On the Habitability of Planets around M dwarfs

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Abstract

Since M dwarfs comprise 75% of the stars in our galaxy, including many nearby stars, they may be a critical location to search for habitable planets. Classically these systems have been thought to be inhospitable to life due to concerns such as tidal locking, constant exposure to atmospheric stripping radiation, high levels of magnetic activity, and formation concerns. I address several of these issues, and review current literature on the subject of M dwarfs as habitable stellar systems. The present (somewhat loose) consensus is that M dwarfs are worth targeting for nearby planetary studies.

1 Introduction

The search for extraterrestrial life, even within the local neighborhood of stellar systems, is a tedious and speculative exercise. We are just now beginning to observe a (highly biased) fraction of extrasolar planets in systems near the sun. The possibility of detecting bio-signatures or directly resolving planets is at least a generation of telescope technology away. Until recently we had been able only to extrapolate from our own solar system the conditions for life and the structure of planet–star systems. With the discovery of radically different planetary configurations, we have now entered the era of informed statistical planetary searches.

The ability for a planet to host life is known as habitability. As is apparently seen in our solar system, there may be only certain locations within a stellar system which are capable of harboring life. There are a great number of parameters which are involved in the creation of a habitable zone (HZ), some of which I shall discuss in the sections below. These range from the properties of the parent star, to the formation history and mechanisms of the host planet, and almost certainly contains many factors unknown or unconsidered as of yet.

The HZ is not a static boundary. Stars are known to change in luminosity over their main sequence lifetimes, with our own sun believed to have been as much as 30% fainter than its present luminosity in its youth (e.g. Rampino & Caldeira, 1994). This heating causes the inner boundary where liquid surface water can exist to recede from the star.

The early stages of stellar evolution, when highly luminous protostars settle onto the stable hydrogen burning main sequence, can also be particularly upsetting to the HZ. The outer boundary of the habitable zone is a more ambiguous boundary. “Freeze-out” of liquid water is contingent on both the impinging flux from the parent star on the planet, as well as the planets’ own internal heat and atmosphere. One can imagine a large hot rocky planet with a dense greenhouse gas rich atmosphere sustaining life at 2AU from our own Sun, past Mars’ orbit.

There are many techniques used to search for extrasolar planets today. M dwarfs make good observational targets for finding planets because of their low mass, high number density, and small radius. Radial velocity studies are highly biased towards the “Hot Jupiter” scenario, where planets are very close to their parent star. Since M dwarfs are so low mass, smaller planets can be detected with current technological limits on radial velocity measurements. Their intrinsically small radius also allows smaller transiting planets to make larger fractional effects in their lightcurves.

The size and evolution of the HZ is strongly related to the mass of the parent star in many ways. Stellar mass is correlated with stellar luminosity, which can be a dominant constraint on the HZ boundaries. Figure 1 shows an estimation of the HZ boundaries for a range of stellar masses. Naturally the HZ is much closer for smaller mass stars. The lifetime of the parent star is also highly dependent on the stellar mass, with O and B stars leaving the main sequence in a few 10^7 years, and low-mass M stars living longer than a Hubble time. For sustained habitability, one must look at stars with relatively long and stable lifetimes.

For the lowest mass stars, habitable planets are located within the “tidal lock radius”, the distance at which tidal forces cause the planets’ orbit period to equal its rotation period. These include HZs around most stars of spectral type M, which have masses in the range $0.08M_\odot \leq M \leq 0.5M_\odot$. As I will discuss below, stars in this mass range have many properties, including tidal locking, which may decrease the likelihood of habitability for any orbiting planets. However, M dwarfs make up $\sim 75\%$ of the stars within our galaxy, and as such may be a useful and intriguing hunting ground for extraterrestrial life (e.g. Tarter et al., 2007).

2 Dynamical Concerns

There is not a single preferred method which causes planets to migrate within stellar systems. Dynamical friction in the solar nebula tends to decay the orbits of planets, pulling them closer to the central star in circular orbits. Gap formation may also work to push planets outwards. Orbital resonances between planets can cause a multitude of effects. These range from “inflating” the orbits of many planets (as seen in the Nice model for our solar system), to knocking planets into the parent star or even out of solar system entirely. Inward migrating gas giants may destroy or scatter any habitable planet around a star in the formation of a “Hot Jupiter” type solar system. In summary, the dynamical prospects for HZ planets is always complex, and often grim.

Planetary orbits may become so close to their parent star that they become tidally locked,

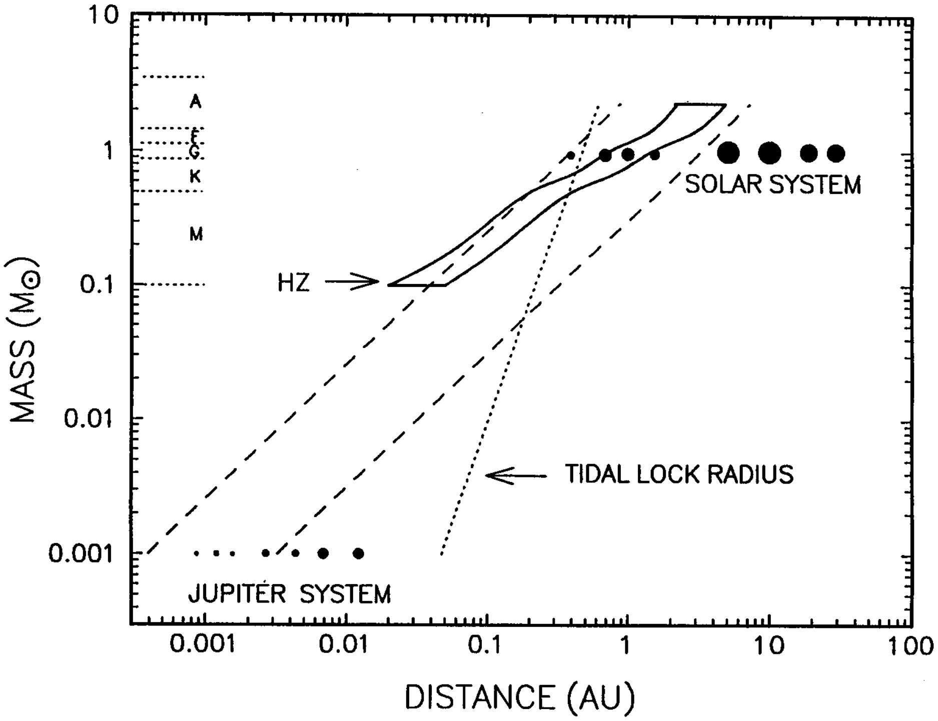

Figure 1: From Kasting et al. (1993), the HZ boundaries for stars with spectral type A–M, as listed on the left.

always keeping one side of the planet facing the star as it orbits. This boundary is noted in Figure 1 above. Not all planets within this radius will be tidally locked. In our own solar system (noted in Figure 1) Mercury is well within the tidal locking radius, but is itself not tidally locked to the Sun. It is instead in a 3:2 resonance, rotating three times every two orbits.

The HZ for an M dwarf is so close in that nearly all habitable planets are at risk of being tidally locked, even at the far freeze-out edge of the HZ. A tidally locked planet faces clear challenges to habitability. The constant exposure to the nearby star is fixed to a single side of the planet. This could create a "night" side which is far too cold, or a "day" side far to hot for life. A small day–night boundary could be the only region capable of sustaining liquid water.

As the freeze-out limit for the HZ can be mitigated by a dense heat-trapping atmosphere, so too can the day–night concerns for tidally locked planets. A very dense atmosphere could thermally distribute the solar radiation to the night side (e.g. Tarter et al., 2007). This could bring enough heat to the eternally dark face of the planet to support life (Joshi et al., 1997).

3 Formation concerns

Creating habitable planets may require more than just having a planet form in the HZ. A protostar which is very metal deficient may not have enough heavy materials to build large rocky planets (e.g. Gonzalez et al., 2001). The metallicity also effects the opacity and timescales of the protostellar nebula, but this is beyond the scope of our discussion here.

It has been suggested that there may be regions of the galaxy where habitable planets are more likely to be found. Gonzalez et al. (2001) argue that a Galactic Habitable Zone may exist. This is a region in the galaxy where a confluence of chemical abundances, age, star formation rate, and stellar density make it more probable that any given star would host a habitable world. They conclude that the inner thin disk of our galaxy is the most ideal location to find Earth-like worlds, with the bulge being host to many rocky planets which are not necessarily in their stellar HZ. It seems likely that galactic scale dynamical mixing is critical in establishing a Galactic Habitable Zone. It is unclear in the context of hierarchical galaxy formation (which is the present preferred scenario) if such a Galactic Habitable Zone concept can be expected to hold beyond simple statistical arguments. Searching specifically for planets around M dwarfs within our own galaxy we are bound to be biased towards older stellar populations where M dwarfs make up an even higher fraction of the stars.

In addition, it seems that M dwarfs with acceptable [Fe/H] values may still form terrestrial planets with low amounts of volatile materials, such as water. Lissauer (2007) investigated the formation timescales of HZ planets around M dwarfs, finding that such planets for much more quickly than around Sun-like stars. This is due to shorter orbital periods and higher densities of planetesimals. Lissauer concludes that such planets, if formed within the main sequence HZ boundaries, would suffer from the increased luminosity and high energy flux from the protostellar M dwarf. This would likely deplete the planet's atmosphere of any useful levels of volatiles, most notably water. In addition, the planet is likely to be smaller, for similar reasons. Lissauer (2007) concludes that M dwarfs are not ideal candidates for HZ planets.

4 Magnetic concerns

The primary concerns for habitability around M dwarfs stem from magnetic activity of the M dwarf. M stars are known to be highly variable, even during their main sequence lifetimes (e.g. see Kowalski et al., 2009). Magnetic activity in the star creates many hazardous effects. Phenomena such as stellar winds, flares, and coronal mass ejections (CMEs) are shielded from Earth's surface by the planetary magnetic field. I describe the habitability concerns for stellar and planetary magnetic fields/activity below.

4.1 Stellar Activity

M dwarfs have very magnetically active lives. Large portions of the stellar interior are dominated by a convective envelope, with stars at spectral types later than about M4 being fully convective (from the photosphere to the core). The convective dynamo, it is thought, creates more magnetic turbulence which must be released at the surface. This takes the form, evidently, of flares, CMEs, and other magnetically driven phenomena. West et al. (2008) found that magnetic activity on M dwarfs declines with age, making long term habitability possible for older stars. They also found a spatial correlation to M dwarf magnetic activity in the galaxy, which suggests the Galactic Habitable Zone theory might be applicable to stellar activity for these stars.

These low mass stars emit up to 100 times more flux in the extreme UV and X-ray wavelengths than solar type stars, even in their quiescent (non-active) state. This radiation is particularly harmful to volatiles (as discussed above) and planetary atmospheres. Khodachenko et al. (2007) and Lammer et al. (2007) investigated the effects of CMEs on the atmospheres of HZ planets around M dwarfs. Using numerical modeling of Earth-like atmospheres and M dwarf XUV flux levels, they conclude that CMEs are able to both heat and possibly destroy the planetary atmospheres. While the impact of such magnetic events is dependent on orbital distance and planetary magnetic field strength (discussed below) it is concluded that the high levels of activity are indeed capable of removing the HZ altogether in some circumstances.

4.2 Planetary Magnetic Fields

Magnetic fields around planets are created by convective dynamos motion in their core. This is driven by the rotation and temperature of the planet, mixing the molten metal core. The strength of magnetic fields for planets and large moons varies greatly in our solar system. The Earth's magnetic happens to protect the atmosphere from ionizing radiation, from sources such as outlined above. This is critical for the habitability of our planet and the survival of our atmosphere.

As the planetary core cools, the magnetic field strength decreases. Eventually a magnetosphere which previously protected a habitable world will not extend above the planet's atmosphere. This happens on timescales of several Gyr for Earth-like planets.

Figure 2 shows three possible configurations of planets, both with and without magnetic fields. In the first case (top) we have an Earth-like planet, whose magnetic field extends beyond the atmosphere and shields it from harmful ionizing radiation and stellar winds. The next case (bottom left) is Venus-like; a planet with no magnetic field (at least above the surface). The stellar wind and radiation ablates the atmosphere, stripping off material into a tail seen to the right. Material is taken from the upper atmosphere, only being stopped by the dense lower atmosphere. The end result of these planets is total atmosphere loss, and are not good for long term habitability. Finally an intermediate case (bottom right) is shown, for a planet whose magnetic field extends within the atmosphere. This will eventually be ablated to look like the Earth configuration.

For the case of planets around M stars, which are likely tidally locked within the HZ, the planet must have a strong and long-term magnetic field protecting it from the high levels of XUV radiation. Lammer et al. (2007) suggest that large planets, likely several Earth mass, would be capable of producing the magnetic field strength needed for long periods of time.

Being tidally locked, however, may inhibit the generation of convection in the liquid metal core, and could diminish magnetic field strength to non habitable levels.

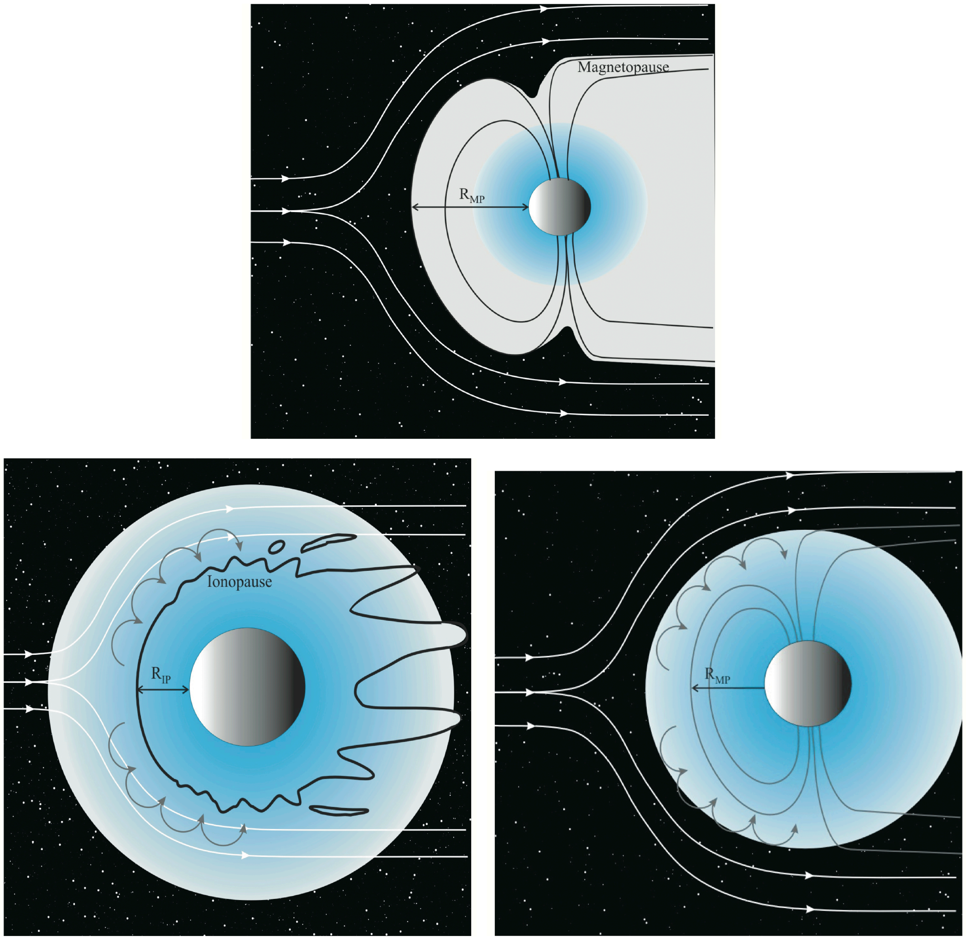

Figure 2: Magnetic field configurations for planets, from Lammer et al. (2007)

5 Conclusions

Many obstacles are present for the sustained habitability of terrestrial planets around M dwarfs. While M dwarfs dominate our local neighborhood by number, they may not be chemically able to develop many rocky planets in their HZs. Those planets which do form in the HZ are very likely to be tidally locked to their star, and may be unable to retain enough volatiles to have the thick atmospheres needed to redistribute heat to the night side. The HZ around M dwarfs is so close to the parent star that any planets will be bombarded with high levels of UV and X-ray flux, enough to possibly strip the atmosphere. Strong transient events such as flares and CMEs only compound this problem. The defense of the planetary atmosphere is further complicated by possible dampening of the planet's magnetic field due to tidal locking and small planet size.

It would then seem that M dwarfs are not a haven for Earth-like worlds. However, for every obstacle they face, there is a possible solution. M dwarfs are not uninhabitable systems. Large, volatile-heavy, terrestrial planets can be formed, and migration forces can conspire to form these planets further our and bring them closer to the star at the right times. Habitability is always more tenuous around M dwarfs, but their sheer strength in numbers makes them interesting candidates for planet searches and understanding planet formation processes.

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