Potential habitability of planets around red dwarf stars.

II. Re-investigation & critique 2007 to 2010.

Work conducted by the Ecospheres Project collaborators in the period 1994 to 2007 demonstrated that objections raised previously to the possibility of life developing on planets in synchronous rotation were largely mistaken (Heath *et al.*, 1999).

Subsequent papers by other workers have confirmed many of our key conclusions. The paradigm continues to evolve, however, and whilst, at the time of writing (December, 2010), there is cause for optimism about the potential habitability of planets of M dwarfs, some papers have presented very cogent challenges. In our opinion, it is probably too early to assert with confidence that MV star planets could support complex life, but there is, nonetheless, a case to be answered.

Theoretical studies are instructive, but ultimately, relevant issues must be addressed through observational astronomy.

The photosynthetic potential of M star sunlight continues to be explored. Workers have published positive conclusions, and organisms equivalent to Earth's higher plants remain a realistic possibility. Kiang *et al.* (2007a;b) published seminal papers, drawing on knowledge of the photosynthetic metabolism of plants on Earth, and discussing how photosynthesis might operate on planets receiving sunlight with different spectral profiles to that radiated by our own Sun. This work is of direct relevance for our own research looking at options for forest-type ecosystems on other planets.

Following a personal communication from P. Rich, we had noted the possibility of linked photosystems, harvesting energy from the IR region of the spectrum. Kiang and her co-workers very helpfully took speculation forwards in quantitative terms. Kiang *et al.* (2007b, p. 256): "*a three-photosystem series that utilizes wavelengths up to about 1,040 nm* [10,040 Å] *could provide the same energy input as the two PS II and PS I systems in the visible. A four-photosystem series that utilizes wavelength up to about 1,400 nm* [14,000 Å] *could also provide that same energy input, as could a six-photosystem series that utilizes wavelengths up to 2,100 nm* [21,000 Å]. *These would be equivalent to quantum requirements of, in order, 12-18, 16-24, and 24-36 photons per* CO_2 *fixed, or perhaps there might be a mix of these.*" Given four linked photosystems (2 x quantum requirement over 4,000 Å to 14,000 Å), a planet orbiting an M1 dwarf could maintain a productivity close to that of the Earth. Planets of cooler M4.5 and M5 dwarfs could manage 80% Earth productivity. With triple or quadruple quantum requirements, productivity there would drop to two thirds to half that of the Earth. With longer wavelengths harvested, productivity would still be lower than that on Earth.

Kiang *et al.* (2007b) noted also that (p. 270): *"The M stars could have several different PAR bands: they might have multiple critical absorption wavelengths in the visible, because of their noisy spectra in this region; and the dominant photosynthetic organisms would most likely harvest light over 0.4-1.1 μm* [4,000 Å and 11,000 Å], *with potential but unlikely extensions to 1.4 and 2.5 μm* [14,000 Å and 25,000 Å]."

We had discussed how photosynthetic pigments on Earth (as illustrated by plants to harvest light given low light levels under water) could be multiplied to fill in the gaps across the spectrum, to scavenge every last available photon. If plants are obliged to do this in the surface environment of a planet orbiting an MV star, where sunlight is compromised by deep absorption features, they may well adopt a similar stratagem. We were not explicit about the implication of dark or even black vegetation in the 1999 paper, but we did mention it to various students, and a comment we received was that the prospect was rather depressing. When we devised forested worlds for Big Wave's "*Alien Worlds*" documentaries (2003-2004), we actually raised the idea of black plants on planets of MV stars with the producer, but the macroscopic photosynthesisers that made it to the screen for our prime time viewers had a more upbeat pink tinge.

Kiang (2008) left the possibility of other hues open, but was quite explicit about the possibility of black foliage, which was illustrated nicely for her *Scientific American* article. We concur with her analysis (Kiang, 2008, p. 55): "*The range of M-star temperatures makes possible a very wide variation in alien plant colors. A planet around a quiescent M star would receive about half as much energy that Earth receives from our sun. Although that is plenty for living things to harvest – about 60 times more than the minimum needed for shade-adapted plants – most of the photons are near-infrared. Evolution might favor a greater variety of photosynthetic pigments to pick out the full range of visible and infrared light. With little light reflected, plants might even look black to our eyes.*" Another possibility which we posited in our 1999 paper, and which we would like to note again here, is that of photosynthetic organs harvesting infrared could be overlain by another that harvested radiation in the visible region of the spectrum, and through which IR could penetrate.

We were encouraged that these three seminal papers from Kiang and co-workers, which explored the issue in more detail than had we, did not undermine our earlier optimistic conclusions. Instead they reinforced and extended them: significant photosynthetic production would not be precluded by the spectral quality of M star sunlight. There are positive implications also for the possibility of photosynthetic production around evolved M stars on the red giant and asymptotic giant branch of the Hertzsprung Russell diagram.

The implications of stellar variability, notably the flare activity that is commonplace amongst red dwarfs, and particularly amongst the lowest mass and youngest examples, has received attention from a number of workers.

Buccino *et al.* (2007) considered the problems of lack of UV in quiescent MV star output for forming molecules essential for initiating life, and the problems of strong UV flares in tandem. Buccino *et al.* (2007, p. 1): "*our results show that terrestrial-type planets within the LW-HZ around inactive M stars do not receive enough UV radiation to perform the synthesis of complex macromolecules, and would therefore need an alternative energy source to start the biogenesis. . . . In contrast to what has been believed for a long time, moderate flare activity could play an important role in the origin and evolution of life . . . M stars with moderate flares are the best candidates to host habitable planets.*" This paper had inverted a common assumption that flares must be biologically damaging and opened up discussion about the importance of UV for habitability.

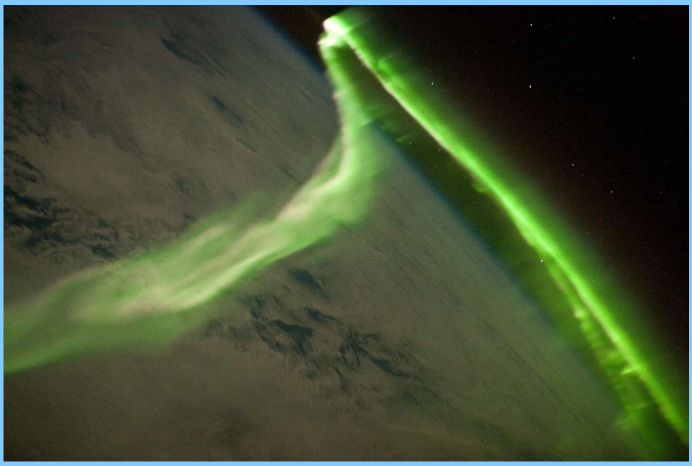
The re-investigation of the habitability of MV star planets by Scalo *et al.* (2007) was a definitive milestone in this new field. these workers observed (2007, p. 97): "*Overall, the radiation environment, stable in some respects, almost violently fluctuating in others, remains the most puzzling and intractable of astrobiologically related properties of M stars, and the biggest question mark concerning habitability in a type of environment with which we have little experience.*"

We (Heath *et al.* 1999) had considered data from the Great Flare of AD Leonis (Hawley & Pettersen, 1991), observed on April 12, 1985, estimating (the process was rather crude and preliminary) that at the distance at which a planet received Earth-level insolation, UVA (3,900 – 3,150 Å) would have peaked at 1.8 Earth level, and that UVB (3,150 – 2,900 Å) plus UVC (< 2,900 Å) would rise by < 4.0, for < 20 min. Å

Segura *et al.* (2010) analysed the output of the flare and explored its implications for atmospheric physics and chemistry. They adopted similar band widths to ours (UVA = 4,000 – 3,150 Å; UVB = 3,150 – 2,800 Å; UVC = < 2,800 Å). They calculated that at the peak of the flare at 15.25 min, the UV received at the top of the atmosphere would compare with respective values for Earth levels in the proportions UVA = 1.1, UVB = 2.6 and UVC = 54.8. Respective values at the planet's surface would be UVA = 1.0, UVB = 1.2, and UVC = 0.9, and elevated irradiation relative to Earth levels would be encountered for < 100 s. In addition, some flare events would occur on the side of a star that happened at that time to face away from an orbiting planet. Derived figures differ, but the overall conclusion, namely that the elevated levels of UV associated with an extreme flare need not pose fatal problems even for forms of biology known here on Earth, where no special adaptations for flares have been necessary.

Scalo *et al.* (2007) had noted (p. 152) the potential problem of: "*persistent and annoying series of high-amplitude flares whose frequency and intensity, especially during the first few Gyr of an M star's life are so great that the atmospheric photochemistry, if an atmosphere remains, could be in a state of continual variation, affecting all couplings of the atmosphere to the biosphere.*"

Segura *et al.* (2010, p. 769), however, concluded that: "*For an oxygen-rich, Earth-like planet in the habitable zone of an active M dwarf, stellar flares do not necessarily affect habitability. Much of the potentially life-damaging UV radiation goes into photolyzing ozone in the stratosphere which prevents us from reaching the planetary surface. Ozone variations cause temperature fluctuations in the upper atmosphere, but these fluctuations are small, and the climate at the surface is unaffected. Ionizing particles emitted during a flare may be more dangerous depending on how much of the particle flux strikes the planet. The additive effects of repeated flares over the duration of the planet's lifetime are not well understood; given that M dwarfs can be active on timescales of days to weeks, the atmosphere may not return to equilibrium before another flare occurs.*"

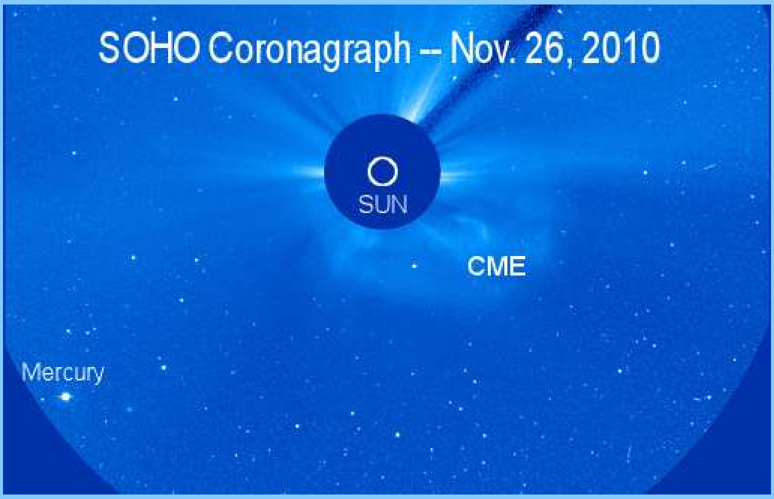


Our 1999 paper was not so comprehensive as to look at the charged particle environment in the vicinity of M stars, although we had raised concerns about atmospheric stability in informal discussions, stressing that we would like to see them addressed by workers in relevant fields.

This was a significant problem, because planets close enough to M stars to receive Earth-like levels of insolation would lie much deeper within the electromagnetic and charged particle regime of their parent star than does the Earth.

Other workers independently took up the issue, which threatened to become a fundamental objection to the concept of habitable planets around red dwarfs. In particular, a hazard is posed by the episodic release of masses of plama in events known as Coronal Mass Ejections. The image above left shows the appearance of the Earth's aurora from space (NASA).

Lammer *et al.* (2007) investigated the erosion of CO_2-rich atmospheres of Earth-size exoplanets as a result of CME-induced ion pick up within close-in habitable zones of active M-type dwarf stars. M stars can exhibit significant activity in the X-ray and extreme ultraviolet radiation (XUV) range. They applied a thermal balance model for thermospheric heating by photodissociation and ionization processes and found that intense XUV radiation of active M stars results in atmospheric expansion and extended exospheres. CMEs were able to remove several hundreds of bars of atmosphere from Earth-like planets lacking magnetic fields. The implication was that larger and more massive terrestrial-type exoplanets could best protect their atmospheres, since they would have larger cores capable of generating stronger magnetic moments, and because higher planetary gravities would constrain the expansion of the thermosphere-exosphere regions and thus reduce atmospheric loss.



Coronal Mass Ejections, otherwise designated as coronal transients, are loops of matter, with masses of up to several 10^8 tonnes which are ejected into space at velocities which may be as high as > 400 km s^{-1}.

Left: A CME moving outwards from the Sun (NASA).

Khodachenko *et al.* (2007) noted that planets in tidal lock close to M stars, might have as a consequence, relatively weak intrinsic planetary magnetic moments, which could result in little or no magnetospheric protection of their atmospheres from dense CME plasma flows, such that magnetospheric standoff distances of weakly magnetized Earth-like exoplanets at orbital distances of ~ 0.1 AU could be shrunk by impact of CMEs, to altitudes of ~ 1,000 km above the planetary surface.

Scalo *et al.* (2007) highlighted such problems and emphasised how, given the strong stellar activity of MV stars and the small size of circumstellar HZs, the strength of planetary magnetic fields would be of vital importance in deciding whether even planets with thick atmospheres could retain them against stripping by CMEs (p. 149) "*The combination of expected weak magnetic moments due to tidal locking, strong CME plasma exposure, and thermospheric heating by XUV could be a crucial factor in the evolution of atmosphere and water inventories of Earth-like exoplanets within the HZ of M stars. Hence the similarity of Earth-like exoplanets within M star HZs to the present Earth in these circumstances is uncertain.*"

Could habitable planets around MV stars be restricted to larger bodies than the Earth? Possible problems for such an option could be posed by the lack of mass available to form

Earth-sized planets in planet-forming disks around MV stars. This result emerged in dynamical simulations by Raymond *et al.* (2007), who found that the mean mass of bodies forming in the HZ of a star of 0.5 M should be < 0.1 M , rather less than the mass of Mars, which has been far less geologically active than the present day Earth for most of its history. The minimum mass adopted for a planet able to sustain significant geological activity for several Gyr was $0.3\ M_{\oplus}$. These workers reported (p. 606) that “*Our results suggest that the fraction of systems with sufficient disk mass to form > $0.3\ M_{\oplus}$ habitable planets decreases for low-mass stars for every realistic combination of parameters. This habitable fraction is small for stellar masses below a mass in the interval 0.5-0.8 $M_{\odot}$, depending on disk parameters, an interval that excludes most M stars. Radial mixing and therefore water delivery are inefficient in the lower mass disks commonly found around low-mass stars, such that terrestrial planets in the habitable zones of most low-mass stars are likely to be small and dry.*”

In contrast, Delfosse *et al.* (2012), reporting continuing results from the European Southern Observatory’s High Accuracy Radial Velocity Planet Searcher (HARPS) survey, noted in their abstract that: “*M dwarfs have been found to often have super-Earth planets with short orbital periods. Such stars are thus preferential targets in searches for rocky or ocean planets in the solar neighbourhood.*” We note that the terrestrial character of objects denoted as “*super-Earths*” remains to be confirmed and that in most cases, the option of water-rich bodies, perhaps with affinities to Neptunian-type planets, cannot be dismissed.

A further significant reappraisal of the problems for biology on planets of MV stars was undertaken by Barnes *et al.* (2010).

The crucial CME problem was amongst the issues explored, and the conclusions now presented were more optimistic than those of earlier studies. It was observed (p. 7) that: “*Many planets in the HZs of M dwarfs will be exposed to denser stellar winds and be tidally locked. As a consequence, the exoplanet community initially reached the consensus that the slow rotation of the planets will prevent the development of magnetic fields strong enough to shield surface life.*” However, (noting room for uncertainties due to unmodelled geophysical processes), they were obliged to conclude from their own studies that (p. 9): “*1)* ***the magnetic moment of a planet does not depend on its rotation rate,*** *2) the magnetic moment depends instead on its mass and size, its chemical composition, and the efficiency of convection in its interior; and 3) any terrestrial planet up to a few earth masses in the HZ of an M-dwarf might have a strong enough magnetic field to shield its atmosphere and surface.*”

This is a paper which deserves to be studied closely by any workers in astrobiology who wish to pursue their own research into this topic. We note here the overall conclusion of this group (Barnes *et al.* , 2010, p. 11) that: “*In spite of early scepticism, planets orbiting M dwarfs can be inhabited. Although many issues have been identified, such as tidal locking and atmospheric removal, more careful modeling has shown that these phenomena are not so deadly.*”

Barnes *et al.* (2010, p. 1): “*no known phenomenon completely precludes the habitability of terrestrial planets orbiting cool stars.*”

We invite members of the scientific community representing diverse disciplines to continue to critique the conclusions which we published in Heath *et al.* (1999), and in particular to re- calculate our estimates of PAR available in M star sunlight, and irradiation from stellar flares, which, we emphasise, were rough and ready, being intended not to serve as the final word, but rather to set a discussion in motion.

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