A Comprehensive Analysis of the Habitability of TRAPPIST-1 Exoplanets

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ABSTRACT

TRAPPIST-1 is the most studied star system other than our Solar System. The announcement of the discovery of the system fostered international attention for its potential to harbor extraterrestrial life, and maybe one day even human life. This paper aims to evaluate the validity of this excitement by interpreting and compiling all available information regarding factors that could potentially affect habitability. To do this, we look at all data regarding the Habitable Zone and Water Presence, Tidal Forces, and Atmospheric Composition resulting in Extreme UV (EUV) Flux. Specifically, we compare Transmission spectra of the four planets in the habitable zone with synthetic, potentially habitable atmospheres, we compare composition and density of the planets with Earth and other density models to determine water composition, and we consider both high and low stellar activity to determine EUV flux in an anoxic, Earth-like and very thin atmosphere. This paper shows that on net, due to the lack of a thick atmosphere, various issues arise that lead to the conclusion that the planetary system is uninhabitable for even the most resistant terrestrial organisms. This set of considerations could be used in studying other planetary systems and evaluating their habitability as well.

1. Introduction

TRAPPIST-1 is a cool red dwarf star with 7 exoplanets in its orbit[1]. It has a mass of about 0.0898 $M_\odot$[6] and 0.1192 $R_\odot$[6], with a surface temperature of about 2566K[6] and a rotational period of about 3.295 days[24]. Its significance is owed to the fact that it is the first star system discovered to have seven Earth-sized planets around a single star. It is estimated to be 7.6 billion years old[25], about 1.66 times older than the Solar System.

It was first discovered in sample C of the 2 Micron All-Sky Survey in 1999. The observation is considered among the most important observations done by the Spitzer Space Telescope, with the exoplanets being observed by TRAnsiting Planets and PlanetesImals Small Telescope using the radial velocity technique[26]. This technique allows for better constraints on a planet's mass, but limited by the faintness of the star. Available data, however, has allowed for the discovery of the seven exoplanets. Recent K2 (Kepler) observations[2] have allowed teams to calculate updated masses for the system despite visual limitations. These observations also show various similarities between the TRAPPIST-1 system and the Kepler-90 system, also containing 7 exoplanets, similar orbital periods for the Earth-sized planets, and TRAPPIST-1's planets orbiting in resonance and Kepler-90's planets orbiting in near resonance. The planets have a low density and may contain many volatile materials, but still attract attention from the scientific community and pop culture due to the potential for liquid water in four of the exoplanets - d, e, f, and g - all orbiting within the star's habitable zone.

This paper aims to compile all available data pertaining to the exoplanets discovered in the TRAPPIST-1 star system, and reach a conclusion on the feasibility of any life whatsoever, and human life on the planets. This will take into account various significant observations, Habitable Zone, Tidal Forces, Atmospheric Content and Stellar Wind, Size and Density, and Radiation.

The seven exoplanets are named TRAPPIST-1b, 1c, 1d, 1e, 1f, 1g and 1h, with orbital radius increasing in alphabetical order. No comets, Kuiper Belt or Circumstellar disk were detected in the star system[3][4][5]. The ecliptic is less than 0.1, making it the flattest planetary system in NASA's exoplanet Archive[6].

Planet	Mass ($M_\oplus$)	Radius($R_\oplus$)	ρ (kg m^{-3})	Orbital Period (day)	Semimajor Axis (AU)
b	0.79 ± 0.27	1.086 ± 0.035	3405^{+1636}_{-1367}	1.5108739 ± 0.0000075	0.01154775
c	1.63 ± 0.63	1.056 ± 0.035	7642^{+4081}_{-3391}	2.421818 ± 0.000015	0.01581512

d	0.33 ± 0.15	0.772 ± 0.030	3960^{+2527}_{-2034}	4.04982 ± 0.00017	0.02228038
e	$0.24^{+0.56}_{-0.034}$	0.918 ± 0.039	1713^{+4790}_{-413}	6.099570 ± 0.000091	0.02928285
f	$0.36^{+0.12}_{-0.061}$	1.045 ± 0.038	1742^{+853}_{-442}	9.20648 ± 0.00053	0.03853361
g	0.566±0.036	1.127 ± 0.041	2183^{+420}_{-354}	12.35281 ± 0.00044	0.04687692
h	$0.086^{+0.084}_{-0.017}$	0.7150 ± 0.047	1299^{+1850}_{-19}	18.76626 ± 0.00068	0.06193488

Table 1. The Mass[7], Radius[7], Density[7], Orbital Period[7] and Semimajor Axis[2] of all TRAPPIST-1 Planets

2. Habitable Zone

Considering the Habitable Zone (HZ) is crucial to determine the possibility for human civilization on the planets. The habitable zone is the orbital radius at which liquid water can form, a prerequisite for human life on a planet. Specifically, the energy from a star, in conjunction with greenhouse effects and albedo, must produce a surface temperature between 0 and 100ºC, or 273-373 K[8].

Being an M8V spectral type[1], Figure 1 demonstrates where the goldilocks zone is located for TRAPPIST-1 exoplanets. Planets 1d, 1e, 1f, and 1g are seen to be within or on the border of the theorized habitable zone, highlighting them as prime candidates for the formation of liquid water and therefore a home for life. Habitable zone maximum and minimum radii are calculated with a manipulation of the Stefan-Boltzmann law.

$$HZR = \frac{T_s^2 R_s(1-a)}{2T_p^2}$$

Where T_s is the temperature of the star, R_s is the radius of the star, a is surface albedo, and T_p is desired temperature of the planet. The discrepancy between results from the equation and actual distances can be attributed to atmospheric composition. Distance from the star is only one part of defining a habitable temperature. If Mars had a CO_2-rich atmosphere, we would likely see it with liquid water today, and if Venus had an atmosphere with very few greenhouse gases, we might see the same case.

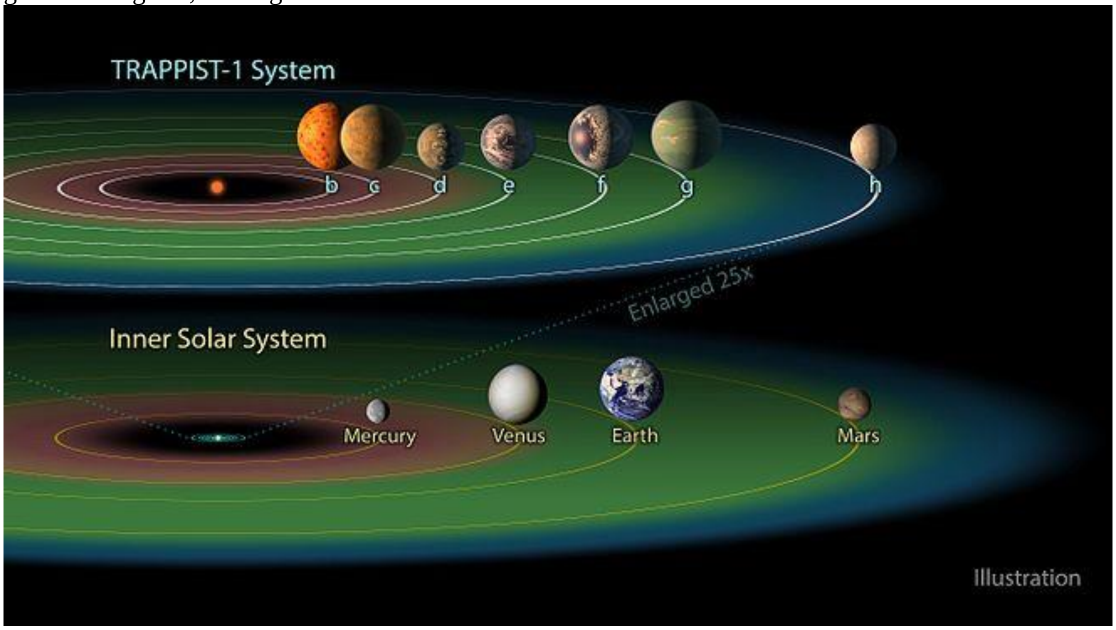

Fig. 1 A model of the TRAPPIST-1 Solar System (top panel). The areas in green show where the ideal amount of solar radiation reaches the planets for liquid water to form, while the red area shows levels of radiation too high, and areas in blue being levels of radiation too low. The bottom panel shows the habitable zone in our Solar System, allowing for comparisons between Earth and TRAPPIST-1 exoplanets in terms of potential for life[9].

3. Effect of Resonance and Tidal Forces

Tidal forces are the dominant source of interior heat in the planets. This is because at the TRAPPIST-1 planets' orbital periods, the energy released by decay in a planet's crust and/or mantle is in the order of tens of milliwatts per meter squared, while tidal heating at this period can range from a few to tens of watts per meters squared[7].

Simulations find that the orbital eccentricities in the system are very low, reaching ~0.01 in a few Myr. The value does not decrease to zero, instead reaching an equilibrium value determined by planet-planet interactions and tidal damping[10]. The tidal energy produced from tidal dissipation in a synchronously rotating body is calculated with

$$E_{tidal} = -\frac{21}{2}\mathrm{Im}(k_2)\frac{R^5\omega^5e^2}{G}$$

Where $\omega = 2\pi/P$ represents orbital frequency of the planet, P is the planet's orbital period, R is the radius, e is the planet's eccentricity, and G is the gravitational constant[11]. The quantity $Im(k_2)$ is the imaginary part of the k_2 Love number, describes how the tidal dissipation affects the gravitational field[11]. The value is dependent on the structure and flow mechanics of the planet[11], and can sometimes be represented as k_2/Q, where Q describes the fraction of orbital energy lost per tidal cycle[12], and is accepted to normally be between 10 and 200[13]. This energy is dissipated over the surface of the body, so the tidal flux from the same body can be calculated with

$$F_{tidal} = \frac{E_{tidal}}{4\pi R^2}$$

Where R is the radius of the body[7]. This tidal heating model is only viable for $e \leq 0.1$[7], a condition which the TRAPPIST-1 planets fulfill. Planets b, c, d, e, and f values for tidal forces are listed in Table 2, planets g and h have a negligible tidal dissipation in the rock mantle, but a more sophisticated k_2 model is necessary to calculate the dissipation in an ice mantle[7]. All values are shown in Table 2. High flux, such as that seen in TRAPPIST-1b and c, could be expected to result in high volcanic activity on the surface of the planet[14]. While the radius for appropriate temperature for liquid water without an atmosphere was given in section 2, stellar flux must still be considered, which is calculated with

$$F_{stellar} = \frac{L(1-a)}{16\pi s^2(1-e)}$$

Where L is the luminosity of the star, a is surface albedo, s is semimajor axis and e is eccentricity[7]. From this formula, values of stellar flux for each planet, shown in Table 2. From these values and the corresponding day-side temperatures of the planets, TRAPPIST-1d and particularly e may have extended liquid water reservoirs[15].

Planet	F_{Tidal} (W m^{-2})	F_{glob} (W m^{-2})	F_{RG} (W m^{-2})	T_d (K)	T_{avg} (K)
b	$2.68^{+1.33}_{-1.81}$	1014 ± 289	283^{+11}_{-15}	515	433
c	$1.32^{+0.3}_{-0.47}$	540 ± 154	308^{+14}_{-18}	438	382
d	$0.16^{+0.35}_{-0.16}$	271 ± 78	277^{+14}_{-20}	370	336
e	$0.18^{+0.09}_{-0.18}$	157 ± 45	258^{+38}_{-7}	307	287
f	$0.14^{+0.05}_{-0.14}$	91 ± 26	262^{+10}_{-7}	211	203
g	0 ± 0	61 ± 18	270^{+4}_{-4}	188	182
h	0 ± 0	35 ± 10	244^{+22}_{-1}	156	153

Table 2. Tidal Forces[7], Global Stellar Flux from the top of the atmosphere[7], Runaway Greenhouse Limit (the max flux where a runaway greenhouse effect cannot occur)[7], Temperature on day side, and Average Temperature of each exoplanet[16].

4. Albedo, Atmosphere and Stellar Wind

Albedo is the measurement of surface reflectivity. High albedo means high reflectivity and therefore low energy absorption by the surface, decreasing surface temperature of the planet. Low albedo means low reflectivity and therefore high energy absorption by the surface. However, due to the immense distance and overpowering light from the host star, we are unable to accurately observe the surface of the planet, and therefore are unable to measure albedo. However, atmospheres also shape the planet's temperature, that too by a much larger margin. HST transit depths and Spitzer Space Telescope's IF Array Camera imply a lack of significant absorption features, in turn suggesting a lack of hydrogen-dominated atmospheres[17].

Hydrogen, being a significant greenhouse gas, could prevent water from staying in its liquid form, wherever it could be found in the system. The lack of hydrogen-dominated atmospheres allows for the conclusion that planets d, e, f and g are terrestrial and potentially habitable[18]. The Transmission spectra is shown in Fig 2. However, though the graphs show that the atmospheres are not rich in H_2, they also demonstrate a lack of abundance in other compounds. The lack of remote similarities to other atmospheric compositions leads to the conclusion that there is likely no atmosphere in the four subject planets. It is unreasonable to believe that these planets will develop a habitable atmosphere in a reasonable amount of time, or that humans will be able to artificially create an atmosphere. The cause of the lack of atmosphere could be low planetary density or overpowering solar radiation. The similarity between transmission spectra of all four planets could be attributed to similar surface composition.

One of the key factors to consider for planetary habitability is the planet's ability to maintain an atmosphere over long timeframes. The two main ways of an atmosphere dissipating or being lost are a large-scale impact (massive meteorite), or kinetic energy from solar wind. Because we can't predict a large-scale impact, we'll focus on the latter. Due to space weather conditions being unknown from observations in the TRAPPIST-1 system, we rely on simulations. These simulations have revealed that stellar wind has a much higher density for the TRAPPIST-1 exoplanets than is experienced by Earth[19]. TRAPPIST-1b experiences 10^3-10^4 times greater dynamic wind pressure, and the farthest planet, TRAPPIST-1h, experiences 100-300 times the dynamic wind pressure experienced by Earth[19]. Similar pressures were observed in Proxima Centauri B, where ~10^3 times greater wind pressure compressed PCb's planetary magnetic field, compressing it by a factor of 3[20]. As a result, TRAPPIST-1e, the prime candidate for human civilization, has the upper bound for ion escape rate placed at 7.40×10^{26} s^{-1} and the lower bound placed at 2.74×10^{26} s^{-1} for O^+, O_2^+ and CO_2^+ ions (all values shown in Table 3)[19]. Because the escape rates decrease with orbital radius, TRAPPIST-1h is seen as the most "stable" planet when viewed from an atmospheric loss perspective, being able to retain its atmosphere over Gyr timescales. When including that perspective, it can be concluded that TRAPPIST-1g could be the planet in the Habitable Zone with the highest likelihood of habitability and life. Though it may be entering a snowball state inhospitable to life, considerable tidal heating effects could neutralize the effect of distance. However, due to the same conclusion, the inner planets are likely to be unable to maintain their atmospheres over Gyr timescales.

Earth-sized planets in Space Weather Affected Habitable Zones are very vulnerable to XUV flux, resulting in planets orbiting low luminosity M-dwarves becoming uninhabitable within a few hundred Myr[21]. However, scaling of O^+ may suggest that planets with an orbit $\geq$0.3 AU be able to withstand wind pressure, and may be habitable if a strong greenhouse effect is present [21]. This means that the most likely candidate stars for habitable planets from an atmospheric loss perspective are K to G dwarfs providing a mild environment.

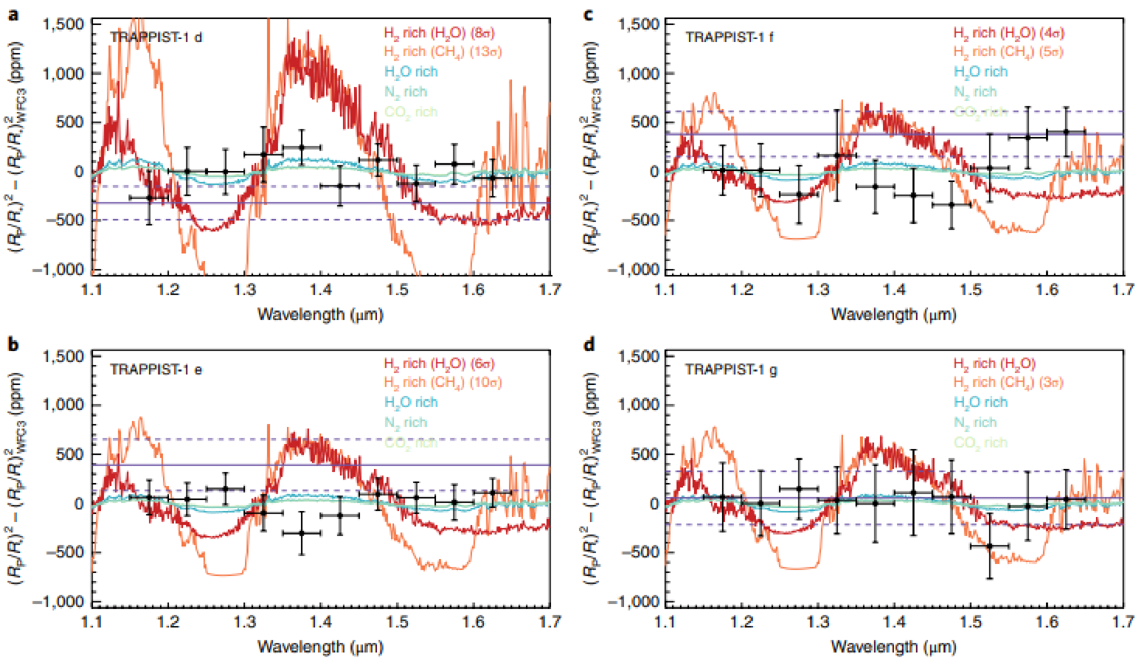

Fig. 2 Transmission spectra of TRAPPIST-1 d, e, f and g compared with synthetic atmospheres dominated by H_2, H_2O, CO_2, and N_2[18]. HST/WFC3 data is shown in black lines with 1σ and 3σ confidence. Observed spectra are inconsistent with all tested compositions, results can be generalized to all seven planets.

Planet	O^+	O_2^+	CO_2^+	Total
Maximum Total Pressure				
b	5.56×10^{27}	2.09×10^{26}	1.52×10^{26}	5.92×10^{27}
c	1.54×10^{27}	1.38×10^{26}	1.32×10^{26}	1.81×10^{27}
d	1.29×10^{27}	3.80×10^{25}	1.14×10^{25}	1.34×10^{27}
e	7.01×10^{26}	2.83×10^{25}	1.10×10^{25}	7.40×10^{26}
f	5.23×10^{26}	3.37×10^{25}	1.19×10^{25}	5.68×10^{26}
g	2.17×10^{26}	2.71×10^{25}	1.32×10^{25}	2.58×10^{26}
h	1.06×10^{26}	1.65×10^{25}	6.98×10^{24}	1.29×10^{26}
Minimum Total Pressure				
b	9.33×10^{26}	4.99×10^{25}	2.92×10^{25}	1.01×10^{27}
c	4.23×10^{26}	9.22×10^{25}	2.76×10^{25}	5.42×10^{26}
d	2.81×10^{26}	3.07×10^{25}	1.04×10^{25}	3.23×10^{26}
e	2.20×10^{26}	4.19×10^{25}	1.25×10^{25}	2.74×10^{26}
f	1.88×10^{26}	4.30×10^{25}	1.10×10^{25}	2.42×10^{26}
g	9.33×10^{25}	5.85×10^{25}	1.38×10^{25}	1.66×10^{26}
h	4.52×10^{25}	2.69×10^{25}	4.39×10^{24}	7.66×10^{26}

Table 3. Ion escape rates (s^{-1}) under maximum and minimum wind pressure for all TRAPPIST-1 exoplanets[19]

5. Size, Composition and Density

Planets form as a result of condensing matter in the protoplanetary disk of a protostar. As a result, planets in a star system have similar interior compositions to each other. Furthermore, the radii of the planets are estimated to be between 0.775 and 1.129 $R_\oplus$[7]. However, due to the considerably lower density than Earth, the exoplanets may contain large quantities of volatile chemicals[2]. Alternatively, if they have a similar composition to that of Earth, the large quantities of iron may be oxidized, resulting in abundant FeO, also decreasing the density of the planet[1]. TRAPPIST-1 c and e likely have largely rocky interiors, while planets b, d, f, g, and h have envelopes of_volatiles in the form of thick atmospheres, oceans, or ice, with the probability to be volatile-rich[2], $p_{volatiles}$, to be 0.96, 0.99, 0.66, 1, and 0.71 respectively. Meanwhile, planets c and e are likely rocky and terrestrial with $p_{volatiles}$ closer to 0.24 and <0.01 respectively[2]. A comparison of masses and radii with an idealized interior model with m_{water} = 5% shown in Fig 3 reveals that all planets except b and d very likely have a water composition less than 5%. Planets b and d, drawing from the same comparison, display a 50% and 70% probability, respectively, of having a water composition of <5%[2]. The low densities further support the observation of a lack of an atmosphere, not having enough mass to hold a thick atmosphere, let alone keep one on a Gyr timescale.

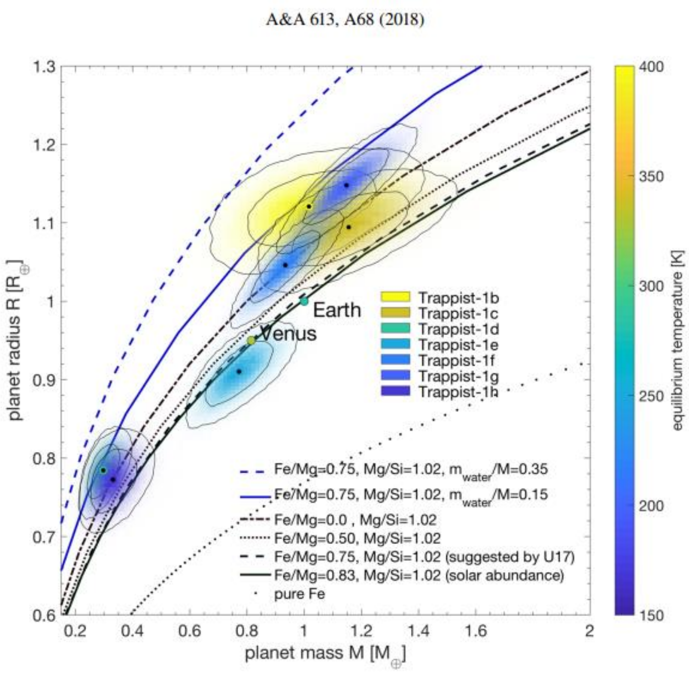

Fig 3. Mass–radius diagram for the TRAPPIST-1 planets, Earth, and Venus[2]. The curves trace idealized compositions for rocky and water-rich interiors. Solid blue line represents an idealized interior composition of 5% water.

6. Stellar Light

As a result of the tidal locking between the TRAPPIST exoplanets and the host star, one side always faces TRAPPIST and one side of each planet always faces away, resulting in a "dark side," similar to that of the moon. Because TRAPPIST is a red dwarf star, it undergoes fusion at a much slower rate than an average main sequence star, and therefore is much cooler. This results in most of its emissions being in Infrared wavelength (700nm-1mm). Prolonged exposure to Infrared emissions causes an irreversible opacity of the human lens, commonly known as cataracts. Low exposure can still cause eye redness, swelling or hemorrhaging[27].

Further investigation is required into the effect of surface Ultraviolet (UV) radiation on the planets and how it could affect biology. TRAPPIST-1's X-Ray observations show that it is a strong coronal X-Ray source, with similar X-Ray luminosity to that of a quiet Sun[22]. Because the planets are orbiting so close to the star, they likely experience significant Extreme UV (EUV) flux. However, current models do not allow for reliable and consistent modelling of the UV region of M dwarfs consistently. As a result, two scenarios are compared to evaluate the most likely extent of UV flux and its effect on the planets:

(i) Active Spectrum: Considerations using the most active UV measurements of M dwarfs

(ii) Inactive Spectrum: Based on a model without a chromosphere, representing the lowest theoretical UV flux[23]

A planet's atmospheric composition directly influences the effect of UV radiation on a surface environment. UV fluxes near 240nm, present in a high activity model, increase the photodissociation of Oxygen, and in turn increase the rate of O_3 production. However, no Ozone production occurs for either model in a scenario where water does not contain dissolved oxygen, a factor that is also inversely proportional to orbit radius. Additionally, M stars emit lower fluxes in 200-300nm, decreasing the rate of CH_4 photodissociation, resulting in a longer lifetime for Methane in the atmosphere for M star exoplanets than Earth[24]. Closer to 200nm, atmospheric CO_2 and H_2O blocked all UV radiation from reaching the ground[24].

To accurately asses the mortality rates of life in the environments presented in either scenario, *Deinococcus radiodurans*, one of the most radiation-resistant organisms on Earth, was used as a benchmark for habitability. The findings were such that for both an active and inactive scenario, the wavelength of UV flux necessary to induce a 90% mortality rate was lowest for the Anoxic scenario and highest for the P = 1 bar (Earth-like) scenario, as seen in Fig. 4[24]. If an Earth-like atmosphere exists on the planets, UV environments would be similar to Earth, but in an anoxic atmosphere, or lack of an atmosphere altogether, not enough UV radiation would be blocked, resulting in a hostile environment event to the most radiation-tolerant organisms[24].

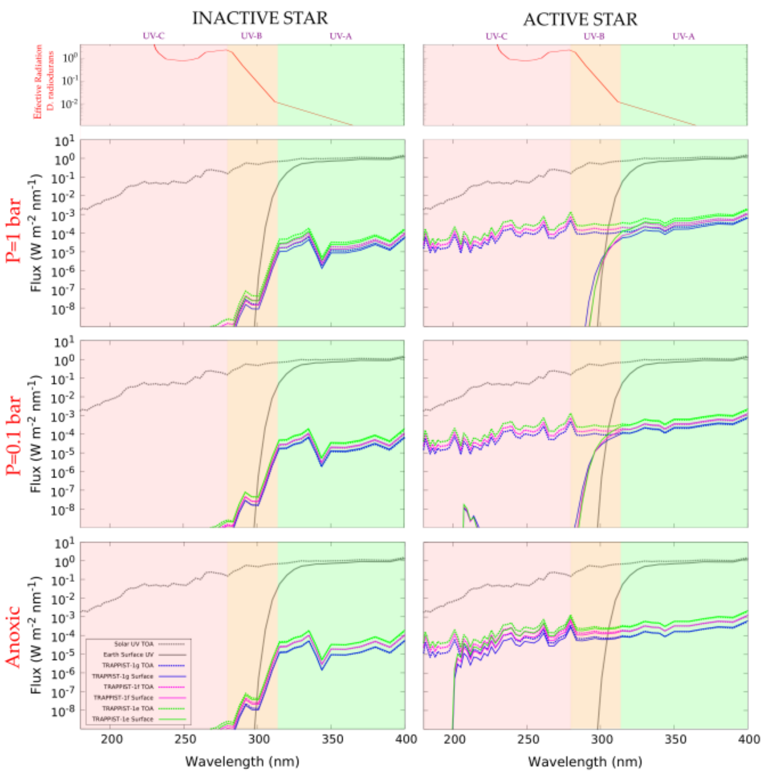

Fig 4. The UV top-of-atmosphere and surface fluxes for TRAPPIST-1e, f, and g[23]. The top panels show the UV action spectrum for *D. radiodurans*. The left column shows the results for the "inactive" scenario, while the right column shows the results for an "active" scenario. Both scenarios are considered with an Anoxic atmosphere, and atmospheres where P = 0.1 bar and 1 bar.

7. Discussion and Conclusion

This paper was a compilation of the most important information regarding the habitability of exoplanets orbiting TRAPPIST-1. All seven planets were considered by the following factors: Habitable Zone, Tidal Forces, Atmospheric Content and Stellar Wind, Size and Density, and Radiation.

The temperature of the star gives us a theoretical Habitable Zone, allowing for the determination of which planets to focus on in studies – in this case, planets d, e, f and g. The radius at which water can be found, though it is the most well-known factor, is by no means the only important factor for the presence of liquid water.

Tidal dissipation is especially prevalent in the TRAPPIST-1 system due to its orbital resonance, making it the dominant source of heat in the planets' interior, with Tidal fluxes on planets d, e, and f being twenty times higher than that of Earth. Planet d can avoid a runaway greenhouse effect if its albedo is ≥ 0.3, and planet e, the prime candidate for life in the system avoids a runaway greenhouse effect altogether[7]. The same values also lead to the conclusion that planets d and e may have extended interior liquid water reservoirs[15].

Transmission spectra of TRAPPIST-1d, e, f and g display inconsistency with all models of atmospheric composition. Findings show that planets orbiting M dwarfs may be able to maintain their atmospheres over Myr timescales if they orbit at a semimajor axis $\geq$0.3 AU, leaving only planets f, g and h with potentially stable atmospheres[21]. They may be habitable with a considerable greenhouse effect, however generalized spectra showing lack of an atmosphere and the low stellar flux and negligible tidal forces in g and h do not transfer enough energy to heat the surface of the planet to a habitable temperature, reflected by the day side average temperature of said planets[7][16].

In scenarios of both high and low stellar activity, even the most radiation-resistant organisms face at least a 90% mortality rate without thick atmospheres and Ozone due to UV flux. This directly damages terrestrial ecosystems, fostering increasingly uninhabitable environments[23]. Additionally, Methane photodissociation decreased in a lower activity environment, leading to an increased lifetime in the atmosphere and creating a toxic atmosphere for humans[23].

On net, TRAPPIST-1 appears to be uninhabitable for the most resistant lifeforms, let alone humans. The lack of an atmosphere is the "nail in the coffin," per se, for whether or not human civilization can exist in the star system. Other than the fact that human technology cannot add a full atmosphere to a planet, the planets for which day side temperature can maintain liquid water have ion escape rates too high to maintain said atmospheres over Myr timescales[19], and their current state, EUV flux is far too dangerous to consider a human civilization[23].

The next step for habitability however would be identifying aerosols in the atmospheres, potentially revealing more about a potential greenhouse effect, as well as modelling atmospheres with greater mean molecular mass, all achievable mainly with James Webb Space Telescope (JWST). If thicker atmospheric models match the transmission spectra, that could ameliorate all of the current major issues: EUV flux, ion escape rate and a lack of a greenhouse effect.

Acknowledgements

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