Potential habitability of planets around red dwarf stars.

I. **1994-2007: Initiating a paradigm shift.**

The opportunities for life on planets in synchronous rotation around their parent stars, and in particular, on planets orbiting low mass, low luminosity stars, have been a major focus of interest for the Ecospheres Project collaborators.

The number of stars increases exponentially with decreasing mass. Around 4% of the stars in our Galaxy are of the same spectral class as our Sun, but > 70% are red dwarfs of spectral class M (Zelik, 2002). Notwithstanding, MV stars were generally dismissed as suitable primaries to support life-bearing planets.

We were able to demonstrate that a long-standing paradigm, which rejected the habitability of planets orbiting red dwarf stars, was flawed. Our work proved helpful in encouraging US government funding for a new area of planetary habitability and SETI research. It drew an enthusiastic response in popular literature, amongst documentary-makers, and even in the science fiction community.

Later papers from other workers raised serious new problems, although these appeared not so formidable by the close of 2010. The Ecospheres collaborators continue to address the implications and to explore new possibilities.

Above left: A planet in synchronous rotation, with sea-ice and continental ice sheets extending into daylight from a permanently unlit hemisphere. Devised by the Ecospheres Project collaborators for Big Wave TV.

The main reasons for dismissing the habitability of planets around red dwarf stars were:

i) It has long been understood that stellar luminosity declines exponentially with decreasing mass. Red dwarf stars are very faint. A spectral class M0 star of 0.47 $M_\odot$ would have a luminosity of 0.063 $L_\odot$, and a M8 star of mass 0.01 $M_\odot$, a luminosity of a mere 0.0008 $L_\odot$ (as tabulated by Allen, 1973). Planets orbiting sufficiently close to receive Earth-like levels of insolation would become tidally locked into synchronous rotation, such that they kept the same face pointed permanently towards their parent star. Under these conditions, it was feared, any atmosphere or ocean would condense out on the permanently dark hemisphere.

ii) M dwarfs are notable for frequent flare activity, and this implied that irradiation of the daylight hemisphere would be inimicable to biology.

iii) The light from M stars was deemed to contain too little Photosynthetically Active Radiation to permit useful higher plant photosynthesis.

According to this conventional view, the majority of stars would be excluded *a priori* from consideration as possessing habitable planets. Such arguments re-inforced the credibility of the argument that truly Earth-like planets are uncommon, whose most high-profile proponents have been Ward & Brownlee (2000).

It was at the 1994 First International Conference on Circumstellar Habitable Zones, convened by one of us (Laurance R. Doyle) at NASA Ames, that the *status quo* regarding planets of red dwarf stars began to be questioned.

Haberle *et al.* (1996, p. 29) summed up succinctly what had been the conventional standpoint: "*tidal torques acting on any planets within them could ultimately force them to synchronously rotate (Dole 1964, Kasting et al. 1993). Thus these planets would have a side that is always in sunlight, and a side that is always in darkness. It would appear then, that synchronously rotating planets could not sustain life since heat loss on the dark side would eventually freeze out the atmosphere. In this case, M stars would not be suitable candidates in the search for extraterrestrial life.*"

A group at NASA Ames, namely Bob Haberle, Chris McKay, Daniel Tyler and Ray Reynolds, now challenged this long-held wisdom. Their own studies had indicated (Haberle, *et al.*, 1996, p. 29) that: "*when atmospheres are differentially heated they generate a circulation that transports heat from regions of net gain to regions of net loss. Thus, a synchronously rotating planet would generate a circulation that would transport heat from the light side to the dark side. If the transport is sufficiently vigorous, temperatures on the dark side could be kept high enough to prevent the atmosphere from freezing out.*"

It had seemed, even so, that such a planet's water might freeze and accumulate on the dark side. This prospect was unhelpful for habitability, because life as we know it requires liquid water. These workers invoked a somewhat forlorn prospect that the tongues of ice sheets, spreading outwards from the side of the planet where it was permanently night, could suffer ablation, in the twilight zone around the terminator. The day hemisphere would thus not be *entirely* arid, and there could, at least, be relatively small quantities of water for exploitation by biology.

Another problem appeared to exist with regard to the amounts of the greenhouse gas CO_2 which might be needed in the atmosphere to prevent it from freezing out on the dark side.

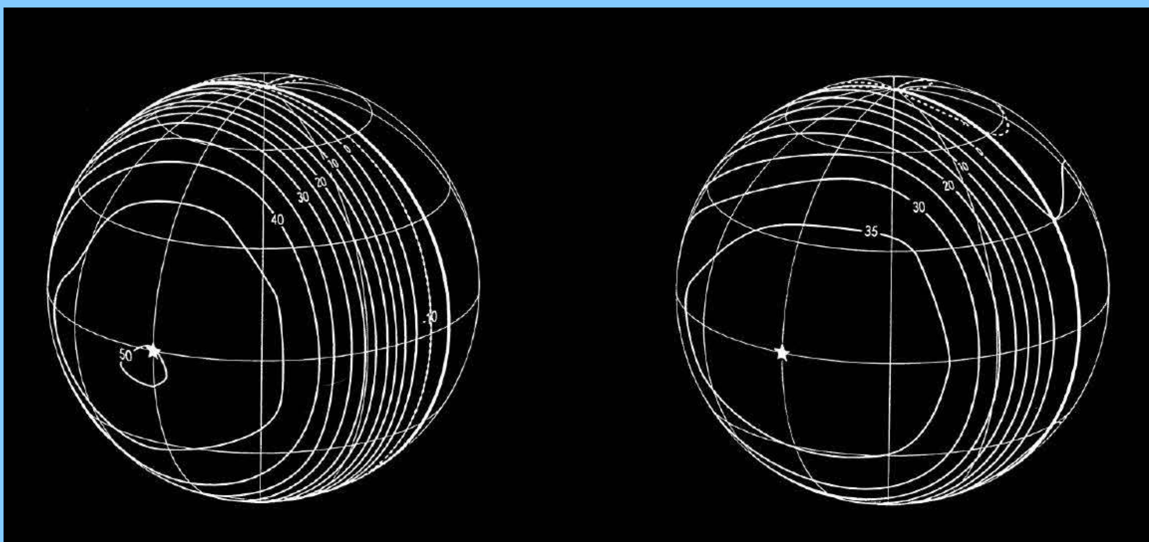
To Haberle, *et al.* (1996) the quantity seemed relatively modest (p. 33): "*the amount of CO_2 required to prevent freeze-out is not that large. A synchronously rotating planet, receiving about the same insolation as Earth does today, would require only about 100 mbars of CO_2. This is well within estimates of the CO_2 inventory for terrestriallike planets.*"

Above right: Snout of the John Hopkins Glacier. L. R. Doyle.

This value, as it stood, was not necessarily reassuring. As recognised in Heath *et al.* (1999, p. 407) : "*Maintaining a pCO_2* [partial pressure of CO_2] *hundreds or thousands of time higher than that on the present Earth on a planet subject to Earth-level insolation could be problematic.*" *p*CO_2 = 0.1 bar is certainly much higher than the equilibrium values adjusted by the carbonate-silicate cycle on a planet subject to Earth-like styles of geological activity, rates of CO_2 outgassing, insolation, and CO_2 drawdown through weathering. Ward & Brownlee (2000) in their sceptical work "*Rare Earth. Why Complex Life Is Uncommon in the Universe*," cited this in passing as an unrealistic requirement.

This was not an unreasonable response. However, the premise of this objection was mistaken. Manoj Joshi, a climatologist working with Bob Haberle, at NASA Ames, and a co-author of Heath *et al.* (1999), confirmed in the latter paper (p. 407) that: "*since the effective grey optical depth of the present terrestrial atmosphere (containing just 350 ppm CO_2 with H_2O as the principal greenhouse gas) is approximately 0.9 as against 1.0 for a 1000 mb pure CO_2 atmosphere, we can use the latter as an approximation (for an Earth-type atmosphere temperatures would be just a few degrees lower over the lit hemisphere), and need not postulate or explain a pCO_2 higher than that on present day Earth.*"

Climate simulations indicated that the surface regimes of Earth-sized SRPs could be much more clement than earlier writers (such as Dole, 1964) had supposed.



Above: Two simulations of climate on a planet of a planet in synchronous lock, using models by M. M. Joshi and R. M. Haberle. Planetary albedo was assumed to be 0.2, consistent with the reduced rayleigh scattering of red and IR- biased MV star sunlight. Left: Insolation = 1.0 $I_\oplus$; pCO_2 = 1.0 bar; τ optical depth = 1.0. Right: Insolation = 0.8 $I_\oplus$; *p*CO_2 = 1.5 bar; τ optical depth = 1.5. It should be remembered that Earth-like atmospheric composition may be substituted for CO_2 with a reduction of just few degrees in surface temperatures. Isotherms are labelled in degrees Celsius. See Joshi *et al.* (1997). Images were prepared by the late Adrian Lloyd for Lloyd for Heath *et al.* (1999). A more detailed model of climate on a synchronously rotating planet was published by Joshi (2003).

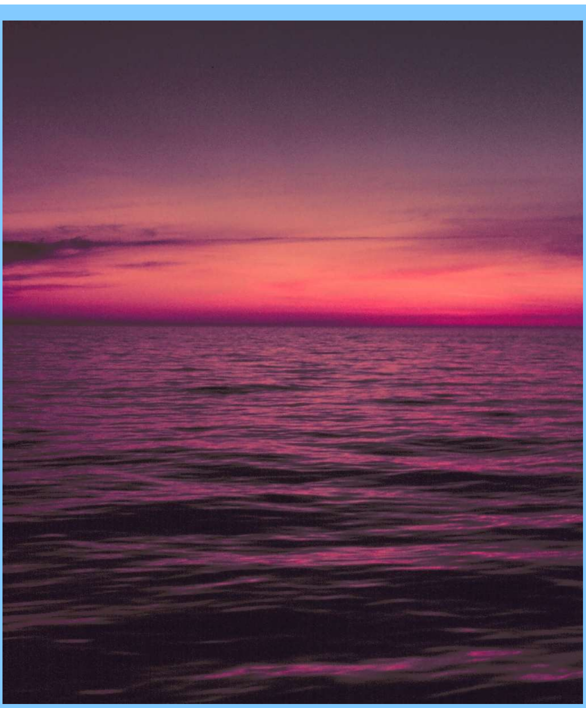
It was noted that in these simulations, temperatures were appropriate not only for a robust microbial biosphere, but would have been compatible also with Earth-type forest trees.

Of course, organisms with similar physiological tolerances to Earth-type higher life could flourish in such situations only if all other relevant parameters were appropriate, but we were able to say that on climate grounds, ecosystems with complex life were a possibility worth exploring further.

The problem of water accumulating in ice sheets on the dark hemisphere turned out likewise to be overly pessimistic. Main sequence stars increase in luminosity with age, and in canonical models, our own Sun arrived on the main sequence with ~ 72% of its present luminosity. High pCO_2 sustained by the crude planetary thermostat of the carbonate-silicate cycle offers one explanation of how the Earth managed to avoid freezing over at this time. However, Bada *et al.* (1994) demonstrated that for Earth-like levels of geothermal heat, the Earth's oceans need not have frozen to their bases even without an enhanced greenhouse effect.

We adapted this model to show how a vigorous hydrological cycle might take place on a planet which had been trapped into synchronous rotation. A layer of ice could form on the dark side of the planet, but an Earth-like geothermal flux through its base would constrain its thickness. This means that water lost as rain or snow falling on the surface of the sea ice would have to be balanced by melting at the base of the floating ice. If the ice overlay sufficiently deep ocean basins (such as those on the present day Earth) which communicated with ocean basins on the daylight hemisphere, water would not be lost on the planet's dark side. We adopted a heat flow of 53 ergs cm^{-2} s^{-1} (that of the ocean basins on the present day Earth, rather than the early Earth, which was hotter inside), and a pessimistic temperature of -78.5^{o} C for the dark side (a limiting case where a thin atmosphere was itself about to freeze out). If the base of the floating ice was at the freezing point for saline ocean water (-2^{o} C), the ice sheets would be about 2.9 km thick (the average depth of Earth's oceans is 3.8 km). The ice layer becomes thicker if one takes into account how the thermal conductivity of ice varies with temperature (Klinger, 1980), which we did not in that paper, but the basic mechanism still works (particularly since the night hemisphere should be much warmer than -78.5^{o} C). Also, with a higher equilibrium pCO_2 at consistent with slightly greater distances from the parent star, there need be no dark-side ice to lock up water.

Images left: NOAA.



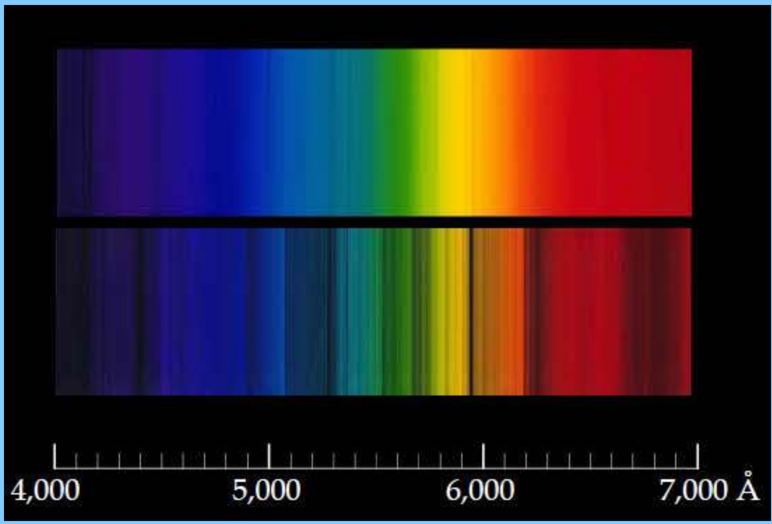
Previous attention had focussed on the environmental status of planets that were already locked into synchronous rotation. The actual spin-down phase, which could be protracted under some circumstances, had escaped interest. Heath & Doyle (2004) explored the sequence of events on planets that passed through a phase of near-synchronous rotation, when the close but not perfect agreement between the rotation of the planet and its orbital cycle could allow nights to stretch out into days, years, decades, centuries, or even longer. This would pose serious survival problems for photosynthetic organisms.

The early phase, where nights are months in duration, does not appear to pose insuperable problems. At various times during the Phanerozoic, forests thrived in Earth's polar regions. Trees here were able to survive months of darkness. If the Earth were to suffer spin-down, however, forests would face an ever-escalating challenge. When nights became around a decade long, many trees would become extinct as their seeds could not survive this period of dormancy. Trees with seeds able to survive for longer would nonetheless face problems because a decade-long day might not allow them to achieve maturity. Even on the equator, tropical conditions would not be sustained. The sun, having climbed to the zenith over a period of years, would descend just as slowly. As it did so, low sun angles and the necessity for sunlight to penetrate an increasing air mass at lower altitudes would bring cooling conditions. This is not to argue that some kind of ecosystem could not lay dormant for years and then exploit immensely long days, nor to argue against the possibility of mobile organisms tracking the sun. The potential for evolutionary adjustment amongst organisms equivalent to multicellular eukaryotes remains to be investigated in depth.

The problems of the spin-down phase would be avoided in the case of the least masssive and faintest MV stars, where spin down would be rapid, but most pronounced for the largest and most luminous M dwarf stars. Otherwise, it might have implications for Earth-like planets around more Sun-like stars which, as a result of the last giant impacts which they suffered, ended up with slow rotations, rendering them susceptible to tidal lock.

A classic fictional exploration of a far future Earth which has been reduced to synchronous rotation as a result of solar and lunar tides was provided by Brian Aldiss in his novel "*Hot House*" (Aldiss, 1962).

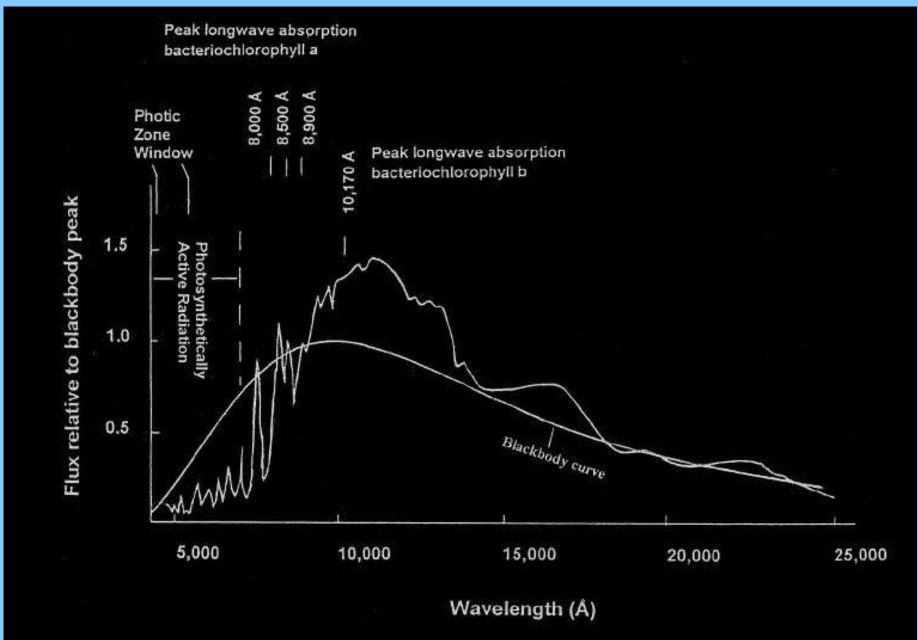
Images: NOAA.



Left: Representation of the spectra of a G0 star (Sun is spectral class G2) and an early M dwarf across the Photosynthetically Active Range (4000 to 7,000 Å) exploited by higher plants on Earth. This range is of biological interest because photons are of sufficient energy to drive metabolic processes readily, but not so energetic that they pose a hazard to living organisms. PAR is smaller for MV stars than in a simplistic blackbody treatment, because absorption features (notably from titanium oxide) crowd this region of the spectrum. Allard *et al.* (2000) discussed TiO and H_2O absorption features in cool stellar atmospheres.

The differences between the spectral quality of sunlight falling on the Earth from its G dwarf Sun and the sunlight arriving from an M dwarf are crucial to the investigation of habitability.

A reduction in PAR in the insolation of an MV star compared with the Sun (5770 K), is predictable on the basis of blackbody calculations, but these would not take into account the substantial obstruction of the PAR region of the spectrum in cooler stars. A consequence of this line blanketting effect is that there is back-warming of the continuum as radiation escapes at other wavelengths. This helps to fix peak output for cooler stars in the vicinity of 10,000 Å.



Left: A simplified synthetic spectrum for red dwarf of solar-metallicity and T_{eff} = 3,000 K (after Allard & Hauschildt, 1995), and the smooth emission curve of a perfect blackbody radiator.

Peaks for absorption by bacteriochlorophyll after Rabinowitch & Govindjee (1969). Indicated also is the longer wave end of the PAR range, and the photic zone window. Image: Heath *et al.* (1999).

Many bacteria carry out types of photosynthesis that exploit the IR part of the spectrum. The peak response of bacteriochlorophyll b lies close to the peak output of MV stars.

Above: A landscape of a planet in synchronous lock around a red dwarf star as envisaged in preliminary work by the Ecosphere collaborators for the television programmes *"Alien Worlds"* by Big Wave Productions. A volcano emphasises the contribution of geological activity on a planet supporting an ecosphere. The plant life consists of leaves or leaf arrays orientated towards the red dwarf sun, which always sits in the same place in the sky.

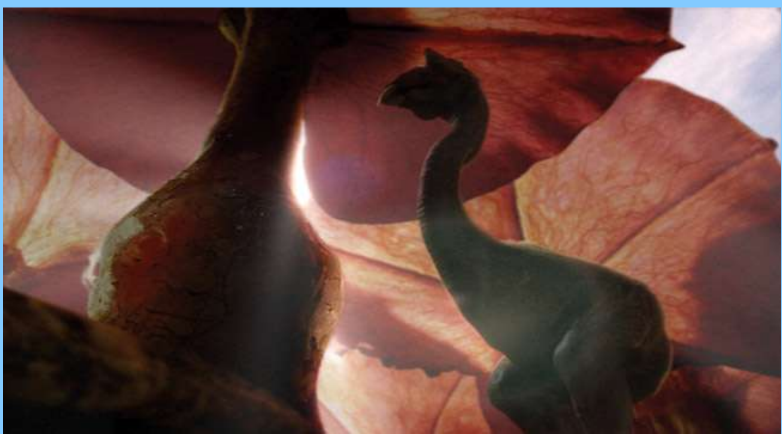
Bacterial metabolic pathways for IR photosynthesis do not split water and liberate O_2 - the latter being essential for the active respiratory metabolism of higher plants and animals on Earth. actually slightly hotter than the hottest red dwarf at 3,700 K) would be about a third that in solar insolation. At the sub-stellar point, the reduction in PAR could be compensated by perpetual noon conditions (albeit cloudiness could modify that figure). It must be noted, moreover, that a proportional increase in red light need not be disadvantageous, because higher plants on Earth make less efficient use of blue light, squandering the higher energies of blue light photons, and, also red light has higher atmospheric transmission coefficients and is much more effective at penetrating the progressively greater thicknesses of atmosphere which must be traversed by a beam of light arriving at increasing distances from the sub-stellar point.

In Earth history, both plants and animals are believed to have evolved originally in aquatic environments. The amount of light available underwater is of key interest here. Light in the range 4,500 Å to 5,500 Å is most effective at penetrating water, enabling a photic zone where vigorous photosynthesis is possible in the upper part of the water column. We termed this part of the spectrum Photic Zone Window Radiation (Heath *et al.*, 1999). The proportion of PZWR in the insolation of a 4,000 K star would be about a quarter that in solar insolation. For a 2,800 K star, we estimated that PAR would be a twelfth, and PZWR would be a twentieth that in solar insolation. Certainly, there would be sufficient PAR available for many types of plant, but cloud cover and atmospheric turbidity could reduce the amount of light arriving at the sea surface. further. Howbeit, photosynthetic production may be metabolically profitable at very low light levels. Bunt (1983) studied diatoms living ~ 4 m deep in the sea ice of McMurdo Sound, Antarctica. They maintained carbon fixation at 20 % the rate observed for sea surface illumination, with just 0.127 W m^{-2} = 9 x 10^{-5} solar constant.

In principle, it might be possible for water-splitting photosynthesis to harness energy from the infrared. We noted (Heath, 1999, p. 418): '*Water-splitting, O_2-liberating photosynthesis could be possible, in principle, with a series of linkled photosystems using energy right out to 21 000 Å, though we must be cautious about the prospects for such complex and convenient metabolism evolving through natural selection (P. Rich, Pers. Comm., 1995).*' There was an uncorrected typographical error here; the figure we had been given was actually a more generous 28,000 Å!

Stellar variability has always been considered to be problematic for biology on planets of MV stars. We concluded that aspects of the problem had been exaggerated. Joshi *et al.* (1997) modelled the implications of star spots and concluded that in the extreme case of a 40% decrease in insolation for 4 months. This caused areas to suffer a maximum decrease in surface temperature of 27 K. Areas near the eastern terminator in particular would have been susceptible to falling below freezing point.

Such events, however, whilst not so regular as seasons, would not produce more extreme weather changes than do the seasons on Earth in some climatic zones. Otherwise, MV stars are notorious for flares. Flares are more common in the younger M dwarfs, and also, for all ages, with less massive stars. We pointed out that *relative* increases in UV flux over quiescent levels should not be confused with *absolute* UV irradiance. It was possible to show in many cases, flares on M dwarf stars would not raise UV levels to those incident above the atmosphere on Earth.



Many higher forms of life could be protected from UV and direct heating from flares by living immersed in water. Also, some might possess hard coverings as protection against predation. On Earth, such features exist in many organisms that live in subaerial environments.

Above: Organisms living on a planet orbiting a red dwarf star shelter from a flare – a frequent occurrence.

Examples of organisms exploiting protective coverings are numerous and commonplace; snails have shells, tortoises have carapaces, and the caddis fly larvae of freshwaters manufacture protective cases for themselves from small pebbles and detritus. The evolution of suitable exoskeletons and/or more effective repair systems for nucleic acids would be appropriate evolutionary stratagems on planets subject to severe flares.

The tentative conclusion from our study was that there was, at the very least, a case to be answered for the possibility that planets of M dwarfs might possess complex life, perhaps even some kind of forest-type biomass (without postulating unknown biology).

Chris Chyba, a former student and co-worker of Carl Sagan, and also, at that time incumbent of the Carl Sagan Chair for the Study of Life in the Universe at the SETI Institute, used the paper as supporting evidence at a congressional hearing exploring funding for SETI (Search for Extra-Terrestrial Intelligence).

Above: SETI Institute, 2005. M. J. Heath.

In July 2005, funding arrived for studies of the habitability of MV stars. NASA sponsored a three day *Workshop on the Habitability of Planets Orbiting M Stars* at the SETI Institute, which, at that time, was located on North Whisman Road, Mountain View, CA, close to NASA Ames.

At this meeting, we circulated a paper drawing attention to the possibility of what we called "*Hestian planets.*" These were named for Hestia, the hypothetical central fire around which the Earth orbited according to some Pythagoreans. There were different versions of this idea in antiquity, and differing modern interpretations. According to one (Pannekoek, 1961, p. 100): "*the centre of the universe is a fire, called 'Hestia' (i.e. the hearth); the spherical earth describes a daily circle around this fire, always turning its uninhabited side towards it. Thus day and night alternate; we cannot see the central fire, since (to make the number of world bodies ten) another dark body, the counter-earth, is interposed between us and the fire.*" We denoted a hestian planet as a planet in synchronous lock around a red dwarf, which received insolation also from a more distant stellar companion of earlier spectral class.

This international and multidisciplinary gathering, organised by Peter Backus, and overseen by Jill Tarter, Director of the SETI Institute, re-examined the problems from first principles upwards. In that sense it provided a valuable peer review of our work. It endorsed our previous conclusions in a new paper, Tarter *et al.* (2007). Peter Backus performed a herculean labour in pulling this paper together from the contributions and mutual interactions of no less than thirty one authors. This paper appeared in a special 2007 issue of *Astrobiology*, devoted to M Star Planet Habitability (preface by Lammer, 2007).

In their classic paper, Kasting *et al.* (1993) had drawn a line truncating their Habitable Zone on its inner margin for tidal lock radius at 4.5 Gyr (approximate age of the Earth), making certain assumptions about primordial rotation and tidal dissipation. We consider ourselves privileged to have been able to re-open debate in a field which had, for so long, appeared to have reached a dead end.

With regard to SETI searches, one might bear in mind not only the possibility of native life, but also the possibility of colonists from other habitable planets, possessing technology to exploit or transform sub-optimal, but, perhaps, not overwhelmingly hostile global environments. Transmissions from automated exploration stations in the vicinity of red dwarf stars are another possibility to be considered in devising SETI programmes.

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