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Habitable worlds with *JWST*: transit spectroscopy of the TRAPPIST-1 system?

J. K. Barstow[1,2★] and P. G. J. Irwin[2]
[1]*Physics and Astronomy, University College London, WC1E 6BT London, UK*
[2]*Department of Physics, Atmospheric, Oceanic and Planetary Physics, Clarendon Laboratory, University of Oxford, OX1 3PU, UK*

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ABSTRACT

The recent discovery of three Earth-sized, potentially habitable planets around a nearby cool star, TRAPPIST-1, has provided three key targets for the upcoming *James Webb Space Telescope (JWST)*. Depending on their atmospheric characteristics and precise orbit configurations, it is possible that any of the three planets may be in the liquid water habitable zone, meaning that they may be capable of supporting life. We find that present-day Earth levels of ozone, if present, would be detectable if *JWST* observes 60 transits for innermost planet 1b and 30 transits for 1c and 1d.

Key words: radiative transfer – methods: data analysis – planets and satellites: atmospheres.

1 INTRODUCTION

The infrared *James Webb Space Telescope* (*JWST*), due to launch in 2018, is predicted to dramatically change our understanding of exoplanet atmospheres. Included in this is the tantalising possibility that, if a suitable target is obtained, *JWST* might provide the first atmospheric data for an Earth-sized planet orbiting in the habitable zone of its parent star.

The TRAnsiting Planets and PlanetesImals Small Telescope (TRAPPIST; Jehin et al. 2011) is a 60-cm robotic telescope at La Silla observatory. It was designed for detection and characterization of exoplanets, as well as observations of small Solar system bodies. The recent discovery of the TRAPPIST-1 planetary system (Gillon, Jehin & Lederer 2016) has provided not one, but three, potential targets for *JWST* follow-up. TRAPPIST-1 is an ultracool dwarf of spectral type M8, only 12 parsec away and hosting three planets with $R < 1.2R_{\oplus}$. The innermost two planets b and c have 4× and 2× the irradiation experienced by Earth; the orbital period of the outermost planet d is not yet constrained, but the most likely period of 18.2 d would make it slightly cooler than Earth.

Depending on their albedos and the presence or absence of strong greenhouse warming, all of these planets could have the appropriate conditions for liquid water to be present. As this is considered to be a likely requirement for the presence of (Earth-like) life, this is an important criterion for any of these planets to be inhabited. Bolmont et al. (2016) have modelled the escape of H_2O during the evolution of each of these planets and find that, whilst there is a strong possibility that TRAPPIST-1b and 1c may have lost substantial amounts of water during their early life, cooler planet TRAPPIST-1d may have retained a substantial amount provided it started off with a sufficiently high water content. Wheatley et al. (2016) have observed the star in the X-ray with *XMM–Newton* and find that the likely combined X-ray and extreme ultraviolet (EUV) budget could be 50× higher than that assumed by Bolmont et al. (2016), which increases the likelihood that 1b and 1c are dry planets. The likely chemistry and observational possibilities for habitable or inhabited worlds evolving around M-dwarf stars has been discussed at length by various authors, including Segura et al. (2005), Deming et al. (2009), Kaltenegger & Traub (2009), Rugheimer et al. (2015) and Tabataba-Vakili et al. (2015). Predicted abundances of possible biosignature gases such as O_3 are highly dependent on a variety of factors, including the level of stellar activity and the UV flux profile of the star. This is still only known for a handful of M dwarfs and information is even scarcer for ultracool dwarfs, making it difficult to determine whether substantial amounts of O_3 could be sustained on a terrestrial planet orbiting a star like TRAPPIST-1.

In this Letter, we aim to see whether ozone might be detected by *JWST* in the atmospheres of the TRAPPIST-1 planets and make the following assumptions: (1) each TRAPPIST planet is capable of retaining liquid water, and therefore of hosting life; (2) on each planet, life has evolved and resulted in an atmosphere with ∼ 20 per cent molecular oxygen; (3) on each planet, a stratospheric ozone layer has formed, with ozone column abundance comparable to that of the Earth. For a detailed discussion of assumptions about ozone chemistry, we refer the reader to Barstow et al. (2016) and references therein, in which we consider the case of an Earth-like planet orbiting an M5 star at 10 pc. The assumption that liquid water is retained is most likely to be valid for TRAPPIST-1d.

2 THE TRAPPIST-1 SYSTEM

The TRAPPIST-1 system consists of three planets (b, c, d from the star outwards), of which the orbits of b and c are constrained. The

★E-mail: j.eberhardt@ucl.ac.uk

Table 1. Basic parameters for the newly discovered TRAPPIST-1 planets, taken from Gillon et al. (2016). The orbit of TRAPPIST-1d is not yet constrained. Masses, scaleheights and gravities are estimates based on the measured radii and T_{eq} range, and the assumption that each planet has a bulk density equal to Earth's. Scaleheight and gravity are quoted at 1 bar.

Planet	R ($R_\oplus$)	M ($M_\oplus$ – est.)	g (ms^{-2} – est.)	T_{eq} (K)	H (km – est.)	Period (d)
1b	1.113 ± 0.044	1.38	11	285—400	7.4—10.4	1.510 848 ± 0.000 019
1c	1.049 ± 0.050	1.15	10	242—342	6.7—9.4	2.421 848 ± 0.000 028
1d	1.168 ± 0.068	1.60	11	75—280	1.8—6.9	4.551–72.820 (18.202 most likely)

orbital period of planet d is not yet determined, so a wide range of temperatures are possible for this planet. The most likely period is determined to be 18.202 d, which is the value we retain when calculating noise models. A summary of the system parameters is given in Table 1. The system is located very close to the celestial equator (Skrutskie, Cutri & Stiening 2006), so unfortunately is not within the polar continuous viewing zone of *JWST*. This means that the maximum continuous visibility duration will only be of the order of 50 d, with long gaps where the system cannot be observed and observations only possible for around 100 d per year.

3 MODEL ATMOSPHERES

We use the NEMESIS radiative transfer and retrieval code (Irwin et al. 2008) to simulate transmission spectra of the TRAPPIST-1 planets, under the assumption that each of them could have an Earth-like atmosphere. NEMESIS couples a fast correlated-k (Goody & Yung 1989; Lacis & Oinas 1991) radiative transfer model with an optimal estimation retrieval algorithm (Rodgers 2000). It has been extensively used to model both exoplanets and Solar system worlds (e.g. Tsang et al. 2010; Fletcher 2011; Lee, Fletcher & Irwin 2012).

Each planet is treated as though the atmosphere at the terminator, the region probed in transmission spectroscopy, has identical chemistry to Earth's present-day atmosphere. The likelihood of this scenario for planets around cool stars is discussed in detail by Barstow et al. (2016) and references therein. The temperature profile is shifted from the present-day Earth case according to the assumed equilibrium temperature of each planet; we take this to be the mean temperature from the possible range indicated by the observations, corresponding to 343, 292 and 180 K, respectively, for planets b, c and d. For comparison, Earth's equilibrium temperature is 255 K. The Earth atmospheric model is based on that used by Irwin et al. (2014) and later by Barstow et al. (2015, 2016). Gas absorption data are taken from the HITRAN08 data base (Rothman 2009). H_2O clouds are also included in the model, although since they are relatively deep in the atmosphere they do not have a significant effect on the spectrum. No masses have yet been measured for these planets, but we estimate masses assuming that all planets have the same bulk density as the Earth (Table 1).

The stellar spectrum used is taken from the PHOENIX model atmosphere library (Husser et al. 2013), for a 2500 K, solar metallicity star with a log(g) of 5.0. We choose the cooler available model of 2500 K over 2600 K, although the star temperature is 2550 K, because a fainter star provides a more conservative error estimate. The spectrum is extrapolated as a blackbody at wavelengths longer than 5 μm, for which no model information is available. The stellar radius of 81 373.5 km is taken from (Gillon et al. 2016).

Whilst a surface pressure consistent with Earth's present-day atmosphere is used for all input models, for the retrieval, we extend the atmosphere to 90 bar, the surface pressure of Venus, since we have no way of telling from initial observations whether the planet has a surface at 1 bar or at higher (or indeed lower) pressures. The

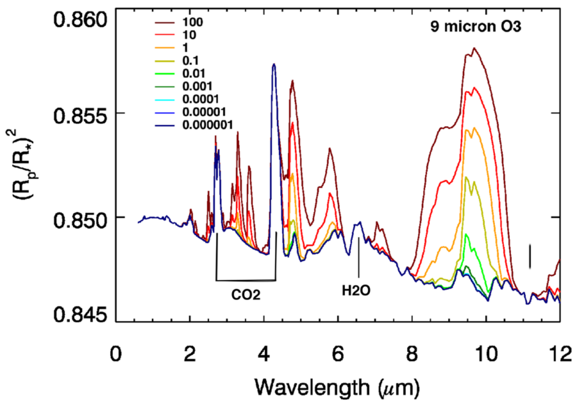

Figure 1. Synthetic spectra assuming bulk properties of TRAPPIST-1d with an equilibrium temperature of 280 K, for different stratospheric abundances of O_3. This provides the largest transit signal out of the three planets. Stepping down from maroon through to navy, O_3 abundances go from 100× the present-day Earth profile to 10^{-6} ×. Present-day Earth is shown in orange. The black bar to the right of the plot indicates the 1σ error bar for TRAPPIST-1d in the region of the 9 μm O_3 feature, assuming 90 transits are observed with the *JWST*/MIRI instrument. This is the smallest error bar obtained. The 9-μm O_3 feature for an abundance of 10^{-2} × the Earth value is above the noise floor for this case, but O_3 at lower abundances would appear to be undetectable.

radius at the bottom of the atmosphere is a variable in the retrieval, which tests our ability to account for lack of knowledge of the surface pressure. For each planet, we perform two retrievals assuming fixed isothermal temperature profiles, at stratospheric temperatures based on the maximum and minimum equilibrium temperatures as given in Table 1, where $T_{strat} = T_{eq}/2^{0.25}$.

Most importantly, the a priori model atmosphere in the retrieval contains a very low (undetectable) abundance of ozone. The retrievals we perform therefore test whether an ozone signature could be detected from the spectra. An approximately Earth-like abundance of ozone will only appear in the retrieved atmospheric state vector if there is information in the spectrum that suggests it should be there. In Fig. 1, we show the effect on the transmission spectrum of changing the O_3 abundance. As the abundance decreases below the present-day Earth value, the feature disappears rapidly and becomes undetectable. Anything below 10^{-2} ×, the Earth present-day O_3 value would appear not to be observable.

4 *JWST* AND NOISE MODEL

We model the planets assuming that they will be observed by both the Near InfraRed Spectrograph (NIRSpec) and Mid-InfraRed Instrument (MIRI) Low-Resolution Spectrometer on *JWST*. NIRSpec is assumed to be used with the prism, providing a continuous spectrum from 0.6 to 5 μm. The noise model used for *JWST* is adapted

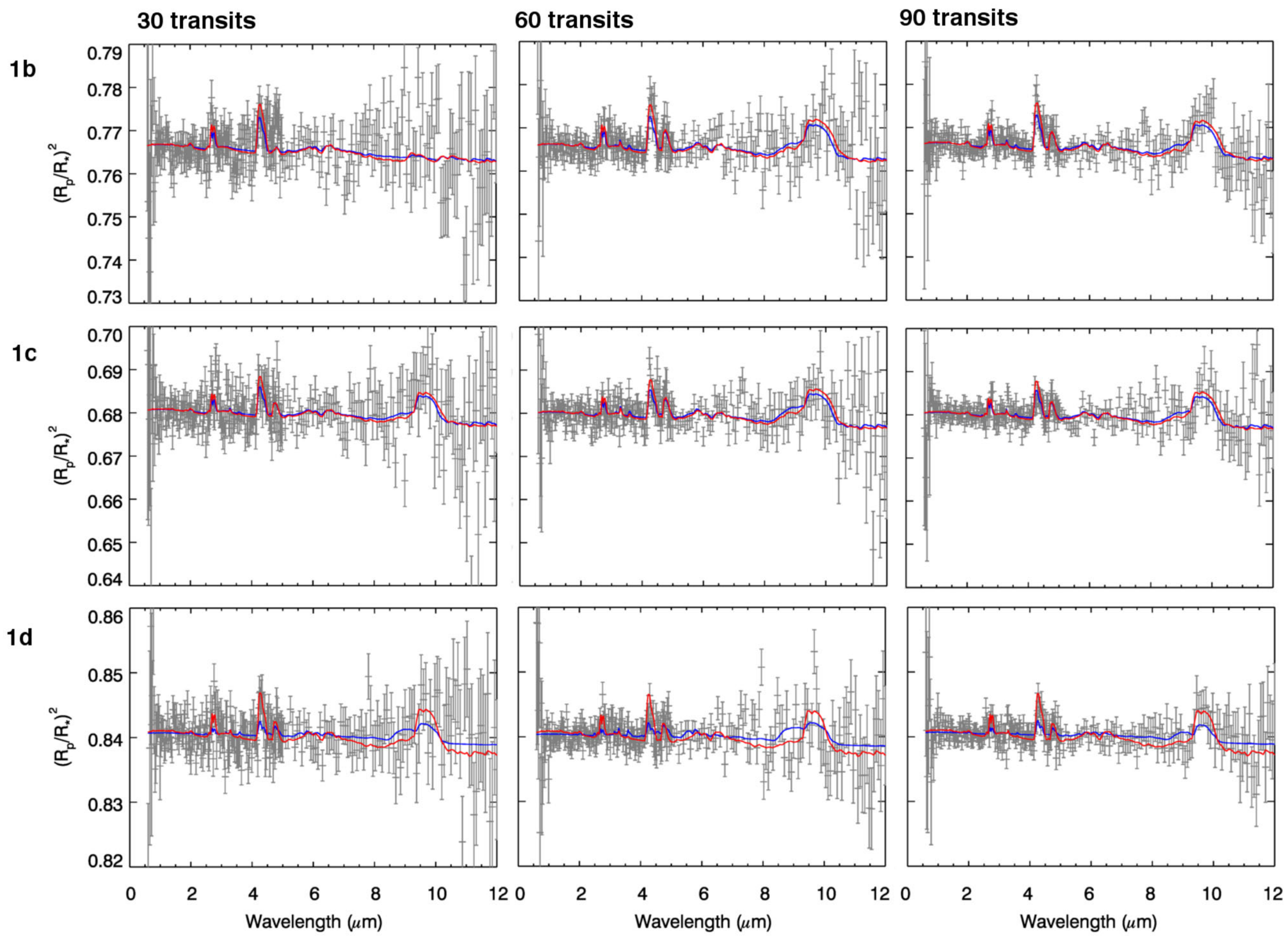

Figure 2. Simulated *JWST* observations of the TRAPPIST-1 planets, assuming 30, 60 and 90 transits are observed. Fits to the synthetic observations are shown for each case in blue (coldest equilibrium temperature) and red (hottest equilibrium temperature). For TRAPPIST 1b, at least 60 transits would be required with each instrument for O_3 to be detected, but for 1c and 1d, 30 is sufficient.

from Barstow et al. (2015, 2016). The photon noise is calculated using the following equation:

$$n_\lambda = I_\lambda \pi (r_\star/D_\star)^2 (\lambda/hc)(\lambda/R) A_{\mathrm{eff}} Q \eta t, \quad (1)$$

where n_λ is the number of photons received for a given wavelength λ, I_λ is the spectral radiance of the stellar signal, $r_\star$ is the stellar radius, $D_\star$ is the distance to the star, h and c are the Planck constant and speed of light, R is the spectral resolving power, A_{eff} is the telescope effective area, Q is the detector quantum efficiency, η is the throughput and t is the exposure time. The effective exposure time is taken to be the transit duration from Table 1, assuming an 80 per cent duty cycle, and therefore planets with shorter transit durations will have noisier spectra. Values for all instrument parameters are identical to those used by Barstow et al. (2015, 2016), and system specific values are as discussed elsewhere in this work. Noise added to the synthetic spectra is random and white – no correlated noise is included. To calculate the noise on the stellar radiance I, we take the square root of the number of photons and then invert the above equation. The noise on the transit depth is given by $\sqrt{2} \times \sigma_I / I$.

5 RESULTS

We present simulated spectra assuming 30, 60 and 90 transits of each instrument (NIRSpec and MIRI), with spectral fits from retrievals based on the extreme equilibrium temperatures for each planet (coldest blue, hottest red; Fig. 2). Retrieved properties are the O_3 volume mixing ratio (VMR), planetary radius at the solid surface (90 bar pressure level), and H_2O and CO_2 VMRs. The H_2O and CO_2 VMRs do not deviate far from the prior and we conclude that the retrieval is relatively insensitive to these properties. We present the retrieval results for radius offset and O_3 VMR in Fig. 3. Here, the radius offset quoted is at 1 bar to facilitate easy comparison with the true value. The retrieved radius compensates for temperature deviations from the true value, as it is smaller for the higher temperature retrievals and larger for the lower temperature ones. As well as just increasing the size of the planet, increasing the radius also increases the scaleheight as the gravity is slightly reduced.

The a priori abundance of O_3 is set to be 10^{-8} × the present-day Earth value. This value is low enough such that no O_3 features are visible at all in the spectrum. We then retrieve a scaling factor on the present-day Earth profile starting from this prior assumption. Our results show that O_3, if present in quantities similar to present-day Earth, would be detectable on all TRAPPIST-1 planets if at least 60 transits are obtained with both NIRSpec and MIRI.

TRAPPIST-1d is the most likely of the three planets to be Earth-like. O_3 can be detected for 30 transits each of NIRSpec and MIRI, regardless of the temperature profile used in the retrieval. CO_2 features can also be seen at shorter wavelengths, with the 4.3 μm

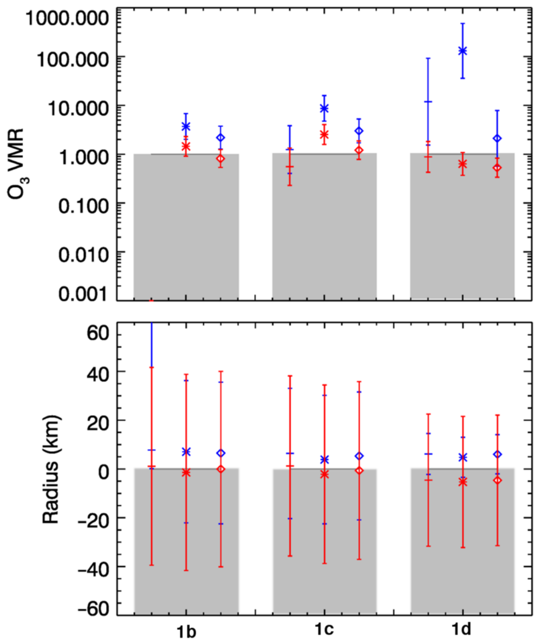

Figure 3. Retrieval results for O_3 abundance and 1-bar radius. Input values are indicated by grey bars. Retrieved values are coloured blue and red for cold/hot temperature retrievals. Crosses/asterisks/diamonds correspond to 30/60/90 transits. No 30 transit points are shown in the top panel for 1b as no O_3 detection was possible. There is degeneracy between the retrieved parameters, with smaller/larger retrieved radii compensating for hotter/colder temperatures; hotter atmospheres have a larger scaleheight, as do planets with a larger radius for a given mass. The balance of this degeneracy affects the retrieved O_3 abundance, as seen for the cold TRAPPIST-1d scenario with 60 transits, for which O_3 is significantly overretrieved to compensate for a small atmospheric scaleheight.

feature visible above the noise in most cases. Where detected, the O_3 feature looks very different for the cold and hot TRAPPIST-1d temperature profiles. This is because, to compensate for the small scaleheight for the cooler 80K profile, the retrieved O_3 abundance is more than an order of magnitude higher than the input value for all noise levels. This alteration in band shape for high O_3 abundances can clearly be seen comparing Figs 1 and 2. This is because the scaleheight is smaller for cooler temperatures, so the retrieval compensates by increasing the O_3 abundance. Conversely, the O_3 abundance is slightly underretrieved for the hotter temperature retrievals. Therefore, a reliable detection of the absolute O_3 abundance would be challenging for these planets.

6 DISCUSSION

We find that O_3 at present-day Earth levels would be detectable for TRAPPIST-1c and -1d if at least 30 transits each with NIRSpec and MIRI are observed, and for TRAPPIST-1b with 60 transits. However, TRAPPIST-1b and TRAPPIST-1c are likely to be hotter than present-day Earth, and may in fact have very different atmospheres. The fact that we could detect O_3 (and CO_2 features are also clearly visible) indicates that these would be interesting targets regardless of their atmospheric chemistry as other molecular species might be similarly detectable.

Regarding TRAPPIST-1d it is likely that, even if life evolves and produces an atmosphere with approximately 20 per cent O_2 and broadly Earth-like conditions, the photochemical processes producing O_3 will be very different. The extent to which this is true is difficult to determine at present, due to a lack of detailed information about the host star. UV and further X-ray observations of the host's output could provide constraints for photochemical models, that might allow a prediction of the likely O_3 abundance. The possibility remains that, even in the case where the atmosphere is oxygen-rich, insufficient O_3 will be produced for detection. Detailed chemical modelling of all three planets will be necessary prior to *JWST* observations to determine whether observable signatures are likely, as this will be an important consideration for time allocation committees.

Approximately 30 transits with each instrument are needed to detect O_3 on TRAPPIST-1d, so 60 transits in total. Since the TRAPPIST system is located close to the celestial equator, and TRAPPIST-1d has a likely orbital period of ∼18 d, this may present a problem. If TRAPPIST-1 is visible for around 100 d per year, then only 5 or 6 transits per year could be observed. Assuming *JWST* remains operational for 10 yr, this would just allow us to reach the 60 transit mark. If biosignature detection is the goal, the obvious choice for the sake of economy would be to observe with MIRI only, as the 9-µm O_3 feature is the most prominent. We performed this test, and find that detecting O_3 may be possible with 30 transits of MIRI alone, but the dependence on the temperature used in the retrieval becomes more critical. The abundance is under retrieved for the high-temperature case and over retrieved for the low-temperature case to a greater extent. A possible alternative to obtaining 30 transits with each of NIRSpec and MIRI would be to obtain photometry over a handful of transits at shorter wavelengths, which could help to break these degeneracies.

TRAPPIST-1d may have a closer and shorter orbit. If, for example, the orbit is 10 d, the problem becomes more tractable, with 30 transits each with NIRSpec and MIRI observable within 6 yr. The transit duration will decrease slightly, and this will increase the noise level on the spectrum, but the signal to noise will still be better than for 1b and 1c. Of course, the orbits for TRAPPIST-1b and 1c are considerably shorter, with periods of only 1.5 and 2.4 d. Although these planets are probably less likely to be Earth-like due to their hotter temperatures, 60 or even 90 transits with each instrument would be far more easily accomplished. 180 transits of TRAPPIST-1b could be accomplished in 270 d, within 3 yr of *JWST* observations.

Regardless of the adopted strategy, *JWST* observations of this new system are likely to be a significant challenge, and final results may be the result of several years of accumulated data. However, it is hoped that this discovery is only the first of many similar systems. The TRAPPIST survey is a prototype for a much more ambitious project, the Search for habitable Planets EClipsing ULtra-cOOl Stars (SPECULOOS; Gillon et al. 2013). Targeting further ultracool stars may result in the discovery of similar systems to TRAPPIST-1, but closer by, or within the *JWST* continuous viewing zone. Such a system within 10 pc and closer to the celestial pole would present exciting opportunities.

7 CONCLUSIONS

We perform radiative transfer simulations for the newly discovered TRAPPIST-1 planets, under the assumption that each may have an atmosphere similar to that of present-day Earth. We find that the biosignature ozone, at present-day Earth levels, could be detectable for TRAPPIST-1b with at least 60 transits each with NIRSpec and MIRI, and for 1c and 1b with 30 transits. TRAPPIST-1d, as the coolest planet in the system, is most likely to be habitable and therefore have substantial amounts of ozone; however, this planet is currently thought to have an 18-d orbit, and the system is far from the continuous viewing zone for *JWST*, meaning that 30 transits with each instrument would take 10 yr to obtain. The inner planets 1b and 1c are more favourable targets from this perspective, due to their much shorter orbits, although they are probably too warm and heavily irradiated to have Earth-like atmospheres.

As a first step in preparation, detailed photochemical modelling of this system is necessary, based on further measurements of the star in the X-ray and UV if possible. This will allow us to determine the likelihood of surface liquid water, and of biosignature gases being present, on all three planets. Determination of radial velocity masses, whilst likely to be challenging, would also be highly desirable. This first planetary system around a nearby ultracool dwarf is very promising, and it is to be hoped that further systems will be discovered in future with both TRAPPIST and SPECULOOS.

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