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Special Paper

A Reappraisal of the Habitability of Planets Around M Dwarf Stars

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ABSTRACT

Stable, hydrogen-burning, M dwarf stars make up about 75% of all stars in the Galaxy. They are extremely long-lived, and because they are much smaller in mass than the Sun (between 0.5 and 0.08 M_{Sun}), their temperature and stellar luminosity are low and peaked in the red. We have re-examined what is known at present about the potential for a terrestrial planet forming within, or migrating into, the classic liquid–surface–water habitable zone close to an

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M dwarf star. Observations of protoplanetary disks suggest that planet-building materials are common around M dwarfs, but N-body simulations differ in their estimations of the likelihood of potentially habitable, wet planets that reside within their habitable zones, which are only about one-fifth to 1/50th of the width of that for a G star. Particularly in light of the claimed detection of the planets with masses as small as 5.5 and 7.5 M_{Earth} orbiting M stars, there seems no reason to exclude the possibility of terrestrial planets. Tidally locked synchronous rotation within the narrow habitable zone does not necessarily lead to atmospheric collapse, and active stellar flaring may not be as much of an evolutionarily disadvantageous factor as has previously been supposed. We conclude that M dwarf stars may indeed be viable hosts for planets on which the origin and evolution of life can occur. A number of planetary processes such as cessation of geothermal activity or thermal and nonthermal atmospheric loss processes may limit the duration of planetary habitability to periods far shorter than the extreme lifetime of the M dwarf star. Nevertheless, it makes sense to include M dwarf stars in programs that seek to find habitable worlds and evidence of life. This paper presents the summary conclusions of an interdisciplinary workshop (http://mstars.seti.org) sponsored by the NASA Astrobiology Institute and convened at the SETI Institute. **Key Words: Planets—Habitability—M dwarfs—Stars.** Astrobiology 7, 30–65.

1. INTRODUCTION

STARTING WITH THE WORK OF HUANG (1959, 1960) and continuing with Dole's *Habitable Planets for Man* (1964), astronomers have considered stars whose masses greatly exceed or fall below the mass of the Sun to be inhospitable to biology, particularly the complex, intelligent variety. This conclusion stemmed from simple arguments. Massive stars live their lives too quickly—measured in millions of years—and exhaust their nuclear fuel too rapidly (self-destructing in spectacular fashion) to permit the multi-billion year evolutionary time scales that, on Earth, were required to convert stardust into beings capable of contemplating the stars. While low mass stars have much longer lifetimes, their luminosity is so feeble that any planet would need to be nestled very close to the star to permit the possibility of having a surface temperature conducive to liquid water, which seems to be the *sine qua non* of life as we know it. In such small orbits [0.1–0.35 astronomical units (AU) for an M0 star, and closer still for smaller stars], any planet would become tidally locked to the star. That is, it would keep the same side continuously facing the star (an analog is the Earth's moon). Early, and perhaps overly simplistic, arguments suggested that such a planet's atmosphere would boil off on the star-facing side and freeze out on the dark side—not the most clement conditions for life. As a result, for decades, exobiologists and search for extraterrestrial intelligence (SETI) researchers excluded M dwarf stars from their consideration. However, in 1994, an international conference reconsidered the question of circumstellar habitable zones (HZs) and concluded that late K and early M dwarf stars provide the best opportunity for the existence of environments that are continuously habitable over a 4.6-Gyr period, as was required by evolutionary time scales on Earth (Doyle, 1996). Based on a simple energy-balance model, it was argued that atmospheric heat transport could prevent freeze-out on the dark side (Haberle *et al.*, 1996). More sophisticated three-dimensional climate modeling by Joshi *et al.* (1997) suggested that a surface pressure of as little as 0.1 bar could prevent atmospheric collapse on the dark side, while a surface pressure of 1–2 bars could allow liquid water on most parts of the surface. However, the magnetic activity and consequent flaring of M dwarfs were considered problematic because of the large flux of ultraviolet (UV)-B that would be delivered to the surface of the planet. Later studies (Segura *et al.*, 2005) indicated that abiotic production of atmospheric ozone could mitigate any flare activity. However, because planets in the HZs of dwarf M stars would likely be so very unearthly, they have not attracted a great deal of attention until now.

The discovery of the first extrasolar planet (Mayor and Queloz, 1995) and the realization that type I and II migration plus N-body dynamics can dramatically rearrange the geometry of planetary systems subsequent to their formation (numerous authors in Deming and Seager, 2003) and, thus, deliver and remove potentially habitable planets from an HZ expanded astronomers' attention beyond planetary systems that were exact analogs of our Solar System. This broadening of astronomical perspective combined with the discovery of hydrothermal habitats that are apparently independent of the Sun (Corliss *et al.*, 1979), an increasing appreciation for the incredible tenacity of extremophiles on Earth (Rothschild and Mancinelli, 2001), and the realization that M dwarfs make up perhaps 75% or more of the stars (excluding brown dwarfs) and half of the total stellar mass in the Galaxy (Henry, 2004) have, once again, raised the issue of the suitability of M dwarfs as hosts for habitable worlds. Several authors (for example, Basri *et al.*, 2004) have even challenged their colleagues with conference posters arguing that M dwarfs may be the *favored* locations for the origin and evolution of life.

We have every reason to believe that M stars are favorable hosts for planets. Protoplanetary accretion disks are as common around low mass stars as they are around solar-type stars, with around half of all objects at ages of a few Myr possessing such disks (*e.g.*, Haisch *et al.*, 2001; Liu *et al.*, 2004; Sicilia-Aguilar *et al.*, 2005; Lada *et al.*, 2006). Older debris disks around M stars are thus far rare, but their paucity may be due to the limited sensitivity of previous surveys. One of the very nearest young M stars—the 12 Myr old M0.5 star AU Mic, at a distance of only 10 parsecs (pc)—possesses a prominent cold, dusty disk, which is easily detected by thermal continuum emission and scattered light (Kalas *et al.*, 2004; Liu *et al.*, 2004). The AU Mic disk likely represents a late stage of planetary accretion in which planetary-mass objects have stirred up remnant planetesimals to collide and fragment in a Kuiper Belt-like structure. Thus, the potential for planet formation around M stars appears to be robust.

Ground-based radial velocity searches have been looking for extrasolar planets around several hundred M dwarfs and have found several planets to date (http://exoplanets.org, http://obs www.unige.ch/~udry/planet/planet.html). The lowest mass exoplanets orbiting main sequence stars, with claimed masses of 5.5 and $\geq 7.5\ M_{\mathrm{Earth}}$, orbit M dwarfs (Rivera *et al.*, 2005; Beaulieu *et al.*, 2006). Regardless of whether small planets are preferentially formed around M dwarf stars, the current detection technologies preferentially detect them there. For a given planet mass and radius, both the radial velocity reflexes and the photometric transit depths are larger for lower mass stellar hosts. However, no rocky planets have yet been discovered within an M dwarf HZ, and N-body simulations (Ida and Lin, 2005; Montgomery and Laughlin, 2006; Raymond *et al.*, 2006) provide conflicting answers regarding the likelihood of such planets. Ground-based observations using radial velocity techniques as well as transit photometry may soon resolve the issue.

Plans for increasingly sophisticated space missions to search for terrestrial planets around nearby stars and biosignatures in their atmospheres (*e.g.*, Darwin at http://sci.esa.int/science-e/www/area/index.cfm?fareaid=28, CoRoT at http://sci.esa.int/science-e/www/area/index.cfm?fareaid=39, and the Terrestrial Planet Finder Coronagraph and Inferometer at http://planetquest.jpl.nasa.gov/TPF/tpf_index.html) demand high-fidelity finding lists of nearby stars that are most likely to harbor habitable planets. If these should turn out to be M dwarf stars, then constraints imposed by the planet/star contrast ratio will be eased, but the challenges of spatially resolving a planet in the HZ will be significantly enhanced (Turnbull, personal communication). The Kepler mission (Borucki *et al.*, 2003) is scheduled to launch in 2008 and should provide, within a few years thereafter, the demographics of terrestrial-size planets within the HZs of stars as a function of spectral type, from F to at least M5 dwarfs.

The Allen Telescope Array is currently under construction in Northern California (http://astron.berkeley.edu/ral/ata/), and efficient use of its wide field of view for commensal search for SETI observations requires a large list of target stars around which habitable planets and their life forms might exist. In creating a list of "Habstars" to be used to guide SETI observations with the Allen Telescope Array, Turnbull and Tarter (2003a,b) did not explicitly exclude M dwarfs, except for those that express high levels of chromospheric activity. Even so, the magnitude limit of the parent Hipparcos sample meant that proportionately few M dwarfs ended up in the final target list (~600 M stars of ~19,000 total Habstars). A SETI target list of Habstars incorporates an additional selection criterion related to the stellar age, requiring at least 3 Gyr for evolution to have potentially led to technological civilizations. If M dwarfs are viable Habstars, then additional efforts will be required to inventory the local neighborhood and overcome the biases of magnitude limited sampling.

Although we may soon know whether appropriate planets lie within the HZs of M dwarf stars, we are a long way from knowing whether they are likely to be inhabited. This paper presents the summary conclusions of an interdisciplinary workshop (http://mstars.seti.org) sponsored by the NASA Astrobiology Institute and convened at the SETI Institute to consider what is reasonably known about the topic and what theoretical and observational projects might be undertaken in the near term to constrain the possibilities. Section 2 assesses what is known about M dwarf stars, the formation of planets around M dwarfs, the probable atmospheric characteristics of planets orbiting within the HZ of such stars, and the basic requirements for the origin and evolution of biology on any such planets. Section 3 makes a differential comparison between a G dwarf and M dwarf stellar host, enumerates the most favorable and unfavorable environmental conditions for biology (in a relative way), and examines those processes that might terminate the habitability of a favored planet long before the host M dwarf star ceases fusing hydrogen in its core. In conclusion (Section 4), we suggest a framework for research to be conducted in the next 2 years that should better delimit the constraints on the spectral type and ages of M dwarf stars that may be appropriate targets for missions in search of evidence of life beyond Earth, including that of technological civilizations. A second workshop in 2008 will provide the opportunity for re-examination and further refinements to our approaches.

2. REQUIREMENTS FOR HABITABILITY

2.1. Nomenclature

To deal with large numbers and phenomenology they can measure, but perhaps not understand, astronomers have a long history of using classification schemes that are not always intuitively understood by scientists in other fields or the general public. At the risk of offending some well-schooled readers, this section presents a miniguide to those classification schemes that are used in this paper to discuss the habitability of planets orbiting M dwarf stars.

"M" is a stellar classification based on the characteristic features found in relatively low-resolution spectra, initially obtained at optical wavelengths nearly a century ago. It was later understood that the observable spectral features provide information about stellar surface temperatures and mass, but by then the classification alphabet was well established, requiring the ordering OBAFGKML from the hottest most massive star to the coolest objects, some of which may not be massive enough to be true stars and stably fuse H to He at their cores. These alphabetical classifications also have fractional divisions from 0 to 9, running from hottest to coolest within the class. Colors are also used as an abbreviation for temperatures; as one might expect, blue stars are hot, and red stars are cool. Also, astronomers use the terms "earlier" and "later" to refer to the spectral sequence from hotter to cooler. "Dwarf" (as opposed to supergiant, giant, and subgiant) is a luminosity classification and tells us that a star resides on the "main sequence" (a locus of points in a plot of stellar luminosity vs. temperature) where it will spend the majority of its lifetime in a stable configuration with nuclear fusion as its power source. These same named luminosity classes are also numbered for abbreviation; I, II, III, IV, and V runs from supergiant to dwarf. Our own Sun is spectral type G2 and luminosity class V (or dwarf). Less massive dwarf stars are cool, such as M dwarfs. The length of time a particular star remains on the main sequence and the rate at which the end phases of its evolution cause it to expand, contract, change its surface gravity, and, therefore, appear within other luminosity and spectral classifications are determined by its mass. Massive stars consume their nuclear fuel rapidly, while M dwarfs remain stable for a very long time. In the history of the Milky Way Galaxy, no M dwarf star has yet had sufficient time to evolve away from the main sequence and end its life.

Since the human eye is a logarithmic sensor, astronomers have historically used a logarithmic or magnitude scale for recording and relating stellar brightness. On this scale, a difference of 5 in magnitude implies a factor of 100 difference in the brightness, and the sense of the comparison is such that a 6th magnitude star is 100 times fainter than a 1st magnitude star. The zero point of this scale is set by observations of A0 V stars, which are assigned a magnitude of 0. To distinguish between the brightness of a star as it appears on the sky, which depends on its distance, and the intrinsic luminosity of the star, there are two magnitude scales: apparent magnitudes,

Table 1. Basic Characteristics of Stars with M Dwarf Characteristics

Spectral type	M_V	M_K	*V-K*	*Temperature*	*Mass*	*Luminosity*
Sun (G2V)	4.8	3.3	1.5	5,800	1.00	100%
M0 V	9.0	5.3	3.8	3,900	0.50	6%
M3 V	11.7	6.8	4.9	3,600	0.29	3%
M6 V	16.6	9.4	7.2	3,000	0.10	0.5%
M9 V	19.4	10.5	8.9	2,400	0.08	0.02%

which are designated as lowercase m, and absolute magnitudes, which are designated as uppercase M and defined as the apparent magnitude that a star would have if it were at a distance of 10 pc (~33 light years) from the observer. Observations were historically made with the naked eye, then eyes with telescopic assistance, then recorded on photographic plates, and now recorded with instrumentation spanning a much larger range of frequencies than can be perceived by the human eye. Each of these sensors has different sensitivities over different spectral ranges. Significant energy has been expended and continues to be invested in calibrating different measurement results against one another. One approach is to attach a letter designation to magnitude measurements, where the letter indicates the spectral band and response of the receiver, *e.g.*, M_V denotes absolute magnitude as measured in the visual or V band. The difficulty comes in practice when not all "V" bands are the same, but that level of detail is beyond the scope of this paper. Common spectroscopic bands are: U (UV), B (blue), V (visual), R (red), and I [infrared (IR)], plus J, H, and K (other near-IR). The difference between the brightness of an object in two spectral bands, *e.g.*, M_B-M_V, is an astronomical color and designated (B-V). In contrast to these wavelength-specific measurements, astronomers use the term bolometric to connote a property, such as luminosity, that includes contributions from all wavelengths.

Finally, because of the ungainliness of astronomical quantities when expressed in cgs or other scientific systems, astronomers tend to use relative measures, *e.g.*, the mass of an object expressed in terms of the mass of the Sun ($M_{\mathrm{Sun}} = 1.99 \times 10^{33}$ g), the distance light travels in 1 year (l year = 9.46×10^{17} cm), or the pc, which is the distance of an object whose measured angular parallax is 1 arc sec (1 pc = 3.08×10^{18} cm).

Most of the stellar members of the solar neighborhood and, presumably, the Universe are red dwarfs (low mass, cool, main sequence stars). They make up at least 75% of all stars (excluding brown dwarfs) and continue to be found at distances less than 5 pc (Henry *et al.*, 1997; Jao *et al.*, 2005; Henry *et al.*, 2006). These objects span a huge range in brightness ($9 < M_V < 20$), have masses between 0.5–0.6 and 0.08 M_{Sun} (Delfosse *et al.*, 2000; Henry *et al.*, 2004), and have been assigned spectral type M. Because of their overwhelming numbers, they contribute more to the total stellar mass budget of the Galaxy than any other spectral-type star, even at their relatively low masses. Their intrinsic faintness makes them elusive, evidenced by the fact that not a single one can be seen with the naked eye.

Table 1 outlines the basic characteristics for stars that represent the broad range of M dwarf characteristics, with our Sun as a benchmark. Absolute brightnesses at optical (M_V, 0.55 μm) and IR (M_K, 2.2 μm) wavelengths are provided, as well as a broad baseline color (V-K). Guidelines for effective surface temperatures and the masses and luminosities relative to our Sun are also listed. It is worth noting that, for the later M types, the mass inferred from color temperature can depend on age (younger stars are hotter, then cool off).

Given that a magnitude of 1 corresponds to a factor of ~2.5 in brightness, one notes that an M0 V star produces only 1.9% of the light in the visual band as the Sun, but 16% of the light in the IR K band. Corresponding values for an M9 V star are 0.00014% at V and 0.13% at K. Thus, the balance of radiation relative to our Sun is very different for M dwarfs, which produce relatively more IR radiation than visible.

The range of different stellar environments is larger for dwarf stars defined as spectral type M than for any other stellar type. The full gamut of stellar spectral types runs OBAFGKML. To match the range in visual brightness of the M dwarfs (magnitudes 9.0–19.4), more than four full spectral types of stars are required: A0.0 V stars have

M_V ~0, whereas K7.0 V stars have M_V ~9. When considering stellar mass, which is arguably the single most important characteristic of a star in that mass determines nearly every other characteristic, the factor of 6 in mass from M0.0 V to M9.0 V is again only matched by spanning types AFGK.

In summary, M dwarfs are low mass stars that span a substantial mass range (~0.1 to ~0.5 solar masses) and exhibit a wide range of fundamental properties. During an extended youth (ages less than ~1 Gyr), they are significantly more magnetically active at UV and X-ray wavelengths than solar-type stars and exhibit powerful flares whose radiation could inhibit the emergence of life. They dominate the local stellar population by number and contribute approximately half of the stellar mass in the Galaxy.

2.2. The stellar properties of M stars

As described above, M stars have relatively low stellar temperatures, which makes their light red. They also have smaller radii (the size scales approximately with the mass), so that a 0.1 solar mass object is roughly 0.1 solar radii as well. This accounts for their low luminosities, though one could also say that these low luminosities are caused by the low central pressure and temperature required to support the lower mass against gravity, which leads to much smaller nuclear fusion rates. On the other hand, the surface pressures are actually higher than for solar-type stars despite the low mass (because gravity is an inverse square force). Because of the low outer temperatures and high pressures, the atmosphere can support molecules as well as atoms, and the optical and IR spectra are dominated by molecular bands. In the optical, these arise from heavy metal oxides like TiO and VO, not because those molecules are abundant but because they happen to have high optical opacities. In the IR, the spectrum is dominated by steam and carbon monoxide spectral features.

The high outer opacities and generally lower temperatures throughout mean that the interior opacities are also higher, and the stars find it easier to move luminosity outward by convection rather than radiation throughout their bulk. This convective mixing has the effect of making the whole star available as nuclear fuel. Given that the Sun only burns 0.1 of its mass (because of its radiative core), coupled with the fact that M stars have much lower luminosities, this makes their hydrogen burning lifetimes (the main sequence) much longer. These can range from 50 Gyr for the most massive M stars to several trillion years for the least massive ones. The mixing also means that the core composition has an extremely slow gain in mean molecular weight and a consequently very slow change in emitted flux. This is in contrast to stars like the Sun, in which hydrogen is converted to helium in an isolated (nonconvective) core, and the relatively faster increase in mean molecular weight results in a steady brightening of solar-type stars even while on the main sequence. As a result, the HZ (discussed next) for an M star stays in place for much longer as well, and the continuously HZ is a much larger percentage of it. Thus, if a planet exists in the HZ of a typical M star, it may remain in that zone for 100 Gyr. In essence, therefore, M stars last so long that the length of habitability becomes more of a planetary than a stellar issue. An important exception to this could be the effect of magnetic activity on the star; we defer discussion of this until subsection 3.1.

2.3. The HZ

The HZ is a concept that is used extensively in the context of searching for planets that might be suitable abodes for life. There are a number of different definitions of the HZ (*e.g.*, Dole, 1964; Heath *et al.*, 1999), but here we define it as that region around a star in which a planet with an atmosphere can sustain liquid water on the surface. This is because liquid water is the basic requirement for life on Earth, so its presence would appear to be the most important criterion for including a given location in any search for life, if indeed any selection of locations is desirable in the first place. An additional reason for the choice of this definition is that extrasolar planets on which liquid water and life are present at the surface should be observable spectroscopically in a search for evidence of life (Leger *et al.*, 1993; Angel and Woolf, 1996; Tinetti *et al.*, 2005), whereas subsurface biospheres may not be detectable.

The nature of the HZ around F, G, and M stars has been dealt with elsewhere (Kasting *et al.*, 1993; Heath *et al.*, 1999), and the reader is referred to those papers for detailed overviews of the subject. We only summarize some of their results here. The outer and inner edges of the HZ are defined as those values of the stellar insolation (SI) at which liquid water ceases to be stable at a planetary surface. In terms of actual size, the HZ around an M dwarf will be smaller in size than the HZ around a G star. The edges of the HZ are closer to the star because of the lower luminosity of M dwarfs and the inverse square law decrease of radiation with distance. The wide range of M dwarf masses means that the width of the HZ will vary by an order of magnitude from 0.2 AU to 0.02 AU. The seriousness of this constraint on habitability, given the likelihood of a planet forming at a given distance from its star, is discussed in subsection 3.2.

For the outer edge, Kasting *et al.* (1993) considered that, on geological time scales, the amount of CO_2 in the Earth's atmosphere is controlled by processes such as weathering. The dependence of weathering rate on temperature ensures that, if a planet's surface freezes, weathering ceases, and CO_2 builds up in the atmosphere and thus warms the planet up again. This negative feedback acts to extend the width of the HZ outward in terms of distance from the parent star and lower values of SI. The limit to the negative feedback, *i.e.*, the outer edge of the HZ, occurs at that value of SI at which CO_2 condenses in the atmosphere, rendering the weathering feedback irrelevant.

The inner edge of the HZ can be defined as that point at which a planet's stratosphere (which on Earth lies between 15 and 40 km in altitude) changes in composition from being orders of magnitude drier than the surface (as it is on Earth) to being almost as wet. The rate of hydrogen production from water photolysis in the middle atmosphere increases accordingly, as does escape of hydrogen to space. Over time, the planet's surface dries (Kasting and Pollack, 1983). A number of caveats on this mechanism, such as climate feedbacks, are present and are reviewed by Kasting *et al.* (1993).

An M dwarf presents specific issues for the habitability of planets that lie in the HZ. For decades, the main problem was thought to be tidal locking; a planet in the HZ of an M dwarf would lie so close to its parent star that it was very likely to become tidally locked. In other words, the planet always presented the same face to its star, much as Earth's moon does to the Earth (Dole, 1964). It was assumed that a consequence of locking was that atmospheric volatiles would freeze out on the dark side on the planet and result in an atmosphere where the surface pressure is controlled by a balance between the latent heat of condensation and radiative cooling on the dark side. Such an atmosphere would have a surface pressure orders of magnitude below that of present-day Earth and far below the triple point of water—the minimum pressure at which water can stably exist as a liquid. It would therefore be considered not habitable.

The above view was first challenged by Haberle *et al.* (1996), who used an energy balance model that parameterized atmospheric heat transport to show that an atmosphere containing only 100 mbars of CO_2 transported enough heat to the dark side to prevent freezing of volatiles. The result of Haberle *et al*. (1996) was given significantly more weight by Joshi *et al.* (1997), who explored the sensitivity of surface temperature gradient to factors such as surface pressure and atmospheric IR optical depth using a three-dimensional global circulation model that actually simulated the climate and weather of the atmosphere. They, like Haberle *et al.* (1996), found that approximately 100 mbars of CO_2 was enough to prevent atmospheric collapse. Joshi (2003) showed that inclusion of the hydrological cycle (including advection of water vapor) on a tidally locked Earth did not destabilize the climate, and achieved qualitatively similar results to Joshi *et al.* (1997).

Note that the above studies are "worst-case" scenarios. For instance, not all close-in planets become tidally locked; another possibility is that they have a spin/orbit resonance like Mercury, which rotates three times every two orbits around the Sun. If a planet is not tidally locked or the effect of heat transport by oceans is included, the temperature difference between day and night will be significantly lower than the model predictions. It is perhaps counterintuitive to think that atmospheric motions can dramatically change the surface environment of a planet. Nevertheless, the models do show that while tidal locking might alter the expected edge of the HZ (see below), it can no longer be considered a serious barrier to habitability.

For a given SI, the substellar point (SP), the location directly beneath the star, is warmer than if the stellar radiation was distributed evenly in longitude (Joshi, 2003). Thus, one might expect the inner edge of the HZ (as defined by a wet stratosphere) to happen at a lower value of SI than is the case for a G star. On the other hand, climate model studies show that the planetary albedo of an ocean-covered synchronously rotating Earth is 0.35, which is 20% higher than if tidal locking did not happen (Joshi, 2003). A higher albedo would move the inner edge of the HZ nearer its parent star. The rise is due to the presence of ice and clouds, and works in the opposite direction to the relatively low planetary albedo expected of a planet orbiting an M dwarf (Kasting *et al.*, 1993).

The distribution over wavelength of the UV radiation from M dwarfs could lead to a different photochemistry in their planets, moving the outer edge of the HZ away from the star, because gases such as CH_4 or N_2O might exist in much higher concentrations than on Earth (Segura *et al.*, 2005). The CO_2 condensation limit would no longer apply, as even without any CO_2, significant greenhouse gases would exist in the atmosphere. This effect would make the HZ wider.

Kasting *et al.* (1993) used the concept of a continuous HZ to take account of changes in SI over billions of years. Since M dwarfs are very long lived, the continuous HZ might exist for an order of magnitude longer in time around an M dwarf than around a G dwarf. The time that life would have to take hold on a planet orbiting an M dwarf would, therefore, be much longer, and life might, therefore, be more likely on such a planet. Such considerations are, of course, based on the premise that a planet orbiting an M dwarf could keep a substantial atmosphere despite the various loss processes that would inevitably occur. This is discussed in subsection 3.3 below.

While the amplitude of long-term variability of SI on an M dwarf is small, short-term variability might present a problem. For instance, stellar radiation can oscillate by several percent on time scales of days because of rotationally modulated starspots (Rodono, 1986). However, Joshi *et al.* (1997) showed that an atmosphere that has a surface pressure of 1 bar would not freeze out even if subjected to a starspot that reduced SI by 40% and lasted a month. In addition, a tidally locked planet would be prevented from undergoing large swings in obliquity that might destabilize climate. A tidally locked planet in the HZ of an M dwarf would have an orbital period of days to weeks (Heath *et al.*, 1999), and so the climatic consequences of an eccentric orbit would be heavily damped by a planet's atmosphere and oceans. We further discuss the effects of stellar variability and, indeed, orbital variations in subsection 4.2.6. The effects of flares, which might present an obstacle to habitability (Kasting *et al.*, 1993; Heath *et al.*, 1999), are also considered later in subsection 3.4. The potential effects of coronal mass ejections are discussed in papers by Khodachenko *et al.* (2007) and Lammer *et al.* (2007) in this issue.

To summarize, the limits of the HZ around an M star might be expected to be defined by similar processes to those that define the limits around a G star. However, the atmospheres of planets in the HZ of M stars would certainly be very unfamiliar to us in terms of their circulation, radiation, and chemistry. However, if planets can keep their atmospheres and water inventories, none of these differences presents a large obstacle to their potential habitability. Therefore, from the point of view of atmospheric and climate science, planets in the HZ of M dwarfs should have almost as high a chance of being habitable as planets in the HZ of G stars.

2.4. Planets within the HZ

The formation of planets around M stars requires that the protostar be surrounded by a protostellar disk with sufficient material. Primordial (optically thick) circumstellar disks are readily detected by their strong thermal IR emission, far above that produced by stellar photospheres. Both ground-based and space-based IR surveys have identified many disks around low mass stars and brown dwarfs in the nearest young star-forming regions (*e.g.*, Muench *et al.*, 2001; Jayawardhana *et al.*, 2003; Liu *et al.*, 2004; Luhman *et al.*, 2005), with about half of the low mass population (spectral type of M0–M9) having disks. In at least some cases, the masses of these primordial disks appear to be quite substantial, about a few percent of the stellar host mass (*e.g.*, Andrews and Williams, 2005). Thus, it appears that M stars are as likely a venue for planet formation as more massive stars.

Less theoretical work has been done on planet formation around low mass stars because of the emphasis on explaining the origin of our own planetary system. Our terrestrial planets are universally thought to have formed through the collisional accumulation of successively larger solid bodies—starting with submicron-sized dust grains, through kilometer-sized planetesimals, Moon-sized planetary embryos, and culminating after about 30 Myr in the formation of the Earth and the other terrestrial planets (Wetherill, 1990). Wetherill (1996) extended his Monte Carlo models of collisional accumulation to include the case of lower mass stars. He found that Earth-like planets were just as likely to form from the collisional accumulation of solids around M dwarfs with half the mass of the Sun as they were to form around solar-mass stars. More recent modeling by Ida and Lin (2005) investigated the effects of varying stellar (and presumably protoplanetary disk) metallicities and mass. The results are consistent with the detection statistics on exoplanets and predict a peak in formation of Neptune-mass planets in short orbits around M stars. Simulations by Montgomery and Laughlin (2006) suggested that terrestrial mass planets form consistently in the HZ of late-type M stars, whereas Raymond *et al.* (2006) found that it may only be the early-type M stars that form terrestrial planets within the HZ having sufficient mass to retain an atmosphere and a favorable water content.

Because the collisional accumulation process is inherently stochastic, it is not possible to make definitive predictions regarding the outcome of a given set of initial conditions for the protoplanetary disk, but basic trends can be discerned, of which perhaps the most important is the effect of Jupiter-mass planets on terrestrial planet formation (Wetherill, 1996). If a Jupiter-mass planet forms prior to the final phases of terrestrial planet formation, as seems to be necessary to explain the gaseous bulk composition of a Jupiter-like planet, then the location of such a massive gravitational perturber can have a controlling influence on the formation of Earth-mass planets in the HZ of solar-mass stars; a Jupiter closer than about 4 AU to its star could prevent the growth of Earth-mass planets at 1 AU. In the early stages of planetary evolution, it may well be necessary for life to have a long-period Jupiter-sized planet to scatter water-bearing planetary embryos toward inner planets as was the likely case for the early Earth (Morbidelli *et al*., 2000). In later stages, a Jupiter-like planet could intercept and reduce the cometary flux onto the inner planets that might otherwise frustrate the evolution of advanced life though periodic catastrophic impacts (Wetherill, 1994). N-body simulations with many more particles by Raymond *et al.* (2007) suggested that the delivery of water to terrestrial planets near the HZ is statistically more robust than previously thought, particularly if the water-bearing embryos form slowly. A long-period Jupiter might then be a prerequisite for a habitable Earth-like planet.

Interstellar dust is the main contributor to the formation of accretionary disks and, thence, to the formation of Earth-like planets. The interstellar dust consists largely of silicate minerals, mostly olivine and pyroxenes (Draine and Lee, 1984; Adamson *et al.*, 1990; Greenberg and Li, 1996), or of amorphous condensates in the multicomponent system MgO-FeO-SiO_2 (Rietmeijer *et al.*, 1999; Rietmeijer *et al.*, 2002a,b). Judging from the relative intensities of the silicate and "organic" bands in the IR spectra, a surprisingly large fraction, about 10%, of the mineral dust grains in the diffuse interstellar medium across our galaxy and even in neighboring galaxies consists of organics (Sandford *et al.*, 1991; Pendleton *et al.*, 1994). Most of these organics are expected to survive intact the accretionary processes leading to planetesimals and comet-sized bodies. A smaller but still significant fraction may survive collisions between planetesimals and even cometary impacts on larger planets such as the Earth (Chyba, 1989). In this way, organics that formed in the outflow of distant dying stars (Dey *et al.*, 1997; Matsuura *et al.*, 2004) and persisted for hundreds of millions of years in the interstellar medium may have contributed to the pool of complex organic molecules on the early Earth from which life arose.

The organics associated with the interstellar dust have the spectroscopic signature of fully saturated (aliphatic) hydrocarbons, in which C atoms are linked to other C atoms by single bonds and each C atom is bonded to either two or three H atoms. They are essentially straight or branched C_n chains, where n can be a large number, such as in carboxylic (fatty) acids or parafinic sections linking more sturdy polyaromatic hydrocarbons (Sandford *et al.*, 1991; Pendleton *et al.*, 1994; Pendleton and Allamandola, 2002). How the delicate saturated hydrocarbons survive the intense UV radiation field that permeates the diffuse interstellar medium and the incessant bombardment by high-energy particles has long been a question of great interest and discussion.

Various models have been proposed, of which the "core–mantle" concept (Greenberg, 1968) has received the widest attention (Sandford *et al.*, 1991; Allamandola *et al*., 1999). It is based on the assumption that dust grains that form in the outflow of stars acquire a layer of ice composed not only of H_2O but also other gaseous components such as CO, NH_3, etc. Through UV photolysis in the ice matrix, organic molecules would form that, upon sublimation of the ice, will remain on the grain surface as a thin veneer (Greenberg *et* *al.*, 1995). Such a thin veneer of organic matter on the surface of grains, however, is not expected to survive for long the intense radiation field and constant sputtering in the diffuse interstellar medium. Another model (Mathis *et al.*, 1977) postulates separate grain population of silicate minerals and hydrogenated amorphous carbon to account for the observed IR spectral features and the dielectric properties of the dusty interstellar space (Draine and Lee, 1984; Draine, 2003; Zubko *et al.*, 2004). It is in disagreement with the observational fact that the silicate-to-organics ratio throughout our galaxy and even other galaxies is surprisingly constant, at about 10:1, in spite of very different conditions of dust formation in different astrophysical environments.

Recently, a dust grain model was presented, based on the laboratory observation that C-H bonds can form inside the mineral matrix (Freund and Freund, 2006). The model treats the organics associated with the dust as C_n–H_m entities embedded into the mineral matrix of the dust grains, the combination forming a single phase, solid solution. This model appears to be most consistent with the astronomical observations (Sandford *et al.*, 1991; Pendleton *et al.*, 1994). It explains both the complexity and hardiness of the organics in interstellar space and their survivability through time and space.

While a general consensus exists regarding the basic mechanism for terrestrial planet formation, the situation is quite different for the formation of giant planets. The conventional wisdom is that gas giant planets form by the process of core accretion, where a roughly 10 Earth-mass solid core forms first by collisional accumulation, and then accretes disk gas to form a massive gaseous envelope (Pollack *et al.*, 1996). However, even when the surface density of solids is high enough for runaway accretion (Lissauer, 1987) to assemble a seed mass for the solid core in about 0.5 Myr, the time scale for subsequent growth and accretion of the gaseous envelope can be sufficiently long (typically a few to 10 Myr) to raise the danger that the disk gas will have dissipated well before the solid cores can accrete enough gas to grow to Jupiter-mass. Instead, "failed cores" similar to Uranus and Neptune might result. An alternative mechanism has been proposed and investigated, where gas giant planets form rapidly through a gravitational instability of the gaseous portion of the disk (Boss, 1997, 2001). Disk instability can occur within thousands of years, well before the disk dissipates, and if this mechanism occurs, it would presumably outrace the core accretion mechanism.

Boss (1995) studied the thermodynamics of protoplanetary disks around stars with masses from 0.1 to 1.0 solar mass and found that the location of the ice condensation point only moved inward by a few AU at most when the stellar mass was decreased to that of late M dwarfs. In the core accretion model of giant planet formation, this implies that gas giant planets should be able to form equally well around M dwarf stars and, perhaps, at somewhat smaller orbital distances. However, the longer orbital periods at a given distance from a lower mass star mean that core accretion will generally be too slow to produce Jupiter-mass planets in orbit around M dwarfs before the disk gas disappears (Laughlin *et al.*, 2004). In the competing disk instability model for gas giant planet formation, however, calculations for M dwarf protostars (Boss, 2006a) show that Jupiter-mass clumps can form in less than 1,000 years in marginally gravitationally unstable disks with masses of 0.02–0.07 solar masses orbiting around stars with masses of 0.5 and 0.1 solar masses. These ongoing models suggest that, if disk instability occurs, there is no reason why M dwarf stars might not rapidly form gas giant protoplanets. Hence, it may well be that mini-solar systems, similar to our own except reduced in spatial scale, are able to form in orbit about M dwarf stars. Zhou *et al.* (2005) have recently proposed an observational test to discriminate between these two models of planet formation. Numerous short-period terrestrial planets can be expected to be found in systems with jovian mass planets as the result of sequential accretion, but not as the result of gravitational instability. However, models of terrestrial planet formation by Kortenkamp *et al.* (2001) have shown that rapid formation of gas giant planets by disk instability can actually facilitate the growth of inner rocky planets, contrary to the assumptions made by Zhou *et al.* (2005). Ground-based spectroscopic surveys have begun to detect planets in orbit around M dwarfs, with masses ranging from about 7.5 Earth-masses to Jupiter-mass and above (Rivera *et al.*, 2005). Boss (2006b) has shown that disk instability in the outer regions coupled with collisional accumulation in the inner regions is able to explain the super-Earths and gas giants found in orbit around M dwarfs by both microlensing and spectroscopic planet searches.

2.5. Atmospheres of habitable planets

Since the circulations of terrestrial planetary atmospheres are primarily driven by the spatial distribution of short-wave radiation, one can expect that the atmospheres of planets orbiting M dwarfs will be significantly different in character to the terrestrial paradigm, in terms of both circulation and composition. Again, for a fuller description of the atmospheric circulation on tidally locked planets, the reader is referred to Joshi *et al.* (1997), who used a simple two-stream gray radiation scheme to model IR emission and assumed that all solar radiation hit the surface, and Joshi (2003), who explicitly modeled the effects of the hydrological cycle and had higher horizontal and vertical resolution. The effect of a water cycle was to have more uplift on the dayside and downwelling on the nightside than in the dry model, which resulted in different flow at low levels across the terminator. The strengths of the east–west, or zonal, jet streams in the upper layers of each model were also different as a result of the different configurations.

It appears to be quite commonly thought that, even if atmospheric collapse is prevented on tidally locked planets, the large thermal gradients and associated high winds across the terminator inhibit habitability, especially forest habitability. However, atmospheric heat transport tends to reduce thermal gradients, both by reducing their amplitude and by smearing them out to larger horizontal scales. Figure 8 of Joshi *et al.* (1997) shows the so-called radiative-convective equilibrium temperature field (obtained by running the atmospheric model without the effect of large-scale horizontal motions) and the actual time-averaged temperature field. The former case has large gradients on the terminator, which are completely smeared out in the latter case. Thermal gradients and any potential high wind speeds associated with them should, therefore, not be considered a barrier to habitability.

The terminator is thought to present the most likely location for life due to the relatively small effect of flares at that location (potentially damaging radiation travels through a longer atmospheric pathlength suffering greater degradation, and the absolute flux is diminished by the slant angle). However, the terminator would also receive far less sunlight than the SP, the location where the parent star is directly overhead, and so forest habitability might be impeded here (Heath *et al.*, 1999). The presence of thick clouds associated with convection would have an effect on this conclusion, by changing the amount of direct and diffuse solar radiation at the SP. Plants at this location, for instance, might be less susceptible to flares.

The remotely observed IR properties of a tidally locked planet will be greatly affected by the presence of an atmosphere with an active hydrological cycle. On a dry world or a planet whose atmosphere has collapsed, IR emission mostly comes from the surface, so that the dark side will appear far colder than the dayside when viewed at these frequencies. However, with a hydrological cycle comes the presence of water vapor and clouds—the SP will have clouds present for most of the time—and so IR emission here will come mostly from the cold cloud tops. Indeed, the dayside of such a planet might actually appear as cold in the IR as the darkside, in the same way as the Western Pacific region, which has the hottest sea surface temperature, appears very cold when seen in the IR. Such observations might actually provide evidence for a planet with an active hydrological cycle. Significant efforts have been expended on predicting and interpreting the spectra to be observed by the Terrestrial Planet Finder Coronagraph and Terrestrial Planet Finder Inferometer missions, which seek to directly image terrestrial planets in the HZs of nearby stars. The moisture content and average planetary albedo are critical to these models, as are considerations of phase and smearing over orbital cycles (Segura *et al.*, 2003). A great deal more research needs to be done on the topic.

Photolysis processes on a planetary atmosphere are controlled by the UV radiation of its parent star. Because of the peculiar flux distribution over wavelength of the active M dwarfs and the low radiation in the UV region of the spectrum from quiescent M stars, the atmospheric chemistry of trace species may be greatly affected. Simulations of planets that lie in the HZ of an M star and have the same atmospheric composition and input of biogenic compounds as present-day Earth showed that the atmospheric lifetimes of compounds like methane, nitrous oxide, and methyl chloride are larger than on Earth (Segura *et al.*, 2005). As a result, the abundance of these compounds could be potentially three orders of magnitude more than their terrestrial abundance (Table 2). Planets around quiescent M stars (referred as “model” in Table 2) show a “methane

TABLE 2. MIXING RATIOS OF BIOGENIC GASES CALCULATED BY A ONE-DIMENSIONAL PHOTOCHEMICAL MODEL FOR EARTH-LIKE PLANETS AROUND DIFFERENT STARS (SEGURA *ET AL.*, 2005)

Parent star	*Methane*	*Nitrous oxide*	*Methyl chloride*
Sun	1.6×10^{-6}	3.0×10^{-7}	5.0×10^{-10}
AD Leo (M4.5V)[a]	4.6×10^{-4}	1.3×10^{-6}	1.4×10^{-6}
GJ 643 (M3.5V)[a]	3.8×10^{-4}	1.1×10^{-6}	8.8×10^{-7}
Model[b]			
M1 (T_{eff} = 3,650 K)	5.0×10^{-4}	3.5×10^{-7}	1.2×10^{-7}
M3 (T_{eff} = 3,400 K)	5.0×10^{-4}	1.0×10^{-4}	2.0×10^{-7}
M5 (T_{eff} = 3,100 K)	5.0×10^{-4}	1.3×10^{-3}	5.4×10^{-7}

[a] For these planets the surface flux of these compounds was consider to be the same as present Earth: 9.54×10^{14} g of CH_4/year, 1.32×10^{13} g of N_2O/year, and 7.29×10^{12} g of CH_3Cl/year.

[b] On these planets the boundary conditions were: fixed mixing ratio for CH_4 (5.0×10^{-4}), fixed deposition velocities for H_2 (2.4×10^{-4} cm/s) and CO_2 (1.2×10^{-4} cm/s), and fixed surface fluxes for N_2O and CH_3Cl.

runway," *i.e.*, methane builds up in the atmosphere because there is not enough UV radiation to destroy this compound in the stratosphere, and the main sink of methane, OH, is highly reduced in the troposphere (see discussion in Segura *et al.*, 2005). To avoid this problem, a methane mixing ratio of 500 ppm is set for the simulated planets around the quiescent M stars. The methane flux needed to maintain this mixing ratio is 21% of the present methane production on Earth for a planet around the coolest star considered in Segura *et al.* (2005). Since methane is a greenhouse gas, this result points to the possibility of extending the outer limit of the HZ for planets that produce methane either biologically or not.

For life detection purposes, these biogenic gases may be more detectable on planets around quiescent or active M dwarfs than on Earth (Figs. 5–8 in Segura *et al.*, 2005). Finally, a planet with the present concentration of O_2 in the HZ of an active M dwarf may be able to develop an ozone layer as large as the terrestrial one, which will protect the planetary surface from UV radiation (Tables 2 and 3 in Segura *et al.*, 2005).

Another aspect of synchronously rotating planet habitability that needs attention in future work is how the carbonate–silicate cycle would control the partial pressure of the atmospheric greenhouse gas CO_2 (pCO_2) and, thereby, climate on time scales of >0.5 Myr. Changes in outgassing rates from the interior of the planet and in continental weathering regimes due to changes in the distribution of continents across climatic zones would be expected to be associated with adjustments in pCO_2. As mentioned earlier, Kasting *et al.* (1993) used the classic work by Walker *et al.* (1981), which demonstrated how the carbonate–silicate cycle could act as a natural thermostat to dampen climatic change and establish the limits of the HZ. The greenhouse gas CO_2 enters the atmosphere through outgassing from the Earth's interior and is removed from the atmosphere as it dissolves in rainwater to form dilute carbonic acid. In the event that insolation increased, the effect on weathering processes would be to adjust pCO_2 downward. This would reduce the atmospheric greenhouse effect and so compensate for increased insolation. Reduced insolation would result in an increased pCO_2 so that an accentuated greenhouse effect would compensate and prevent a geologically active planet from freezing over.

In the early climatic models for synchronously rotating planets, rather high pCO_2 values of up to 1,000 mbars and 1,500 mbars were assumed, but it is now clear that extreme values are not needed. The model of Joshi *et al.* (1997) actually employed a gray radiation scheme whose optical depth τ could be specified independently of the surface pressure. The only aspect of their model atmosphere that was actually "CO_2" was the gas constant. A value of τ of 1.0 was chosen for their control scenario because this happened to approximately match the gray optical depth of the present terrestrial atmosphere with ~350 ppm CO_2 (τ ~0.9), as well as an atmosphere having 1,000 mbars pure CO_2 (τ ~1). It is, therefore, not necessary to invoke high pCO_2 to prevent freeze-out on synchronously rotating planets—a conclusion that was repeated by Joshi (2003), who used present-day atmospheric composition.

These results meant that it was not necessary to limit discussions of habitable synchronously rotating planets to planets on which pCO_2 was constrained to extreme values, nor was it necessary to invoke and explain special circumstances in which this was possible with Earth-level insolation. Once again, then, the discussion of forest habitability was found to follow on naturally from the climatic models without unduly contrived conditions.

There has been no investigation of the possible long-term evolution of climate in relation to the carbonate–silicate cycle on synchronously rotating planets; values of pCO_2 for different continental distributions have not been estimated. This is a major area for future work, the results of which will be of fundamental importance to taking discussion of synchronously rotating planet habitability forward.

The geophysical regime of a synchronously rotating planet will play an important part in determining whether it is habitable. On a planet with plate tectonics, the drift of plates through the colder zones near the terminator would extinguish Earth-type arboreal forms, while drift onto the dark side would spell extinction for a wide range of organisms. Alternatively, one-plate planets such as Mars and Venus with histories of long-term geologic activity (*e.g.*, Basilevsky *et al.*, 1997; Hauck *et al.*, 1998; Head *et al.*, 2001) may also have regions of persistent habitability. In particular, volcanically active localities can act as a source of juvenile or recycled volatiles and generate surface heat fluxes commensurate with plate tectonics settings.

It was pointed out in Heath *et al.* (1999) that, even if a layer of ice were to form on the dark side of a synchronously rotating planet, Earth-like levels of geothermal heat from the interior of a geologically active planet should ensure that oceans would not freeze to their floors. Bada *et al.* (1994) had advanced this mechanism to demonstrate that liquid water environments would have been possible on an early Earth that received reduced insolation from the early Sun, even in the absence of a massive atmospheric greenhouse effect. What it means for a synchronously rotating planet is that a supply of snow to the top of a thick layer of sea ice should be balanced by melting at its base, and so, if deep ocean basins communicate between the dark and lit hemispheres, a vigorous hydrological cycle is possible. This mechanism demonstrates one way in which the hydrological cycle and geological activity are linked, and future research should investigate how the volume of liquid water beneath the ice responds as a planet's internal heat flux diminishes with time and the thickness of the oceanic crust declines.

However, it should be noted that the connection between climate and geological activity is not one-directional. Rather, geologic activity, especially through volcanism, may be necessary to provide appropriate greenhouse gasses to the atmosphere. In the case of some planets, such as Venus, there may be a closed feedback loop where increasing or decreasing atmospheric temperatures temper the amount of geologic activity (*e.g.*, Phillips *et al.*, 2001). Water also strongly affects the melting and deformational behavior of the silicate minerals that make up the crust and mantle of terrestrial planets (*e.g.*, Mackwell *et al.*, 1998), and hence affects the type and vigor of geological activity such as has been suggested for Venus (Kaula, 1995). However, water alone likely does not explain even the diversity of tectonic regimes within our own Solar System. For example, like Venus, Mars is a one-plate planet; however, it clearly has had water throughout its history. Geodynamical regimes of geologically active Earth-sized planets subject to substantial tidal torque remain to be investigated.

2.6. *Requirements for life*

The envelope of physical conditions for life on Earth is in many ways remarkably wide. Environmental pH can range from <1 to 12, pressure from <1 to >500 bars, salinity from zero (freshwater) to saturation in saline lakes, and temperature from ~380K (>100°C) to below 233K (−40°C), the absolute limit for undercooled water at a pressure of 1 bar. The discovery of so-called extremophiles that have expanded the boundaries of habitable real estate has dramatically changed perceptions about the possibility of life beyond Earth; a modern review of currently understood limits on habitation can be found in Rothschild and Mancinelli (2001). Life as we know it does, however, depend on the presence of liquid water, and the existence of the liquid state ultimately sets the boundary conditions for life on Earth. Not only does water provide the solvent for biochemistry, but there are very few physiological processes in which water does not play a part as reactant or product.

Life on Earth depends on solution chemistry in water, a solvent that possesses unique physical and chemical characteristics, a set of chemicals primarily consisting of a few simple and common atoms (C, H, N, O, P, and S), and relatively small differences of free energy (Ball, 2004; Benner *et al.*, 2004). Within organisms, energy tends to be transduced using electrical gradients across membranes or by the oxidation of organic molecules to generate energy-rich molecules (typically containing phosphate) and organic electron pair carriers (often involving sulfur) that are used to drive the synthesis of essential biomolecules. Such energy transduction processes frequently involve the use of transition metals, which makes their presence in trace amounts necessary.

It is often assumed that life elsewhere, if it exists, will be based on liquid water and carbon. Liquid water has a complex and intimate involvement in all life processes on Earth, and carbon's four valence electrons endow it with extraordinary versatility to create multiple chemical bonds. Further, water and carbon are common in the universe.

Alternative physiologies may exist, however, that could widen the range of physical conditions over which life could exist. Extrapolation from the one example of life known to us, however, would suggest that the two solvents most likely to act as a basis for life are water and ammonia. In the absence of evidence, however, it seems pragmatic to confine our search to life based upon water and carbon (Ball, 2004; Benner *et al.*, 2004).

Given the basic requirements outlined above, we are therefore looking for a rocky planet, with subsurface or surface liquid water (the latter requiring an atmosphere), that is geologically active to provide a continual recycling of elements and capable of supporting liquid water for a sufficient period of time for life to arise and evolve. The question of life on planets around M dwarf stars thus centers on whether these planets could exist within the continuously HZ of their host star, and how these conditions might be altered by the effects of tidal locking on the climate and the effects of an M dwarf's radiation on life.

Since we are also interested in the ways in which M dwarf planets might contribute to the evolution of technological civilizations (of interest to SETI searches), it is worthwhile to describe the requirements of ecosystems with multicellular organisms, such as plants, that have been termed "forest habitability" (Heath, 1996). On Earth, forests dominate biomass at the crust–atmosphere interface. It is estimated that, in the absence of human interference, forests would cover around 40% of our planet's land area and account for 60% of net primary productivity in land environments. This massive photosynthetically produced biomass implies that photosynthesis is a highly favorable solution to the problem of harvesting and exploiting natural energy sources, and not merely an accident of history. Further support for this is the fact that alternative forms of autotrophy exist among the prokaryotes, and yet none has dominated any but small, specialized niches. Forests also play an important role in biogeochemical cycles, the hydrological cycle, and the modification of climate (notably through control of transpiration and by changing ground albedo). In addition, they have provided an important environment in which our own primate ancestors developed key adaptations concerned with hand–eye–brain cooperation that was important in the evolution of toolmaking.

The temperature tolerance of higher plants on Earth is narrower than the $-40°C$ to $>100°C$ range of microorganisms. For example, the sclerophyll trees and shrubs include forms that suffer cold injury at $-5°C$ to $-2°C$ and heat injury at 50–60°C. The cold and hot limits of CO_2 uptake are -5 to 0°C and 45–50°C, respectively (Larcher, 1995). The temperature ranges at which CO_2 uptake is 50% that at the temperature optimum are 15–20°C to 40–45°C. Also, in the Earth's seasonal regime, full-sized trees are found where mean daily temperatures exceed 10°C for a minimum of 1 month a year. On synchronously rotating M dwarf planets, therefore, where there are no seasons, we might take the 10°C isotherm as the cold limit for trees. Although another planet would have its own unique biosphere, these Earth-biased considerations suggest that the temperature range of M star "forest habitability" would probably be near 10–50°C. Furthermore, since the Joshi *et al.* (1997) model predicts typical wind speeds near the surface to be 5–10 m/s (even at the terminator), no special biomechanics would be required for tree growth.

In summary, if a rocky planet orbiting within the HZ of an M dwarf star possesses liquid water and the chemical constituents necessary for life, and if these conditions persist for a sufficient time to allow life to originate (a time scale that is not yet constrained) and evolve (again this is relatively unconstrained, but the bias is certainly toward billions of years), then there is no reason to conclude that the planet is not habitable.

3. A DIFFERENTIAL ANALYSIS BETWEEN G DWARFS AND M DWARFS

3.1. *Magnetic activity and stellar evolution*

M dwarf variability was first detected and reported by Ejnar Hertzsprung in 1924 and Adrian van Maanen in 1939 and 1945. However, the realization that these changes in brightness were due to short time scale flares only came in 1947, when Edwin Carpenter noted a 3 magnitude brightening of UV Ceti (M5.5e, 2.7 pc) in 12 min. By 1970, 50 flare stars were known, and it was recognized that they were nearly all mid- to late-type M stars lying within 15 pc of the Sun (Gurzadyan, 1970). By the 1990s, the number had doubled. A much greater number of flare stars was found in young open clusters; the Pleiades alone has over 500 observed with another 500 estimated to be present (Ambartsumian *et al.*, 1970). A considerable phenomenology of M star flares has been garnered in the optical and UV bands (Houdebine, 2003, and references therein; Walkowicz *et al.*, 2004; West *et al.*, 2004). The U band flux is correlated with Balmer line emission for M dwarf stars whose levels of activity span 5 orders of magnitude. Chromospheric surface fluxes in hydrogen Balmer lines can reach 10^8 erg/s/cm^2, as seen in the young system AU Mic. Flare intensity and duration are correlated from 1- to 100-min decay phases. The chromospheric cooling budget is often dominated by UV continuum, rather than emission line. Stars earlier than M7 maintain a persistent quiescent chromosphere and transition region between flares as indicated by Hα activity, with later-type stars remaining active longer (Hawley and Johns-Krull, 2003; Silvestri *et al.*, 2005). Significant fractions of the stellar photosphere can be covered with long-lived, cool, strongly magnetized starspots.

The activity of M stars follows a rotation–activity relation, as seen in hotter solar-type stars, but only when the rotational velocities are below 4 (10) km/s for mid- (late-) M dwarfs (Mohanty and Basri, 2003). For the more rapidly rotating stars, the dynamos or surfaces of most M stars appear to be fully saturated. The fact that M stars are convective, conductive, and spin means that they can generate magnetic fields by dynamo action. When they are fully convective (those M3 and later), the cyclical solar-type magnetic dynamos (which operate at the radiative–convective interface) cannot work, and the magnetic fields must come from partially or fully turbulent dynamos. This likely means that the typical field structures tend to be smaller and the sensitivity to rotation less, which may account for the generally longer spindown time for M stars (perhaps through the field geometry). There is no evident transition in activity properties around M3–M4 when the radiative core disappears and the interior becomes fully convective. This is not understood and suggests that a saturated convective dynamo either dominates the field generation or alters the interior structure of the cooler stars (Mullan and MacDonald, 2001).

We do know that M stars, when they are young, can generate fields stronger than solar because of the higher gas pressure, and that they can cover nearly the whole star (Saar and Linsky, 1985; Johns-Krull and Valenti, 1996; Valenti and Johns-Krull, 2001). These lead to flares that sometimes reach stellar dimensions (Osten *et al.*, 2005; Güdel *et al.*, 2004) and create bursts of luminosity that are a greater fraction of the total stellar luminosity than the strongest solar flares. The range of flare intensities is very wide (up to 10^5 or more), with young flare stars at the maximum values. Flare luminosities decrease with stellar mass and maintain roughly a maximum ratio of 10^{-4} with the bolometric luminosity (Pettersen, 1991). Of course, similar energies are also emitted at shorter wavelengths, including X-rays. A number of recent X-ray studies with simultaneous multi-wavelength coverage provide a close-up view of individual flares. On Proxima Centauri, low-level X-ray emission formerly labeled "quiescent" is now clearly shown to be the superposition of many small flares, and modeling a powerful X-ray flare implies a loop size comparable to the stellar radius (Güdel *et al.*, 2004). A continuous study of EV Lac (M4.5e, 5.1 pc) over 2 days revealed a powerful radio flare accompanied by an impulsive U-band event. It also revealed numerous optical white light and X-ray flares (Osten *et al.*, 2005). For EV Lac, and in other M stars, flare emissions in the different wavebands are largely decoupled from each other (Smith *et al.*, 2005).

The activity in electromagnetic radiation is undoubtedly accompanied by high-energy particle fluxes as well. Since the X-rays in flare stars are harder (have relatively more high energy photons) than those of solar flares, it is reasonable to assume that the particles may be more energetic as well. They also sometimes expel substantial quantities of mass at high speed (mostly in the form of energetic protons). Such ejections may be a substantial contributor to the early mass loss rates, which could be as high as 10^4 greater than the current solar rate (Mullan *et al.*, 1992). These mass ejections can also affect the atmosphere of a planet in the HZ (Khodachenko *et al.*, 2007; Lammer *et al.*, 2007). We also know, however, that by the age of several Gyr (for example, Proxima Centauri), and likely well before that, the mass loss rate has fallen below the solar rate (Wood *et al.*, 2001). Thus, it is unlikely that an M star loses a significant amount of its mass in either coronal mass ejections or a steady stellar wind. Perhaps the best evidence for this is that we do observe spindown in most M stars. The spindown is a feedback mechanism that has the seeds of its own destruction; the slower the star spins, the less activity and mass loss it has.

The M flare stars identified prior to 1970 constitute roughly $1/10^{\text{th}}$ of the dM population in the solar neighborhood (Gurzadyan, 1970). Comparison of flare star populations in clusters of different ages shows a decay of activity over several hundred million years, and several groups found that the lowest mass M stars exhibit a longer flare star phase than higher mass M stars (Mirzoyan, 1990; Stauffer *et al.*, 1991; Hawley *et al.*, 2000). However, a kinematic study of 93 UV Ceti stars within 25 pc of the Sun show a fairly high velocity dispersion $\sigma = 30$ km/s, which indicates a mean age of around 3 Gyr and no dependence on mass (Poveda *et al.*, 1996). A small fraction of these nearby flare stars are either identifiable members of young disk groups or members of an old thick disk population.

Two recent studies give new insight into the long-term decay of M star activity. Silvestri *et al.* (2005) examined a sample of 139 older M stars whose ages can be estimated from their white dwarf companions. Using V-I color as a chromospheric activity indicator, they found that many dM and dMe stars with ages 1–10 Gyr are more magnetically active than predicted by the decline of chromospheric activity seen in younger clusters with ages <1 Gyr. Feigelson *et al.* (2004) obtained a small sample of 11 X-ray selected stars from a very deep Chandra X-ray Observatory field at high galactic latitude. Seven of these are dM stars at distances 50–500 pc and represent the high-activity tail of older stars in the upper disk. Most of these stars exhibit X-ray flares with peak luminosities around 10^{27}–10^{28} erg/s, similar to young flare stars. Comparison with evolution models suggests a steep decay law $L_x \sim t^{-2}$ in flare activity. This is consistent with X-ray studies of dM stars in younger cluster populations and the solar neighborhood, which indicate a flare decay law of $L_x \sim t^{-1}$ for ages <1 Gyr and steepening at later ages (Preibisch and Feigelson, 2005).

The fraction of M stars with Hα emission denoting strong magnetic activity was known to be low among early-M stars, but increases to nearly 100% around M5.5–7 stars, and declines rapidly among early-L stars (Joy and Abt, 1974; Gizis *et al.*, 2000). The largest samples studied to date include 499 M dwarfs from the volume-complete Palomar/Michigan State University survey of nearby stars and nearly 8,000 M- and early-L-type stars from a flux-limited sample obtained from the Sloan Digital Sky Survey (Gizis *et al.*, 2002; West *et al.*, 2004). The Palomar/Michigan State University sample suggests that the magnetic activity of M0–M3 stars is bimodal, with most exhibiting no Hα emission, some strong Hα emission, but with few emisions at intermediate levels. The Sloan sample shows the fraction of dMe stars peaks at 75% of M8 stars with >50% between M5 and L0; the somewhat lower fraction of dM3 stars is probably due to the higher fraction of older stars in this high galactic latitude survey. Using a more quantitative measure, however, the average $L_{\mathrm{H}\alpha}/L_{\mathrm{bol}} = 2 \times 10^{-4}$ from M0 to M5 and declines to 5×10^{-5} for M7–L0. The Palomar/Michigan State University sample shows an average around $L_{\mathrm{H}\alpha}/L_{\mathrm{bol}} = 1 \times 10^{-4}$ from M0 to M3, followed by an increased range of activity (with a small decline in average $L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}$) from M3 to M5.

3.2. *Truncation of planetary habitability*

Although the stable lifetimes of M dwarf stars can be counted in the hundreds of gigayears, habitable planets that form initially may not remain habitable for the lifetime of the star.

3.2.1. Mass loss and the evolution of planetary position relative to the HZ. Mass loss from young solar-type stars was first suggested by Whitmire and Doyle (1995) as an explanation for the faint Sun paradox (Sagan and Mullen, 1972). Using the $-2/3$ spectral index excess indicative of a stellar wind at radio wavelengths, Mullan *et al.* (1989, 1992) placed limits on the stellar wind from a K2 dwarf and two M dwarf stars, the latter indicative of mass loss at the rate of up to 10^{-10} solar masses per year. Following this procedure, Doyle *et al.* (1996) put an upper limit on mass loss from two young solar-type stars, the smaller upper limit being about 9×10^{-11} solar masses per year, which also indicates what the effect of such mass loss would have been on the early Solar System (the circumstellar HZ migrating inward while the planets migrated outward). The migration of the circumstellar HZ due to mass loss and tidal friction (from the hydrological cycle on a synchronously rotating planet) and the possible loss of a tidally locked planet's atmosphere due to a reduced magnetic field have been pointed out in Doyle (2006) and Lammer *et al.* (2007).

We calculate what level of stellar mass loss would significantly affect a planet's habitability. As the star loses mass, its luminosity decreases, and the HZ will contract. But, stellar mass loss will also cause the planet's orbit to spiral outward by conservation of angular momentum. On such a planet, the combined effects of stellar mass loss on the position of the HZ and the planet's orbital position would exacerbate life's ability to survive. A planet initially within the HZ could find itself outside after sufficient mass loss by the parent star.

The calculation proceeds as follows: letting m = stellar mass, m_{p} = planet mass, L = stellar luminosity, r = planet orbit radius (orbit assumed to be always circular for slow mass loss), then in order to keep constant insolation, $r^2 \propto L$ (applies to center or boundaries of HZ).

Main sequence luminosity evolution (theoretically understood to be driven by stellar structure and nuclear fusion rates) depends on stellar mass, with $L \propto m^q$. For high-mass stars, $q \sim 4.5$, but for M dwarfs the luminosity relationship has flattened to $q \sim 2.5$. Therefore, since $r \propto L^{1/2}$, constant insolation requires that the radius decrease with mass as $r \propto m^{1.25}$. But, to conserve orbital angular momentum of the planet as the parent star loses mass, $m_{\mathrm{p}}vr$ must remain constant, and, therefore, the radius must increase in time as $r_1/r_{\mathrm{o}} = m_{\mathrm{o}}/m_1$.

A factor of 2 characterizes the inner and outer radii of the HZ for the Solar System (about 0.75–1.5 AU). So for stellar mass change to cause a planet starting out at the inner edge of the HZ to drift to the outer edge of the (shrinking) HZ requires that $r_1/r_{\mathrm{o}} = 2$, and, therefore, $m_1/m_0 = 2^{-1/(1+1.25)} = 0.73$. Therefore, the star can lose at most about 25% of its mass before a planet once resident at the inner edge of the HZ moves out beyond the outer edge.

At the Sun's mass loss rate of $2 \times 10^{-14}\ M_{\mathrm{Sun}}$ per year, a main sequence M star would take several hundred billion years to lose 25% of its mass. Wood *et al*. (2005) found that the sustained mass loss rate from M dwarfs is far below solar, so even an initial burst of mass loss cannot produce any substantial effects on orbital change. Migration out of the HZ due to sustained mass loss of the M dwarf star is unlikely to be a contributing factor to early truncation of habitability; a terrestrial planet that starts in the HZ will remain there.

3.2.2. Planetary interiors. For planets of both M and G dwarfs, truncation of planetary habitability is likely to occur with the loss of large-scale endogenic geologic activity. Loss of heat via convective heat transfer in a terrestrial planet's silicate mantle is the primary driver of endogenic geologic activity over solar system time scales. Mantle convection, in turn, can prove important for chemical recycling, mantle degassing of atmospheric components, and sustaining sufficient internal heat flow to power a magnetic dynamo in the planet's metallic core. The lifetime of mantle convective motions will tend to increase with (1) the thickness of the mantle (which will tend to increase with planetary radius) and (2) the radioactive element content that provides heat during the decay process. The time scale over which radioactive decay is relevant is roughly 3–10 Gyr time scales for Earth-like planets (*e.g.*, Sleep, 2000). However, the dynamics of mantle flow may be rather different on planets considerably more massive than Earth because of the effects of extreme pressures and temperatures on mantle materials (*e.g.*, Van den Berg *et al.*, 2005). In addition to planetary radius, the other primary control on the depth of the mantle is the relative amount of metallic iron in the planet. For example, the Earth's metallic core makes up ~55% of the planet's radius compared with ~75% inferred for Mercury (*e.g.*, Lodders and Fegley, 1998). Therefore, bulk composition and internal structure of 1–10 Earth-mass planets (*e.g.*, Valencia *et al.*, 2006) will also affect the truncation of terrestrial planet habitability. Assuming typical enrichment in radioactive elements, planetary geological activity on planets orbiting M dwarfs is likely to follow a similarly broad spectrum as observed in our Solar System. In addition, tidal dissipation may be an important additional mantle heat source on bodies in eccentric orbits, as occurs on the galilean satellites (Showman and Malhotra, 1999; Moore, 2003).

Internally generated planetary magnetic fields are just as likely to occur on planets orbiting M dwarfs as on planets around G dwarfs. Planetary magnetic fields are generated on terrestrial planets by fluid motions within the liquid portion of the planet's metallic core (Olson and Aurnou, 1999; Stevenson, 2003). Such fields can create a magnetosphere that surrounds the planet, which buffers it from the surrounding space environment and limits the atmospheric loss rate from cosmic ray sputtering (Johnson, 1994; Grießmeier *et al.*, 2005). The critical ingredients for planetary dynamo action are a sufficient volume of electrically conducting fluid, an energy source to drive motions in the fluid, and net organization of the flow field (Roberts and Glatzmaier, 2000; Aurnou, 2004). Typically, Coriolis forces produced by planetary rotation act to organize the planetary core flow. Planetary rotation periods within the M dwarf habitability zone are estimated to be between 10 and 100 days. These rotation rates, though slower than that of Earth, will still produce strong Coriolis forces in ~100–1,000-km-deep core fluid layers. Thus, in terms of dynamo theory (Stevenson, 2003), tidally locked planets orbiting M dwarfs are viable candidates for core dynamos.

Recent numerical studies of planetary dynamo action propose the following scaling law for planetary magnetic dipole moment (Christensen and Aubert, 2006; Olson and Christensen, 2006):

$$M \sim (Q_B D)^{1/3} R_C^3 \tag{1}$$

where M is the magnetic dipole moment, Q_B is the buoyancy flux, D is the thickness of the dynamo generation region, and R_C is the radius of the planet's core. This study has been carried out using only dipole-dominant dynamo solutions. Multipolar numerical dynamo solutions also exist, although no clear scaling behavior has been identified for these cases (Christensen and Aubert, 2006). In Eq. 1, note that, quite surprisingly, the scaling predicts that the planetary dipole moment does not depend on the rotation rate of the planet. This does not mean that rotation rate is irrelevant in the dynamo process. It means, instead, that in the regime where the core convection is dominated by the effects of planetary rotation, the typical strength of the dynamo field is controlled by the amount of available buoyancy power (Christensen and Aubert, 2006). Thus, in terms of planetary dynamo action, a fast or slow rotator is correctly defined by the ratio of buoyancy forces versus Coriolis forces (Aurnou *et al.*, 2006), not by the ratio of a planet's rotation rate versus that of the Earth. A planet that is a fast rotator must have a buoyancy flux large enough to generate core convection, but not so large that the buoyancy forces swamp out the Coriolis forces that lead to the production of a well-organized planetary-scale magnetic field.

3.2.3. Atmospheric escape. The ability of planets orbiting M stars to retain their atmosphere will depend critically on the nature of atmospheric escape processes that such planets experience. There are a variety of ways by which an atmosphere can escape into space. Perhaps the most well known are the thermal escape mechanisms of Jeans escape and hydrodynamic escape (for details, see Walker, 1977). Jeans escape occurs above the exobase where molecular collisions are infrequent and some of the upward traveling molecules have high enough velocities to escape into space. This type of escape will occur in any planetary atmosphere with the escape flux dependent on planet mass. For the terrestrial planets, only the lightest elements (hydrogen and helium) can escape by this process, and the total loss over the lifetime of the solar system does not significantly deplete their atmospheres. This type of escape is also likely to be inconsequential for M star planets.

Hydrodynamic escape, however, may be more of a factor. This kind of escape occurs when thermospheric temperatures are high enough such that the thermal energy of molecular motions is comparable to the kinetic energy at escape velocity. In this situation, the escaping molecules, generally hydrogen, expand into the vacuum of space with such intensity that they can drag the heavier elements with them (*e.g.*, C, O, N, etc.). Though still hypothetical, hydrodynamic escape has been invoked to explain the fractionation of the xenon isotopes in the atmospheres of Mars and Earth (Hunten *et al.*, 1987; Bogard *et al.*, 2001). It is believed to have occurred very early in Solar System history, when the solar extreme UV flux was much higher than it is today because it is the absorption of solar extreme UV that powers hydrodynamic escape (Chassefière, 1996). Since M stars are very active in the extreme UV for much longer periods of time than G stars (Allard *et al.*, 1997), it raises the possibility that hydrodynamic escape could significantly deplete the atmospheres of planets that orbit them (Scalo *et al.*, 2007).

Nonthermal escape mechanisms include dissociative recombination, ion escape, and sputtering (Chassefière and Leblanc, 2004; Lammer *et al.*, 2007). Unlike thermal escape, which mainly affects the lightest elements, nonthermal escape can remove heavier elements and molecules. Dissociative recombination occurs when UV photons ionize molecules, which then recombine with electrons and produce energetic neutrals that can escape. This process is most efficient for small planets with weak gravity fields, and is believed to drive the escape of O, C, and N at Mars (McElroy, 1972; Hunten, 1993; Fox and Hac, 1997). However, the only flux of escaping material measured at Mars is due to ion escape, wherein the electric field associated with the solar wind directly accelerates ions to the escape velocity (Lundin *et al.*, 1989). This process differs from sputtering in that the latter occurs when the ions reimpact the atmosphere with sufficient energy to eject all molecules at the exobase (mainly C, O, CO, N, N_2, and CO_2). Both ion escape and sputtering are facilitated by the lack of a magnetic field (which allows direct interaction of the solar wind with the atmosphere) and are sensitive to the UV flux. Thus, M star planets that lack a strong enough magnetic field are susceptible to loss by each of these nonthermal escape mechanisms.

This is far from a simple problem, and though some effort has been expended to understand the evolution of the atmospheres of close-in hot-Jupiters (Grießmeier *et al.*, 2004), very little research on atmospheric escape from M star planets appears in the published literature. Clearly, this is a major issue and needs to be investigated.

3.3. Origin versus sustainability of biology

Heath *et al.* (1999) explored the opportunities for known types of higher plants in terms of three main factors: the distribution of climatic zones across the surfaces of synchronously rotating planets, the amount of photosynthetically active radiation (PAR) arriving in M star insolation, and stellar variability.

PAR, from about 4,000 Å to 7,000 Å, is rather of special biological interest because it is neither so energetic that it damages cells, nor so weak that it cannot power water-splitting photosynthesis. As regards a perfect black body, the wavelength of peak energy output is inversely proportional to its temperature (Wien's displacement law). However, stars are more complex than this because light emitted from any level of the photosphere (a layer hundreds of kilometers deep) can be absorbed and re-emitted by the higher layers of the star in a manner determined by stellar composition. The proportion of IR in M star insolation is substantially greater than that of our Sun, and as effective photospheric temperatures drop through the range for spectral class M, the amount of PAR falls. Molecular bands of TiO_2 are particularly important in reducing emitted stellar radiation in the PAR range, and red dwarf stars achieve energy balance by back-warming of their continua at other wavelengths, notably around 10,000 Å. Stars that form out of material with low contents of "metals" (astronomical parlance for elements heavier than hydrogen and helium) should put out the most PAR but will have smaller amounts of material with which to form terrestrial planets. These would be stars of the ancient galactic halo and the older stars of the disk, while stars with the highest metallicities, those of the galactic bar/bulge and the intermediate and young disk populations, will have more material to form terrestrial planets but suffer the greatest reduction in PAR output.

Rough estimates were made of the amount of energy in and adjacent to the PAR region by reference to published (Allen, 1973) stellar luminosities in the U, B, V, R, and I bandpasses and to synthetic spectra for stars and substellar brown dwarfs in the effective temperature (T_{eff}) range of 4,000–2,000 K (Allard and Hauschildt, 1995). It was estimated that the amount of PAR received at the top of a planet's atmosphere (assuming identical insolation to that on Earth) from a star of T_{eff} 4,000 K (slightly hotter than a M0 star) would be roughly a third of that incident on Earth and that the photic zone window radiation (PAR in the range that penetrates clear ocean water most effectively; 4,500–5,500 Å) received would be a quarter. The respective figures for a star of T_{eff} 2,800 K are less than 1/12th and 1/20th. These values are, nevertheless, sufficient for photosynthesis to be metabolically profitable. Most of the Earth's forest trees are C3 plants, and they are often found to reach light saturation at a fraction of full sunlight (Black, 1973).

Heath *et al.* (1999) also considered the way light, as it penetrates an Earth-like atmosphere, passes through greater air masses with distance from the SP. The efficiency with which light that passes through the atmosphere is subject to Rayleigh scattering is inversely proportional to the fourth power of the wavelength. This means that red light (which is much more important than blue light in red dwarf insolation) suffers significantly less scattering than blue light, and transmission coefficients for direct irradiation of light of 7,000 Å out to about 60° from the SP would be about 80% or greater than that for the SP. Also, some blue light would be down-scattered from the sky as a diffuse component, but the blueness of the sky would fade for stars of progressively later spectral type. Detailed studies of the direct and diffuse illumination available on planets of M dwarfs, which would benefit from ongoing studies of M star spectra, remain to be undertaken.

It is important to note that photosynthesis need not be impaired with red-biased light. Blue light is not used efficiently by plants on Earth because, when chlorophyll absorbs a photon of blue light, an electron is promoted to an unstable upper excited singlet state that decays within a mere 10^{-12} s. This means that both blue light photons and less energetic red light photons produce the first excited singlet as the starting point for energy transfer (Nobel, 1974). Moreover (for example, Salisbury and Ross, 1978), action spectra of certain crop plants and trees are very much biased toward red light (blue spruce does not respond at all to radiation of wavelength <5,000 Å). There is also an effect known as the red drop, whereby photosynthesis is impaired when plants are illuminated *only* with radiation of > 6,800 Å. However, they can benefit from the Emerson effect (Emerson *et al.*, 1957), whereby the efficiency of photosynthesis at around 7,000 Å is boosted if a shorter red wavelength, such as <6,500 Å, is present and the combined level of photosynthetic efficiency is greater than that expected from the sum for both wavelengths taken separately. Heath *et al.* (1999) also outlined the role of accessory pigments in increasing light harvesting in environments with reduced PAR (such as under water), and they considered the role of known types of non–water-splitting near-IR photosynthesis, noting the possibility of linked photosystems that harvest in the near-IR and transfer energy to water-splitting photosynthesis.

There will be advantages and disadvantages when the sun is stationary in the sky. Light from a nonstationary sun casts illumination from a changing direction and can penetrate through the forest canopy from different angles at different times, which benefits foliage in different layers, including that of the understory. In the case of Earth, seasonal changes allow PAR and summer warmth to be distributed to higher latitudes, while rains in many areas are strongly seasonal. On a synchronously rotating planet, photosynthetic surfaces could be permanently angled perpendicular to incoming light beams, and for the hottest M dwarfs, continuous daylight and absence of a yearly migration of the star between the tropics would mean that reduced PAR could be compensated effectively at the SP. Unfortunately, the model of Joshi (2003) indicates that this part of the globe will be subject to possible climatic extremes, so other parts of the daylight hemisphere will need to be considered in terms of the optimum location for photosynthesis. This is a problem presently under investigation. In the model of Joshi (2003) with a global ocean, there was intense cloudiness, as well as massive precipitation that might have implications for erosion of both soil and bedrock. In his simulation with the northern hemisphere covered with land, cloud cover was reduced, but temperatures could reach 80°C in some regions, which is decidedly unhealthy for Earth-type higher plants. Other land–sea combinations or changing the distance of the planet from its star need to be explored in future work. Nevertheless, the existence of such problems regarding the PAR-rich SP, where light has to penetrate minimal thickness of atmosphere, cannot but detract from the global potential for photosynthetic productivity of a synchronously rotating planet.

Starspots and flares pose potential problems for life, but in the analysis of Heath *et al.* (1999), they would not be insurmountable. The climatic implications of starspots was modeled in Joshi *et al.* (1997), who noted that spots on red dwarf stars can reduce insolation by 10–40% for a few Earth months. A 40% decrease for 4 months would reduce surface temperature by 27 K in some areas and may allow regional temperatures to fall below the freezing point of water. However, many Earth tree species have evolved to cope with seasonal cycles where temperatures fall far below freezing during the winter, while within the Earth's boreal forest zone, annual temperature maxima and minima range from about −40°C to 70°C.

Heath *et al.* (1999) discussed the danger posed by stellar flares, which can be commonplace from dwarf M stars. The key issue here is the amount of flare UV that could actually penetrate a planetary atmosphere to ground level. Atmosphere-penetrating UV has been subdivided (Koller, 1965) into UV-A (3,150–3,900 Å), UV-B (2,900–3,150 Å), and UV-C (<2,900 Å). On Earth, UV-B is the most dangerous, since it is not only biologically damaging but can reach the ground in significant amounts. Although peak germicidal efficiency occurs at ~2,600 Å, not much UV-C arrives at the Earth's surface. The U-bandpass used by astronomers [3,310–3,990 Å in Allen (1973); 3,260–3,940 Å in Hawley and Pettersen (1991)] corresponds quite closely to UV-A, so apart from certain data obtained from above the Earth's atmosphere by satellite (the International Ultraviolet Explorer satellite had provided observations in the ranges 1,150–2,000 Å and 1,900–3,100 Å), there was limited information about UV-B and UV-C in M dwarf flares.

Heath *et al*. (1999) also put the biological implications of an increased proportion of UV during M star flares into perspective with reference to the very low quiescent UV outputs of M dwarfs and flare data for specific stars. Data, both ground-based and from the International Ultraviolet Explorer satellite, were used to show that in many cases UV output that reaches the surface of a planet would be comparable to that provided continuously on Earth from the Sun, or exceed terrestrial norms in transient events. Biological means of avoiding, tolerating, or repairing damage caused by UV were discussed, and it was concluded that flares need not be a fatal problem for either microorganisms or higher plants.

These optimistic conclusions were based, however, on limited data about flaring on dwarf M stars, and it is essential that they be reconsidered in the light of future observation programs that investigate flare output across the spectrum.

Recently, Grießmeier *et al.* (2005) considered the biological implications of cosmic ray impact on synchronously rotating terrestrial planets in HZs around M dwarfs. They concluded that because of tidal locking, the magnetic moment and, therefore, protection against primary cosmic rays will be reduced and allow ~50–100% of the planetary surface to be reached by secondary cosmic rays, which can have adverse biological consequences.

It would appear from preliminary considerations that red dwarf stars may well boast planets that support not only super-robust prokaryotic-type organisms, but organisms comparable to our plants. Notwithstanding, many problems are evident with the environments available on such planets, and this conclusion must be treated with caution.

4. LIFTING THE VEIL

4.1. Input data required for accurate modeling

As has been stated throughout this paper, there are several issues concerning the interaction between a planet and its parent M star that have not been addressed yet by the science community. In part, this is related to the intrinsic characteristics of the M dwarfs. For example, since M dwarfs are fainter than other stars, it is difficult to measure their spectra, especially on the short wavelengths (UV, X-rays) unless the star is very active. Other problems, such as atmospheric escape and geologic activity, are related to planetary processes that need to be better understood for any planet regardless of the spectral type of its parent star. Habitability analysis must also consider stellar age, as the flaring activity appears to decay over the first 1–3 Gyr.

To study the ways by which an M star affects the chemistry and climate of a planet in the HZ, it is necessary to have spectra that range from the UV to the IR. Such spectra from the blue part of the spectrum to the IR are available for a number of nearby M stars with large apparent brightness. However, much of the photochemistry in a planetary atmosphere is driven by UV photons, so spectra below 3,000 Å are needed. In this wavelength region, spectra exist only for a few of the most active M stars, not only because of the interest in understanding the processes that drive their activity, but also because they are bright enough in the UV and shorter wavelengths to allow spectra to be recorded above the instrumental noise.

To obtain a better sense of the average radiation environment to which a planet in the HZ would be exposed, it will be necessary to obtain UV spectra of M stars with a range of activity levels. Flares affect the visible spectrum, and because of that it is important to have simultaneous observations of the UV and visible, in particular the blue part of the spectrum. Such observations will require new space instrumentation. Until recently, the Hubble Space Telescope was the only means by which to obtain UV spectra of astronomical objects, and previous instruments (*e.g.*, the International Ultraviolet Explorer) only detected the few most active M stars. The situation is improving as the recently launched GALEX satellite is already providing new insights into the near- and far-UV emission of M star flares (Robinson *et al.*, 2005; Welsh *et al.*, 2006a,b).

In the future, observations of terrestrial planets orbiting M dwarfs may be obtained by ground-based radial velocity and gravitational microlensing measurements, the Kepler transit mission, and NASA's Space Interferometry Mission and the Terrestrial Planet Finder Coronagraph and Interferometer missions. Using data obtained from these missions as input to models, we will be able to derive information on the actual climate of these planets.

For one-dimensional radiative–convective climate modeling, the planetary mass, radius, orbital parameters, albedo, and atmospheric composition provide a comprehensive set of model input data. These parameters will allow us to model the planetary surface temperature, which is the most crucial characteristic by which to determine habitability. For three-dimensional climate modeling, other parameters such as planetary and atmospheric rotation rate, and the distribution of ocean and land are important to determine the day–night and equator-to-pole variation of surface temperature.

Planetary radius and mass (and hence surface gravity) could be determined from the combination of radial velocity and transit detection observations (Charbonneau *et al.*, 2000; Henry *et al.*, 2000). Time-resolved photometry will most likely reveal variability in planetary cloud cover, if present, and may assist in the determination of atmospheric rotation rate. The observational signature of changes in viewed surface composition on a planet with clouds are likely to be more subtle than the cloud patterns, but may also be detected (Ford *et al.*, 2001; Tinetti *et al.*, 2006). However, time-resolved spectroscopy of different views of the planet, combined with three-dimensional planetary spectral models, will be required to determine the fractional coverage of different surface types (Tinetti *et al.*, 2006). To determine planetary atmospheric composition, radiative transfer and climate models will be required to simulate the observed spectrum and infer the presence and abundance of atmospheric gases. If some observational data are missing or unobtainable, modeling will also allow us to constrain possible planetary characteristics (see, *e.g.*, Kasting *et al.*, 1993; Joshi *et al.*, 1997; Segura *et al.*, 2005).

4.2. Planned research for the near term

4.2.1. Hubble Space Telescope Advanced Camera for Surveys prism snapshot survey of M stars in the near-UV. The surface habitability of a planet is a complicated balance between having enough UV to provide the oxygen atoms needed to form ozone and enough ozone to shield the planet's surface from the UV. Preliminary studies of M dwarf habitability zones indicate that typical chromospheric UV flux will produce observable ozone layers comparable to that of Earth on terrestrial planets around M dwarfs (see Fig. 3b in Segura *et al.*, 2005). These results also indicate that the 9.6 μm ozone band will be more prominent than that of Earth because of colder stratospheres on these planets [the ozone band is seen in absorption—a cold stratosphere above a warm surface will produce a deep absorption feature (Segura *et al.*, 2003)]. Thus, it may actually be easier to pick out ozone absorption in these planetary atmospheres than that of an Earth-like planet around a star like our Sun. In addition, vertical mixing ratio calculations for terrestrial planets around M dwarfs point toward an increased atmospheric concentration of the biomarker gases N_2O and CH_4 relative to Earth. This result is due to the differing UV energy distribution from the parent M dwarf, and it is notable that these increased atmospheric concentrations are found for planets around both active and inactive stars (Segura *et al.*, 2005). However, the stability of planetary atmospheres around inactive M stars is based on stellar model photospheres in the far UV, rather than actual observations of such stars.

Despite these intriguing results and those discussed earlier in this paper, modeling of the HZs around M dwarfs is severely limited by the lack of spectral data in the near-UV (1,700–3,000 Å). Because of the delicate balance of UV flux necessary, it is essential to model individual stars using empirical UV spectra as input. Composites of measured UV spectra of representative dwarfs have adequate signal/noise for F, G, and active K stars, but are insufficient for M dwarfs. To remedy this lack of data, a Hubble Space Telescope Snapshot survey is currently underway, led by Hawley and collaborators. This survey will use the Advanced Camera for Surveys prism to capture near-UV spectral snapshots of a sample of 107 M dwarfs in the immediate solar neighborhood. The sample has been extensively studied in the Palomar/Michigan State University survey of nearby stars (Reid *et al.*, 1995; Hawley *et al.*, 1996) and is composed of stars bright enough to be observed with short snapshot exposures. The Palomar/Michigan State University survey has homogeneous spectroscopic data of the H† region for all of these stars. Transition region spectra obtained with the Space Telescope Imaging Spectrograph in the far-UV are also available for several of the targets. In addition, two of the targets in our sample, Gl 876 and Gl 581, have recently been found to harbor Neptune-mass planets.

The Hubble Space Telescope Snapshot Survey will provide data in the important near-UV wavelength region for M dwarfs with a wide range of spectral types and activity strengths. As of fall 2005, observations have been taken for roughly 1/10th of the sample, with new observations being scheduled regularly. We anticipate that these new data will be ready for inclusion in the Virtual Planetary Laboratory photochemical models by early 2006 and vastly improving our understanding of conditions on M dwarf planets.

4.2.2. An improved census of nearby M dwarfs. There is no question that current nearby-star catalogues become incomplete at relatively small distances from the Sun, though there is some debate over the extent of incompleteness (Henry *et al.*, 1997; Reid *et al.*, 2003). Between 30% and 50% of M dwarfs within 20 pc remain uncatalogued. The main complication in finding the missing stars is contrast: sifting out the small numbers of nearby dwarfs against the much more numerous, distant background stars at faint magnitudes.

Trigonometric parallax is the most reliable method of distance determination, which achieves accuracies better than 1% for the nearest few hundred systems. There are two fundamental compendia of trigonometric parallax measurements: the Fourth Edition of the Catalogue of Trigonometric Parallaxes (van Altena *et al.*, 1995), which includes ~16,000 parallaxes measured from the ground; and the Hipparcos catalogue (European Space Agency, 1997), which includes ~118,000 parallaxes measured by the Hipparcos satellite. The latter catalogue is effectively complete for A, F, and G dwarfs to ~40 pc (~2,000 systems), but includes only a few hundred M dwarfs, since the Hipparcos survey is complete to V ~ 8.5, with the faintest stars at only V ~ 12.5.

At present, there are currently only two robust parallax programs in operation. In the Northern Hemisphere, astronomers at the U.S. Naval Observatory in Flagstaff, AZ, have both a CCD-based (charge-coupled device) effort led by Conard Dahn (Dahn *et al.*, 2002) and an IR array-based effort led by Fred Vrba (Vrba *et al.*, 2004). In the Southern Hemisphere, the RECONS group at Georgia State University in Atlanta has a CCD-based effort carried out at the Cerro Tololo Inter-American Observatory in Chile, led by Todd Henry (Jao *et al.*, 2005). Both programs, however, involve star-by-star targeted observations rather than wide-field surveys and, combined, will produce only ~500 parallaxes over the next few years. Future projects will measure parallaxes for large numbers of stars (see subsection 4.5), but at the present juncture trigonometric parallax programs are not the solution to finding the missing nearby stars.

Instead, the task of completing and expanding the sample of nearby cool stars rests on photometric and spectroscopic techniques. Because of the correlation between surface temperature and luminosity (or mass and energy generation) for core-hydrogen burning stars, absolute magnitudes for main-sequence dwarfs can be estimated from color (Reid *et al.*, 2002; Henry *et al.*, 2004) or from spectral type (Cruz *et al.*, 2003). The resulting photometric or spectroscopic parallaxes are both statistical (*i.e.*, they refer to the average luminosity of single stars at the given color/spectral type) and less accurate than trigonometric parallaxes. At best, the uncertainty in distance, σ_d, is ±15–20%, but in some regions of the Hertzsprung-Russell diagram, the uncertainties more than double to ±60% [*e.g.*, spectral types M3/M4 (Reid and Cruz, 2002; Williams *et al.*, 2002)].

Nonetheless, with the completion of the DENIS and 2MASS near-IR sky surveys, photometric selection is a viable means by which to find nearby M dwarf candidates, particularly when coupled with proper motion data. Several major efforts along these lines are currently underway and feeding targets to the trigonometric parallax programs:

- The RECONS survey (Henry *et al.*, 1997) is focused primarily on identifying stars within 10 pc of the Sun. A crucial part of that program is using photometric parallaxes to select nearby candidates from the SuperCOSMOS southern proper motion survey (Hambly *et al.*, 2004). As of September 2006, there were 348 objects in 249 systems with $d < 10$ pc and trigonometric parallax accuracy $\sigma_d < 10\%$. This is a ~20% increase since 2000, though many of the new stars had prior photometric or spectroscopic distance estimates; nearly all of the additions are M dwarfs.
- The New Neighbours program (Crifo *et al.*, 2005) uses DENIS IJK photometry to identify nearby candidates and employs follow-up optical spectroscopy to refine the classification and distance estimates. The program is mainly targeted toward late-type M dwarfs within 30 pc.
- The 2MASS NStars survey targets M (Reid and Cruz, 2002) and L (Cruz *et al.*, 2003) dwarfs within 20 pc of the Sun. L dwarf candidates are identified directly from the 2MASS JHK photometry, with more refined distances derived from optical and near-IR spectroscopy; the current survey places 80 systems within 20 pc, though only ~30% have trigonometric parallaxes. Most of the M dwarf candidates are selected from the New Luyten Two-Tenths proper motion survey, with refined distances based on photometric and (optical) spectroscopic parallaxes. With follow-up observations for approximately half the sky, over 300 systems have been added to the 20-pc census (Reid *et al.*, 2004).
- The LSPM catalog (Lépine and Shara, 2005) is a proper motion survey of (at present) the northern sky. Follow-up spectroscopy has so far concentrated on candidate cool subdwarfs (local members of the metal-poor galactic halo), but by combining 2MASS data with optical photographic photometry, this survey will identify new M dwarfs within 30–40 pc of the Sun.

The combined results from these surveys are likely to lead to great improvements in the local M dwarf census over the next few years, with the potential of identifying almost all systems within 20–25 pc.

4.2.3. The frequency of planets around M dwarfs compared to G dwarfs from debris disks surveys. Measuring the incidence of debris disks for stars that cover a wide range of masses is a promising means by which to study the relative frequency of planet formation around Sun-like stars and M dwarfs. After dissipation of their primordial planet-forming disks of gas and dust, many stars possess debris disks (*e.g.*, Backman and Paresce, 1993), which are composed solely of regenerated dust produced by collisions from larger parent bodies that are otherwise undetectable. These systems represent the extrasolar analogs of the asteroid belt and Kuiper Belt in our own Solar System. Therefore, debris disks provide signposts that indicate that large solid bodies have formed, and hence, they can shed light on the likelihood of planets around M dwarfs compared to more massive stars.

Ground- and space-based photometric studies have identified over a hundred debris disks around A, F, and G-type dwarfs from the IR thermal emission of the circumstellar dust grains (*e.g.*, Greaves and Wyatt, 2003; Bryden *et al.*, 2006). However, only a handful of confirmed examples of M dwarf debris disks are known (Song *et al.*, 2002; Liu *et al.*, 2004; Low *et al.*, 2005). One of them, the nearby (10 pc) M dwarf AU Mic, has proven to be a rich opportunity for studying disk and planet formation up close, given its proximity to Earth (Kalas *et al.*, 2004; Liu, 2004; Metchev *et al.*, 2004; Krist *et al.*, 2005; Roberge *et al.*, 2005). Many past searches for debris disks have neglected and/or overlooked M dwarfs, largely because of sensitivity limitations. Since the dust emission originates from heating by incident starlight, the much lower (a factor of 10–1,000 lower) luminosity of M dwarfs compared to G dwarfs means that debris disks around M dwarfs are much harder to detect (*e.g.*, Wray *et al.*, 2005).

New ground-based (mid-IR and submillimeter) and space-based (IR) astronomical instruments at last have the sensitivity to detect and characterize debris disks around large numbers of M dwarfs and, thereby, probe the frequency of planet formation as a function of stellar mass. The Spitzer Space Telescope has an unprecedented level of sensitivity at far-IR wavelengths (24–160 μm) and could readily detect debris disks around M dwarfs. Spitzer observations at 70 μm of 37 M stars closer than 5 pc revealed no excesses (3 σ limit) from planetary debris at temperatures around 50–100 K (N. Gautier, personal communication). However, only debris disks as exceptionally dense as the ones around beta Pictoris and AU Mic could be detected at 5 pc around a mid-M star. Such disks are rare [<1% (Jura *et al.*, 1993)], and thus the null result from the Spitzer work to date is consistent with detection statistics for debris disks around more luminous stars. A much larger sample of stars needs to be surveyed to determine how common debris disks are around low mass stars. Future surveys should focus on the youngest M dwarfs in the solar neighborhood: AFG-type dwarfs show a higher incidence of disks and larger dust masses at younger ages (*e.g.*, Zuckerman and Becklin, 1993; Decin *et al.*, 2003; Habing *et al.*, 2001; Liu *et al.*, 2004; Najita and Williams, 2005; Rieke *et al.*, 2005; Moor *et al.*, 2006), and thus young stars are the most appealing targets for detecting disks.

4.2.4. Response of planetary atmospheric structure, chemistry, and escape processes due to stellar winds, flares, and other variability. As explained in subsection 2.5 the chemistry of a planet around an M star is different because of the UV distribution of the stellar spectrum. Those models obtained steady-state solutions for atmospheres that are subjected to the same stellar flux on time. As we know, active M stars exhibit strong and variable emissions on the UV and shorter wavelengths. It is not clear how the atmospheric chemistry and the climate of the planet would respond to these variable fluxes. This issue will be studied by the Virtual Planetary Laboratory project (http://vpl.ipac.caltech.edu/), which is currently developing a coupled photochemical/radiative–convective model to study the effect of the M star variability on Earth-like planets on their HZ.

4.2.5. Evolutionary changes in stellar flux. Since the incoming stellar radiation S drives the climate of a planetary atmosphere, significant variability in this quantity will have consequences for the potential habitability of a planet orbiting an M dwarf. The variability of S can be divided into two components: long-term (periods $>>$ orbital period) and short-term (periods $\leq$ orbital period).

The long-term variability of S can be due to long-term changes in stellar luminosity, mass loss (see subsection 3.5), or changes in planetary orbits (see subsection 3.4). Although it has long been recognized that very low mass stars can potentially live for many tens of Gyr, most estimates of M star main sequence lifetimes have been based on extrapolations of evolutionary calculations for higher mass stars. Laughlin and Bodenheimer (1993) and Laughlin *et al.* (1997) produced evolutionary calculations for stars in the mass range 0.08–0.50 M_{Sun}. The main sequence lifetimes at 0.50, 0.20, and 0.08 M_{Sun} turn out to be about 100, 1,000, and 10,000 Gyr, and stars less massive than 0.2 M_{Sun} surprisingly never evolve through the red giant phase (Laughlin *et al.*, 1997). These calculations indicate that, in the time since the beginning of the big bang, no M star should have increased its luminosity by more than a percent or so, and M star planets have an exceedingly stable radiation environment over long time scales. An interesting exception for astrobiology is that the time to reach the main sequence, during which the stellar luminosity decreases significantly, is about 0.3 Gyr for 0.15 M_{Sun} and approaches 1 Gyr for 0.1 M_{Sun} (Laughlin and Bodenheimer, 1997; Burrows *et al.*, 2001). Thus retention of an early outgassed atmosphere or an early origin of life may be challenging for (eventually) habitable planets orbiting the least massive of main sequence stars.

A change in S caused by changes in a planet's orbit can also provide a constraint to habitability. Such changes will be minimal if a planet within the HZ becomes synchronously rotating. However, changes in S may be important during the time required for tidal locking (Heath and Doyle, 2004) or circularization. Other factors may prevent tidal locking and cause changes in S. These factors include an orbit with a large initial eccentricity and semi-major axis, or perturbation of the orbit by a third body. Variations of this sort can be studied quantitatively using so-called radiative–convective models, which model the mean atmospheric radiative properties in a one-dimensional vertical column and make simple assumptions for the effect of vertical heat transport by dynamics (*e.g.*, Kasting *et al.*, 1993).

The short-term variability of S can also be due to changes in stellar luminosity. M dwarfs display starspots whose magnitude compared to S is large when compared to spots on G stars. While the effect of a starspot would be significant on climate, it is unlikely that an Earthlike atmosphere on a planet in the HZ of an M dwarf would collapse as a result (Joshi *et al.*, 1997). Further research is needed, however, on quantifying the effect of starspots on specific aspects of climate such as forest habitability.

Tidally locked planets should have circular orbits, since the tidal removal of spin angular momentum increases the orbital angular momentum, which reduces the eccentricity. It is nevertheless possible that non–tidally locked planets around M stars might have eccentric orbits and, hence, experience cyclical changes in *S*. However, even if this were the case, the effect of orbital eccentricity should be far less severe on a planet orbiting an M dwarf than one orbiting a G star. This is because the orbital period of a planet in the HZ of an M dwarf is much smaller than the orbital period of a planet in the HZ of a G star (Heath *et al.*, 1999), and so the effects of changes of *S* are lowered in the former case than the latter case by the thermal damping effect of a planet's atmosphere.

More research is needed to quantify the effects of large orbital eccentricity on habitability. To do this, one has to employ a combination of the one-dimensional model described above, more complex energy-balance models that parameterize the effect of horizontal transport on climate (*e.g.*, Williams and Pollard, 2002), and three-dimensional climate models (*e.g.*, Joshi, 2003). While three-dimensional models are computationally expensive, they do explicitly represent the important large-scale physical processes.

4.2.6. Radiation damage to life. Radiation damage to a potential life form on a planet orbiting an M dwarf star can only be estimated from what is known about radiation damage to terrestrial life. This is complicated by four unknowns: what life would be like on a planet orbiting an M dwarf star, what the radiation regime would be like (discussed elsewhere), what radiation regime would the organisms be exposed to, and what countermeasures would such organisms take. In the next decade, all of these estimates will improve.

Life on a planet in an M dwarf system is likely to be based on organic carbon (Rothschild and Mancinelli, 2001). Thus, estimates of the stability of organic compounds, particularly long-chain polymers, in the presence of radiation should give us an idea of the radiation tolerance of any potential life forms. Similarly, experiments with terrestrial organisms on radiation damage (a field that has recently been re-invigorated by NASA's announcement in September 2006 of the selection of 12 new proposals to study space radiation damage) are important for understanding how organisms evolved on early Earth where the radiation levels were much higher than today.

The radiation regime to which an organism is actually exposed can vary enormously as a result of physical changes in the planetary environment, such as cloud cover and the rotation of a planet. The behavior and physiology of the organism, and the ecology in which it lives, are of consequence as well. For example, organisms can live in or under protective layers, migrate in and out of exposed areas, and produce protective pigmentation (*e.g.*, Rothschild and Mancinelli, 2001; Rothschild and Giver, 2003).

Countermeasures to deal with radiation exposure range from avoidance, such as outlined above, to repair of damage. There is enormous interest in the study of radiation damage repair because of its medical importance as well as its critical role in determining the ability of humans to survive in space. Thus, while direct research is not currently planned for mimicking the radiation exposure on a planet orbiting an M dwarf, terrestrial-based research will certainly provide an increasing base for understanding what countermeasures such organisms might be driven to evolve.

4.3. Opportunities for research that would be particularly enlightening

4.3.1. In M star disks, are there proportionately more volatiles at a given radius? Given that temperatures at a fixed orbital distance will be somewhat lower around an M dwarf than around a G dwarf (Boss, 1995), one would expect that volatile compounds (*e.g.*, water) will be found in greater abundances closer to an M than a G dwarf. Volatile abundances in a solar system's objects are generally thought to be primarily a result of the global temperature gradient in the nebula (Cassen, 1996, 2001; Boss, 1998; Woolum and Cassen, 1999). However, mixing and transport processes in the gaseous disk (*e.g.*, Boss, 2004), as well as those produced by the chaotic orbital evolution of planetesimals (*e.g.*, Morbidelli *et al.*, 2000), can have a significant effect on the radial distribution of volatiles and their delivery to planetary surfaces.

4.3.2. Prediction of duration of geothermal activity within planets in the HZ of M dwarf stars. The authors are not aware of any quantitative or qualitative studies that characterize the duration of geological activity on terrestrial planets as a function of radii and composition. However, because of the similar metallicities of G and M dwarfs, we broadly expect the sizes and compositions, and hence the range of potential thermal histories, to be similar on rocky planets orbiting either type of star. Mantle convection provides a mechanism for cycling and release of materials between the surface and atmosphere. Thus, a first-order measure of the duration of endogenic geologic activity is the time period over which convective motions are generated in the planet's interior. Planetary thermal evolution could be studied via parameterized convection models (*e.g.*, Schubert *et al.*, 1979, 2001; Hauck and Phillips, 2002). In such a study, one could vary the radius from 0.1 to 10 times that of the Earth and vary the radioactive element content from 0.1 to 10 times that of the chondritic values that are typical of our Solar System (Stacey, 1992). The results of such calculations would give ballpark estimates of the geological lifetimes of extrasolar rocky bodies, as well as the longevity of conditions conducive to planetary dynamo action. Further studies might extend these calculations to include the effects of mantle tidal dissipation (*e.g.*, Showman and Malhotra, 1999; Moore, 2003).

4.3.3. Mass loss measurements from M dwarf stars. One can ask whether relevant mass loss rates can be detected in the radio region (1–10 GHz) for nearby M dwarf star systems (*i.e.*, those within the range of the Terrestrial Planet Finder as currently designed ~15 pc). For a typical mid-M dwarf stellar mass of about 0.3 solar masses, a loss of 10% of its mass over 5 billion years would constitute a mass loss rate of 6×10^{-12} solar masses per year. Such a mass loss would cause the circumstellar HZ to migrate inward by about 7% of its initial distance using the mass–luminosity relationship for solar-type stars of $L \propto M^{2.5}$. At the same time, the planet (if angular momentum as conserved) would be expected to migrate outward by about 4%. (The impact of stellar mass loss on planetary habitability is discussed in subsection 3.2.2).

Thus, such a mass loss rate would have significant repercussion on the habitability of any planets initially formed within the narrow circumstellar HZ of M dwarf systems. Joshi *et al.* (1997), however, suggested a *proportionately* wider circumstellar HZ for M stars compared to other dwarf systems in that their peak flux is in the IR, where the moist runaway greenhouse mechanism is not directly applicable for the inner boundary and the outer boundary albedo is much smaller.

The radio flux, S_ν (in milliJanskys), expected for an optically thick free-free electron wind may be formulated (Wright and Barlow, 1975; Leitherer and Robert, 1991; Doyle *et al.*, 1995; see also Lamers and Cassinelli, 1999) as:

$$S_\nu = 2.32x^{10}(\dot{M}Z)^{4/3}(\gamma\, g_\nu \nu)^{2/3}(\nu_\infty\, \mu)^{-4/3}\, d^2 \quad (2)$$

where $\dot{M}$ is the stellar mass loss rate in solar masses per year, Z is the root mean square ionic charge of the wind particles, γ is the number of electrons per ion, g_ν is the free-free Gaunt factor = $10.6 + 1.90 \log T - 1.26 \log \nu - 1.26 \log Z$ (at radiofrequencies) where T is the stellar wind temperature, ν is the frequency in Hertz, ν_∞ is the stellar wind velocity in km/s, μ is the mean molecular weight of the wind particles, and d is the distance to the star in pc.

If we assume a single wind velocity [see Doyle *et al.* (1995) for a five-segment model based on the solar wind], with the simplifying assumptions for the wind that $Z = \gamma = \mu = 1$, $T \approx 10^6$, $\upsilon_\infty \cong 200$ km/s, and $d \approx 15$ pc, then the above equation simplifies to:

$$S_\nu = 8.8 \times 10^4\ \dot{M}^{4/3}\ \nu^{2/3}\ (21.8 - 1.26 \log \nu)^{2/3} \quad (3)$$

where the units are as stated above. The maximum opaque frequency (wind detectable above the stellar photosphere) would then be about 15 GHz. For the mass loss rate of about 6×10^{-12} solar masses per year, the flux expected at a distance of 15 pc at 10 GHz would then be about 0.003 milliJansky. This may be within the capability of, for example, the Square Kilometer Array, but days-long integrations may be necessary to ensure detection. Measurements of mass loss from stellar wind and coronal mass ejections are important for a better understanding of the evolution of the radiation (X-ray, far-UV, etc.) and particle/plasma environment of planets in the HZ as a function of spectral type and stellar age.

4.3.4. Construction of a large catalog of M dwarf stars. The combination of M dwarfs' overwhelming numbers and relative obscurity mirrors a situation familiar to biologists—it is the numerous, but tiny, microbes for which comprehensive catalogs are least complete. As outlined above, M dwarfs remain poorly catalogued at distances beyond 10–20 pc of the Sun. To conduct efficient commensal SETI observing programs on the Allen Telescope Array requires a catalogue of on the order of 1 million stars, more than 700,000 of which will be M dwarfs, if a volume-limited sample is desired. Here we consider how such a catalogue might be constructed.

As an estimate of scale, there are ~110 M dwarf systems within 8 pc of the Sun and ~2,000 G dwarfs within 40 pc. Extrapolating those number densities, with due allowance for the density gradient in the disk perpendicular to the galactic plane, a megastar survey limited to G dwarfs would need to reach ~450 pc; a megastar survey combining FGK dwarfs (300,000 stars) and M dwarfs (700,000 stars) would need to extend to ~250 and ~150 pc, respectively. Compiling reliable catalogues at those distances is not a trivial prospect. To date, large catalogues of SETI targets have been constructed from magnitude-limited samples (Turnbull and Tarter, 2003a,b).

Photometric parallax surveys offer one option, namely, estimating the distances for low mass stars from their colors and magnitudes. The Sloan Digital Sky Survey covers π steradians at moderate and high galactic latitude in the regions of the celestial sphere accessible from northern terrestrial latitudes; combining those data with the IR 2MASS data could produce substantial numbers of low mass stars (*e.g.*, Hawley *et al.*, 2002; Bochanski *et al.*, 2005). In the near future, both the Pan-STARRS project in the Northern Hemisphere (Kaiser *et al.*, 2005) and the Large Synoptic Survey Telescope in the Southern Hemisphere (Tyson, 2002) will provide multiple photometric scans at optical wavelengths of the northern sky, which will greatly surpass the Sloan Digital Sky Survey data in both depth and areal coverage.

There are, however, limitations to photometrically selected samples. First, the uncertainties in photometric parallax vary with spectral type, which leads to nonuniform selection effects, notably, Malmquist bias (the tendency to include stars that are brighter than average at a given spectral type). Second, unresolved binaries will also populate the sample in large numbers. Approximately 30% of M dwarfs are binary, half of which are nearly equal-mass systems; since such binaries are twice as bright, they are sampled over a larger volume and may contribute almost half of the stars in the photometric sample. These binaries are not necessarily the best candidates for habitable planetary systems. These two biases effectively degrade the efficiency of SETI's survey by contaminating the target sample. Follow-up spectroscopic observations can address these issues to some extent, but obtaining such data for ~10^6 stars would be a very challenging task.

The aforementioned Pan-STARRS project will be an unprecedented resource for constructing the first *volume-limited* catalog of low mass stars. Pan-STARRS comprises a unique optical survey instrument of four co-aligned 1.8-m telescopes, each equipped with a wide-field (7 square degrees) charge-coupled device camera, with an estimated completion date in 2010. As a prototype and testbed for the complete four-telescope system, the project is now finishing the first 1.8-m telescope ("PS-1"), and science operations are scheduled to begin in 2007. The large survey power (etendue) of PS-1 will enable a deep, multi-band, multi-epoch optical survey of the entire sky observable from Hawaii (3π steradians). While the depth and area of the PS-1 survey will greatly exceed all previous photographic and digital optical surveys, it is the high astrometric precision of the multi-epoch dataset (one-dimensional root mean square error of 10 milliarcseconds per observing epoch) that will enable a transformational parallax census; in contrast to all previous parallax programs, which obtained measurements on a star-by-star basis, PS-1 will determine parallaxes over most of the sky. Therefore, low mass stars can be directly selected as objects with faint absolute magnitudes, without the need for additional spectroscopic confirmation. Simulations of PS-1 performance (E. Magnier, personal communication) suggest that PS-1 parallaxes will be obtained for all M dwarfs out to around 100 pc.

In the more distant future, even larger volume-limited samples will come. The full resolution of this issue may have to await results from the Gaia satellite (Perryman, 2005). Slated for launch in 2011, Gaia aims to observe 10^9 stars brighter than 20th magnitude and obtain trigonometric parallaxes accurate to <11 μarcsec at $V < 15$, degrading to 160 μarcsec at $V = 20$. These observations will provide a reliable catalogue of G dwarfs to well beyond 500 pc, and early- and mid-type M dwarfs to 100–200 pc. Unfortunately, the catalogue will not be available until approximately 2018, at the earliest.

5. CONCLUSION

We have tried to summarize what is known about the potential for habitable planets to orbit around M dwarf stars. Given the large percentage of all stars of this type, two scientific efforts would be strongly impacted by the conclusion: (1) attempts to image terrestrial planets in orbit around nearby stars and conduct a spectroscopic assay of their atmospheres for evidence of biosignatures and (2) commensal radio searches for technosignatures using the Allen Telescope Array now under construction. Much is unknown, but we conclude that M dwarf stars are back on the table—for now.

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7. ABBREVIATIONS

AU, astronomical units; HZ, habitable zone; IR, infrared; PAR, photosynthetically active radiation; $p\mathrm{CO}_2$, partial pressure of the atmospheric greenhouse gas CO_2; SETI, search for extraterrestrial intelligence; SI, stellar insolation; SP, substellar point; T_{eff}, effective temperature; UV, ultraviolet.

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