IS THERE A POSSIBILITY OF EXTRASOLAR HABITATION?

A study on the habitability of earth like exoplanets on the prospect of extra-terrestrial life, intelligent or otherwise, particularly in and around long lived M-Dwarf stars

Abstract

This study focuses on the possibility of M-Dwarf stellar systems being suitable locations for the development and evolution of life from an astrophysical standpoint, from simple chemical processes to complex cellular organisms, looking in particular at the exoplanets within the TRAPPIST-1 planetary system at possible habitable candidates: e, f, and g. It

Jack Lloyd-Walters
Peter Symonds

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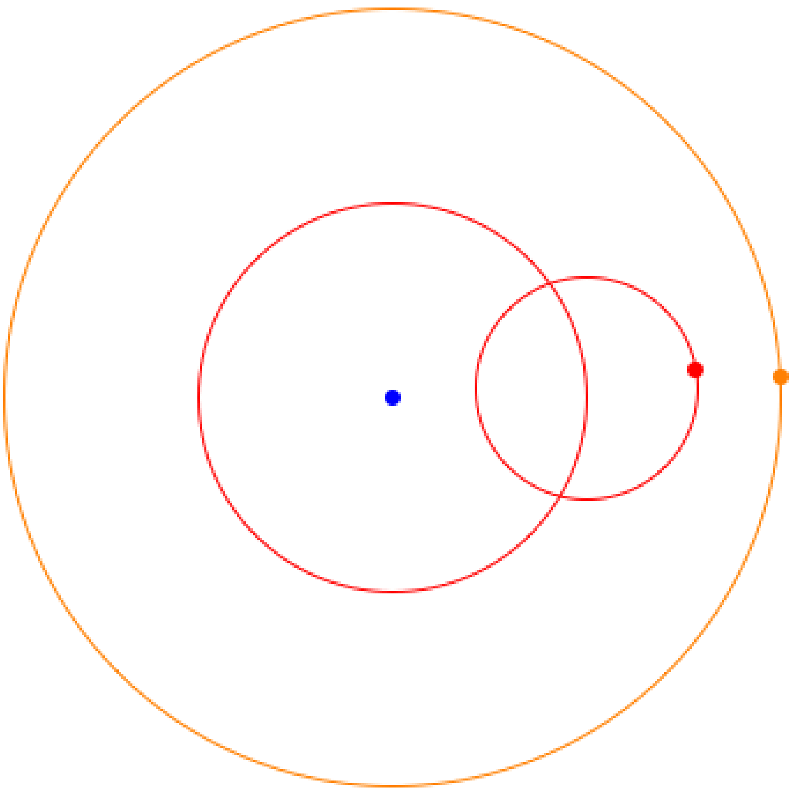
Introduction

History

Since the earliest civilisations of human history, from the Babylonians and the Greeks, to the Egyptians and the Maya, mankind has looked towards the heavens and performed methodical observations of the night sky. Astronomy, from the Greek: "ἀστρονομία", ἄστρον (Astron) meaning star, and -νομία (Nomia, from nomos) meaning law or culture, is such defined as "law of the stars", or "culture of the stars" depending on the translation, is the earliest of the natural sciences and applies the fields of physics, mathematics, and chemistry in an effort to explain the origins and find an understanding of celestial objects and other such phenomenon. Though generally it may be used interchangeably with the field of astrophysics, astronomy refers to "the study of objects and matter outside the Earth's atmosphere and of their physical and chemical properties" [1] whereas astrophysics refers to the branch of astronomy dealing with "the behaviour, physical properties, and dynamic processes of celestial objects and phenomena" [2].

The inner planets mercury and Venus, along with the outer planets of mars, Jupiter, and Saturn, were identified by Babylonian astronomers in the second millennium BCE [3], due to their being visible to the naked eye. According to Greek philosopher Ptolemy's geocentric model of the solar system, the five above listed planets, along with the moon and sun, were placed in an orbit of earth in order of increasing distance from such. The discovery and subsequent observations of other celestial objects in the solar system would not occur for nearly four thousand years, in the 17th century CE in the year of 1610, when Italian physicist Galileo Galilei observed the largest of Jupiter's moons Ganymede, Calisto, Io, and Europa which are now named after their discoverer as the Galilean moons of Jupiter. Their discovery brought forth solid evidence for the heliocentric model, first proposed by Aristarchus of Samos in the third century BCE, and the invent of observational astronomy.



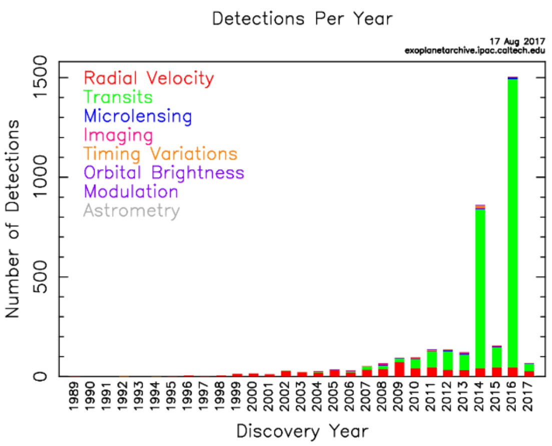
left; Figure 1; geocentric projection of the primary (blue), secondary (red) and central body (orange) in a 2:1 orbital resonance, showing the deferent (large red circle) and epicycle (small red circle) of the secondary orbit. [4]

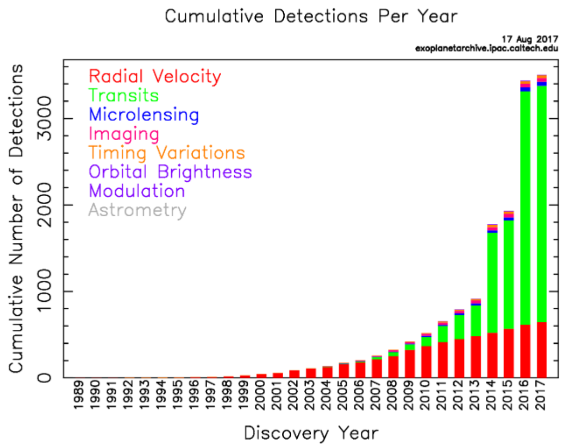
Giordano Bruno proposed the idea that other stars were more than points of light and were in fact distant suns possibly surrounded by their own exoplanets in the 16th century CE. The same possibility was mentioned in Isaac Newton's "General scholium" which concludes his principia, writing that "And if the fixed stars are the centres of similar systems, they will all be constructed according to a similar design and subject to the dominion of one."[5]. In 1952, Otto Struve proposed the use of Doppler spectroscopy (More commonly called the Radial Velocity Method, In which a star's 'wobble' caused by minute gravitational effects from its orbiting planet can be observed) and the transit method to be used to detect planets following his writings that there were no compelling reasons why planets could not orbit closer to their parent star than observed in the solar system. It was not until 1988, however, that the first exoplanet was discovered, though it would not be until 1992 that the first exoplanet was confirmed, with the discovery of a several terrestrial mass planet orbiting the pulsar PSR B1257+12.

The next biggest discovery for exoplanet hunters would come in the year of 1995, on October 6th, where Swiss astronomers Michel Mayor and Didier Queluz announced the discovery of an exoplanet orbiting the main sequence star of 51 Pegasi, confirmation of which would occur on October 12th the same year by Geoffrey Marcy and Paul Butler. The discovery was made using the radial velocity method on a telescope at Observatoire de Haute-Provence in France, using the ELODIE Spectrograph [6]. Following this, most exoplanets have been since observed using the Radial velocity method, or the Transit method (wherein the planet passes in front of its parent star), though few have also been found by other methods, such as direct imaging or gravitational microlensing (in which curved space-time due to gravity around a planet deflects light, causing a distortion of the background)

It would be in the year of 1999 that two of the most important discoveries for present day exoplanet hunters would occur. The first of which was made by research teams led by David Charbonneau and Greg Henry independently of one another, where they discovered a planet transiting its parent star of HD 209458 on November 5th. The importance of this discovery lies in its method of discovery; a transiting exoplanet allows astronomers to observe the light that passes through any atmosphere present of the exoplanet, and analyse the composition of such through spectroscopy. Analysis of the atmosphere demonstrated a chemical composition of water, oxygen, nitrogen, and carbon, though the planet orbits too close to host organic life as we know it. The second such discovery was that of the first multi-planetary system, independently discovered by astronomers from San Francisco state University and the Harvard-Smithsonian Centre for Astrophysics. The planetary system around Upsilon Andromedae marks the first system found to have multiple planets, with four exoplanets discovered as of 2010, when observations were last made. The Central star orbited by these exoplanets, Upsilon Andromedae A, also known as "Titawin", marks a first for exoplanetary discovery in that besides the four discovered planets, the star is also orbited by a binary star counterpart, Upsilon Andromedae B, making it the first known multi planetary system of a multiple star system.

Below; figures 2 and 3; exoplanet plots of detection number, from the Exoplanet archive [7]





The dramatic rise in discovered exoplanets in the early years of the twenty first century comes from the use of the space borne observatory Kepler [8], launched march 7th 2009 CE by NASA [9], so named after the famous astronomer Johannes Kepler, who formulated the three equations of planetary motion in the seventeenth century CE scientific revolution. To this day, Kepler is the most successful exoplanet discovery platform, having found 5017 exoplanet candidates, 2494 of which have been confirmed, 30 of which are less than twice the mass of earth within the habitable zone of their parent star [10]. The Kepler craft, however, has been forced to observe a narrow swathe of the cosmos due to two failed reaction wheels in the observatory (July 2012 and May 2013) extending the original mission to hunt exoplanets under the new name K2 [8]. To date, of the several thousand exoplanets discovered, 650 have been confirmed to be orbiting a star below 0.8 solar mass (or about 18.4 % [21]). It is with a very specific one of these relatively ordinary stars, TRAPPIST-1, and its cohort of planets that this dissertation shall focus upon.

Literature Review

What is an M-Dwarf star?

A star [16] is defined as a “self-luminous gaseous spheroidal celestial body of great mass which produces energy by means of nuclear fusion reaction”. The importance of that definition lies in the last half ‘produces energy by means of nuclear fusion’ as ultimately it is here we're stellar classification revolves around. Nuclear fusion within stars begins simply as the H Cycle, in which two Hydrogen nuclei are pushed close together under immense temperatures and pressure to overcome their mutual repulsion and fuse into a single larger nucleus, which in the case of stellar fusion is a deuterium. A more massive star would thus have more fusible hydrogen within its core which is at that all important temperature and pressure, and so would thus be able to fuse a greater amount of hydrogen at any given time, leading to a greater outgoing of energy from that star.

This increase in energy causes the star to become hotter, as the outgoing radiation excites nuclei further from the core, and glow brighter colours according to its surface temperature. These different colours are where the easiest form of classification arises: O,A,B,F,G,K, and M stars; which range from Blue/white, at approximately 30000 Kelvin to a very dull red, at 1000 or 2000 degrees kelvin. This simple classification is for main sequence stars, or stars in the middle of their lifetime, as older stars will not necessarily fit this simple model (see red giants or white dwarves)

The seven spectral types, as they are known, are further subdivided into 9 categories, for example A0, A1, etc… with 0 being hottest. This sequence also accounts for stars that don't fit the classical system, namely D and C for Dwarf and Carbon stars respectively. In the MK system, a Roman numeral is also attached to the spectral type to demonstrate the width of certain absorption lines in a stellar atmosphere (where light is absorbed by certain chemical elements) and from this, their density can be extrapolated, separating Dwarf stars from Giants.

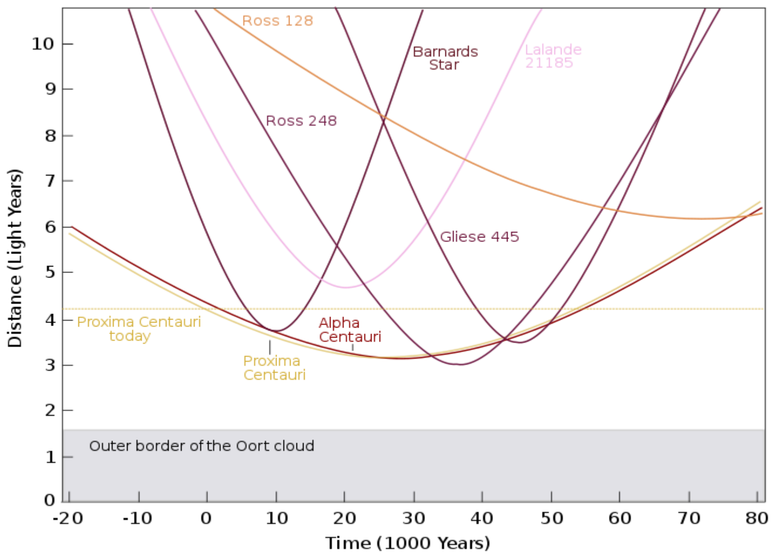
A Red dwarf, or M dwarf, is a small and relatively cool star of spectral type K or below, with surface temperatures never exceeding 4000 Kelvin, and masses between half that of the sun, and 0.075 times that of the sun (which is also the lowest possible mass that is predicted to allow nuclear fusion) these stars burn relatively cool compared to other main sequence stars, and so exhaust their hydrogen supply at a much lower rate, resulting in lifetimes that can exceed trillions of years. They also have fully convective fusion shells, their supply of fusible material is not limited to the core, but is mixed throughout the entire star, burning the whole mass in fusion to again increase lifespan.

Red dwarfs are by far the most common stars in the Milky Way galaxy, the closest of which being Proxima Centauri, an orbiting star of the binary pair Alpha Centauri, which is itself the closest star to earth barring the sun. However, at spectral type M5, it's diminutive size and temperatures cause it's luminosity to be below that which would allow viewing from earth without the aid of large telescopes. Trappist-1, the star with which this dissertation will focus, is in fact, an M8V type star, very barely above the limit of viable fusion in a star.

What defines extrasolar or Extra-terrestrial in the current scope?

Extra-terrestrial, “originating, existing or occurring outside the earth or its atmosphere” [17] may be loosely used interchangeably with Extrasolar, “Originating or existing outside of the solar system” [15], however caution should be used here, as Mars, though extra-terrestrial, is clearly within the confines of the solar system. Extra-terrestrial, therefore, is the blanket term of anything outside of earth’s atmosphere (or 10000km from the surface of earth [14]), while extrasolar is anything outside of the solar system.

This definition of extrasolar is rather loosely defined, having no definite boundary in space. There may therefore be several ways of defining this distance. The simplest method would simply be to half the distance between the sun and it’s nearest stellar neighbour, defining everything within this domain as part of the solar system. This method, while certainly a good rule of thumb, has several problems associated with it, first and foremost being that the sun moves relative to its neighbours.



Left; figure 4; graph of the relative motion of nearby stars [18]

This is most evident by the graph left, which demonstrates this motion. Most evidentially problematic is how this boundary changes from 3 light years, to 1.4 light-years and back to 3.2 light years over the course of the time period demonstrated by the graph.

The next most obvious definition of extrasolar may be read from the graph also, the average outer border of the Oort cloud, 1.6 Light years. However, this distance is also ill defined, as there are two Oort cloud borders, the imaginatively named inner (where the cloud is a disc oriented with the solar equator) and outer (a sphere surrounding the sun), the largest being up to 200000 AU (200000 times the distance from the earth to the sun) or about 3.2 light years.

The third presumption may be from a discovery made by the voyager probes, the heliopause. This region of space is such that the outflowing solar wind is decelerated to, and merges with the galactic wind caused by the motion of the sun through the interstellar medium, not to dissimilar from how quickly flowing water interacting with slower flowing ones creates a circular ridge at the bottom of kitchen sinks. This distance is defined as approximately 120 astronomical units (AU) from the sun, though this distance changes similarly to how earths own magnetic field is pulled into a tail by the momentum of outward flowing solar particles.

The fourth presumption may be simply as that of the furthest known aphelion of any solar system object (aphelion [19] "The point farthest from the sun in the path of an orbiting celestial body")) This could be simply defined as the Oort cloud, or several long period comets, however if one assumes to include only massive objects (Dwarf planets and upwards) then this boundary lies at 3700±2600 AU, the furthest projected point of the orbit of the trans-Neptunian object 2014 FE_{72}.

The fifth and final presumption, which will be used in this dissertation to define the boundary of the solar system, and extrapolated as the boundary of any other celestial object is in the form of the Hill sphere, or Roche sphere, so named as its definition is from George William Hill, who used the work of Édouard Roche, in which it is defined as the distance through which the gravitational influence of the orbiting body dominates that of the larger one:

$$r \approx a(1-e)\sqrt[3]{\frac{m}{3M}} \approx a\sqrt[3]{\frac{m}{3M}} \;(In\ the\ case\ of\ an\ eccentricity\ close\ to\ 0)$$

Where: r is the radius of the hill sphere, e is the eccentricity of the orbiting object, A is the semi-major axis of the orbiting object, m is the mass of the orbiting object, and M is the mass of the object being orbited. (Where $M_{\odot}$is short hand for solar mass?)

$$r \approx (7860 \pm 140\, parsecs)\sqrt[3]{\frac{1\, M_{\odot}}{3\,(4.02 \pm 0.16)x10^{6}\, M_{\odot}}}(with\ a\ presumed\ 0\ eccentricity)[20]$$

$$r \approx (2.45343x10^{20} \pm 4.319949x10^{18}\ metres)\sqrt[3]{12.06x10^{-6} \pm 0.48x10^{-6}}$$

$$r \approx 5.626x10^{18} \pm 3.38x10^{16}\ meters \approx 594.7 \pm 3.575\ Light\ years$$

Now, this is evidentially out by at least two orders of magnitude compared to every single other answer, and is simply down to the assumption made when formulating this answer: that Sagittarius A* is the only mass around which the sun orbits. This is obviously not the case, and so by accounting for a vast majority of the galactic centre, which may be derived with the following:

$$T = \tau\sqrt{\frac{a^3}{GM}} = 2\pi\sqrt{\frac{a^3}{GM}} \qquad\qquad \therefore M = \frac{\tau^2 a^3}{T^2 G} = \frac{4\pi^2 a^3}{T^2 G}$$

Where T is the orbital period, a is the semi major axis, M is the orbited mass, and G is the gravitational constant, we get the following equation for r which accounts for the approximate mass interior to the solar galactic orbit:

$$r \approx a\sqrt[3]{\frac{M_{\odot}}{3M}} \approx a\sqrt[3]{\frac{M_{\odot}T^2G}{3\tau^2 a^3}} \approx \sqrt[3]{\frac{M_{\odot}T^2G}{3\tau^2}}$$

Curiously enough, the semi major axis of the orbit cancels out in the equation, which may lead someone to infer that distance does not a Roche sphere make, however the orbital period is proportional to the semi-major axis, and thus that assumption would be wrong.

$$r \approx \sqrt[3]{\frac{(1.98855x10^{30} \pm 2.5x10^{26}kg)(6.67408x10^{-11}m^3kg^{-1}s^{-2})(225x10^{6}Years)^2}{3\,(6.2831853071 \ldots)^2}}$$

$$r \approx 3.835x10^{16} \pm 1.921x10^{15}\ Metres \approx 4.054 \pm 0.203\ Light\ years$$

This approximation, while much larger than that which has been proposed earlier due to uncertainties in the solar mass and orbital period, is the one for which it shall be used to define a gravitational boundary for any celestial body henceforth, and so shall also be used to define the absolute spherical boundary of extra solar in the scope of this dissertation.

Discussion

Introduction

Focus

In the years of 2015 and 2017 that the then ordinary dwarf star of 2MASS J23062928-0502285 had an important discovery that would shatter several records and cause intrigue among the exoplanetary community. The star, so named following its discovery by the Two Micron All Sky Survey (2MASS) in 1999, has a location in the night sky of 23^{h} 06^{m} 29.28^{s} (RA), −05° 02′ 28.59″ (DE), placing it very close to the constellation of Aquarius (Where RA and DE are right ascension and declination respectively, the equivalent of latitude and longitude used for locating objects in the celestial sphere)

Observations by the Transiting Planets and Planetesimals Small Telescope (TRAPPIST, which is actually a backronym alluding to the nationality of the Belgian telescope) at la Silla observatory in Chile in 2015 led by Michaël Gillon showed three earth-sized exoplanets orbiting the star by use of transit photometry, named TRAPPIST-1 [11] b, c, and d, in order of their discovery (although what was called TRAPPIST d when discovered is actually very different to what is now called TRAPPIST d). On the 22nd of February, 2017, the Exoplanets TRAPPIST-1 e, f, g, and h were discovered using data from the Spitzer Space Telescope [12] and the Very Large telescope at Paranal [13], among others, and named in order of their discovery (which conveniently lines up with their distance from their parent star). The planetary system marks the first earth sized exoplanets orbiting an M8V Ultra cool Dwarf star, and one of the five largest planetary systems discovered to date, of which three systems contain seven orbiting planets (HD 10180, HR 8832, and Kepler-90) and only one contains eight (Sol).

Habitability Benchmarks

Extrapolating from earth based observations, Habitability can be said to be dependent on four key variables which may be analysed from an astrophysical standpoint in order to comment of the habitability of the system. They are as follows:

<u>Temperature of a planet:</u>
All life as we know it, ***without exception***, requires water to function, and so we may extrapolate that any planet which is warm (or cool) enough for liquid water to exist may be habitable. We may make initial assumptions based on having a temperature that allows surface water.

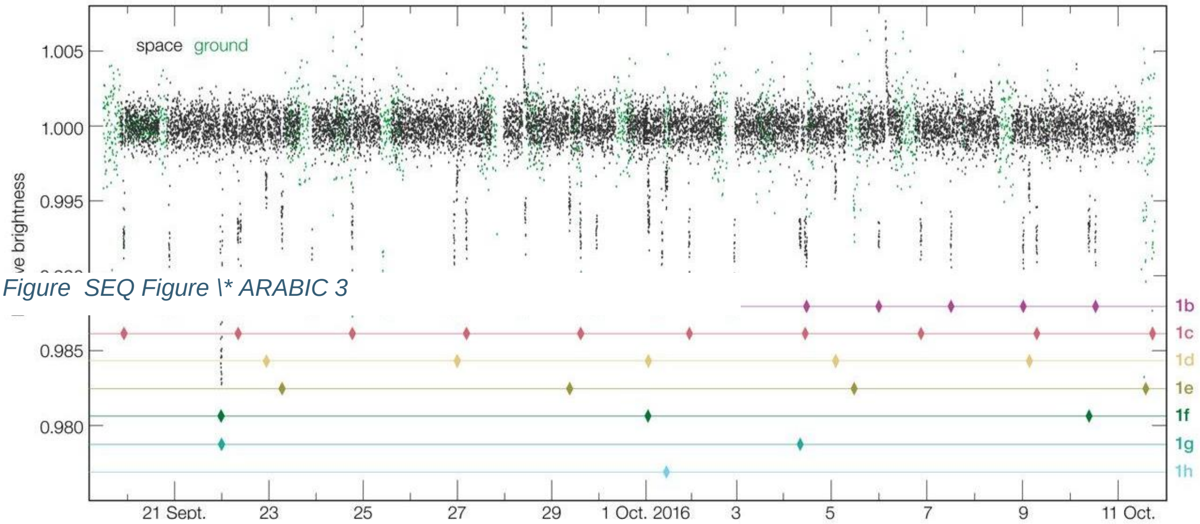
<u>Atmosphere of a planet:</u>
Asides from containing the oxygen and carbon dioxide necessary for respiration and photosynthesis, the atmosphere of earth (and thus any exoplanet) would be required to act as a shield against high energy photons (X-ray and ultraviolet) and also allow for heat retention and convection (allowing the temperature to be less rigidly set)

<u>Orbital characteristics:</u>
Must be stable over the long time scales necessary to allow life to evolve, and lower orbital eccentricities (difference between closest and furthest distance in an orbit (periapsis and apoapsis)) to allow for a stable temperature. At this point it should be obvious that temperature is a very, *very,* sensitive variable, and arguably the most important one for the development of life as well.

<u>Magnetosphere:</u>
A planet must be able to retain surface water and/or an atmosphere from solar bombardment due to the stellar wind, and thus must be able to generate a magnetic field capable of deflecting or damping those high energy particles.

And so, following on from this, it is these four key characteristics through which this discussion shall focus upon (in the order that they were given) when discerning the habitability of the Trappist system, with particular importance being given to the supposed temperature of any of the planets, due to how sensitive terrestrial life is to even minor changes of it on the Earth.

Preliminary Data



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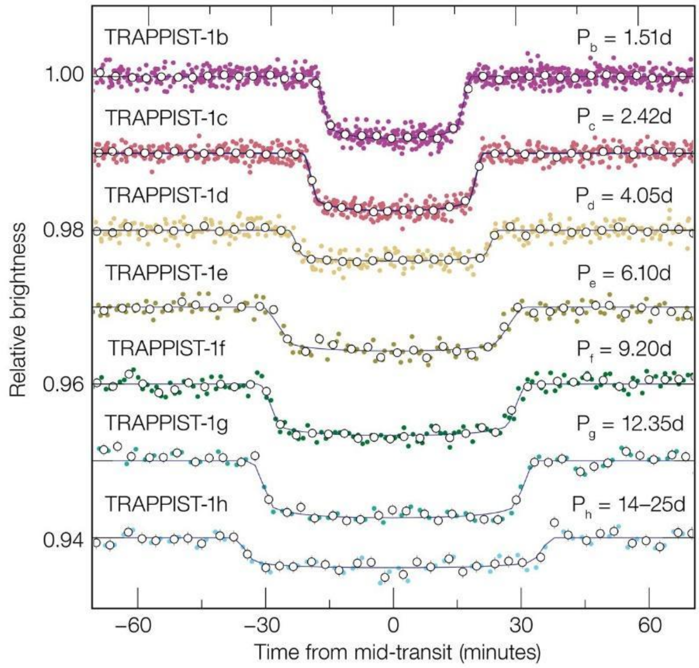


Knowing the depth in brightness of the host star as a planet transits in front of it, it is possible to calculate the ratio of observed radius between the star and planet. Due to the large distance between earth and TRAPPIST-1, this ratio can be presumed to be close to (and thus equal to) the true ratio between the two objects, such that:

$$\frac{\Delta L}{L} = \frac{{R_p}^2}{{R_s}^2}$$

Where ΔL is the change in luminosity, L is the original Luminosity, R_p is the radius of the planet, and R_s is the radius of the star.

This equation can be very easily derived from the basic assumption that the star is a uniform sphere emitting radiation equally in all directions, such that the measured luminosity is proportional to the area of the star. The measured luminosity while the planet is transiting would therefore be proportional to the area of the star, minus the area of the planet:

$$\frac{L_N - \Delta L}{L_N} = \frac{\pi {R_s}^2 - \pi {R_p}^2}{\pi {R_s}^2}$$

Which can be rewritten in an alternate form to simplify:

$$\frac{L_N}{L_N} - \frac{\Delta L}{L_N} = \frac{\pi {R_s}^2}{\pi {R_s}^2} - \frac{\pi {R_p}^2}{\pi {R_s}^2}$$

$$1 - \frac{\Delta L}{L_N} = 1 - \frac{{R_p}^2}{{R_s}^2}$$

$$\frac{\Delta L}{L_N} = \frac{{R_p}^2}{{R_s}^2}$$

$$\sqrt{{R_s}^2 \frac{\Delta L}{L_N}} = R_p$$

And thus we have the equation found above, which when using on the TRAPPIST system from the data in figure 1, we arrive at the following list of ratio, and using the knowledge that TRAPPIST-1 has a radius of 0.114±0.006 Solar radii, or 79309.8±4174.2 km:

Planet	Measured drop in luminosity (%)	Expected Planet radius (km)
b	0.00809	7133 ± 375
c	0.00742	6830 ± 359
d	0.00397	4997 ± 263
e	0.00569	5984 ± 315
f	0.00667	6475 ± 341
g	0.00734	6795 ± 358
h	0.00397	4997 ± 263

Table 1; luminosity against radius.

We can see from the expected radii, that these planets are all nearly earth sized, ranging from ~1.2 times the size of the earth down to ~0.78 times the radius of earth (about halfway between Mars and Venus)

Knowing these radii, there are then several things that astronomers can compute, the most important of such being semi major axis. The semi major axis, or SMA for short, is defined as the furthest point of an ellipse when taking distances from the centre as opposed to a focus, which would be the apoapsis. The SMA is also the average of the apsidies, the two most extreme points of the orbit, called apoapsis (from ἀπ (ό) (ap (o)) meaning away from) and periapsis (from περί (peri), meaning near). The SMA can then be approximated using three well known equations:

$$Force\ due\ to\ Gravity, F_g = \frac{GMm}{r^2}$$

$$Centripedal\ Acceleration, a = \frac{v^2}{r}$$

$$Newton's\ second\ law\ of\ motion, F = ma$$

$$F = \frac{GMm}{r^2} = ma, where\ a = \frac{v^2}{r}$$

$$\frac{GMm}{r^2} = \frac{mv^2}{r}$$

$$\frac{GMm}{r} = mv^2$$

$$\sqrt{\frac{GM}{r}} = v$$

Which is coincidentally, the exact equation for orbital velocity when the orbit has zero eccentricity (is a perfect circle). Now of course, there are two unknowns in that equation: r, the orbital radius; and v, the orbital speed, however we can compute the orbital speed using some basic maths. Speed is distance over time, or velocity is displacement over time, using the transit period.

Now, it may seem simple to take the diameter of the star and divide by the transit time, however this assumption is slightly wrong. Transit time is defined as the time taken for the stellar luminosity to return to nominal, and as such is from when the planet first until last blocks any portion of light. As such, a single point on the planet will have travelled slightly more than the diameter of the star, for example the leading point of the planet when it first touches one side, is the only part of the planet blocking light, however on the opposing side, it is the only point not blocking any light, and so we must take the radius of the planet into account:

$$v = \frac{D_{Star} + D_{Planet}}{T_{Transit}} = \frac{2(R_{Star} + R_{Planet})}{T_{Transit}}$$

$$\sqrt{\frac{GM}{r}} = \frac{D_{Star} + D_{Planet}}{T_{Transit}}$$

$$\frac{GM}{r} = \frac{(D_{Star} + D_{Planet})^2}{T_{Transit}^2}$$

$$r = \frac{GMT_{Transit}^2}{(D_{Star} + D_{Planet})^2} = \frac{GMT_{Transit}^2}{4(R_{Star} + R_{Planet})^2}$$

Which when we apply this to the TRAPPIST system from the data in figure 2, we get the following table, where the mass of TRAPPIST-1 is:
0.0802 ± 0.0073 solar mass, or 1.596x10^29 ± 1.455x10^28 kg

Planet	Transit time (s)	$D_{Star} + D_{Planet}$ (km)	speed (ms-1)	expected circular SMA (km)
b	2197	172886 ± 9099	78681 ± 4141	1734551 ± 182080
c	2546	172279 ± 9067	67668 ± 3561	2345118 ± 246173
d	2968	168614 ± 8874	56819 ± 2990	3326179 ± 349157
e	3738	170588 ± 8978	45638 ± 2402	5155576 ± 541193
f	3843	171571 ± 9030	44642 ± 2350	5388157 ± 5388157
g	4111	172210 ± 9064	41892 ± 2205	6118854 ± 642311
h	4524	168614 ± 8874	37268 ± 1961	7731289 ± 811572

Table 2; semi major axis from transit time.

Now, in the table above there is a slight problem with the orbits of e, f, and g, in that the lowest bound of g is lower than the higher bound of e (which may just be due to a tight orbital configuration). However there is a second way that gives a very good approximation of the SMA without having to compute much else; the time between transits.

Now, this will only ever be an approximation, as the gravitational influences of each orbiting body will cause the time period to oscillate, however this can be minimised by taking an average across as many sweeps as we can. Using the orbital period equation, where by definition orbital period is equal to the time between transits, we can compute the SMA of each planet, and compare our two answers:

$$T_{orbit} = 2\pi\sqrt{\frac{a^3}{GM}}, \qquad and\ thus, a = \sqrt[3]{\frac{GMT_{Orbit}^2}{4\pi^2}}$$

Which when using the mass of TRAPPIST-1 and the data from figure 1, we get:

Planet	average time between transits	SMA from Orbital period (Mm)	SMA from Transit time (Mm)
b	1.51 days	1661 ± 50.580	1735 ± 182
c	2.42 days	2274 ± 69.272	2345 ± 246
d	4.05 days	32060 ± 97.645	3326 ± 349
e	6.10 days	42120 ± 128.300	5156 ± 5411
f	9.2 days	5539 ± 168.700	5388 ± 539
g	12.35 days	6741 ± 205.300	6119 ± 642
h	14-25 days	9110 ± 200.5000	7731 ± 812

Table 3; semi major axis from orbital period.

There are larger and larger discrepancies as the time between transits increases. In fact, when we look back at the equations, we find that the first calculated the *Distance* between the two orbiting bodies at the transit location, while the second actually computed the SMA.
If we compare the results in the exoplanet catalogue [21] we find the computed values to be quite close, in fact the data calculated is *almost exactly the same as ours.*

Now, the next biggest thing for astronomers would be to calculate (or discover) the mass of the orbiting planet. This is typically done by use of the radial velocity method, wherein minute perturbations in the velocity of the central body are measured, and then the mass is calculated from the planetary mass required to cause that perturbation. For simplicities sake, I shall use the data from exoplanet catalogue [21], as it has been proven to be almost exactly the same as what can be computed from the Spitzer data provided above, all of which is in the table below:

Planet	Orbital Period (days)	SMA (Mm)	Mass (kg)	Mass (Earth)
b	1.511 ± 0.00000060	1661 ± 50.580	5.068e+24 ± 4.309e+24	0.849… ±0.721…
c	2.422 ± 0.0000017	2274 ± 69.272	8.238e+24 ± 3.644e+24	1.379…±0.610…
d	4.0496 ± 0.000063	32060 ± 97.645	2.468e+24 ± 1.518e+24	0.413…±0.254…
e	6.099 ± 0.000011	42120 ± 128.300	3.796e+24 ± 3.416e+24	0.636…±0.572…
f	9.207 ± 0.000015	5539 ± 168.700	3.986e+24 ± 1.138e+24	0.667…±0.191…
g	12.35 ± 0.00012	6741 ± 205.300	8.010e+24 ± 5.257e+24	1.341…±0.880…
h	18.80 ± 0.0035	9110 ± 200.500	Unknown	Unknown

Table 4; mass of the Trappist planets from derived orbital characteristics.

This simplicity with transit photometry and radial velocity calculations to compute orbital and physical parameters of an orbiting body is an especially powerful and useful tool of modern astronomy. Using only the drop in brightness of a star and its minute "wobble", a huge variety of useful information has been discovered using relatively simple equations and a touch of logic, which should now be ample information to analyse each planet.

Temperature

For any world hoping to play host to life, temperature is an incredibly important benchmark to set stock by. A planet that has a global temperature too hot cannot support surface liquid water, as it would vaporise instantly. Likewise, a planet with a global temperature too low would cause that water to freeze instantly. Temperature affects much more than the state of water on extra-terrestrial surfaces, however due to the dependence on water by life as we know it, the temperature of a planet, and thus whether it can support surface water, is a crucial point in the study of habitability.

Circumstellar habitable zone

Typically, any planet found within the "[circumstellar] habitable", "Goldilocks" zone of its parent star, is one such that were no other factors to come into play, the temperature of the planet would be within the temperature range that water exists as a liquid under a single atmosphere of pressure (273.15 - 373.15 Kelvin, or 0 - 100 centigrade). It is certainly possible for liquid water to exist outside of the habitable zone around a star, due to any number of reasons such as albedo, atmospheric pressure, or simply a subsurface ocean like the moon Europa, but this is typically the first indication of habitability used by astronomers.

The habitable zone around a star is defined by the inner and outer boundaries, given by the equations:

$$R_i = \sqrt{\frac{L}{1.1}} \; and \; R_0 = \sqrt{\frac{L}{0.53}}$$

where R_i, R_o are the inner and outer boundaries of the habitable zone, L is the absolute luminosity of the host star, and 1.1, 0.53 are constant values representing stellar flux at the boundaries (Based on Kasting et. al. [23])

Now, these equations require the absolute luminosity of the star, which can be calculated using any of the following equations if it isn't already known: $M_V = m_V - 5 \log \log \left(\frac{d}{10}\right)$

$$M_{Bol\ Star} = M_V + B_C$$

$$\frac{L_{Star}}{L_{Sun}} = e^{\left[\frac{M_{Bol\ Star} - M_{Bol\ Sun}}{-2.5}\right]}$$

Where L_{star}/L_{sun} is the absolute luminosity of the host star in terms of the absolute luminosity of the sun, M_{bol} star is the bolometric magnitude of the host star, M_{bol} sun is the bolometric magnitude of the sun which is 4.83, M_v is the apparent magnitude of the star in the visual spectrum d is the distance from Earth to the star in parsecs, B_C = bolometric correction constant, and 2.5 is a constant value used for comparing stellar luminosities known as "Pogson's Ratio."

Luckily, for our purposes, the luminosity of Trappist-1 is known (0.000525±0.000036 solar luminosities [24]) and so it becomes a simple method of substituting, therefore the two boundaries of its habitable zone are at approximately:

$$R_i = \sqrt{\frac{0.000525 \pm 0.000036\ L_{\odot}}{1.1}} = 0.0218 \pm 0.000749\ AU$$

$$R_0 = \sqrt{\frac{0.000525 \pm 0.000036\ L_{\odot}}{0.53}} = 0.0315 \pm 0.00108\ AU$$

Using this, and the SMA from above, it can be shown that d is skirting the inner edge of the habitable zone, while only e sits inside of this. This is contrary to what has been reported by other places, NASA included, as this is known as the "conservative estimate" for habitable zone, as opposed to the "extended estimate" which places the planets of f and g firmly within it. Now, whether a planet is actually within the temperature required to support liquid water does not necessarily require it to be within the habitable zone, as this value is calculated independently of any of the planets actually in the system.

Effective and surface temperature

Instead, astronomers use something known as the effective temperature of a planet, which is where the amount of radiation emitted by the planet is set as equal to the amount of incident radiation it receives, and thus its equilibrium temperature is calculated. While not a perfect approximation, it is a better indicator than merely the habitable zone alone.

$$Power_{in} = Power_{out}\ The\ definition\ of\ thermal\ equilibrium$$

$$Power_{in} = L * (1 - a) * \frac{\pi * Radius_{Planet}^2}{4 * \pi * Radius_{orbit}^2}$$

Where the power in is the energy supplied by the star that the planet absorbs, such that a planet will receive energy proportional to the surface area of a sphere at that orbital height. Where *L* is the luminosity of the host star, and *a* is a measure of how much energy the planet reflects (albedo)

$$Power_{out} = \epsilon * \sigma * T^4 * 4 * \pi * {Radius_{Planet}}^2$$

Where energy is radiated according to the Stefan Boltzmann law across a spherical surface of equal area to the planet.

$$L * (1 - a) * \frac{\pi * \ Radius_{Planet}^2}{4 * \ \pi * \ \ Radius_{orbit}^2} = \epsilon * \sigma * T^4 * 4 * \pi * \ Radius_{Planet}^2$$

$$L * (1 - a) * \frac{1}{4 * \ \pi * \ \ Radius_{orbit}^2} = \epsilon * \sigma * T^4 * 4$$

$$\frac{L(1 - a)}{4 * \ \pi * \ \ Radius_{orbit}^2} = \epsilon * \sigma * T^4 * 4$$

$$\frac{L * (1 - a)}{16 * \ \epsilon * \sigma * \pi * \ \ Radius_{orbit}^2} = T^4$$

$$T = \sqrt[4]{\frac{L(1 - a)}{16\epsilon\sigma\pi \ Radius_{orbit}^2}}$$

$$where\ \sigma\ is\ the\ stefan - boltzman\ constant\ 5.670367(13) \times 10^{-8} Wm^{-2}K^{-4}$$

For most natural instances, **ε** will be very close to one (E of earth = 0.96) and so if **ε** is presumed 1 for the Trappist System, with an albedo of 0 (a perfect absorption), and the Luminosity of Trappist 1 is 0.000525±0.000036 Solar luminosities (2.0097e+23 ± 1.37808e+22 W); the following temperatures can be found:

Planet	SMA (Mm)	Temperature (K)
b	1661 ± 50.580	400.0 ± 13.00
c	2274 ± 69.272	341.8 ± 11.07
d	32060 ± 97.645	287.9 ± 9.33
e	42120 ± 128.300	251.1 ± 8.14
f	5539 ± 168.700	218.9 ± 7.09
g	6741 ± 205.300	198.5 ± 6.43
h	9110 ± 200.5000	174.2 ± 22.35

Table 5; temperature from semi major axis.

Here we can see, as affirmed in the conservative estimate, that Trappist-1 e is firmly inside of the habitable zone, in fact with a temperature equivalent to that of the earth. Now, this is evidentially not the entirety of the picture, as running earth through that equation gives an effective temperature of approximately 255 Kelvin, which is about 35 kelvin too low.

Surface temperature is closely linked to effective temperature, in fact one simple approximation of it is derived from the effective temperature formula, introducing planetary spin and a simple understanding of surface heating:

$$Power_{absorbed} = L * A_{absorbed} * (1 - a) * \frac{\pi * \ Radius_{Planet}^2}{4 * \ \pi * \ \ Radius_{orbit}^2}$$

$$Power_{radiated} = \ A_{radiated} * \epsilon * \sigma * T^4 * 4 * \pi * \ Radius_{Planet}^2$$

Where $A_{absorbed}$ and $A_{radiated}$ are some fractions of the planet surface that absorbs and radiates energy while rotating.

$$L * A_{absorbed} * (1 - a) * \frac{\pi * \ Radius_{Planet}^2}{4 * \ \pi * \ \ Radius_{orbit}^2} = A_{radiated} * \epsilon * \sigma * T^4 * 4 * \pi * \ Radius_{orbit}^2$$

$$\frac{L * A_{absorbed} * (1-a)}{4 * \pi * Radius_{orbit}^2} = A_{radiated} * \epsilon * \sigma * T^4 * 4$$

$$\frac{L * A_{absorbed} * (1-a)}{16 * A_{radiated} * \epsilon * \sigma * \pi * Radius_{orbit}^2} = T^4$$

$$T = \sqrt[4]{\frac{A_{absorbed}}{A_{radiated}} \frac{L(1-a)}{16\epsilon\sigma\pi \, Radius_{orbit}^2}}$$

In the new derivation, we can see that the temperature is now proportional (by a factor of a 4th root) to this new value $A_{absorbed}/A_{radiated}$. Common assumptions for the ratio given are ¼ (surface area of a disk/surface area of a sphere) for a rapidly rotating body and ½ for a slowly rotating body or a tidally locked planet on the light side. This ratio would be 1 for the sub stellar point (the point on the planet directly below the host star and would give the maximum temperature.)

As to whether the Trappist planets are tidally locked, that answer is most likely. However, there is also a formulaic derivation that can be used to affirm this suspicion.

$$T_{tidal-locking} = \frac{\omega a^6 I Q}{3 G m_s^2 k_2 R^5} \; where \; I \approx \frac{2 m_p R^2}{5}$$

Where ω is the initial spin rate in radians per second, a is the semi major axis, I is the moment of inertia of the planet, Q is the dissipation function, G is the gravitational constant, m_s is the mass of the central star, m_p is the mass of the planet, k_2 is the tidal love number of the planet and R is it's radius.
With the exception of the moon, q and K2 are very poorly known, therefor it is a common conservative estimate to take Q as 100, and $K2$ as:

$$k_2 = \frac{1.5}{1 + \frac{19\mu}{2\rho g R}} \; where \; g = \frac{G m_p}{R^2}$$

Where ρ is the density of the planet, g is its surface gravity, and μ is the rigidity, which can be taken as roughly 3×10^{10} Nm^{-2} for rocky objects, and 4×10^{9} Nm^{-2} for icy ones.

Due to the high uncertainty in many factors, such as a changing due to tidal acceleration, ω not even being known, and so on, the above formulae can actually be simplified somewhat:

$$T_{tidal-locking} \approx 6 \frac{a^6 R \mu}{m_p m_s^2} \times 10^{10} years$$

Where the values are taken as *K2 = 1, Q=100,* and initial spin rate is 12 hours (the average asteroid is between 2 hours and 2 days) and so, for a culmination of all points for the Trappist planets, we have:

Planet	$T_{Tidal\ locking}$ (Years)	Expected Temperature (K)	Maximum Temperature (K)
b	0.0110 ± 0.0102	336.3 ± 12.96	400.0 ± 13.0
c	0.0129 ± 0.00923	287.4 ± 11.07	341.8 ± 11.07
d	0.340 ± 0.276	242.1 ± 9.33	287.9 ± 9.33
e	4.85 ± 4.64	211.2 ± 8.14	251.2 ± 8.14
f	4.38 ± 2.69	184.1 ± 7.09	218.9 ± 7.09
g	13.614 ± 11.4	166.9 ± 6.43	198.5 ± 6.43
h	*Extrapolated to about 50*	146.5 ± 22.35	174.3 ± 22.35

Table 6; temperature variation and tidal locking time.

We can see that they should all have been tidally locked very quickly (relative to the astronomical timescale) and thus they are almost certainly locked, demonstrating that the value of ½ used for the absorption-radiation ratio is perfectly valid. This has now placed only Trappist-1 c as a location where surface water could occur, however it must be remarked that using earth with this equation will give a value around 255 Kelvin. Now, evidentially this is wrong, but the reason is simply that the above deals perfect blackbody absorbing and radiating heat unhindered.

Atmospheric temperature

Leading on rather nicely, it is the terrestrial atmosphere that causes this increase in around 40 kelvin. The effect that an atmosphere has on the surface temperature of a planet can vary wildly, and makes this a difficult phenomenon to model, however, there are several standard assumptions and approximations that could be made in order to simplify things.

A planetary atmosphere contributes to global temperature in three mains ways. It can absorb incoming stellar radiation and outgoing planetary radiation, heating itself up in the process; it can reflect radiation back into space, or towards the planet; and it can distribute energy across a larger area. The last point requires a complex model of an atmosphere across a supercomputer simulation, however the first two may be written simply:

$$Power_{In} = Power_{Solar}\left(1 - r_{a\ incoming}\right)\left(1 - a_{a\ incoming}\right) + Power_{retained}$$

$$Power_{retained} = \left(1 - a_{a\ outgoing}\right) * r_{a\ outgoing} * Power_{out}$$

Or simply: the energy gained by a planet is equal to the incoming radiation not absorbed or reflected away by an atmosphere added to the energy reflected back by the atmosphere. This uses a few assumptions, and it is quite literally an oversimplification, however for all intents and purposes this can still be utilised for our means. Now it should also be noted that there is the chance for some infinities to occur, as power in is somewhat dependant on power out, however there is a work around that we will use later on. Secondly, there are two different values for the reflectivity and albedo of the atmosphere depending on the radiative frequency, in other words, the ability of the atmosphere to absorb or reflect energy is dependent on the wavelength of that light.

Using some aforementioned equations, we then arrive at the following ones:

$$Power_{abs} = (1 - a_p)\left(L * (1 - r_{ai}) * (1 - a_{ai}) * A_{abs} * \frac{\pi * \ Radius_p^2}{4 * \ \pi * \ \ Radius_o^2} + Power_{retained}\right)$$

$$Power_{radiated} = A_{radiated} * (1 - a_{ao}) * (1 - r_{ao}) * \epsilon * \sigma * T^4 * 4 * \pi * \ Radius_o^2 + a_a Power_{retained}$$

Which when in thermal equilibrium, will give this hideous monstrosity of an equation.

$$(1 - a_p)\left(\frac{LA_{abs}(1 - r_{ai})(1 - a_{ai})\pi Radius_p{}^2}{4\pi Radius_o{}^2} + P_{retained}\right) = 4A_{rad}(1 - a_{ao})(1 - r_{ai})\varepsilon\sigma T^4 \pi Radius_p{}^2 + a_p P_{retained}$$

$$\frac{A_{Abs}}{1}\frac{(1 - r_{ai})(1 - a_{ai})}{1}\frac{L(1 - a_p)}{4\varepsilon\sigma\pi Radius_o{}^2} + (1 - a_p)P_{retained} = 4A_{rad}(1 - a_{ao})(1 - r_{ao})T^4 - (1 - a_p)P_{retained}$$

$$\frac{A_{Abs}}{A_{rad}}\frac{(1 - r_{ai})(1 - a_{ai})}{(1 - a_{ao})(1 - r_{ao})}\frac{L(1 - a_p)}{16\varepsilon\sigma\pi Radius_o{}^2} + 2(1 - a_p)P_{retained} = T^4$$

$$T = \sqrt[4]{\frac{A_{Abs}}{A_{rad}}\frac{(1 - r_{ai})}{(1 - r_{ao})}\frac{(1 - a_{ai})}{(1 - a_{ao})}\frac{L(1 - a_p)}{16\varepsilon\sigma\pi Radius_o{}^2} + \left[2(1 - a_p)P_{retained,}\ (presumed\ 0)\right]}$$

We can now see that in the derived equation, temperature is now dependant on the ratio of incoming radiation absorbed to outgoing radiation absorbed, the ratio of incoming radiation reflected to outgoing reflected, and a small portion of energy retained by the atmosphere from incoming and outgoing energy which will be presumed zero in this case for ease of computation.

Using a culmination of all the equations, it is possible to find the exact values and the temperature change due to the planetary atmosphere

$$\therefore T_{surface} = T_{atmosphere} + T_{effective}$$

$$\sqrt[4]{\frac{(1-r_{ai})}{(1-r_{ao})}\frac{(1-a_{ai})}{(1-a_{ao})}\frac{L(1-a_p)}{16\varepsilon\sigma\pi Radius_o{}^2}} = T_{atmosphere} + \sqrt[4]{\frac{L(1-a)}{16\epsilon\sigma\pi Radius_o^2}}$$

$$\sqrt[4]{\frac{(1-r_{ai})}{(1-r_{ao})}\frac{(1-a_{ai})}{(1-a_{ao})}}\sqrt[4]{\frac{L(1-a)}{16\epsilon\sigma\pi Radius_o^2}} = T_{atmosphere} + \sqrt[4]{\frac{L(1-a_p)}{16\varepsilon\sigma\pi Radius_o{}^2}}$$

$$\sqrt[4]{\frac{(1-r_{ai})}{(1-r_{ao})}\frac{(1-a_{ai})}{(1-a_{ao})}} = \frac{T_{atmosphere}}{T_{effective}} + 1$$

For example, on earth, the surface temperature without an atmosphere is:

$$T = \sqrt[4]{\frac{1}{4}\frac{(3.828\times 10^{26}W)\big(1-(0.29)\big)}{16(0.96)\sigma\pi(149597870700m)^2}} \approx 258\ Kelvin$$

$$(Where\ an\ AU\ is\ now\ defined\ as\ exactly\ 149597870700m)$$

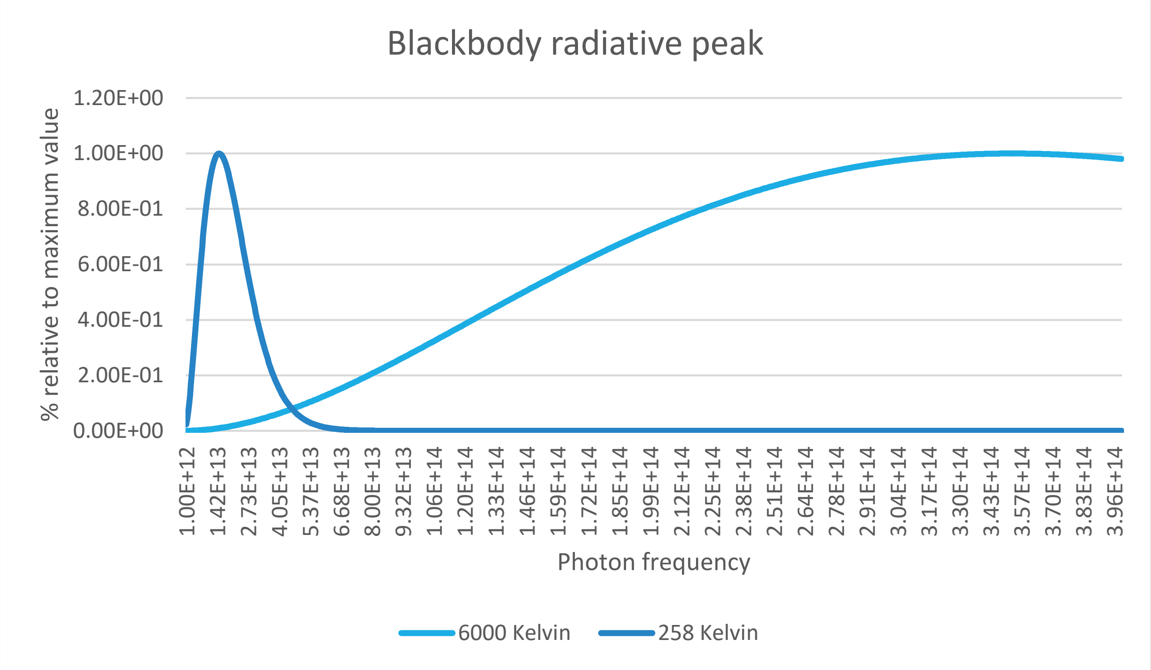
While the average temperature experienced on earth is ≃ 288 Kelvin

$$\sqrt[4]{\frac{(1-r_{ai})}{(1-r_{ao})}\frac{(1-a_{ai})}{(1-a_{ao})}} = \frac{(288-258)}{(288)} = \frac{5}{48} + 1$$

In other words, the amount of radiation that reaches the surface is 48/5 times larger than the amount of energy that leaves it due to atmospheric effects. There are ways to estimate all the values above, using data about the type of radiation incident on the atmosphere and its relative absorption effects, for example using the blackbody emission spectrum of an object at 6000 and 255K (the surface temperatures of the sun and earth) to find the radiation emitted most frequently, and comparing that with the absorption spectra of the atmosphere.

$$B_v(v,T) = \frac{2hv^3}{c^2}\frac{1}{e^{\frac{hv}{k_BT}}-1}\ Planck's\ Law$$

If we plot that equation across multiple frequencies, we get the following graph:

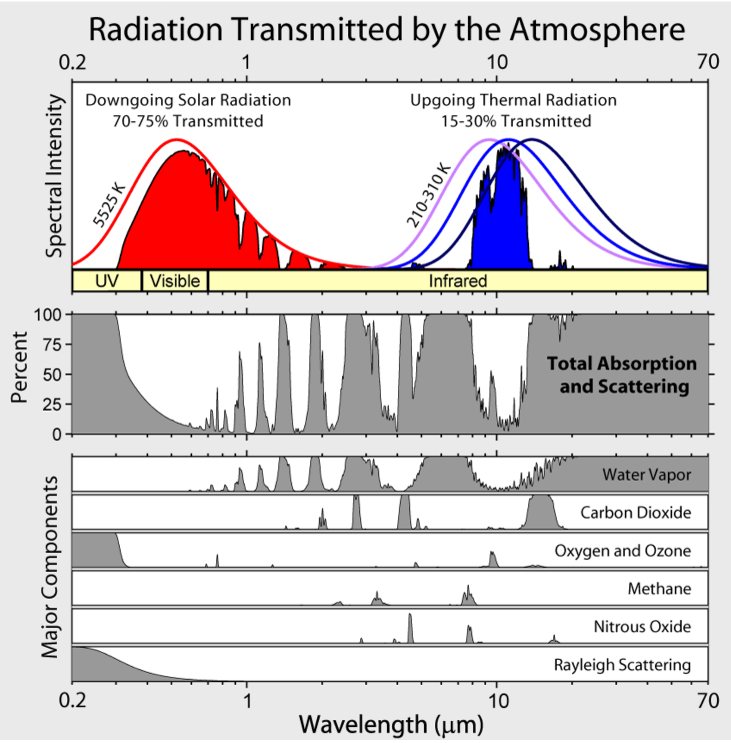


Graph 1; blackbody radiative peak for two objects at 6000 and 258 kelvin respectively.

For an object at 6000 kelvin, its radiative peak occurs at 3.53×10^{14}Hz, or a wavelength of 8.50×10^{-7}m, while for an object at 258 kelvin, this peak occurs at 1.50×10^{13}Hz, or 2.00×10^{-5}m. This places the peak radiative photons at near and mid IR respectively. Now, the radiative peak of the sun is known to be within the green visible light range, and so we find some discrepancy between the graph and experimental data. This is most likely due to propagating rounding errors in excel, and so another equation may be used, Wien's displacement law;

$$\lambda_{max} = \frac{b}{T} \text{ where } b = 2.897729(27) \times 10^{-3} mK^{-1}$$

Which when used, we find maximum wavelengths of 4.83×10^{-7}m and 1.12×10^{-5}m for 6000 and 258 kelvin respectively, or green (on the blue boundary) and mid IR respectively, which much better equates the experimentally derived values. We find that for green light, the atmosphere has near 100% transmittance, (how much light can pass through) yet for mid IR, we find a transmittance around 80%, which when integrating across the entirety of the curve above, we find that for earth's atmosphere, the incoming radiation experiences 70-75% transmittance (25-30% absorption) while the outgoing radiation experiences 15-30% transmittance - (70-85% absorption). Using this, we can



finally apply some numerical values to the equation above to find some earth-like parameters to use:

$$\frac{a_{ai}}{a_{ao}} = \frac{0.275}{0.775}$$

$$\sqrt[4]{\frac{(1-r_{ai})}{(1-r_{ao})}\frac{0.725}{0.225}} = \frac{5}{48} + 1$$

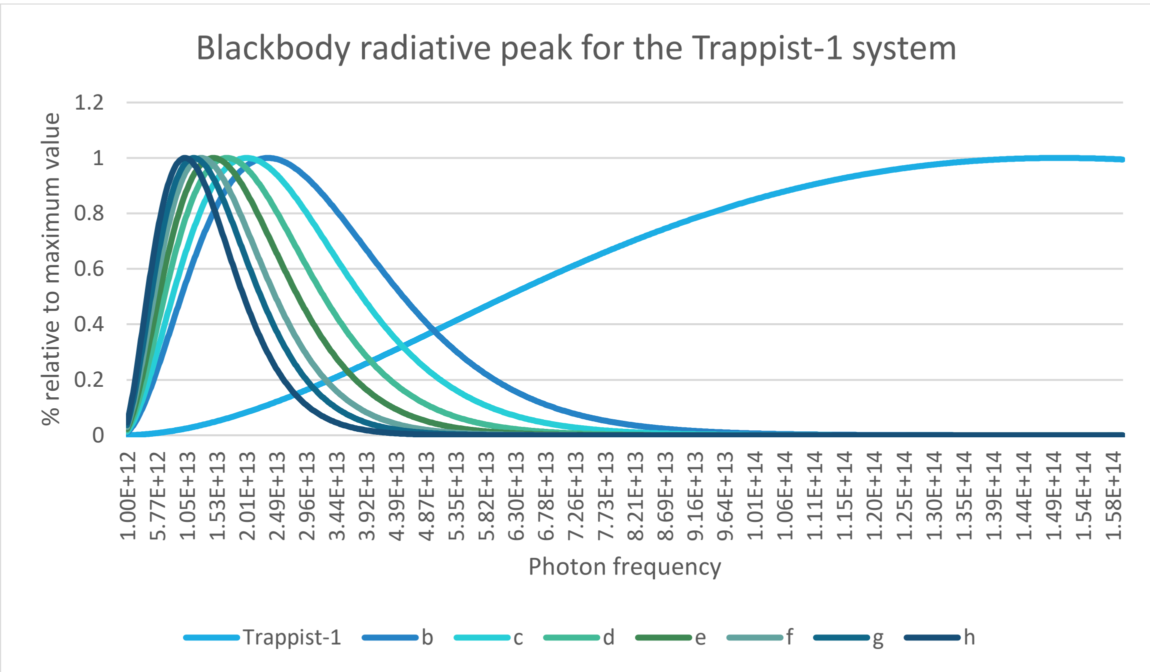
$$\frac{(1-r_{ai})}{(1-r_{ao})}\frac{0.725}{0.225} = \frac{53^4}{48^4} = \frac{7890481}{5308416}$$

$$\frac{(1-r_{ai})}{(1-r_{ao})} = \frac{0.4612996\ldots}{1} \quad \therefore r_{ai} \approx 0.5387, \quad r_{ao} \approx 0$$

Which when used in the equation

$$T = \sqrt[4]{\frac{A_{Abs}}{A_{rad}}\frac{(1-r_{ai})}{(1-r_{ao})}\frac{(1-a_{ai})}{(1-a_{ao})}\frac{L(1-a_p)}{16\varepsilon\sigma\pi Radius_o{}^2}} = 284\ K\ (off\ by\ 4\ due\ to\ rounding\ errors)$$

However, the absorption of each of the Trappist planets for a terrestrial atmosphere will depend entirely on their own blackbody temperature, and that of Trappist-1 itself, which if plotted in excel, gives us the following graph to deduce information from.



Graph 2; blackbody radiative peak given average calculated temperature of the Trappist system.

The peak radiance occurs at 2×10^{-6}m, 1.27×10^{-5}m, 1.49×10^{-5}m, 1.77×10^{-5}m, 2.02×10^{-5}m, 2.32×10^{-5}m, 2.57×10^{-5}m, and 2.93×10^{-5}m for the star and planets respectively, which when compared with the terrestrial atmosphere, gives transmittances of approximately 50-60%, and 10-30% for the light from Trappist-1 and the planets respectively, then we get the following temperatures:

Planet	Blackbody Temperature (K)	Temperature (K) ($a_i = 0.5$, $a_o = 0.7$)	Temperature (K) ($a_i = 0.4$, $a_o = 0.9$)
b	400.0 ± 13.0	314.9 ± 10.20	433.8 ± 14.05
c	341.8 ± 11.07	269.1 ± 8.72	370.7 ± 12.01
d	287.9 ± 9.33	226.7 ± 7.34	312.2 ± 10.11
e	251.2 ± 8.14	197.7 ± 6.41	272.4 ± 8.82
f	218.9 ± 7.09	172.4 ± 5.59	237.5 ± 7.69
g	198.5 ± 6.43	156.3 ± 5.06	215.3 ± 6.97
h	174.3 ± 22.35	137.2 ± 17.60	188.9 ± 24.25

Table 7; temperature variation given terrestrial characteristics.

Now, it can be seen that Trappist-1 b, c, d, and e may all be habitable simply with earth's atmosphere. The average temperature may be overly warm or cold compared to earth, but the error associated with the calculation allows for them to have the same average temperature of earth, or certainly be very close to it.

Habitability comparison for exoplanetary temperature

It could almost certainly be argued that these results are inconclusive in confirming or denying the possibility of life having evolved on the planetary surface, as temperature is a very variable quantity, which in this case has only been considered from stellar flux (the amount of radiation falling on a planetary surface) and an incredibly simple model of atmospheric effects. For example, there are several species of life on earth that are capable of powering themselves through chemosynthetic processes from undersea geysers where temperature is near constant. The number of approximations and suppositions required to come to any clear evidence must then be taken into account, that while it is certainly a possibility that any of the planets, particularly those of c, d, and e to facilitate the conditions necessary for life to evolve, they may also be inhospitable worlds at either end of the temperature extremes.

As such, the habitability of these worlds may be deemed possible, but unlikely given the current simplistic models and assumptions.

Atmosphere

The atmosphere of an exoplanet is certainly the most important factor for every potential surface dwelling, and also some subterranean lifeforms. Its sheer importance can hardly be understated when we look purely at our own solar system and the examples of Venus, Earth, and Mars, the middle planet of which is a temperate thriving ecosphere, while the former is an inhospitable poisonous furnace, and the latter is a barren and cold wasteland. The enormous differences between these three worlds is quite simply a result of their atmospheres, the composition of such and the masses of the atmospheres.

Atmospheric analysis

First and foremost, a planetary atmosphere allows the retention of heat (discussed above) and gives heat transfer between the extremes of temperature. Mars, with its thin atmosphere, has surface temperature variations much greater than that of the earth. Without the thermal retention, the Martian poles in winter can reach temperatures of 148 Kelvin, while the global average is 213 Kelvin. However, this is a delicate balance. Venus, with a much thicker atmosphere, is capable of retaining much of the solar energy that falls upon its surface (even despite the atmospheric reflectivity that it exhibits) Venus' huge atmospheric greenhouse effect, and the mass (nearly 90 times greater than that of the earth) gives rise to an average surface temperature of 735 Kelvin.

Atmospheric composition, therefore, may be considered a vital ingredient in the habitability of a planet. Asides from the obvious health disadvantages to living in an atmosphere of carbon dioxide with thick sulphuric acid clouds, the composition effects a great number of incredibly complicated factors in habitability, the most important of which being temperature (Discussed above) and Important interactions.

Interactions, while a vague word to use, is a broad topic to discuss. However, in the scope of this dissertation, atmospheric interaction may be used to refer to how the molecular composition of the atmosphere interacts with high energy particles (UV and X-ray photons), and its greenhouse effect.

Habitability comparison for atmospheric characteristics

The atmospheres of the Trappist-1 planets are not known to exist, but also not ruled out. Due to their position relative to earth, they are prime candidates for transmission spectroscopy (analysis of the composition of a substance based on which unique frequencies of light it absorbs/emits). The combined transmission spectra for Trappist-1 b and c, obtained by the Hubble space telescope in early 2016, rules out the possibility of cloud-free hydrogen-dominated atmosphere (as would be observed in gas giants). However this did not rule of the chances of other atmospheric structures, from a Venusian atmosphere, to one dominated by water vapour, which would be consistent with the featureless spectrum observed [27]. Further study by the Upcoming James Webb space telescope, or the Extremely Large Telescope, will be able to analyse the composition of each of the planetary atmospheres, and calculate their greenhouse effect (a measure of the planets atmospheric absorption)

As such, it can only be speculated as to how the atmospheric conditions of the Trappist-1 planets, by presumption of an earth-like atmosphere, the planets d, e, f, and g may very well be habitable, however the likelihood of such an atmosphere existing is low. Until such a time when the atmospheric size and composition of the planets is known, there is no way to definitively say how this affects habitability, although when looking at the atmospheric composition of the solar system, it can be presumed that it is certainly unlikely.

Orbital characteristics

The orbital properties of the Trappist-1 system are, unlike the atmospheric properties, very well-known and constrained. Orbital characteristics, while not nearly so volatile as those of an atmosphere (were it to exist) nor as important, play a big role in habitability, especially in the early planetary developmental stages. Secondarily to this, the possibility of any of the planets also hosting a moon could be analysed, as its role in Earthly habitability is not well understood but presumed to play a somewhat significant role.

Orbital Analysis

When looking at the Trappist-1 system, there are two major orbital properties that are instantly visible, and have far reaching consequences. All of the planets have very low orbital eccentricities, having nearly circular orbits, and the ratio of orbital periods between any two bodies is very close to an integer ratio.

Focusing on the second point, where two bodies orbit within integer ratio time periods, what is known as an orbital resonance occurs. This may be most obviously observed in the Jovian system, the moons of Io, Europa, and Ganymede have orbital resonances of 1:2:4, in other words, for every orbit of Ganymede, Europa and Io make 2 and 4 orbits respectively. This will typically give rise to unstable systems, as the mutual gravitational interactions between orbiting bodies becomes enhanced over the course of an orbit, causing perturbations that propagate until the system falls apart. However, in the special case of the Galilean moons, and expected within the Trappist-1 system, orbital resonance actually gives rise to stability, as the gravitational interaction between each of the orbiting bodies causes them to drift back into their original positions, known as a self-correcting resonance.

For the Trappist system, their resonances can be calculated and demonstrated below:

Planet	Orbital Period (days)	Orbital ratio (relative to h)	Integral Periodic ratio
b	1.511 ± 0.00000060	0.0805	24
c	2.422 ± 0.0000017	0.1291	15
d	4.0496 ± 0.000063	0.2158	9
e	6.099 ± 0.000011	0.3250	6
f	9.207 ± 0.000015	0.4906	4
g	12.35 ± 0.00012	0.6582	3
h	18.80 ± 0.0035	1	2

Table 8; Orbital resonances in the Trappist-1 system.

It can be seen that the planets exist in a near perfect orbital chain (the longest ever such discovered), but curiously, another phenomenon also appears, any three adjacent planets exist very close to what is known as a Laplace resonance (the ratio found in the Galilean moons, where orbital period ratios exist as 1:2:4) This kind of resonance produces a very stable configuration of the planets over astronomical time scales, which gives rise to the conclusion that the planets of the system must have undergone planetary migration to arrive at the positions they currently inhabit. A migration event in the past would drastically change how habitable each of these worlds are today, giving them a renewed opportunity at hosting life.

Moving onto the second, point of orbital characteristics, the possibility of any of the Trappist planets playing host to an Exo-Moon similar to earth may be taken into account here. One of the simplest methods here would be to analyse the dip in brightness from the transit photometry data from the spritzer space telescope given above, Any sufficiently large Exo-Moon must case a dip in brightness proportional to its radius, which for something of the same relative size of the earth's moon (approximately 1/5th the earths radius) would cause an additional dip that would be easily visible from the highly sensitive telescopic data. As such, an upper bound on the radius of any given Exo-Moon could be established based on the minimum possible sensitivity of the telescope above which it will filter out noise as well, and from rough back-of-the-envelope calculations deems that no moon of any of the planets would be found to exceed about 200-300km. while still relatively large, these would be no more than 1/20th the radius, and would most certainly not be Earth like.

There is also a second way to demonstrate the unlikely-ness of any of the planets containing a moon, using two equations, Hill sphere, and Roche limit. As encountered previously, the hill sphere is the radius around which the gravitational attraction of an object dominates relative to the larger body being orbited (conveniently it is also the distance to the L1 Lagrange point, which will make sense when you consider that this is the point between which the gravitation attraction of the two bodies sums to zero), while the Roche limit is the closest point of approach that a gravitationally bound object may approach a body before tidal forces tears it apart.

$$R_h \approx a\sqrt[3]{\frac{m}{3M}} \quad R_R \approx 2.44R_p\sqrt[3]{\frac{\rho_p}{\rho_m}}$$

Where R_H Is the hill radius, R_R Is the Roche radius, a is the semi major axis, m is the secondary mass, M the primary mass, and ρ is the density of the planet and the object being analysed. (In this case will be something of similar composition to the moon)

Planet	Mass (earth masses)	Radii (earth radii)	SMA (AU)	Rh (mill AU)	Rr (milli AU)	Rh/Rr	Rh/Rr with hill factor
b	0.85	1.086	0.011	0.244	0.120	2.04	0.510
c	1.38	1.056	0.015	0.393	0.141	2.79	0.698
d	0.41	0.772	0.021	0.370	0.094	3.94	0.985
e	0.62	0.918	0.028	0.557	0.108	5.17	1.29
f	0.68	1.045	0.037	0.756	0.111	6.80	1.70
g	1.34	1.127	0.045	1.154	0.139	8.28	2.07
h	0.31	0.715	0.060	0.936	0.086	10.86	2.72

Table 9; Ratio of Roche limit to Roche sphere for the Trappist-1 system.

From the above, we can see that there exists a small window in which anything of similar composition to the Earth's moon may exist, however a good approximation from Stephen R. Kane [29] would lead to a hill approximation of ¼ to account for migration events of moons near the edge of the hill radius. Furthermore, tidal interactions of the incredibly close in system would mean that even for the outermost planets, the possibility of their containing a moon that hadn't left the stable period over the billions of years since formation is incredibly small, such that we may presume it to be zero.

Habitability comparison for orbital characteristics

A highly eccentric orbit causes planetary temperature to fluctuate wildly, causing a planet that may be habitable will become too hot or cold over time. However, the tight arrangement of the Trappist planets demonstrates that they must exhibit incredibly low, possibly zero, eccentricities, as this is the configuration that would have been formed over the billions of years these planets are estimated to have been around, while still retaining their close proximity. Leading on from that somewhat, it can be said that as a system must be stable enough to facilitate the arisal of life (over a long enough period for life to have arisen) the Trappist planets are an almost impeccable example of long term stability, and thus their chance in this regard of hosting life is said to be almost, but not quite, a hundred percent.

Extrapolating from known data, life on Earth arose almost the moment that the planet was habitable enough for simple single celled organisms to survive, however, had Earth become destabilised and potentially flung out of the solar system, or shifted into a much more hostile orbital configuration, this would have been a very short glimmer of life indeed. Yet, the simple fact that life exists on Earth, which itself is known to have a very stable long term orbit, shows that under assumptions made by the anthropic principle "Conditions that are observed in the universe must allow the observer to exist", and "The universe must have properties that make inevitable the existence of intelligent life" [23], it can be such said that the Trappist system ***must*** demonstrate some form of habitability in this regard, as it exhibits a greater stability, which we have said is a strong dependence for habitability than that of the Earth, which itself is inhabited.

Moving on somewhat to address some known issues with the current orbital configuration of the Trappist system, They orbit close enough to the star that they would have lost most, or all of their surface water, had they had any to begin with (see Temperature, and Magnetosphere sections for explanation). However, one process of planetary formation places these objects far from the star,

with the planets then migrating inwards by exchanging angular momentum with the proto-stellar dust cloud. This is the process that is most commonly thought to create orbital resonance (as seen in our own solar system with the ice and gas giants) and would enable a planet to stay further from its host star in the initial unstable billion years or so, and then migrate inwards to warmer temperatures, and thus having lost less water which could still be around today.
As for the feasibility of such a migration event, it is thought to a very high degree of certainty that this process is what caused the configuration of all the large moons in the solar system, while a somewhat modified version of this process is known with certainty to have caused the exact configurations of the Gas and Ice giants of our own planetary system. As to whether the Trappist planets underwent a migration event soon after their formation, it is certainly a possibility, though not certainly great enough to say for certain. As such, this cannot be used to either prove or disprove their habitability in such a regard, until further analysis is available, most likely from the upcoming (as of this time) James Webb Space Telescope.

As discussed somewhat in the section on surface temperature, tidal locking occurs when one side of an object permanently faces inwards, in other words, the year length and day length are equal. From the derived values from earlier, the time taken to tidally lock the Trappist system is under 100 million years, and so it ca be stated with almost certainty that the planets are tidally locked. Within our own solar system, mercury show the less common 3:2 spin lock configuration, in which two full orbits happened for every three rotations, however when we observe other locked systems, we find this configuration to be rarefied, and thus it would not be a mute assumption to state that the Trappist system exhibits 1:1 tidal locking properties. This would mean that only the terminator boundary, the circle of permanent twilight, would be cool enough to support life (unless there was a sufficiently thick atmosphere to allow for thermal transport)

As such, while the system is certainly stable enough to facilitate life, it fails to meet the necessary criterion for planetary temperature due to the certainty of their tidal locked state. Furthermore, as mentioned previously, their chances of having a moon, which would causes their spin never to settle into a stellar tidal lock is near enough zero to as not even be considered.

Magnetosphere

Magnetospheric analysis

The atmospheres of exoplanets orbiting close to their parent stars are particularly vulnerable to high energy radiation and intense stellar wind conditions which could, in due time, lead to complete atmospheric stripping. These factors must be incredibly important to factor in for exoplanets with temperate climates that are dependent on tight orbits, such as those of the Trappist system. An additional complication may be found from frequency of which red dwarfs produce solar flare events, and though they may be weaker than those generated by more massive stars, the close proximity of the planetary system to their parent star would make conditions less favourable for the development of life.

The modelled solar wind strength in the Trappist system ranges from "3 to 6 orders of magnitude higher than that of the solar wind pressure at 1au" [30]. It should be quite visible here that in order for the Trappist planets to host an atmosphere, in these conditions there must exist a magnetic fields of many orders of magnitude greater than that of the Earth.

There is a somewhat simple way to estimate the required magnetic field strength to retain an earth like atmosphere, using what is known as the "standoff distance" to the magnetopause, which is "the abrupt boundary between a magnetosphere and the surrounding plasma" [31]. The standoff distance is where the magnetic pressure of the generated planetary field is equal to the pressure exerted by the stellar pressure, where the pressure of particles already within the magnetosphere is neglected.

$$P_B = \frac{B^2}{2\mu_0}, \qquad where\ P_B is\ the\ magnetic\ pressure$$

$$\rho v^2 = P_{sw}, \qquad \therefore \rho v^2 = \left(\frac{4B(r)^2}{2\mu_0}\right), \qquad where\ P_{sw}\ is\ the\ solar\ wind\ pressure$$

Where ρ and v are the density and velocity of the solar wind, B® is the magnetic field strength of the planet, and μ_0 is the magnetic permeability of free space, defined as exactly 4π Henry per metre. Given that the dipole magnetic field strength decreases with distance as r^{-3}, the magnetic field strength can thus be re-written as:

$$B(r) = \frac{B_0}{r^3}, \qquad where\ B_0\ is\ the\ planetary\ magnetic\ moment\ in\ Tm^3$$

$$and\ thus\ P_{sw} = \frac{2B_0^2}{r^6\mu_0}, \qquad \therefore r = \sqrt[6]{\frac{2B_0^2}{P_{sw}\mu_0}}, \qquad \therefore B_0 = \sqrt{\frac{r^6\mu_0 P_{sw}}{2}}$$

(Where r is the standoff distance of the magnetopause)

And so, we now have an equation to calculate the required magnetic field strength of the Trappist planets. Now, given that the terrestrial magnetopause occurs at 6-12 earth radii (computed as 10) from the surface, we can calculate the required values for the Trappist system given that assumption, and some Magneto-Hydrodynamic Model data from Garraffo et al [30].

Planet	Radius	Maximum modelled pressure	minimum modelled pressure	Required field strength
b	7133 ± 375	$7\text{x}10^5$ P⊙	$2\text{x}10^5$ P⊙	1240 ± 1130 T⊙
c	6830 ± 359	$1.5\text{x}10^5$ P⊙	$9\text{x}10^4$ P⊙	515 ± 447 T⊙
d	4997 ± 263	$5\text{x}10^4$ P⊙	$5\text{x}10^4$ P⊙	119 ± 98.8 T⊙
e	5984 ± 315	$5\text{x}10^4$ P⊙	$1\text{x}10^4$ P⊙	194 ± 179 T⊙
f	6475 ± 341	$1\text{x}10^4$ P⊙	$5\text{x}10^3$ P⊙	113 ± 99.0 T⊙
g	6795 ± 358	$1\text{x}10^4$ P⊙	$2\text{x}10^3$ P⊙	127 ± 117 T⊙
h	4997 ± 263	$7\text{x}10^3$ P⊙	$1\text{x}10^3$ P⊙	42.1 ± 39.3 T⊙

Table 10; required field strength given the modelled solar wind of the Trappist-1 planets

Where P⊙ is the solar wind pressure of the sun at 1 au and T⊙ is the strength of the terrestrial magnetosphere.

From those values obtained, the magnetic field of Trappist-h, which is furthest from the star, would need to range between 2.8 and 81 times the terrestrial field strength in order to maintain a standoff distance of 12-6 planetary radii over the course of its orbit, while for Trappist-b it is required to be between 115 and 2370 times the terrestrial field.

However, such a magnetic field could exist. However, this is found around Jupiter, whose metallic hydrogen core can generate a field strength 20000 times stronger than that of the earths. Yet the possibility of finding such a strong field around any earth like planet, yet alone any tidally locked earth sized planet is ***incredibly*** unlikely, such that we may say it to be virtually zero.

Although we have demonstrated such a magnetic field to be unlikely in its existence, there may still be a chance for some of the outer planets, whose field may be much more manageable to maintain than the astronomically large requirements of the innermost planets. As to how such a magnetic field could exist, it would first be logical to understand what provides the magnetic fields for the planets of the solar system.

There are two main types of magnetic field evident in our planetary neighbourhood, known as “intrinsic” and “induced”. In essence, one is caused by a liquid metallic core rotating fast enough to generate a magnetic dynamo, while the other is caused by the interaction of the solar wind and the ionosphere of a planet. All the planets bar Venus and Mars, and Jupiter’s moon Ganymede exhibit an intrinsic magnetic field, while Venus demonstrates an induced magnetic field.

Maintaining a liquid core is possible at the current sizes of the Trappist planets, four of the seven have radii larger than earth, and thus presuming similar compositions they must have liquid outer cores. As for the other four, the time scale necessary for their core to have cooled sufficiently for any magnetic dynamo to cease functionality hasn’t likely passed yet. Now, whether the rotation rate alone of the Trappist planets is enough to generate a core that gives rise to the strength magnetic field is unlikely. As each of the planets are tidally locked, then for Trappist-h (whose magnetic field we have determined to be most feasible) would have to be generated from an 18 day or so rotation, which if rotation were presumed to be directly proportional to magnetic field strength produced, would give a field 18 times ***weaker*** than the earth’s, ***almost 800 times weaker than necessary***.

Habitability comparison for Magnetospheric characteristics

The magnetospheres of Trappist-1 planets are almost certainly in existence, their planetary hosts are certainly of the correct mass for an earth-like composition to have retained a liquid outer core, and their relatively rapid rotations could most certainly give rise to a magnetic field through liquid metal dynamo processes, however, this result should be taken with a pinch of salt.

Though the likely hood is that any and all of these planets possess a magnetic field, the likelihood that the intrinsic field alone is strong enough to combat the solar wind to give rise to an earth-like magnetopause is highly unlikely, and as such the chances of any of the Trappist planets retaining an atmosphere under the current conditions is most certainly unlikely.

Despite this, using the aforementioned equation to calculate magnetic field strength, if we presume that the strength of a field is directly related to the rotation rate of a planet, we achieve the following table of results, where:

$$B_{planet} = \frac{B_{earth}}{T_{Rotation}}$$

Planet	Radius	Field strength ($T_{\odot}$)	Maximum standoff distance (planetary radii)	Maximum standoff distance (planetary radii)
b	7133 ± 375	0.66	1.07	0.78
c	6830 ± 359	0.41	1.09	0.91
d	4997 ± 263	0.25	1.39	1.25
e	5984 ± 315	0.16	1.33	0.91
f	6475 ± 341	0.11	1.20	0.96
g	6795 ± 358	0.08	1.20	0.83
h	4997 ± 263	0.05	1.60	1.04

Table 11; magnetopause distance given a basic model of the Trappist system.

And so, it can be seen that while the requirements of a magnetic field 2000 times stronger than that of the earth is required to produce a terrestrial magnetopause, the Trappist planets are certainly capable of producing a magnetic field strong enough to, in two cases, completely envelop the planetary surface (given this simple model of course).

Conclusively, we may state that though the Trappist planets can most certainly produce a magnetic field, the possibility that this field is strong enough to produce terrestrial conditions is null. Yet when given a proportional terrestrial field, it is possible for the smaller planets to generate a magnetopause above the surface throughout the entirety of their orbit. From this, it is impossible to conclusively state whether they have the Magnetospheric characteristics that could allow a terrestrial atmosphere, however it would be a safe bet to say otherwise, and so given their possible magnetic properties, it would appear that the system fails to exhibit some of the requirements for life to have evolved there, and as such it is unlikely in this regard that life exists.

There are also several uncertainties in whether the magnetic field of such a planet may arise given the current conditions, yet the possibility for such a field to be amplified by an induced magnetic field from any interactions with the solar wind is possible. However, as with the intrinsic field given above, this is unlikely to give the necessary strength to allow a terrestrial atmosphere to occur in the planetary system.

It can thus be presumed that, even given the exact conditions necessary to have created an atmosphere similar to the earths the likely hood is that over the several billion year timescale of its existence, any and all water would have undergone Photo-dissociation, the process by which a chemical compound is broken down by photons, with the hydrogen leaking into space and the oxygen not long after. Similarly to mars in the most extreme case, the Trappist planets would have been reduced to a near vacuum with a completely inhospitable atmosphere and any and all life that could have once existed on the surface left to perish, leaving it ***very much unlikely*** in any realistic case that any of the planets currently play host to any known lifeforms.

Conclusion

Positive summarised planetary characteristics for the prospect of habitability

The habitability of the Trappist system may be summarised by five main points, as given below, loosely in order of their certainty, from aspects we can directly observe, to those that may be presumed from other given characteristics:

Orbital stability:

Orbital stability, or the ability of a celestial system to maintain the same orbital configuration over astronomical timescales, is thought to play one of the greatest roles in the determination of habitability of an exoplanet, second only to the orbital characteristics of an exoplanet. Had all other characteristics of a planet been perfect for life to develop, an instability in its orbital configuration would be the one to remove it (bar catastrophic mass extinction of course), whether indirectly or no. The sheer importance of most other characteristics on how minimally the orbit of an exoplanet deviates from a circular one, for example, should give ample reason enough.

Within the Trappist system, with the exception of Trappist-h, whose orbital components have yet to be rigorously defined, is an amazing example of orbital stability in both senses of the word. No defined orbit has an eccentricity exceeding or even marginally approaching that of the earths, and their orbital configuration is certainly proved stable over astronomical timescales. As their current resonance state is unstable over any period of time except in some rare cases, the system must be stable, else we wouldn't be able to observe them today in an orbital resonance.

Given their configuration, it would be wise to say that the Trappist system didn't form in their current locations, the tightly knit Laplace resonance between adjacent planets is something that must occur from some form of planetary migration event. There also is the point that had they formed where they were, the system would have required more than 5 earth masses of material within a comparatively small space, which cannot happen under our understanding of the accretion formation model (where Planetesimals coalesce matter from the protoplanetary disk surrounding the Protostar shortly after its formation)

Concerning the migratory past, which we will presume to have happened to the greatest degree of certainty of any other given aspect of the system, the habitability of the system drastically increases. Under the "formed in place" assumption of the system, entire earth's of oceans could have been lost from some of the planets (as much as 15 times the terrestrial surface quantity for the inner planets) during the violent formation period, rendering them barren sterile wastelands. However, as discussed, a migratory event could mean that the planets formed farther from the unstable Protodwarf star, maintaining a vast quantity of any water they possessed, and then had those planets slowly move inwards under a complex set of interactions between planets, their rotation rate, and the interplanetary dust left from the initial nebula.

While the stability of the system doesn't directly influence the habitability of the system in its initial years, it certainly implies events that dramatically increase the likelihood of life originating on any of the systems planetary surface. It is then, once the migration event we presume to have happened to bring them to their current state had occurred, that the stability directly increases the chance of life being maintained. The longevity of the orbital resonance between planets only sees fit to ensure that, given the initial creation of life on any of the surfaces, they could very well play host to a biosphere that has had more than ample evolutionary time to give rise to anything similar or surpassing the terrestrial one.

Habitable zone:

The habitable zone, the set of points around a stellar object at which any orbiting body would be presumed to have a surface capable of playing host to liquid water, is typically the initially cited 'proof' of potential habitability assigned to any planet by astronomers. In more recent years however, the potential for life to exist outside the habitable zone has been more thoroughly analysed, especially in the case of Europa, yet still it is on a habitable zone planet we find life, and so it is for habitable zone planets we look for life.

The Trappist system, being tightly knit around a low mass star, has planets which exist quite certainly within the habitable zone, both conservative and extended, and thus we find evidence that they must, to some degree, be habitable. Trappist d, e, f, and g are the main examples, as all of them exist within the boundary of the extended habitable zone, in the same relative positions as Venus, Earth, and mars. Though empirically only one in three of those planets are habitable, as so by extrapolation Trappist f (which is in the same relative location as the earth) is habitable, this is in a system that has wild variations in size and composition.
The Trappist system are, however, all relatively earth-like by comparison, and so any of them may be host to life given the extrapolation that an earth like planet in the habitable zone may play host to life.

Given their apparent terrestrial similarities in many aspects, it would seem logical then, to conclude that they *must* be habitable to some degree as demonstrated by how perfectly their orbital alignment sits within the habitable zone of their host star. The stability of the planetary system, as demonstrated early, only helps to accentuate that they would have remained in the habitable zone for a vast majority of their lifespan, and will continue to do so for a very long time, only owing to increase the likelihood that they are, again to some degree, habitable.

As such, it is certainly possible that any of the middling planets of the planetary system (d, e, and f) would be habitable purely from this standpoint, and that given some light modification to some of their potential atmospheric and surface properties that any and all of the outer planets would be habitable.

<u>Temperature given atmosphere:</u>
The atmospheric temperature of any planetary body is one such that, given the defined characteristics of a terrestrial atmosphere, their surface temperature would be such that liquid water may exist upon their surface. When performing number crunching earlier in this document, there were two standard atmospheric conditions that were derived from earth, which when given the maximal and minimal values, gave a planetary system capable of hosting water in a vast majority of cases.

Using the upper limits on temperature, the planets of d, and e, were both found to be above zero Celsius, and when taking the minimum limit, the planets of b, and c, were both found to be within the limits of surface water. Though this may be considered to be cherry picking only the perfect cases for validity, it must be taken into account that no two planets are going to have identical characteristics, and as such it is perfectly possible that the planets would have an atmosphere that would allow habitability.

When observing our solar system, we see a vast multitude of difference in the surrounding gaseous layer of a planet, and so it would not be unreasonable to presume that in the Trappist system, there certainly must exist at least one atmosphere that would be beneficial to life, and in fact, given how similar each of the planets are to our own, it would likely be that at least one of those planets have an atmosphere fit for life.

The possibilities that any of the planets could have for their potential atmospheres are perfectly open for speculation, and given how little modification of a terrestrial atmosphere is need for a basic assumption based model to give them similar parameters for earth, it would not be unreasonable to state that the planets themselves could then also host life.

However, the basic ideas that we have been working with throughout this dissertation have been based on a perfectly earth based example, whereas in the actual planetary system, it would be found under many examples that a less earth –like atmosphere would actually benefit each of the planets. For example, a thick Venusian atmosphere would serve to increases the habitability of some of the more distant planets, while a thinner, cloudier atmosphere would sever to decrease the temperature of some of the hotter planets closer to their host star.

As such, while it is impossible to definitively state how an atmosphere may modify the surface conditions of an exoplanet, it would certainly be possible to state that those we see in our planetary neighbourhood would only serve to increase the habitability of the system, and so from this it is likely in this regard that the system of planets must also be habitable.

Subterranean or undersea life:
Moving on to the more speculative, it is certainly a possibility that any of the negative effects found within the system that do impede their habitability may be counteracted by a very simple as that we find happening all over our own planet. Subterranean, "being, lying, or operating under the surface of the earth" [34] would have it said that life that were to exist on any of the planets would instead be found underneath the lithosphere, in caves or other such underground areas. There is also the possibility that under the surface there could exist a vast subsurface ocean, as we believe to be the case for Jupiter's Europa, and Saturn's Enceladus.

Subterranean life would not require nearly as many of the more uncertain aspects of the habitability of exoplanets to be met, and could instead give rise to life that exists on more extreme planets, perhaps even those nomad or orphan planets that aren't gravitationally bound to and star.
By moving the possibility of life beneath the crust, its possibility becomes so much more apparent, a much thinner, possibly even non-existent atmosphere and magnetic field would be required, as the rocky layers above any lifeforms would shield them from intense and damaging radiation, be it cosmic or stellar in origin.

Any subterranean bio-system would also benefit from the possibility of living in what is essentially a closed system, with very few outside events causing to detriment it in any given way. Any life that could have thus evolved to survive in a subterranean environment would also exist outside of the habitable zone of its parent star, as any lifeforms would ***have*** to find alternate ways of generating energy, most probably from chemosynthesis utilising the chemical sludge that exits in undersea geysers or magmatic caves.
Temperatures in any subterranean environment would also be much less volatile than those of any surface dwelling lifeforms would undergo, as their environment would be contained by the thermally insulating rock, and the heated planetary core. Such an energy source would last countless billions of years, as the major component in the steady heat output of the earth's core by comparison is due to the slow radioactive decay of large quantities of heavy radioisotopes with billion year lifespans, most predominately uranium-238.

A subaquatic bio system would also be quite similar in many aspects to a subterranean one, although the surface layer would either be an insulating layer of kilometre thick ice, or some rocky crust over the vast layer of water. On earth alone, we find a huge multitude of life that exists at the bottom of the deepest oceans, many magnitudes of kilometres less than the faint vestiges of solar radiation can pierce. Yet still we find a complex and almost independent bio sphere existing in what is incredibly an extreme environment from our perspective.

As such, though we have no evidence that proves nor disproves the possibility of a subsurface ocean, nor any lifeforms that exist below the planetary regolith, it is certainly a possibility, in fact a strikingly possible likelihood that we would find any form of life in those environments in this planetary system.

Panspermia:
Panspermia, defined as "a theory propounded in the 19th century in opposition to the theory of

spontaneous generation and holding that reproductive bodies of living organisms exist throughout the universe and develop wherever the environment is favourable", and "the theory that life on the earth originated from microorganisms or chemical precursors of life present in outer space and able to initiate life on reaching a suitable environment." [30][31] Is the postulation that life did not originate on a planetary surface, but is instead found as the precursors of such wandering the empty cosmic void until it happens across favourable conditions to facilitate the arisal of life. The biggest idea of panspermia is that life on one planet may, through one process or another, travel between planetary surfaces and create complex biological life on those worlds. This life precursor may be found to originate inside the system, intra-systemary panspermia, or from another star system entirely, extra-systemary panspermia.

Given the tightly packed nature of the Trappist-1 system, the possibility that panspermia can occur is incredibly high, the average distance between any two of the planets at their point of closest approach is only marginally larger than the distance between the earth and moon. Looking within our own solar system, we find that planetary surfaces are exchanged frequently, with many meteoroids found on earth being found to originate from the Martian regolith. Given how many orders of magnitude further away mars is from earth, as is the closest and furthest Trappist planets from each other, the likelihood is that a significant portion of surface material is being exchanged between the planetary surfaces given the time to do so. It would not then be too difficult to imagine a scenario where some form of life had accidentally been carried from one planet to the next, spreading life through the system.

This idea of planetary life hopping is especially important to consider for the possibility that life does occur in the system. Now, in order for life to occur on any given planet it needs only have formed on the most likely planet to host life, and then been transported there atop a hunk of rock. This also gives rise to the chance that life could have persisted, as wiping out the entire population of life on all of the planets, and floating through the empty space between them is incredibly unlikely to occur.

As for the feasibility of this concept, on earth many forms of life have been shown to survive in the harsh conditions of space, most notably the tardigrade and other such extremophiles. Therefore, it is not too much of a stretch of the imagination to say that any of the Trappist planets may host life, given intra- or extra-systemary panspermia.

Opposing summarised characteristics that hinder habitability

Conversely, there exist five key points for the inhabitability of the Trappist system, as follows, again loosely in an order of most well-known to the speculative based on known and defined parameters:

<u>Magnetosphere:</u>
The magnetosphere, " a region of space surrounding a celestial object (such as a planet or star) that is dominated by the objects magnetic field so that charged particles are trapped in it" [35], is the area around which the planetary atmosphere may be maintained against solar erosion.

Within the Trappist system, as based on simulationary models by Garraffo et al [30] demonstrate that the magnetic field required to be generated by the Trappist planets must be several orders of magnitude greater than those of the earth, which if their earth like properties observed are consistent across all of their characteristics, then they must possess a similar field to that of the earth.

From that, any planet capable of generating a magnetic field strong enough to withstand the solar wind at the tiny distances associated with the close knit system would be similar to that of the field generated by any of the major gas and ice giants of our solar system, and most certainly outside the realm of possibility of that that is available for generation from any terrestrially similar planet.

Using that assumption, the Trappist planets would then be found to have magnetic fields that far underperform if habitability for any period of time is to be observed. Even presuming perfect conditions in every other aspect, the magnetic fields that they would be presumed to have given extrapolation from the earth system would cause their atmospheres to take the brunt of the solar win, stripping them of the flimsy protective layer in a short amount of time over the billions of years that we know them to have been around for.

As such, it would be quite impossible for life to have evolved, or at least sustained itself on any of the planetary surfaces. With its atmosphere stripped and the entire surface bare to the force of the solar wind and any cosmic rays that would fall upon it, any life would be sterilised within a few of the short years it could exist, killing off most all of it within a short amount of time, and even the most hardened extremophiles within the time that it could have possibly existed for.

<u>Atmospheric likelihood:</u>
As demonstrated above concerning the possible magnetospheres surrounding the Trappist planets, any atmosphere that they could possibly have would most likely be stripped from the surface rather quickly across the relatively short timescales compared to the current age of the system.

Even presuming an atmosphere similar to Venus, in which the sheer mass of the air around the planet is enough for it to have both maintained itself across the time since its formation, and to have generated a tenuous induced magnetic field would be detrimental to any life that could possibly have arisen there.

Any atmosphere thick enough to prevent the bombardment on it from the stellar conditions would more likely than not contain several compounds that are known toxic to most all forms of life, and would give a most inhospitable surface condition for life. Such a thick atmosphere would also sever to increase the surface temperature such that liquid water is a remote possibility, and that instead life would have to make do with liquid aluminium instead in some cases.

The uncertainty over the atmospheric characteristics of the Trappist system only aids to its potential in hospitability. Given the known details, only a hydrogen dominated, cloud free atmosphere is ruled out for the innermost planets, and so statistically any of the planets may have any possible configuration of atmosphere, or none at all.

Given that there are more configurations of atmospheric structure and composition that would be detrimental to life as that that would be beneficial, it would only be logical to conclude that there I almost certainly a higher chance that life would be impossible on this planet than that it would be possible. Although there exists a configuration where the planet is habitable, there exist countless other configurations that would destroy any possibility of life occurring. For example, raising the Carbon content on earth would lead to many lifeforms undergoing co2 poisoning and dying out completely. Marginally increasing the temperature globally has had drastic consequences for weather patterns which have the potential to completely annihilate and sterilise entire areas of land in one fell swoop.

Another aspect of the atmospheric conditions that until now hasn’t even been touched upon in this dissertation is the weather. Any number of potentially damaging storms and weather events happen on earth all the time, from mega-hurricanes to drought, and so on. Though it is not exactly possible to speculate on the potential weather patterns of a planet so close to an M-dwarf star, it is more than likely to be violent and almost certainly inhospitable.

As such, despite even the best case scenario for life in this system, it is incredibly unlikely that any life could occur, given just how many little perfect alterations that would have to occur to allow this system to have even a tenuous strain of life upon it. Combined with the lack of Magnetospheric characteristics to allow the stable maintenance of any potential perfect atmosphere, and the chances of anything that would even vaguely resemble habitability is reduced to a virtual zero.

Tidal locking:

Tidally locking, where one side of a celestial object constantly faces another body would be absolutely disastrous to life on any planet, but most especially a close knit planetary system. The time period for any of the Trappist planets to have been tidally locked, as demonstrated in the temperature section earlier, is so small compared to their lifespans that the planets may as good as have been totally locked instantly.

A tidally locked planet would have a constant stream of energy directed across half of its surface, with no night side rotation to allow it to radiate any of the excess energy that would deem it inhospitable to life. The inverse of course would be true for the night side of the planet, there would be little chance for that side of the surface to heat up to anything that could possibly allow the maintenance of life.

Instead, a tidally locked planet is now found to be one far too warm on one side, such that water may in fact boil off completely, and the far side be cold enough that the atmosphere itself (given one exists there at all) may in fact condense onto the surface, similar to how the atmosphere on mars condenses into dry ice at its polar ice caps. Instead, the only potentially habitable location on the planetary surface given no other modifiable conditions would be the terminator boundary, a tiny sliver of land that would exist in permanent twilight around the edge of the permanent day and permanent night sides of the planet.

If it were presumed instead, that the planet may poses an atmosphere such that a tidally locked configuration would not detriment the habitability of that world, it would have to be one such that the night side is heated, while the night is cooled. This could be achieved if a strong permanent wind were to blow, allowing quick transport of heated air from the hot side of the planet to the cooler one to allow for some convection beneficial to life.

Now, this is certainly possible, as we see a very mild form of this occur on tiny particles on the moon, however, the constant wind of such a system would mean that any plant life would have to have very string roots and would constantly be battling to stay upright, while any mobile lifeforms would constantly be buffeted and pushed around by this wind. Communication between those lifeforms would be impossible over the permanent howl of whatever wind would occur, and so pack behaviours that is so evident on earth would be nearly impossible.

The other configuration would of course, to have a very cloudy sky surrounding the planet, to block radiation from both the planet and star from passing through. However, when we observer this in the solar system, we find Venus, a completely lifeless and inhospitable rock.

And so, seeing how tidally locking a planet would only aid in its downfall, there exists only one possibility of the planet for it to have survived that, which is of course for it to not have been locked in a 1:1 tidal lock with its parent star. For example, in the solar system, mercury is found in a 3:2 spin lock configuration, which would certainly help distribute heat throughout the Trappist system planets, however when we observer tidally locked celestial objects, we find this to be a rarefied case, and so it is very unlikely that this has occurred in the Trappist system.

The other method that would allow the Trappist system planets to have no been trapped in a 1:1 spin lock with their parent star is through the presence of a sufficiently large moon, so as to counteract that and either lock the planet to the moon, or to have maintained a sufficiently unstable rotation period to this day to have allowed convection beneficial to life. However, as discussed earlier, none of the Trappist planets could play host to any moon that would have any sufficient effect on their rotation period, and as such, they cannot be considered for habitability in this case.

As such, though it may certainly be possible for life to have formed and subsequently survived in a tidally locked system, the required developments for that life to have been sustained are too unlikely to occur, and in most cases would only serve to detriment life further. Furthermore, there are no scenario that exist that would allow for them to have retained any likely configuration of anything baring the 1:1 spin lock configuration that we expect, and so, therefore, we find life unlikely in any of the tidally locked worlds of the Trappist system.

<u>Less stable star:</u>
Trappist-1, being a dwarf star slowly fusing its way through its fuel supply of hydrogen plasma, is inherently stable compared to its more massive cousins. However, this star was not always so, in its past was a violent point of intense energy output that could have, and most likely did, strip any and all water and other volatiles from the surface of any of these planets that would eventually form around the star.

Trappist-1, though weaker in its overall energy output per solar flare we observe from the sun, were it to be placed at the same distance, is surrounded by a close knit system of planets, that orbit ***very*** much closer to the star. As such, the relative strength of normal flares, x-ray, and UV radiation that is felt by even the most distant planet far exceeds that which we have ever been exposed to one earth. When observing the star with the Spitzer telescope, a flare the strength of the Carrington events, the strongest to have occurred in the past century, was observed, which could destroy any lifeforms that would have existed so many orders of magnitude closer than earth was from the star.

As such, eruptions that could occur in the Trappist system would be ten to ten thousand times the strength of some of the most powerful and violent geomagnetic storms observed on earth. Asides from the damaged caused from the associated radiation of such a flare event, the chemical composition of any atmosphere and the lithosphere of the planet would be altered under a regular basis by those eruption events.
The magnetic field requirements to withstand the strength of such a violent flare on any of the Trappist system would thus become nearly twenty thousand times that of the terrestrial field rather that the twenty hundred expected from just nominal orbiting scenario.

The instability of the star also extends back to the formation of the system. A set of very complicated and sensitive set of events are presumed to have been necessary for life to have developed in the first places, which would hardly be helped by the much more violent conditions in the protoplanetary disk.

As such, the only possibility for the Trappist planets to be habitable given their state today would rely on them having migrated inwards from a point further out, where a smaller portion of their volatiles could have escaped. Though this scenarios is certainly likely, in fact it's almost certain, the amount of volatiles that would be lost is still much more than several times that that would have existed on earth. Therefore, though the process is considered certain, the little events that are required for it to benefit life may be considered just a little too great a stretch of the imagination for all but the furthest out planets.

Therefore, life on these planets would as such be incredibly rarefied, as no known lifeforms exist on earth that may withstand such a strong onslaught (except tardigrades and other similar life, but we shall exclude them in this instance). As such, the chances of finding life in existence on any of the planetary surfaces of the Trappist system is incredibly unlikely, and yet again we find a case where the chance is virtually zero.

<u>Solar energy available:</u>
All life as we know it on earth, baring the few cases at the bottom of the earth's oceans, requires energy from the sun in one way or another, be it photosynthesis and subsequent respiration, or eating those photosynthetic beings, and so on.

Therefore, it may be somewhat logical to say that life, as we know it, to some degree relied on photosynthesis, though this itself is much more speculative and less rigorously defined than any of the previous points encountered concerning of the inhospitality of the Trappist planetary system

In the Trappist system, however, as found when looking at the Planckian radiance spectra of the planetary bodies, the central star of Trappist-1 emits mostly in the infrared, with only a small portion in the visible wavelengths which gives it its characteristic dull red.

Photosynthetic life on a planet orbiting an M-dwarf star such as Trappist-1 would have to somehow perform photosynthesis at much lower energies than that which is available on earth. Instead, they would have to absorb energy across a much broader range of photon frequencies, limited by the minimum possible energy to cause the dissociating of water into free hydrogen and oxygen which is so important in the process of photosynthesis.

Another inhibition to habitability is the fact that water strongly absorbs both red and infrared light, which would make less the amount of available energy for aquatic life on M-dwarf planets. This could also affect any land based life if there was a large water content in the atmosphere of any potentially habitable planet, which is something we know must occur as the atmosphere is slowly stripped away.

Something that has also been untouched in this dissertation is the other form of energy delivered to a planet from its parent star. Tidal heating would cause significant geological changes to the planet over the course of its orbit. An example of such would be Jupiter's moon Io, whose tidal heating is strong enough to cause the most volcanic surface in the solar system.
It could be speculated however, that such tidal heating may allow a planet further from the parent star to have temperatures comparable to earth, or at least allowing the development of life, and it is certainly a possibility. However, that possibility is a remote one, as tidal heating would be only one of many things that must go right to allow life.

As such, though this is very loosely covered, and very much speculative, the lack of solar radiation that each of the planetary surfaces receive combined with the dramatic increase in tidal effects than the comparative amount to earth overall do only to detriment any habitability of the system, and reduce the likelihood that life could have, or does exist there were it to require photosynthesis.

Conclusive evaluation of exoplanetary habitability in the Trappist system.

When we take a qualitative look at all of the aspects of the Trappist system, taking the above ten main characteristics and their arguments, we may thus consider its habitability in the full.

The orbital stability of the Trappist system is such that they could maintain, for astronomical timescales, a very habitable surface that would allow life to flourish, however conversely the same stability could just as well cause the planets never to stray far from a configuration that ultimately would lead to a decline in their viability of life. The biggest obstacle that the Trappist system must face were it to be considered habitable would be to somehow create and retain a magnetic field that would allow the potential of an atmosphere.

Though the planets may indeed have a surface temperature that could allow water to exist in specific areas, the lack of atmosphere to maintain it would be detrimental to the development of life. Some simulator research [36] has shown that a thin atmosphere of only 100 milli-bar would be required to allow effect heat transport between the near and far surface of a tidally locked planet, however the lack of magnetic field to maintain such an atmosphere most certainly ruins the possibility of habitability for the planet.

The habitability of a system may not entirely depend on the habitable zone, and as well as that the tidal heating of any of the planets that would occur over the course of its orbit may increase the range of habitability from their parent star. An ice sheet over any water would allow for it to remain liquid, even at lower temperatures and further from the star, and the preferential absorption of red and infrared light of ice from the stellar radiation would aid in maintaining the liquid water. As such, despite what has been discovered, after analysing al of the main points for habitability of the Trappist-1 planetary system, I would actually say that Trappist-1 h poses the greatest chance at habitability. Its distance from parent star would be such that it would have maintained far more surface water than any other planet, and tying into the migratory even we presume to have almost certainly happened, this planet is the most likely to have any water at all, some of which may remain liquid under several kilometres of life, where subaquatic life may use chemosynthetic processes from deep sea geysers to generate the required energy to survive. Though of course, this is all speculative, it is surprising with Trappist-1 h that I would place any bets that life, if at all, were to exist in that planetary system.

Though we would hope that life could be found elsewhere in the universe, it is not to the Trappist system that we should be looking. Thought there exists a perfect case scenario through which they are paradises host to a plethora of life, the chances are that they are inhospitable is many order of magnitude more. Life as we know it then, would be impossible to find on these planets, bar only the hardiest of extremophiles that could under the greatest conditions do so. However, the chances of any such lifeforms arising on the surface of the planetary system is slim, and even less so are the chances of any lifeforms capable of surviving there of traveling to and starting life on those worlds through extra-systemary panspermia. It is with this argument that the entire question would then blow open, were life to have been delivered to the Trappist-1 system by extra-systemary panspermia, where did that life originate from, and so on.

However, it must be noted that with exception to the rare earth hypothesis, it is a possibility that there exists some form of life that we don’t know that could survive on these worlds that we see as so inhospitable. When we consider what they would be life, we see plants that are black in the visible spectrum, or tardigrades. Very few else that we can imagine would be fit for these planets.

Intelligent life is, however, unlikely. The fermi paradox states that if intelligent life were to exist, we should have seen artificial signs, especially given the attention we’ve paid to the planets the last few years, and so his postulation went “If life is common, where are all the aliens?, if life is rare, why are we here?”
There also is the argument that, as intelligent life took so long to occur on earth, there must exist a special set of circumstances available to give rise to it, which considering the chances of normal life being found on the system, we find intelligent life itself to be slim.
And so, the chances of us possibly communication with or observing the artificial constructs of an alien intelligence are virtually zero in the Trappist system, though single celled life may find itself there. After all, it was found when the earth was a much less hospitable place, so why not there?

Evaluation

<u>Shortcomings:</u>

With such a vast topic to focus upon, there is an equally vast quantity of sources centred on numerous different fields for which one can find and utilise. At times, it was incredibly difficult to navigate to a source that contained relevant, concise, and useful information.

There was also the issue that several of the useful and relevant sources were also incredibly specialised, mostly consisting of research papers or theses which could be incredibly difficult to understand without a wealth of background knowledge to rely on.

In order to overcome this, I would continuously research any topics that I didn't fully understand, until I found something that I did, and then slowly work my way upwards from there, using each successive source to build upon my understanding until I had returned to the original document, armed with this new knowledge. I also chose to prioritise sources that were written by, or for, the specialised locations, and skim read them looking for relevant information, to ensure that they would be able to meet my requirements.

In doing so, it is possible that I may have missed some useful sources, but the sheer number of less useful ones that I have been able to eliminate and thus the time that I wouldn't have wasted reading an irrelevant source outweighs any loses from this method.

<u>Successes:</u>

This topic is an incredibly enjoyable one to read and research about, and as such it is never arduous, though at times it is tedious, to research. When looking through any given source of research, there is always some aspect to pique the interest and allow one to speculate, so it is most certainly a fun and informative thing to do, which could most certainly never be called dull under any definition of the word.

The field itself is also one that is incredibly rigorously peer reviewed and fact checked, which meant that most all of my sources were very reliable, and could be used without much fear for incorrect data and information, although some of the sources are older and would have to be fact checked due to the rapid pace that this field is evolving.

This has also meant that all of my sources are very well written and explain logically everything in a clear and concise matter that is easy to understand, when you have the prerequisite knowledge to understand them.

<u>My learned skills and performance:</u>

As this is such a vast and intriguing topic, I found that it was incredibly easy to be distracted and find something else to read about. As such, though it may have been difficult to sometimes stay on task, I was always learning something new that could, generally, in some way be useful later on down the line. For example, I would never have found that Magnetospheric model of the Trappist system had I not been distracted while I was researching the potential of their atmospheric compositions.

However, I also found that when I was focused on a task, though I may take tangents to read relevant or related information, I would always stay on topic and would be difficult to distract. However, this did mean that on some occasion I would have missed useful whole class information given by the supervisor, as I would be so engrossed in reading a relevant source.

In terms of correctly allocating resources, which in this case was mostly managing my time, I found that I could very accurately predict how long a task would realistically take me to do, however I was unable to factor in the random nature of how one topic would lead to the next, ad nauseum, and so I would have to frequently adjust my estimates, and put in extra time on several occasions to account for this.

Following on, I have also learned some key presentation skills, including how to present a difficult topic to a room of people who aren't necessarily specialists, well read in the area, or have even heard of the topic at hand. This was what I found most difficult, especially being able to get over my mild stage fright and fear of talking to large crowds, though this was somewhat mitigated by the class I presented to being only ten persons.

<u>The outcome:</u>
I certainly didn't expect the Trappist system to be as viable for habitability as that of earth, however I was mildly surprised by exactly how inhospitable to life the system is. This may be primarily due to the fact that initial media coverage of the system, which was how I was first exposed to the potential of habitability in the system, drastically misrepresented any information that would have actually been useful, and though I did find the true data, I found that it took a lot longer to get the original wrong ideas to leave.

In short, I believe I have managed to answer and achieve all of the questions and goals I had when I first started this topic, some of them to much more detail than I had originally intended or anticipated. I also believe that I have aptly explained and demonstrated a secondary question, which is "what are the key aspects for exoplanet habitability" and that this has helped my understanding of the topic, and allowed several aspects of this topic to have been used in the dissertation.

<u>Modifications for future:</u>
Were I to undertake this topic again, I would wait until more relevant data and information was available, as more of this dissertation was speculation from available data than I would otherwise have liked, particularly that of the atmospheric composition and properties of the transiting planets.

Having written this dissertation for the planetary system as a whole, were I to do so again, I would choose to focus more on, and go into much more detail on a single planetary example, as I think that I had to generalise far too much and didn't aptly analyse each planet individually, choosing instead to look at them as a whole.

Finally, I would also choose to have perhaps found some way to avoid being side-tracked by information that, while still relevant, would not necessarily be used nor useful for my actual write up, and would instead choose to focus exactly and singularly on only those sources that were ***explicitly*** useful for what I was writing.

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