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M Dwarf Planet Habitability

1. Introduction

The habitability of M dwarf planets has been debated greatly, as their parent stars possess both beneficial and detrimental qualities for the development of life. Initially, the astrobiological community questioned their habitability (Dole 1964), but as research and modeling techniques have improved, astrobiologists have become more accepting of the idea of life on M dwarf planets (Shields et al. 2016). The question of these planets' habitability has great significance, because their long lifespans and commonality in the universe make them legitimate candidates for a plethora of extrasolar spacecraft missions, and potentially for the first discovery of life in other systems.

The guiding research question of this paper is "How do the characteristics of M dwarf systems influence the habitability of M dwarf planets?" In an attempt to answer this question, I have compiled information from the general scientific literature surrounding M dwarf systems, with specific attention paid to the processes in their protoplanetary disks, their distinct stellar properties, and the gravitational processes between their bodies. In this paper, I attempt to illustrate the common conclusions that the scientific community makes about these factors and how they influence the habitability of M dwarf planets. From my research, I have concluded that despite the initial detriments to the development of life that are observed in M dwarf systems, their planets could still very well support life for extended periods of time.

In order to effectively discuss the characteristics of M dwarf systems listed above, this paper will be organized into various sections, each with a different theme. Section 2 provides a general description of M dwarf characteristics. Section 3 involves the formation of M dwarf systems in the protoplanetary disk. Section 4 covers the radiative properties of M dwarf stars, and Section 5 discusses the gravitational processes that occur in these systems. Finally, in Section 6, general conclusions about the research presented in the paper will be discussed.

2. Definition and Characterization of M dwarf systems

The fact that M dwarf stars exist on one end of the stellar classification spectrum means that their characteristics are more extreme than other classes. These unique characteristics that define the stars have a significant impact upon the likelihood of our finding life on their planets. The most prominent trait of M dwarf stars is their small mass in comparison to all other classes. Ranging from 0.08 to 0.5 solar masses, stars in the M spectral class are the smallest of all on the main sequence, and thus are the least energetic at all wavelengths of electromagnetic radiation (Shields et al. 2016 and references therein). The small mass of the parent star in the system begets smaller planets, as there is less mass for embryos to accrete, making the prospect of Earth-mass planets that can retain an atmosphere less likely (Raymond et al. 2007).

A potential lack of massive planets in an M dwarf system is not the only drawback of the stars' low mass, however. The smaller mass of M dwarf stars also means they radiate the strongest at wavelengths longer than all other stars. This long-wavelength radiation effectively decreases the luminosity of the star. The lower luminosity and temperature of M dwarf stars shortens the semimajor axis of the system's habitable zone (HZ), where water can naturally be found in a liquid state on a planet with the correct atmospheric composition (Kasting et al. 1993). Although the requirements of this model add complexity to its meaning, the HZ has been used as a general guide for determining an extrasolar planet's capability of harboring life. With a HZ closer to the parent star, there come a few potential threats to the development of life, primarily through increased exposure to stellar activity and an increased probability of planets in synchronous rotation[1] (Shields et al. 2016 and references therein). Both of these qualities have been speculated to decrease a planet's habitability, meaning that the close HZ of M dwarf stars can raise serious concern in regards to the search for extrasolar life.

Despite these inhibitory characteristics of M dwarfs, there are a handful of traits that support the notion that life can be found on their planets. The primary factor that increases the habitability of M dwarf planets is the extremely long lifetimes that M dwarf stars have on the main sequence[2]. The lifetime of a star on the main sequence is generally expressed as a function with an inverse relationship to its mass (Shields et al. 2016 and references therein). Therefore, M dwarfs, being the least massive stars, have the longest lifetimes on the main sequence, reaching up to 12 trillion years for the smallest stars (Laughlin et al. 1997). This extended period of time in which the star remains relatively stable gives more time for biogenesis and the evolution of life to occur on M dwarf planets.

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[1] Synchronous rotation, also called tidal locking, occurs when there is a significant difference in the tidal gravitational forces from either end of a star on its planet (or vice versa) that slows a body's rotation to the same period as its orbit.

[2] The period of a star's life where it fuses hydrogen into helium and maintains hydrostatic equilibrium.

M dwarfs present a larger sample size with which to locate extrasolar life, as the majority of stars in the Milky Way are M stars (Segura et al. 2005). Given that there are many M stars in close proximity to Earth, it is logical that potentially habitable M dwarf planets will be the first targets for observational missions to extrasolar planets. One such candidate is Proxima b, an Earth-sized planet with a chance of having liquid water oceans that orbits our closest star, Proxima Centauri (Anglada-Escudé et al. 2016). The sheer number of M dwarf planets within our local region, coupled with the fact that they have a decent chance of being habitable, makes these planets valuable to astrobiologists for future research.

3. Early Development Processes and Properties

The early development of a stellar system is integral to the habitability of the planets in the system, as that is when they accrete most of their mass and gain their most basic characteristics that have great impacts on their habitability (Raymond et al. 2007). For example, if a planet is formed with neither atmosphere nor oceans, there is a small likelihood of that planet being capable of housing life later on in its development. There are qualities of M protostars and M planetary embryos that may detract from their habitability during the formation process. Therefore, the planets in M dwarf systems must develop with certain characteristics that allow them to succeed in the face of these harmful qualities.

M dwarf stars have an extended pre-main sequence phase compared to stars of larger classes, lasting up to 1 billion years (Baraffe et al. 1998). This period of stellar evolution is extremely active in terms of X-ray and Ultraviolet (XUV) radiation compared to the remainder of the star’s life (Shields et al. 2016 and references therein). Luger & Barnes (2015) found that if an M dwarf planet is capable of acquiring enough water to become habitable in the early stages of its evolution, its exposure to the star’s heightened XUV radiation for 10 million to 1 billion years can cause extreme water loss. This loss of up to 10 Earth oceans’ worth of water (in the most extreme cases) could alter the planetary evolution so heavily that it would possibly compromise habitability in later stages (Luger & Barnes 2015).

Extreme water loss is not the only negative consequence of M dwarfs’ XUV radiation in the pre-main sequence phase. M dwarfs in the pre-main sequence phase also have the potential of altering the atmospheres of their planets (Shields et al. 2016 and references therein). In their model of the pre-main sequence phase of M dwarf systems, Lammer et al. (2007) concluded that without a strong magnetic moment or high CO_2 mixing ratio, Earth-like planets would be at a significant risk of having their entire atmosphere stripped. The destruction of both water and atmosphere would decrease the capability of life to evolve on M dwarf planets, given that the existence of these traits are widely regarded to be a requirement for biological development (Lissauer 2007; Wordsworth 2015).

Recent research has begun to show that the XUV radiation from M dwarfs during the pre-main sequence phase may not completely dessicate their planets, thus leaving some room for them to harbor life. Bolmont et al. (2016) has shown that an M dwarf planet with a large enough water reserve can retain a sufficient amount of water so as to be habitable following this tumultuous phase of stellar activity. They modeled water loss during the pre-main sequence phase of M dwarf stars, assuming maximum photolysis of water and XUV-driven escape of hydrogen. Their modeling concluded that certain planets in the HZ of smaller M dwarfs lose less than 1 Earth oceans' worth of water, leaving them with significant reserves of water after the pre-main sequence phase (Bolmont et al. 2016). Although the stellar activity in the pre-main sequence phase of M dwarfs has the potential to dessicate their planets, there is still a chance of M dwarf planets retaining habitability in certain cases. Therefore, a final conclusion cannot yet be made determining whether the early activity of M dwarf stars has a substantial impact on their planets' habitability.

The inherent characteristics of the M dwarf protoplanetary disk may also prevent M dwarf planets from being suitable for life. Raymond et al. (2007) asserts that the relatively low mass of M dwarf stars - and therefore the low mass of their protoplanetary disks - creates a scenario in which most terrestrial planets in the HZ of M dwarfs will be small and dry. This is because the embryos forming in the disk in their model did not gather enough mass to initiate significant gravitational resonances that would transport water-rich material to terrestrial HZ planets (Raymond et al. 2007).

High orbital velocities can also have an adverse effect on the habitability of M dwarf planets during their formation in the protoplanetary disk. The close HZs of M dwarf stars beget faster orbital velocities of M dwarf planets in the HZ due to Kepler's harmonic law. Thus, any planets forming in the HZ of M dwarfs will have higher impact velocities with any bodies in the protoplanetary disk, and a high-speed collision with a sufficiently massive object could remove large amounts of atmospheric gases and water from the HZ planets (Lissauer 2007). A loss of atmosphere and water would be devastating for life, and thus the potential for habitable M dwarf planets is weakened with these findings.

More recent modeling of M dwarf system formation has revived the discussion regarding the characteristics of planets formed in the M dwarf protoplanetary disk. Kopparapu (2013) modeled the frequencies of Earth-sized planets (defined as 0.5 to 2 Earth radii) within the HZ of M dwarf stars. It was found that for any given M dwarf star, the probability of an Earth-sized planet orbiting in its HZ was between 0.51 and 0.61 (Kopparapu 2013). This data contradicts the conclusions drawn by Raymond et al. (2007) that terrestrial planets orbiting M dwarfs would have insignificant mass. Assuming that planetary masses similar to that of Earth are ideal for the development of life, there is a higher probability for potentially habitable planets in the HZ of M dwarfs than previously imagined. Based on the complicated discussion above, it is evident that more research is needed in order to make a definitive conclusion regarding the impacts that M dwarf protoplanetary disks have on M dwarf planet habitability.

4. Radiative Properties of M dwarf Stars

Once they arrive on the main sequence, M dwarf stars become much more tranquil in terms of their XUV radiation, but they still experience periods of intense stellar flaring (Segura et al. 2010; Shields et al. 2016 and references therein). Stellar flares come with increased XUV radiation, and historically, the scientific community has had great concern that this increase would be detrimental to the formation of DNA, and consequently life itself (Segura et al. 2005; Buccino et al., 2007; Segura et al., 2010). Although this assertion has not been refuted, Buccino et al. (2007) qualifies it by noting that XUV radiation may in fact enable the existence of life through its energetic synthesization of organic compounds in the atmosphere. Assuming this is true, in order for life to exist on an M dwarf planet, there must be an ideal amount of XUV radiation that is too low to permanently harm the life there, but not so low that it cannot synthesize a sufficient amount of organic compounds (Buccino et al. 2007). In an M dwarf system, this preferred XUV radiation level would likely be found after the star has reached the main sequence.

An increase in XUV flux for a given M dwarf planet may have a significant impact on its atmospheric chemistry, which could indirectly harm life by rendering the planet uninhabitable. To test this, Segura et al. (2010) modeled how the atmosphere of an M dwarf planet with Earth-like characteristics would react to an increase in

XUV radiation from M dwarf stellar flares[3]. The primary impact of this extraneous radiation from the flare was its depletion of water vapor in the upper stratosphere, reaching a minimum of 0.3 parts per million by volume, compared to its equilibrium density of ~30 ppmv (Segura et al. 2010). Further measurements indicate that methane concentrations remained constant throughout the duration of the flare, and ozone density fell by 5% (Segura et al. 2010).

One of the more pertinent implications of this study lies in the partial depletion of the ozone layer in a planet's atmosphere. The retention of ozone is vital to a planet's habitability, as research has shown that with the ozone layer intact, the habitability of an M dwarf planet with an Earth-like atmosphere is almost unchanged in response to the heightened XUV flux from stellar flares (Segura et al. 2010; Grießmeier et al. 2016). However, the ozone layer is not as vulnerable as it was once imagined to be. It is now believed that M dwarf planets subjected to high levels of stellar activity still retain at least 25% of their ozone column (Tabataba-Vakili et al. 2016). In general, it has been concluded that the atmospheric and biological effects of stellar flares and their increased XUV radiation are insignificant. Thus, a planet's habitability will likely be unhindered by the XUV radiation from stellar flares, especially if it had already retained that habitability through the pre-main sequence phase.

The stellar flares from M dwarfs often emit ionized particles along with their increased XUV radiation, and these high-energy particles have the potential to destroy a planet's atmosphere, which is crucial to the habitability of the planet (Ward & Brownlee 2000). In the most extreme cases, upwards of 90 percent of an Earth-like planet's ozone layer could be worn away by ions emitted from stellar flares (Segura et al. 2010). Coronal mass ejections (CMEs) are events in which plasma is released from a star, usually following stellar flares, that can cause atmospheric runaway similar to ionized particle ejections (Kay et al. 2016). Both the ionized particles brought by stellar flares and powerful CMEs are capable of dealing massive damage to the atmospheres of M dwarf planets, and therefore are a major obstacle for these planets and their chances of supporting life.

[3] A specific stellar flare from the star AD Leonis on April 12, 1985 was used as an analog for this study. AD Leonis is approximately 1000 times more active than our Sun (Segura et al. 2010), and the specific flare modeled radiated more than 10^{34} ergs for 4 hours, making it one of the most energetic stellar flares in recorded history (Hawley & Petersen 1991). Therefore, it is acceptable to view the model data as an upper bound of stellar flare influence.

The presence of a planetary magnetic field can diminish the impact of the threats posed by stellar flares and CMEs. Theoretical modeling has shown that magnetic fields are likely to form inside M dwarf planets (Driscoll & Barnes 2015). These fields have the potential to prevent erosion from stellar winds and ionized particles, which would otherwise eliminate planetary atmospheres (Driscoll & Bercovici 2013; Shields et al. 2016 and references therein). However, large CMEs from M dwarfs in their active periods may still deal immense atmospheric damage to planets with a magnetic field (Buccino et al. 2007; Shields et al. 2016 and references therein). In order to alleviate the damage done by such CMEs, the magnetic fields on M dwarf planets would need to surpass the strength of Earth's magnetic field by factors of tens up to hundreds (Kay et al. 2016). Furthermore, the synchronous rotation of an M dwarf planet likely has a weakening effect on its magnetic field (Lammer 2007). Given that synchronous rotation is likely in M dwarf planets in the HZ, this provides another barrier to the habitability of M dwarf planets.

M dwarf stars themselves have large magnetospheres, and their influence on their planets' magnetic fields has some implications for habitability as well. In certain cases, the magnetospheres of M dwarf stars are so large that they interfere with and diminish the magnetic field strengths of nearby planets. This reduction of planetary magnetic fields exposes a larger portion of their atmosphere to erosion via stellar wind (Vidotto et al. 2013). In these cases, Vidotto et al. (2013) asserts that the only two ways an M dwarf planet can retain an Earth-sized magnetosphere is by either orbiting far outside the calculated HZ, or by having a magnetic field ranging from tens up to thousands of Gauss[4]. Since neither of these scenarios are likely, it is safe to say M dwarf stars with exceptionally strong magnetic fields reduce the habitability of their planets. However, in less extreme cases, Grießmeier et al. (2016) deduced that the biological criteria on M dwarf planets with magnetic fields less powerful than planets orbiting solar-class stars will likely go unaffected, assuming atmospheric conditions similar to that of Earth. In general, the prospect of magnetic fields on M dwarf planets increase their habitability, primarily due to the atmospheric protection they provide against M dwarfs' harmful charged events. However, the magnetic fields on these planets probably need to be much stronger than Earth's magnetic field to ensure habitability with greater confidence.

[4] For a comparison, the strength of Earth's magnetic field ranges from 0.25 to 0.65 Gauss.

5. Gravitational Processes and Properties

In any planetary system, the gravitational processes that occur between planets make significant changes to the characteristics of the planets that are linked to habitability. Spiegel et al. (2009) determined that the gravitational interactions between planets in an M dwarf system can cause axial tilts, which can increase the total habitable surface area of a given planet by exposing a greater surface area to light from its star. This finding is even more promising when it is considered that the majority of M dwarf systems have multiple planets (Shields et al. 2016 and references therein). As the average light exposure of the planet's surface area increases, the global climate becomes stabilized, decreasing the chance of a global 'snowball state,' in which the planet freezes over (Armstrong et al. 2014). A snowball state event is a direct inhibitor to the development of life on an M dwarf planet, and thus a decreased chance of this phenomenon strengthens the planet's capacity to sustain life (Spiegel et al. 2009). In general, Armstrong et al. (2014) found that the HZ of a star increases up to 20% on the outer edge, given that planets in that location have significant obliquities.

Gravitational events that occur between planets in M dwarf systems also have the potential to disperse and deliver important volatiles that kickstart the formation of life. This process has been speculated to explain the origin of water on earth, as comets and planetary embryos rich with water in the outer solar system were gravitationally delivered to Earth by gas giants (Morbidelli et al. 2000; Lissauer 2007). Along with water delivery, planets in the outer region of an M dwarf stellar system can transport chemically complex materials that can initiate biogenesis in a process known as panspermia (Buccino et al. 2007). The gravitational interactions between planets in an M dwarf system can increase climate stability, along with transporting valuable organic materials, both of which increase the habitability of M dwarf planets.

Another prominent gravitational process in M dwarf systems that has a significant influence on habitability is tidal locking. Given the closer HZs of M dwarf systems, planets in the HZ of M dwarfs are typically tidally locked, with half of the surface in perpetual darkness (Dole 1964; Kasting et al. 1993). Tidal locking can be an inhibitor to the development of life, as the temperature disparity between the dark and light sides of the planet can cause vital compounds on the dark side to freeze, leading to the collapse of the atmosphere (Segura et al. 2005; Wordsworth 2015). Atmospheric collapse would effectively eliminate the chances of life surviving on any planet. However, an atmosphere that is dense enough with CO_2 (~ 100 mbar, or 10% of Earth's atmospheric mass) can sufficiently transport heat through gaseous advection to prevent atmospheric collapse from occurring (Haberle et al. 1996; Joshi 2003; Buccino et al. 2007; Wordsworth 2015; Shields et al. 2016 and references therein). This effect is observable in our own solar system, as Venus is a nearly tidally locked planet that retains equivalent surface temperatures between the light and dark sides due to gaseous advection in its thick atmosphere (Segura et al. 2005).

A more complete study of tidally locked atmospheric convection done by Wordsworth (2015) determined that oceanic heating and intense tidal heating can also eliminate the chance of atmospheric collapse. An excessive amount of tidal heating, however, can cause a runaway greenhouse state on the planet, rendering it dry and uninhabitable (Shields et al. 2016 and references therein). Tidal locking can present some challenges for the habitability of M dwarf planets, but these difficulties can usually be overcome relatively easily by various planetary processes. Therefore, the tidal locking of M dwarf planets does not pose a significant threat to their habitability.

Although tidal locking is usually seen as an inhibitor to the development of life on M dwarf planets, it actually has the potential to benefit life on M dwarf planets in some cases. For instance, the smaller mass of M dwarfs modifies their spectra to contain less photosynthetically active radiation (PAR), which is the range of wavelengths of light between 400 and 720 nanometers. Since these wavelengths are essential for photosynthesis, a PAR deficiency would place considerable restrictions on the photosynthetic outputs of any organisms on M dwarf planets (Segura et al. 2005). This complication may be resolved in part by tidal locking, as the perpetual illumination on the light side of a tidally locked M dwarf planet could provide a larger intake of starlight to use for photosynthesis (Heath et al. 1999). Not only are the obstacles set forth by tidal locking easily surpassable, but tidal locking also provides one potential method to overcome some of the other challenges presented by M dwarf stars and their characteristics, making its effect on habitability more positive overall.

6. Conclusion

M dwarf stars have certain characteristics that distinguish them from any other stellar class, and each of these traits has an influence on the planetary characteristics and habitability in their systems. Their long lifetimes and abundance in the universe make them viable candidates in the search for extrasolar life, while their unique radiative properties and low masses make their planets' habitability more questionable.

The early activity of M dwarfs during the pre-main sequence phase has the potential to undermine any habitable characteristics M dwarf planets may have, but this activity can also be negated in the right conditions. The lower protoplanetary disk mass of M stars leads one to the conclusion that their planets may also have low mass, which decreases the probability that they can retain an atmosphere. However, recent modeling of terrestrial M dwarf planet sizes makes this assertion less clear.

Increases in XUV radiation from stellar flares have the potential to dissolve a planet's atmosphere, but models of these processes have shown that a planet that has survived the pre-main sequence phase will likely be unaffected by this. Magnetic fields around M dwarf planets provide a safeguard against ionized particles and other dangerous stellar outputs, but still may be overwhelmed by massive CMEs or strong stellar magnetic fields. Thus, more study is needed to make definitive conclusions regarding the effects of magnetic fields on M dwarf planet habitability.

Large planets in the outer stellar system can potentially transport water and other volatiles to planets closer to the star. This transport of organic compounds can significantly increase the habitability of smaller M dwarf planets in the HZ. Tidal locking - a likely trait of M dwarf planets - can collapse an atmosphere, rendering a planet uninhabitable. However, the setbacks caused by tidal locking appear to be easily surmountable, reducing their overall impact on the habitability of M dwarf planets.

Understanding the habitability (or lack thereof) of M dwarf planets is essential to astrobiology, as their long lifespans and commonality in our galaxy make them legitimate candidates for the discovery of extrasolar life. Based on my research for this review, I have concluded that if a planet is capable of retaining its habitability following the initial formation of the M dwarf system, there still is a definite potential of that planet supporting life later on. Although M dwarf planets are faced with many challenges we do not experience here on Earth, their sheer number in the universe raises the probability of at least a few of them being habitable. Some qualities of M dwarf systems discussed in this review are more or less concerning than others, but overall, the potential for life on M dwarf planets is high enough to warrant further research on the matter, and possibly even observational missions in the future.

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[5] Shields et al. (2016) is a review article on the habitability of M dwarf planets, and compiles research done by others in the field. Therefore, the majority of information in this paper cited to this source comes from separate research projects that are correctly cited in Shields et al. (2016).