarfs (MEOW) Survey: Mid-infrared Excess Reveals a Giant Planet Candidate around a Nearby White Dwarf*
M. A. Limbach, A. Vanderburg, A. Venner, S. Blouin, K.B. Stevenson, R.J. MacDonald, S. Jenkins, R. Bowens-Rubin, M. Soares-Furtado, C. Morley, M. Janson, J. Debes, S. Xu, E. Kleisioti, M. Kenworthy, P. Butler, J.D. Crane, D. Osip, S. Shectman, J. Teske
The Astrophysical Journal Letters, 973, L11 (2024)
5. *Modeling the interiors of Trappist-1f, g, h: Tidal Heating, Subsurface Oceans, and Cryovolcanic Activity*
E. Kleisioti, D. Dirkx, A. Louca, M. Rovira-Navarro, Apurva V. Oza, and M. A. Kenworthy
Submitted to Astronomy and Astrophysics

Non-refereed publications

1. *Could we observe exomoons around ϵ Eridani b?*
E. Kleisioti, D. Dirkx, M. Rovira-Navarro, and M. A. Kenworthy
AASTCS9, Exoplanets 4 (2022)
2. *The MIRI survey for Exoplanets Orbiting White-dwarfs (MEOW)*
M.A Limbach, A. Vanderburg, S. Blouin, M.R Janson, M. Kenworthy, E. Kleisioti, K. Stevenson, A. Venner, C. Morley
JWST Proposal. Cycle 2, ID. 4403 (2024)
3. *Exomoon detection via photometric signal variability due to surface hotspots*
E. Kleisioti, D. Dirkx, X. Tan, and M. A. Kenworthy
AASTCS10, Extreme Solar Systems V (2024)

4. *A socio-demographic study of the exoplanet direct imaging community*
L. Leboulleux, N. Desai, D. Echeverri, E. Kleisioti, L. König, M. Malin, E. Matthews,
S. Perera, S. Wolff, E. Choquet, E. Huby, G. Singh
Submitted to BAAS

Curriculum vitae

I was born in Athens in 1994. As a student, I was well-behaved, never causing trouble, although looking back, I sometimes wish I had been a little more rebellious. In school I felt a special pull towards the natural sciences. I was curious to understand nature in depth and the only books I enjoyed reading as an adolescent were works of science communication.

In Greece, we were raised by a generation that believed children should become engineers, lawyers, or doctors in order to secure a good income. A technical university, known for its competitive entry, was considered the natural choice for many students. Influenced by this culture, I chose to follow that path. Wanting to stay as close as possible to the natural sciences, I decided to study Chemical Engineering at the National Technical University of Athens, after carefully examining the courses offered, as it included courses like thermodynamics, physical chemistry, heat and mass transfer, and chemistry. After the first three years, however, the focus of the program shifted towards industrial applications, and I found myself losing interest. I realized that what I enjoyed most was learning new subjects on natural sciences.

I also longed to live abroad and explore different cultures. This led me to pursue an MSc in Space Science and Engineering in the UK. For my MSc thesis I worked on studying exoplanet atmospheres with TESS observations under the supervision of Dr. Vincent Van Eylen, a project which fueled my excitement about exoplanet systems and inspired me to pursue them further in my research. The end of the MSc coincided with the COVID-19 pandemic, and I had to return to Greece. As the UK began to reopen, I was happy to start an internship with the Rosetta mission at the Open University, studying the cometary environment. This experience confirmed my desire to continue in astrophysical research. Not long after, I was excited to be accepted by Dr. Matthew Kenworthy and Dr. Dominic Dirkx to pursue a PhD on exomoons, in a joint project between Delft University of Technology and Leiden Observatory. That is how I moved to the Netherlands.

Moving to a new country and culture during a lockdown came with challenges. A girl raised in a city full of noise can find it strangely difficult to sleep in the relative quiet streets of Leiden. Yet the guidance of my supervisors, together with the welcoming spirit of my new roommates (also PhD students at the Observatory), the 11th-floor group, and the first-year PhDs, smoothed my settling in. By the time spring arrived, the Netherlands transformed with the change of season. With the easing of restrictions, the Observatory started gradually coming back to life. The research, the multicultural environment, the daily exposure to science and the discussions with scientists at TU Delft and Sterrewacht are experiences I will never forget - and ones I already deeply miss now that I have returned to Greece.

During my PhD I worked on tidal heating in exomoons and exoplanets, and the observability of exomoons with different detection methods. I had the opportunity to present my work to multiple audiences, attended and organized conferences, wrote observing proposals, followed talks from scientists from all over the world, supervised two MSc students, and introduced two high school students to the world of astronomy.

As I write this chapter, I realize that the overall experience has left me a completely

different person. At present, I am exploring the world of industry, yet I find myself missing scientific research.

Acknowledgments

The completion of this PhD would not have been possible without the guidance, support, and encouragement of many people, to whom I am deeply grateful.

First and foremost, I would like to thank my supervisors, Matt and Dominic, for their invaluable guidance and encouragement throughout this journey. Matt, you taught me that even my wildest ideas could be turned into meaningful research. Dominic, your support and ability to frame my thoughts into clear, well-defined steps have been essential. Even in the most challenging moments you both provided understanding and support. Your advice has shaped not only my research but also my growth as a scientist, and I am deeply grateful for the opportunity to have worked under your supervision.

To all the wonderful people I met along the way—thank you for bringing balance and laughter, during the many intense moments of this PhD, as well as stimulating discussions and fun moments at conferences. A special word of thanks goes to our group at 11-th floor group, which still feels very gezellig. Thank you Willy, David, Thijs, Rico, Floor, Kira and everyone there for creating such a warm atmosphere. Specifically, Rico thank you for teaching me "Links Rechts". David your tremendous support and love for our group has moved me. Willy thank you for your warmth and care. I would also like to thank the 1st year (or not) PhDs, including Amy, Christiaan, Christian, Roi, and Elena. Tara we have lived such nice moments together - thank you! Louise and Andrea, I miss our little chats. Moving on to later years, the Groovy Group has been awesome. Michiel, thank you for teaching me "griechischer Wein", and for bringing such a positive atmosphere in the institute. Richelle I think I won the game of forgetting our cards. Pengyu, it was always so nice chatting with you at the office.

I would also like to thank my collaborators in Delft. Marc thank you for your amazing insights and advice. Rania, Sam you were always adding a friendly note when I was coming there. I am grateful to the PEPSci network, which provided me with such inspiring discussions. Thank you Christiaan, Orr, Mark, Vivian, Alexandra, and of course Tara and Willy.

In addition, I would like to acknowledge the Master students, Stef and Quirijn, whose curiosity and dedication continually inspired me, as well as Tin and Ella. Thank you for choosing to do your projects with me. Working with all of you has been a source of motivation and joy.

Outside of academia, I want to thank my roommates Kirsty and Reinier. Kortenaerstraat is in my heart.

Finally, I want to thank my friends and family, who I love and who have been there for me: — the ones sharing the Dutch journey - Chryssako mou and Milino - the ones back in Greece (or abroad) - Nephelako, who is probably an expert in astro after reading all my stuff, Zooulako mou, Vickara I, Vickara II, Dimitrako, Giannako I, Giannako II, Orphiko, Marako, xaderfakia, Yiakouli, Litouli, Iriako, Vatzoula, Leli, and Stelli.

Μαμά, Παππά ευχαριστώ που με στηρίζατε.
(Mum, Dad thank you for supporting me.)

Victorako mou, you were always by my side, merci para poli.

Propositions
accompanying the thesis

Lighting up dark exomoons

Observational signatures of tidally induced volcanism in other worlds

1. The synergy between exomoon transits, infrared flux detection, and tidal modelling offers a pathway to constraining the orbital eccentricity and the internal structure of tidally heated exomoons. (Chapter 2)
2. Spectroastrometry permits detections of solar system-like moons at plausible temperatures and sizes in nearby systems. (Chapter 3)
3. Photometric orbital modulation enables THEM detections at non-transiting inclinations, removing the need for the geometric alignment required by exomoon transits. (Chapter 4)
4. Transmission spectroscopy with JWST is an inefficient route to detecting cryovolcanism in the TRAPPIST-1 system. (Chapter 5)
5. Exomoon detections will move the question from “How many planets?” to “How many worlds per system?”.
6. The astronomical community should adopt the convention that the term “biosignature” is used only when multiple observables, interpreted in planetary context and supported by modeling, favor a biotic interpretation.
7. For an engineer, becoming an astronomer is a retune: the optimization flips from picking the best solution from many to extracting the most information from limited data.
8. Media should report uncertainty and process, not just breakthroughs; otherwise the public learns spectacle, not science.
9. In a society that overprioritizes outcomes, “useful” must be proven in advance, and understanding becomes a byproduct.
10. Communication across cultures fails less on words than on unspoken assumptions.
11. Moons are like bitterballen, colder outside but piping hot inside.