HABITABILITY OF PLANETS AROUND RED DWARF STARS

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Abstract. Recent models indicate that relatively moderate climates could exist on Earth-sized planets in synchronous rotation around red dwarf stars. Investigation of the global water cycle, availability of photosynthetically active radiation in red dwarf sunlight, and the biological implications of stellar flares, which can be frequent for red dwarfs, suggests that higher plant habitability of red dwarf planets may be possible.

1. Numerical Predominance of Dwarf M Stars, and Their Potential Interest to Biologists

Main sequence (MS) dwarfs of spectral class M (dM stars) comprise $\sim$70% of solar neighbourhood stars. At one end of the range are stars of about half a solar Mass ($M_\odot$), with >6.0% solar luminosity ($L_\odot$), and an effective photospheric temperature (T_{eff}) of)3,700 K. At the other are stars of about 0.08 $M_\odot$ (the lower limit for true stellar objects, that produce their energy through nuclear reactions), with <0.1% $L_\odot$, and $T_{eff} \sim$ 2,700 K (Allen, 1976; Bessell and Stringfellow, 1993; see also Rodono, 1986). Characteristics of dM stars, based on Lang (1991) and Gray (1992) are summarised in Tables I and II. Since Earth-mass planets should be able to form around dM stars (Wetherill, 1996), a re-examination of the prospects for such planets to support higher life is of key interest to exobiologists.

TABLE I

Generalised masses, radii and luminosities of dM stars (sun=1.00), after Allen (1973)

Spectral type	M0	M2	M5	M8
Mass	0.47	0.39	0.21	0.10
Radius	0.63	0.50	0.32	0.13
Luminosity	0.063	0.032	0.008	0.0008

TABLE II

Generalised radiative parameters for dM stars (with Sun for comparison)

Spectral type	G2	M0	M1	M2	M3	M4	M5	M6	M7	M8
Radius/solar radius	1.00	0.62	0.58	0.53	0.45	0.39	0.33	0.26	0.18	0.12
Blackbody Teffo (degrees Kelvin)	5860	3850	3720	3580	3470	3370	3240	3050	2940	2640
Ie orbital radius (A.U.)	1.00	0.26	0.23	0.19	0.15	0.12	0.10	0.07	0.04	0.02
Ia orbital radius (stellar radii)	214	56	48	41	33	27	21	14	9	5

Radii data are interpolated from Gray (1992) and Lang (1992), and estimates do not agree exactly with data in Table I. Integrated black body energy for each star and stellar radii were used to calculate the distance from the parent star at which total energy contained in insolation would be equal to present solar insolation (Ie) on Earth (1.360×10^6 ergs/cm^2/sec).

dM stars have generally been dismissed as suitable primaries for planets supporting biology. This is because planets sufficiently close to these stars to receive Earth-like insolation levels should have synchronous rotation due to intense tidal torque (Huang, 1960). It has been supposed that any atmosphere would freeze out on the perpetually dark side of a synchronously rotating planet (SRP). The proportion of photosynthetically active radiation (PAR) in their output is smaller than solar (Pollard, 1979) and many dM stars are notable for the frequency and intensity of their flares ('flare stars'), which has been cited as a problem for higher life habitability (Dole, 1964).

Recent work by Haberle *et al.* (1996) and Joshi *et al.* (1997) has shown that for a planet receiving insolation equal to that on Earth (Ie), a 100 mb pure CO_2 atmosphere would ensure sufficient heat flux to the dark side of a SRP to preclude atmospheric collapse. For a 1500 mb pure CO_2 atmosphere and 0.8 Ie, liquid water (essential for life as we know it) could exist over much of the planet. On a planet with intense volcanism or plate tectonics, it is likely that the atmospheric pressure of CO_2 (pCO_2) representing a balance between CO_2 outgassing and drawdown of CO_2 through weathering processes, will be controlled by a carbonate-silicate-cycle (Walker *et al.*, 1981).

MS lifetime (the period during which a star burns hydrogen in its core) can be approximated by stellar mass divided by luminosity. For example, if a solar composition 0.51 Mo star has 0.077 L$_\odot$ (after Lang, 1991) its MS lifetime will be $\sim 6.6 \times 13.0$ Gyr = 86 Gyr. Moreover (Kartunnen *et al.*, 1994) virtually complete convective overturn in lower mass stars means that a much higher fraction of a star's hydrogen content will be available as nuclear fuel than for the Sun. Luminosity falls off sharply with stellar mass, so that the least massive dM stars

will have the longest MS lifetimes. At MS age 4.6 Gyr, our Sun is nearly 40.0% brighter than its ZAMS value, but the most massive dM stars would be no more than 6% brighter than at ZAMS (for detailed evolutionary models of stars in the mass range 0.08 to 0.25 $M_{\odot}$ see Laughlin *et al.*, 1997).

Other factors being equal, the rise in our Sun's luminosity with MS evolution should, over the Earth's history, have caused net drawdown of the greenhouse gas CO_2 through weathering. Higher past pCO_2's offer at least a partial solution to how the early Earth was warm enough to maintain liquid water on its surface with low initial solar luminosity. With near-constant insolation over ~ 5.0 Gyr, adjustments in equilibrium pCO_2 on planets of dM stars should take place primarily in response to geological factors rather than changes in stellar luminosity (notably the rate of CO_2 outgassing, the area and distribution of emergent land, controlling CO_2 drawdown through weathering) and biological activity (for example, photosynthetic extraction of carbon from atmospheric CO_2) and subsequent burial of a fraction of the organic carbon produced (which will be assisted – see De Marais *et al.*, (1992) – by rifting and basin formation in a planet's crust).

CO_2 is of key interest for the present discussion because of its role as a greenhouse gas and because it is the raw material for photosynthetic carbon fixation. Including below ground carbon, >70.0% of the Earth's global biomass is bound up in forest biomes (Solomon and Kirilenko, 1997). A minimum pCO_2 approaching the value of Earth's present level is necessary for a biosphere organised like the Earth's to thrive (Heath, 1996). Maintaining a pCO_2 hundreds or thousands of times higher than that on the present Earth on a planet subject to Earth-level insolation could be problematic. However, 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 a useful 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 the present day Earth.

As regards wind intensity on a SRP, the 3-D atmospheric model of Joshi *et al.* (1977) predicts continual atmospheric thermal adjustment at the level of the jet streams. Despite the fact that one hemisphere is in perpetual sunlight and the other is always dark, windspeeds near the surface would be typically just 5–10 m s^{-1}, even at the terminator.

It appears that moderate climates are, in principle, possible on SRP's, and that no special hypotheses need be invoked to support this conclusion. This prompted us to re-examine the question of SRP higher plant habitability.

2. Global Water Cycle

To the conclusions published in Joshi *et al*. (1997), we add that given a sufficient ocean depth on a SRP, a vigorous global water cycle would be possible (Heath, 1997), even with dark side surface temperatures low enough to freeze the sea surface ($\sim$ –2 °C for typical salinity), given Earth-like geothermal fluxes. Bada *et al*. (1994) argued that on the early Earth subject to significantly lower insolation from the Sun, the oceans would not freeze down to the sea floor, because the flow of heat from within the Earth would have been great enough to prevent this. We point out that the same conclusion pertains for the dark side of a SRP.

The equilibrium thickness (Et) of sea ice on a SRP's dark side can be derived assuming heat transfer through the ice is by conduction (e.g. Bada *et al*., 1994).

$$Et = k(T_{\text{ocean water}} - T_{\text{ice surface}})/h,$$

where Et is in cm; k is the thermal conductivity of ice (2×10^5 ergs s^{-1} cm^{-1} °C^{-1}); T is the surface temperature; h is the heat flux through the planet's crust (ergs cm^{-2} s^{-1}). Using a value of 53 ergs cm^{-2} s^{-1}, typifying present ocean basin heat flow (Sass, 1972), Et would be 2.9 km in a limiting case where atmospheric collapse is about to begin through dark side CO_2 freeze out (–78.5 °C for 1.0 Earth atmosphere) and the base of ice was at –2 °C. At equilibrium, snowfall on the ice surface would be balanced by melting at its base. Earth's mean ocean depth is 3.8 km, so that with communicating Earth-like ocean basins, water would return to the lit hemisphere and be available to participate again in the water cycle.

3. Suitability of SRP Temperature Regimes for Known Forms of Life

The Joshi *et al*. (1997) model for SRP's assumed orbital and rotation periods of 16 Earth Days. Ie orbits around solar metallicity MO stars would be close to 50–55 days, but this would not alter basic details of SRP's atmospheric flow and temperature regime. A thermally directed longitudinal cell transferred heat to the unlit hemisphere, low level winds returning air mass to the lit hemisphere over the polar regions. Modelled surface temperatures for SRP's with surface atmospheric pressures of 100, 1000 (1.0 Ie) and 1500 mb (0.8 Ie) are presented in Figures 1, 2 and 3. Biological implications are illustrated by reference to physiological tolerances of known Earth organisms (though we cannot rule out physiologies and global modes of biosphere organisation significantly different from those on the present day Earth).

The Subsurface Lithoauthotrophic Microbial Ecosystems (SLiMES) of Stevens and McKinley (1995) would be least influenced by surface regimes (Heath and Doyle, 1996), and could exist on either hemisphere of a SRP, if the geothermal regime permitted liquid water percolating through the crust. Stevens and McKinley (1995) had argued that a population of bacteria within the Snake River Plain basalt

Tsurf in °Celsius: Po=0.1 Bars: 1.0 Earth Insolation
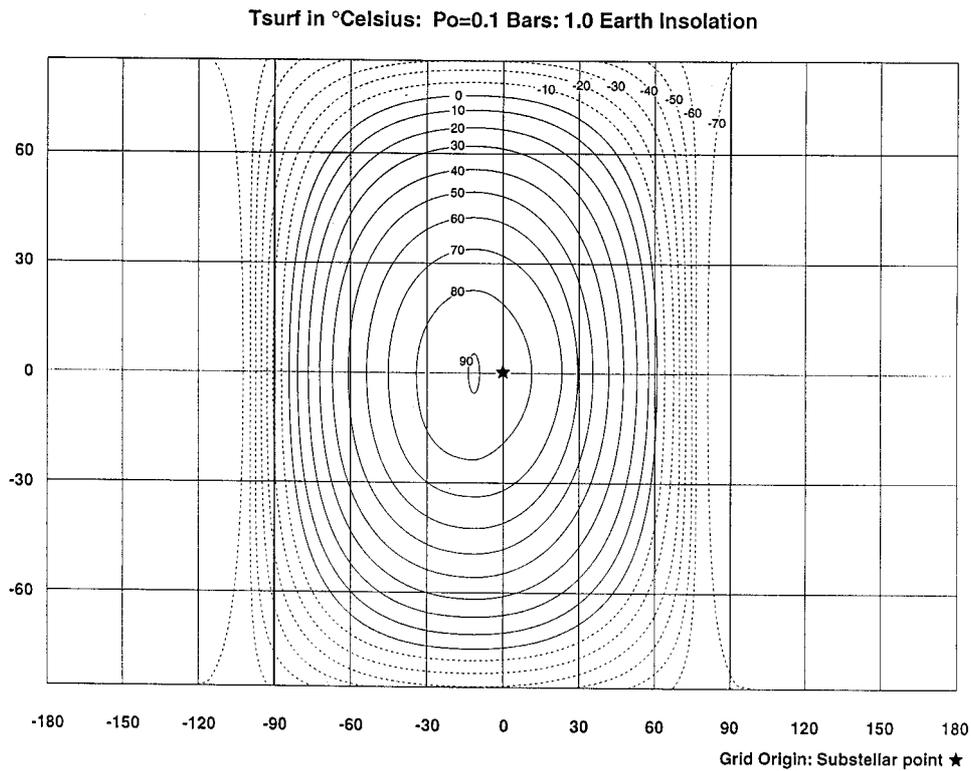
Figure 1a. Predicted isotherms (°C) across the surface of an Earth-mass, Earth radius S.R.P. receiving Earth-level insolation. 0.1 bar atmosphere. Ground albedo set at 0.2. IR optical depth = 0.3. Mercator projection.

existed independently of the surface photosynthetic biosphere, utilising H_2 produced in reaction between ground water and ferrous iron in basalt. However, later studies by Anderson *et al.* (1998) did not confirm this process at environmentally relevant pH; also the claimed rates of H_2 production could not be sustained over geologically significant times given available quantities of iron in the rock. Frederickson and Onstatt (1996) assumed that microbial life in general could extend down to the 110° isotherm, with thermal gradients of 25 °C km^{-1} for continental and 15 °C km^{-1} for oceanic crust. The upper temperature limit for photosynthetic prokaryotes (Brock, 1967) may be 70–75 °C, above which photosynthetic membrane systems are damaged. The eukaryotic alga *Cyanidium caldarium* can survive 60 °C, but occurs only in hot springs with pH < 4.0, where cyanobacteria cannot survive, suggesting that competition with cyanobacteria excludes it from hotter waters (Brock, 1967). Priscu *et al.* (1998) report microbial assemblages living in liquid water inclusions in the permanent ice covers of Antarctic lakes, where the external ambient temperature is well below freezing, and it has long been known
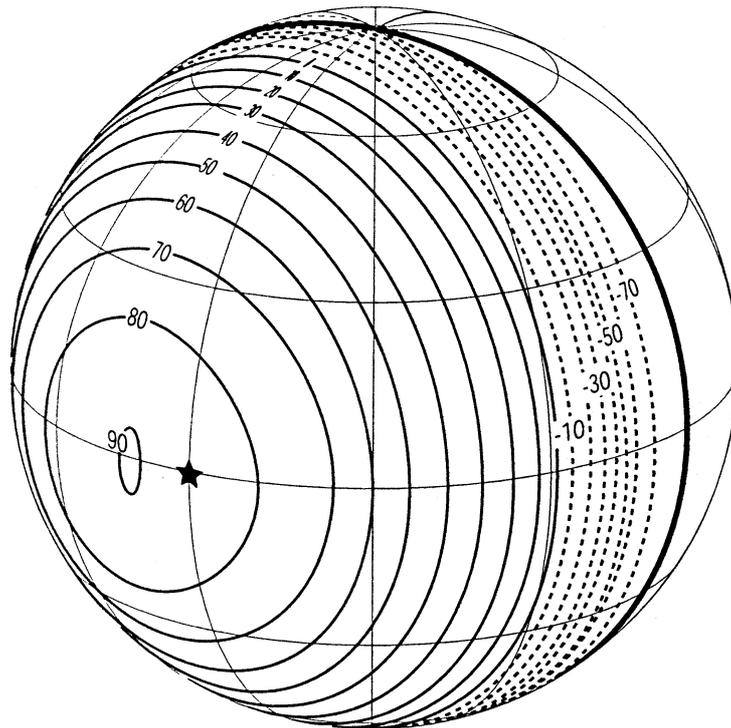
Figure 1b. Isotherms from Figure 1a plotted onto a spherical projection.

that Antarctic soil cyanobacteria can photosynthesise at low temperatures (*Nostoc* sp. at –5 °C; *Prasiola crispa* at –20 °C; Becker, 1972).

Larcher (1995) assembled data on temperature limits for CO_2 uptake by herbaceous and woody higher plants. Considered as groups, C_4 grasses, CAM plants (data obtained at night when their stomata are open for gaseous exchange), and sclerophyll shrubs and trees exhibit the widest range of tolerance. Cold injury to sclerophyll shrubs and trees occurs in the range –5 to –2 °C and heat injury at 50–60 °C. with respective limits for CO_2 uptake being –5 to 0 °C and 40 to 45 °C. C_4 grasses suffer cold injury at about 0 °C and heat injury at 60 to 65 °C; the limits for CO_2 uptake being 0 to –5 °C and 50 to 60 °C. For CAM plants, cold injury takes place at –5 to –3 °C and heat injury at 60 to 65 °C. The limits for CO_2 uptake are –3 to 0 °C and about 35 °C.

However, the same author notes that plants near the temperature extremes for CO_2 uptake are actually suffering temperature stress. He quoted A_{50} temperatures (at which CO_2 uptake is 50% that at the temperature optimum) as an approximation of the limits for healthy growth. These are 15 to 20 °C and 40 to 45 °C for the sclerophyll trees and shrubs, 15 to 20 °C for C_4 grasses and 5 to 10 °C and 20 to 25 °C for CAM plants. For comparison, the values for evergreen confiners from cool temperate regions are 5 and 30 °C. We may modify the frequently used gener-

Tsurf in °Celsius: Po=1.0 Bars: 1.0 Earth Insolation

Grid Origin: Substellar point ★
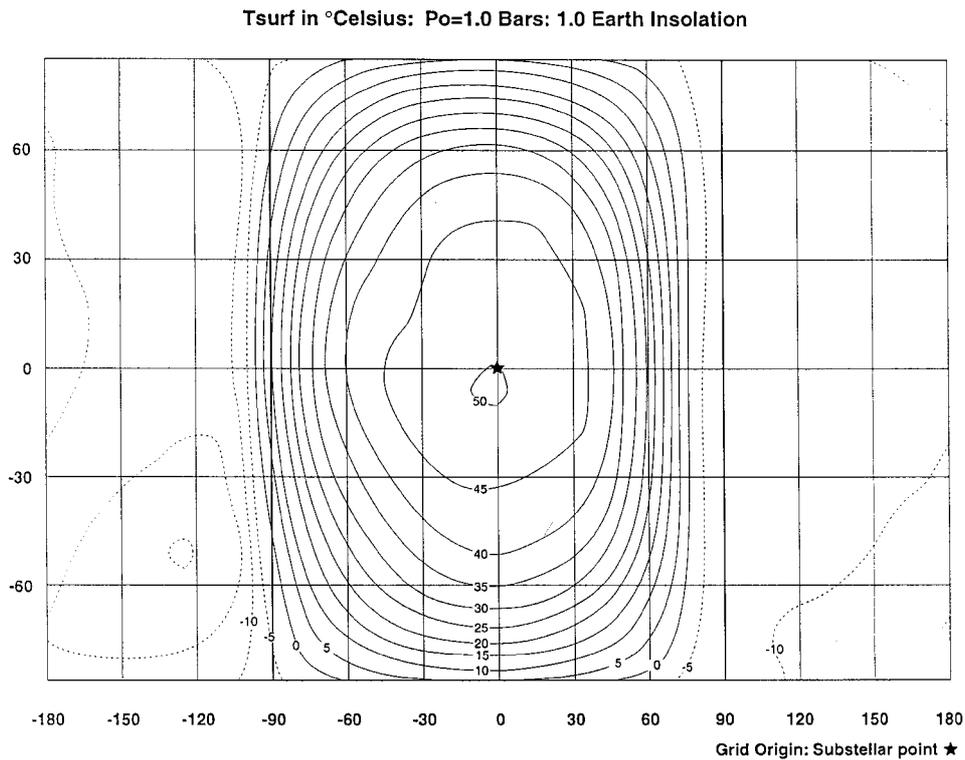
Figure 2a. Predicted isotherms (°C) across the surface of an Earth-mass, Earth radius S.R.P. receiving Earth-level insolation. 1.0 bar atmosphere. Ground albedo set at 0.2. IR optical depth = 1.0. Mercator projection.

alisation that full-sized trees grow only where the daily temperature exceeds 10 °C for one month per year, identifying the tree limit with an SRP's 10 °C isotherm.

It must be remembered that the temperature tolerance for a given species will depend upon a complex interaction of factors, of which competition with other organisms will be one.

In Figure 1, with 1.0 Ie, $pCO_2 = 0.1$ bar, and τ optical depth = 0.3. In Figure 2, also with 1.0 Ie, $pCO_2 = 1.0$ bar, $\tau = 1.0$. In Figure 3, for 0.8 Ie, $pCO_2 = 1.5$, $\tau = 1.5$. Planetary albedo was assumed to be 0.2, consistent with the reduced Rayleigh scattering of red and IR-biased dM star 'sunlight'.

The 0.1 bar run is for a limiting case, since dark side temperatures are low enough for CO_2 to begin to freeze out on the SRP's dark side. Also, water boils at 46 °C when total atmospheric pressure is 0.1 bar, and temperatures are higher than this over three quarters of the lit hemisphere. Hence, if there were ocean basins on the lit hemisphere, there would be a massive influx of H_2O vapour into the atmosphere, and a different surface regime would result. However, as the predictions stand, a wide section of the lit hemisphere would be too hot for algae, and only a narrow band would be suitable for higher plants.
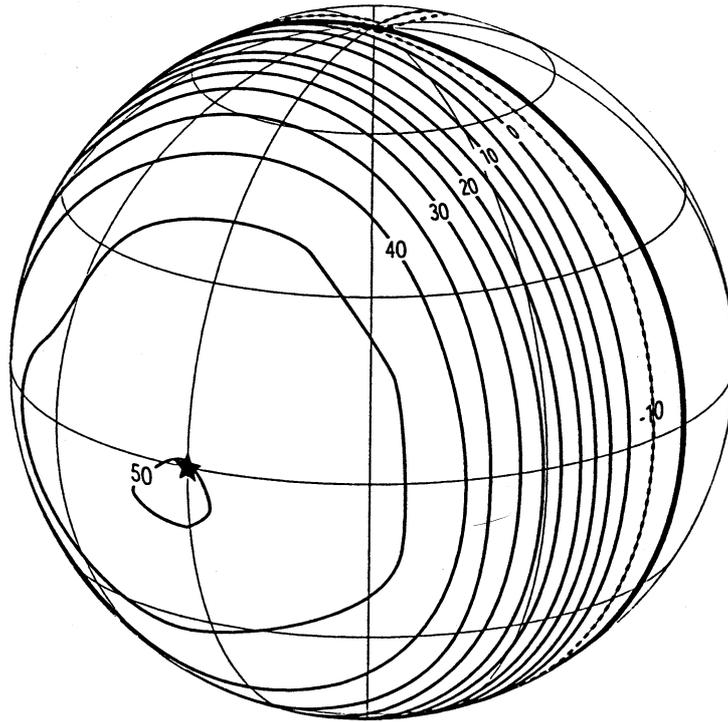
Figure 2b. Isotherms from Figure 2a plotted onto a spherical projection.

On the other hand, the 1000 mb case is a good approximation to Earth's atmosphere; with $\tau = 0.9$ instead of 1.0, temperatures would be just a few degrees lower than those predicted here. This would mean that temperatures suitable for Earth's arboreal forms could pertain over most of the lit hemisphere. The same is true of the temperature regimes predicted for the 1.5 bar case. A wide, equatorially-centred strip of the dark side will be > 0 °C. We may be optimistic but modelled SRP surface temperature at least, make it respectable to open discussion about forests.

4. Availability of PAR in dM Star Output

PAR is of special biological interest because it is neither so energetic that it damages cells, nor so weak that it cannot power water-splitting photosynthesis. Over the PAR-range, dM stars exhibit significant departures from the emission properties of ideal blackbody radiators, because of the large numbers of absorption lines and bands that occur in their spectra, notably molecular bands of TiO_2. Line blanketting reduces emitted PAR, and this must be balanced by backwarming of stellar continua at other wavelengths. Figure 4 compares a synthetic spectrum for a 3000

Tsurf in °Celsius: Po=1.5 Bars: 0.8 Earth Insolation
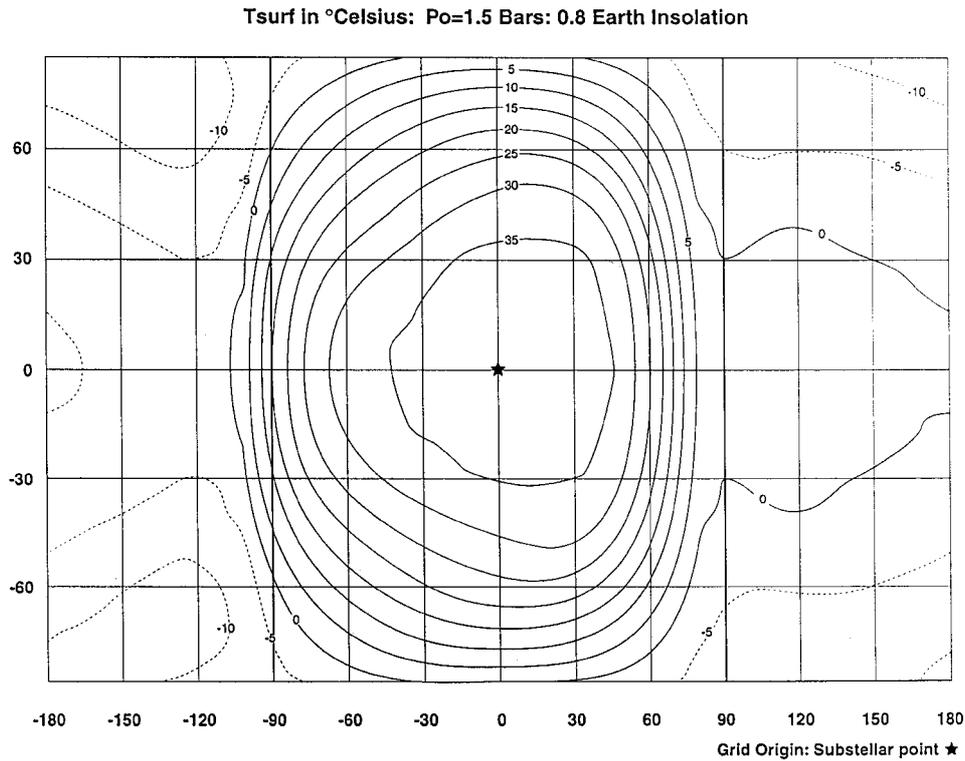
Figure 3a. Predicted isotherms (°C) across the surface of an Earth-mass, Earth radius S.R.P. receiving 0.8 Earth-level insolation. 1.5 bar atmosphere. Ground albedo set at 0.2. IR optical depth = 1.5. Mercator projection.

K star of solar composition, simplified after Allard and Hauschildt (1995), with that of an ideal blackbody. Stars of the ancient Galactic halo and the older stars of the disk exhibit the lowest fractions of elements heavier than hydrogen and helium ('metals' in astronomical terminology), and have spectral profiles corresponding most closely to blackbody approximations, whilst those of the Galactic bar/bulge and the intermediate and young disk populations have the highest metallicity.

Comparison of stellar luminosity in the U, B, V, R and I bandpasses used by astronomers to measure stellar magnitudes (spanning the near-UV to near-IR range) with that of the Sun is interesting, though comparison is complicated by the occurrence of deep absorption lines, particularly when they lie near the effective wavelengths of the filters. Synthetic spectra for stars and substellar brown dwarfs in the T_{eff} range 4000 to 2000 K were presented by Allard and Hauschildt (1995). We estimate that the amount of PAR which would be received at the top of a planet's atmosphere from a star of T_{eff} 4000 K (slightly hotter than a M0 star) at the Ie radius would be roughly a third, and the Photic Zone Window Radiation (PZWR, see below) a quarter that incident on Earth. The respective figures for a star of T_{eff} 2800
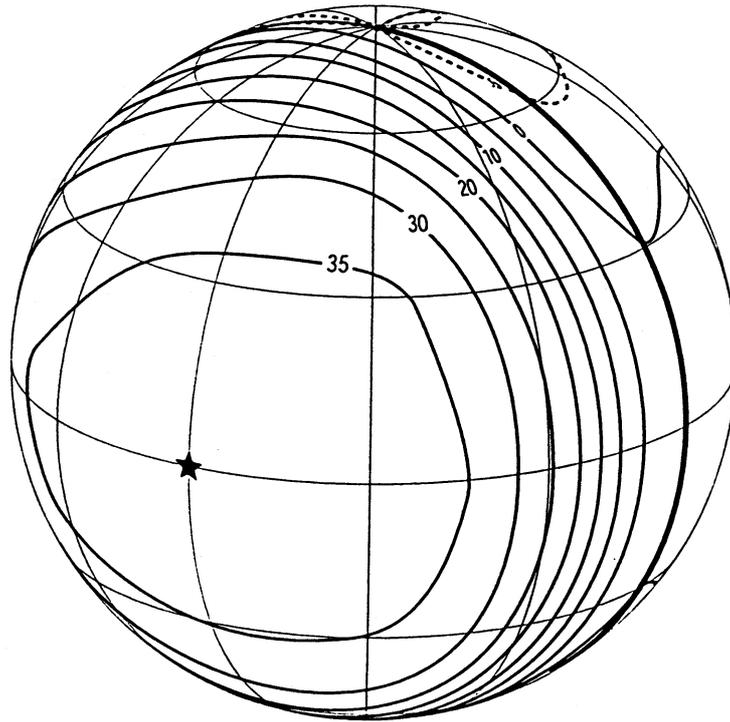
Figure 3b. Isotherms from Figure 3a plotted onto a spherical projection.

K are less than a twelfth and a twentieth. These values are nevertheless sufficient for photosynthesis to be metabolically profitable. In fact, C3 plants, which are the majority of Earth's forest trees, often reach light saturation at a fraction of full sunlight (Black, 1973).

Because a planet's surface curves away in all directions from the Substellar Point (SSP), a beam of light will be weakened by being spread across a greater area of a horizontal surface on the ground (the intensity at a given location relative that to that the SSP will be given by the cosine of the angular distance from the SSP). On a tidally locked planet, we would expect zero obliquity; no diurnal insolation maxima and no summer growth season, or seasonal rains. Given a constant location of the sun in the sky, however, photosynthetic surfaces could be permanently angled perpendicular to incoming light beams, thus avoiding the weakening of light intensity on horizontal surfaces with angular distance from the SSP. Also, some of the light down-scattered from the sky (mostly blue for non-turbid air) will provide an additional few percent more energy. A negative aspect of a fixed sun position is that some areas will be in perpetual shadow due to topography. Organisms themselves will provide shadows, and, because the sun does not move across the sky, there will be no procession of sunflecks beneath any tree canopy. A positive advantage in harvesting PAR is the fact that sunlight (clouds permitting) will be available at
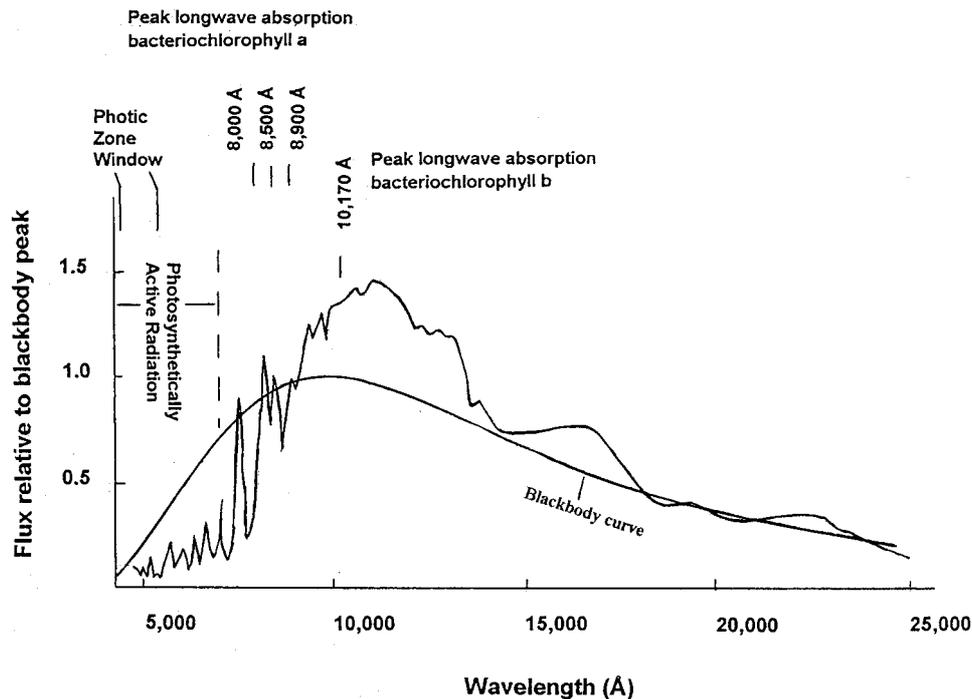
Figure 4. Synthetic spectrum of a solar metallicity red dwarf of T_{eff} = 3000 K (much simplified), after Allard and Hauschildt (1995), compared with the emission curve of a perfect blackbody radiator. Photosynthetic regions indicated. Bacteriochlorophyll absorption peaks after Rabinowitch and Govindjee (1969).

all times. Over a 24 h period, the amount of energy available at the SSP will be over 3 times that arriving in a 24 h period at Earth's equator at an equinox. In the case of a hotter dM star, this could mean that the total PAR received would be Earth-like.

Geophysical regimes of geologically active Earth-sized planets subject to substantial tidal torque remain to be investigated. However, it is evident that drift of continents through the colder zones near the terminator would extinguish Earth-type arboreal forms, whilst drift onto the dark side would extinguish photosynthetically-supported land-based biospheres. However, organisms need not become extinct if the juxtaposition of land and the history of continental assembly, fragmentation and drift permitted the migration of plants across climatically-suitable tracts, with no insurmountable geographical barriers. The demise of photosynthesisers need not prevent deep subsurface heterotrophic microbial communities living for an indefinite time on the organic products of photosynthesis. Such communities have been reported from consolidated Cretaceous shales and adjacent more porous sandstones into which organic matter from the shales has diffused (Krumholz *et al.*, 1997).

A general relation governing the proportion of radiation of any given wavelength penetrating to a given depth (i.e. optical depth) in any medium is:

$$I_d = I_0 e^{-kd}$$

where I_0 = the intensity of radiation of a given wavelength entering the medium, I_d = the fraction penetrating to a given depth, d, and k = the absorption coefficient.

dM stars put out much more red than blue light, and this is scattered far less efficiently by a planet's atmosphere. Beams of light reaching points 30° and 60° distant from the SSP much pass through 1.15 times and 2.0 times the air mass traversed by a vertical beam at the SSP. Atmospheric transmission coefficients under poor conditions can be about 0.62 for light of 4000 Å, and 0.89 for light of 7000 Å (Koller, 1965); respective intensities at 30° and 60° from the SSP will be 0.57 and 0.38 the SSP value for the shorter wavelength and 0.87 and 0.79 for the longer wavelength.

Red-biased sunlight would not preclude Earth-type higher plants. Photosynthesis is not necessarily impaired in red-biased light, because absorption by chlorophyll of a blue light photon promotes an electron to an upper excited singlet state that is extremely unstable. It decays within 10^{-12} sec, to a lower excited singlet state. Hence both blue light and red light produce the first excited excited singlet, as the starting point for energy transfer (Nobel, 1974). It is encouraging that the action spectra of both crop plants and trees can be biased distinctly towards the red (Salisbury and Ross, 1978) – blue spruce actually exhibits zero response to radiation shortwards of the solar energy peak of 5000 Å. Photosynthetic organisms often exhibit impairment of photosynthesis beyond about 6800 Å – the 'red drop', but plants obliged to photosynthesize in red light only can benefit from the well known Emerson Effect (Emerson *et al.*, 1957; photosynthesis can work more efficiently with light of 7000 Å plus a shorter red wavelength, say <6500 Å, than is indicated by the sum of activity for both wavelengths taken separately). The photic (euphotic) zone comprises the upper layers of the ocean, where there is sufficient light for net photosynthesis. This is frequently approximated by assuming that the rates of photosynthetic production and respiration are equal at the depth where transmitted light is about 1% that at the surface. On Earth, this is typically up to 200 m in clear water in the open oceans, 40 m over the continental shelves, and only about 15 m in some coastal water (O.U., 1989). Light in the range 4500 to 5500 Å is most efficient at penetrating water. In the open ocean, some 35% of the light in this range typically penetrates to a depth of 10 m, as compared with just 2% for tubird coastal water, in which yellow-green light (5000 to 5500 Å) penetrates deepest. We term the interval 4500 to 5500 Å the 'Photic Zone Window' (PZW). Penetration of ocean water drops off rapidly to either side of the PZW. Light coming through this window can be termed 'Photic Zone Window Radiation' (PZWR).

Detailed quantitative studies of how PZWR will be transmitted to the water surface though different model atmospheres and reflected from the water surface at increasing angular distances from the sub-stellar point, remain to be undertaken.

Both light loss in the atmosphere and reflection losses (discussions in Iqbal, 1983) will increase sharply towards the terminator.

Whilst blue-green light is the most effective part of the spectrum for penetrating ocean water, varieties of the key photosynthetic pigment chlorophyll have absorption bands in the violet-blue and red. Accessory pigments enable aquatic plants to exploit light underwater. In the Phaeophyta (brown algae) and Bacillariophyceae (diatoms), which occupy the upper layers of the ocean, fucoxanthol, a carotenoid, absorbs in the blue. Rhodophyceae (red algae) use phycoerythrin, a phycobilin, which together with chlorophyll, infills much of the visible spectrum. The deeper a red alga lives, the higher the proportion of phycoerythrin to chlorophyll. Green algae can live at appreciable depth also, but their rate of growth is slow (Rabinowitch and Govindjee, 1969). A problem for aquatic plants on a dM star planet is that PZWR decreases much more sharply with T_{eff} than does PAR. Because of the exponential character of light transmission through water, the depth to the base of the photic zone would still be tens of metres, even if the PZWR were reduced to a twentieth of its solar value. In addition, reduction in stellar PZW radiation will be partially compensated by conditions of perpetual illumination on the lit hemisphere of a SRP most effectively at the sub-stellar point, where illumination will arrive normal to the water surface, and a minimum will be reflected away (assuming, of course, no continuous cloud cover, etc.). However, the climatic and oceanographical implications of strong absorption of infrared close to the water surface are yet another problem that needs to be examined in more detail. If terrestrial planets of early M stars are unable to support photosynthetic biospheres, this is likely to be due to factors other than the spectral quality of received insolation. Perpetual illumination could contribute to a significant increase in photosynthetic potential, so long as productivity was sufficient to satisfy short term metabolic demands.

A quasi-seasonal exploitation of PAR might be possible on a SRP, were there to be active migration, or transport of photosynthetic organisms by wind, or ocean currents (mean winds would not be extreme according to Joshi *et al.*, 1997). Again, in Earth environments where PAR is seriously reduced – such as on forest floors and in deeper water – plants can compensate, to some extent, by reducing their metabolic rate and growing more slowly. Fewer layers of leaves and understory would be one obvious response to reduced PAR.

5. IR Photosynthesis

In view of the enhanced IR in dM star sunlight, it is interesting that some bacteria are known to photosynthesise using IR (discussed in Gregory, 1976). The green sulphur genus *Chlorobium* has a pigment which absorbs at about 8400 Å. The purple non-sulphur bacteria *Rhodospirillum rubrum* and *Rhodopseudomonas capsulata* absorb at about 8700 Å. The purple non-sulphur genus *Chromatium* has a pigment absorbing at about 8900 Å and *Rhodopseudomonas viridis*, a form of

bacteriochlorophyll-b, absorbs at about 9600 Å. These organisms, however, do not use water as a hydrogen donor, and so do not release oxygen as a by-product of photosynthesis (thereby not creating a planetary UV-filtering ozone layer, etc.; note that there is little UV in Mstar nonflare insolation anyway).

How far could higher plant photosynthesis be extended into the near infrared? Water-splitting, O_2-liberating photosynthesis could be possible, in principle, with a series of linked 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).

Well known measurements of the absorption, reflection and transmission of electromagnetic radiation for leaves of *Populus deltoides* (Gates, 1968), imply that a photosynthetic organ functioning at near infrared wavelengths could be overlain by another harvesting radiation in the visible region of the spectrum and still receive substantial transmitted infrared. Another biologically significant property of infrared is that it can penetrate wood to a depth of some millimeters, the depth of penetration being greatest for soft woods and least for dense hardwoods (Vasko, 1968). This raises the possibility of internalized photosynthetic apparatus.

6. Stellar Variability and Ecology

Climatic implications of starspots were modelled in Joshi *et al.* (1997). dM stars generally exhibit spots proportionately much larger than those on our Sun. These can cause decreases in stellar luminosity of some 10–40% for a few Earth months (Rodono, 1986). The extreme of a 40% decrease in luminosity lasting 4 months would result in a maximum decrease in surface temperature of 27 K in a zone running west along the 20°N circle from the 0° meridian. Areas near the eastern terminator, in particular, would be liable to reductions to and below the freezing point of water. However, this would not involve temperature extremes that are excessive in terms of the tolerances of Earth tree species and it is reasonable to conjecture that native plants would evolve with the ability not to suffer fatal injury from low temperatures associated with sunspot growth activity.

Flare activity on dMe stars (chromospherically active red dwarf stars showing hydrogen-alpha in emission) is commonplace and has been studied for decades. Flares on a given star may vary greatly in intensity and duration (Kunkel, 1969; Pettersen and Coleman, 1981; Giampapa and Liebert, 1986; Rodino, 1986; Worden *et al*, 1984), although there are generalised relationships between mean flare energy and quiescent stellar output (Lacy *et al*., 1976). Flaring is most typical of young stars and seems to be related to rapid rotation. It wanes (the e-folding timescale is roughly 1.0 Gyr (Stauffer and Hartmann, 1986; Demarque *et al*., 1986), as rotation decays through stellar winds (but members of binary systems can be spun up, or retain rapid captured rotation; see Zahn, 1994, and references therein). Some stars

flare very frequently, for example UV Ceti was seen to flare about every twenty minutes during observations reported by Mochanacki and Zirin (1980).

Flares will be associated with increases in a star's output of X-rays, UV, visible, IR, and charged particles emitted as stellar winds (which enhance the radio flux, as well), but essentially no radiation of wavelengths less than about 2900 Å would reach the ground through an Earth-like atmosphere.

Biologists (see Koller, 1965) subdivide atmosphere-penetrating UV into UV-A (3150 to 3900 Å; of least biological significance), UV-B (2900 to 3150 Å; biologically damaging and reaching the ground in significant quantities) and UV-C (<2900 Å, very little of which reaches the ground). Peak germidical efficiency occurs at ∼ 2600 Å, declining rapidly towards longer wavelengths (i.e. two orders of magnitude smaller at 3000 Å). TheU-bandpass used by astronomers (3310 to 3990 Å in Allen, 1973; 3260 to 3940 Å in Hawley and Pettersen, 1991) corresponds essentially to UV-A and there exists less long-term information about stellar variability near the UV-B and UV-C regions of the spectrum, although the International Ultraviolet Explorer satellite has provided observations in the range 1150 to 2000 Å with its SWP camera and 1900 to 3100 Å with its LWP camera.

We put the biological implications of observed increases in stellar UV during flares in perspective by pointing out that the quiescent UV outputs of dMe stars are very low compared with the Sun. Using data from Worden *et al.* (1984), YZ Canis Minoris ($T_{\text{eff}} = 3097$ K) has a total luminosity around 0.01 $L_{\odot}$, but in the U-bandpass it is not quite 2.0×10^{-4} as luminous as the Sun. For a planet receiving Ie (0.10 AU), the U-bandpass output of YZ Cmi would have to rise by a factor of 50 (4.2 stellar magnitudes) for incident UV-A to match that arriving continuously at the top of the Earth's atmosphere from the quiescent Sun. UV Ceti with less than 3.0×10^{-3} $L_{\odot}$ (Leggett *et al.*, 1997) has a quiescent U-bandpass output some 1.1×10^{-5} that of out Sun (Lacy *et al.*, 1976). A U-bandpass upsurge of over 260 times (>6.0 magnitudes) would be necessary before incident U-bandpass radiation matched continuous Earth values at the Ie radius of 0.05 AU). Moreover, even when flare UV exceeds the latter, it may be maintained for only a short time. UV Ceti flare stars, as a typical example (described by Mochnacki and Zirin, 1980), generally rise to a peak within 10 s and declined substantially within about 20 sec). The quiescent U-bandpass component of insolation from AD Leonis ($T_{\text{eff}} = 3400$ K), is just 0.03 solar at the Ie radius (0.15 AU). The 'Great Flare' of April 12, 1985 exceeded 4.6 magnitudes (an increase by a factor of >60) in the U-bandpass, so UV-A at the Ie radius would have climbed to the continuous Earth level within about 8 min, peaked sharply at 1.8 times the Earth level at 10 min, and fallen below Earth level after 18 min. Data for the UV-B and UV-C range are minimal, but the IUE satellite's LWP camera obtained data for this AD Leonis flare. They are consistent with a component in the 3200 to 2800 Å range has half the total energy of the U-bandpass. UV-B plus UV-C would rise by a factor of <4.0 solar, at peak, exceeding solar levels for <20 min. The kinematics of the three stars noted above are appropriate for younger stars of our Galaxy's disk, so that, in general

terms, the problems posed by flaring would be reduced substantially for older stars. The Phanerozoic did not commence until Earth age 4.0 Gyr, and forests appeared slightly later.

Whilst the thermal inertia of atmospheres and oceans would preclude sharp rises in surface temperature, there would remain a danger of transient rises in the temperature of exposed surfaces, such as photosynthetic organs. However, were total ground level insolation to double at peak flare output (a very extreme case), and were a surface to absorb all incident radiation, its temperature would rise by <1.2. However, even occasional temperature rises sufficient to initiate fires need not wipe out woody plants, since the seeds of certain well known trees can survive (or will be prompted to germinate by) transient rises of several hundred degrees (Kozlowski *et al.*, 1991).

7. Biological Tolerances to UV and Special Adaptations

There are numerous factors, including biological adaptations which could protect organisms from transient elevated UV. Any wholly subterranean organisms would be wholly out of reach of UV radiation from flares. Sterilization would be difficult in a natural environment, which offered deeper water, water with impurities, porous and creviced rocks, and so on. Also, specific to a SRP, there is a permanent dark hemisphere, where bacteria from ambient waters might be temporarily located (Rambler and Margulis, 1980), noted that microbes in an aquatic environment can be protected by inorganic ions, such as nitrates and nitrites and some organics, such as purines and pyrimidines, absorb UV strongly at 2500 Å. A surface microlayer composed of complex organics and enriched in metallic elements, may also be UV protective. Towards a planet's terminator, we point out, there is a substantial reduction in direct UV radiation (to 0.2% subsolar value for a Sun altitude of 5° at 3400 Å), due to the greater air mass traversed. In near terminator regions (by analogy to the early morning and late afternoon terrestrial sky), UV scattered from the sky should be about four times that received directly.

UV in the range 2800 to 4000 Å can inhibit algal photosynthesis in seas and lakes in mid-latitudes during summer, but there are fewer opportunities for fatal UV irradiation of organisms than it may appear. Rambler and Margulis (1980) noted that the effects of lethal doses of UV can be reversed under illumination by visible light – the process of photoreactivation. (Enzymatic repair processes that do not require light are well known for aerobic bacteria, including blue-green algae); obligate anaerobic bacteria exhibit high degrees of UV tolerance relative to facultative anaerobes and aerobes; a matting habit which requires mucilaginous sheaths, photosensitive motility, spore formation, and repair capabilities (spores can be 3 to 4 orders of magnitude more resistant to UV than vegetative cells of the same species), can afford UV protection to microbial communities. UV exposure often seems to exceed the apparent tolerances of organisms, which Calkins and Thor-

dardottir (1980) point out must be explained for each organisms on an individual basis. *Paramecium aurelia* tends to remain at the surface, but also prefers shielded localities. *Coleps* protects itself by moving into deep water. The freshwater *Rhizoclonium* floats on ponds in summer, forming mats. The surfaces of these are heavily pigmented and senescent while new growth extends downwards protected by the surface layers. Marine diatoms change buoyancy in response to illumination, rising with visible light and falling after UV-B exposure. Any organism whose population at any given time included individuals too deep in the water to be injured by flares (mats of the diatom *Rhizosolenia* rise and sink through the photic zone and deeper waters; Villareal *et al.*, 1993) would survive in the long term. Bothwell *et al.* (1994) reported the surprising observation that greater amounts of algae can accumulate in some UV-exposed habitats than in UV-protected environments, because of the reduction of arthropod consumers. Algae can increase their tolerance of UV by synthesizing protective UV absorbing compounds and by repairing damaged DNA, and Bothwell *et al.* noted succession to algae species believed to be more UV tolerant in longer experiments.

Higher land plants can be exposed to elevated UV-B in alpine terrestrial environments (Flenley, 1992), because early morning insolation is increased by reflection from clouds that formed in valleys at night. Later in the day, clouds can ascend and reduce upper forests almost to darkness, reducing opportunities for photoreactivation. Plants living at high altitudes in the tropics have epidermal layers accumulate phenolic compounds such as flavonoids and flavones (Del Moral, 1972; Caldwell, 1981), or surface waxes (Mulray, 1979), reducing UV penetration. Stunting and development of small thick leaves with a hypodermis, known from alpine plants, can be produced in crop plants by UV irradiation in the laboratory, as well (Flenley, 1992). A number of UV damage repair processes also exist (reviewed by Caldwell, 1978). UV-opaque arboreal forms could survive, so long as heating did not cause them to catch fire, or was so intense as to prevent re-sprouting from roots. The strong UV absorption shown by the photosynthetic *Rhodopseudomonas palustris* (Van Niel Strain 2137) near 2000 Å (Olsen and Stanton, 1966), poses the question as to whether an extraterrestrial organism might absorb UV, then use at least part of that energy to run photosynthesis.

The wide range of credible biological stratagems available to reduce the dangers of stellar flares would give opportunities for macrofauna. Although flares can peak very sharply and rapidly, the initial brightness rise can take ten minutes of more, so motile organisms would have the opportunity to retreat into the deeper water, or into shaded environments. We select the following examples from terrestrial fauna: – molluscs which can retreat into shells, caddis fly larvae, which construct cases out of sand grains, small pebbles, or pieces of wood, and polychaete worms are amongst the many burrowing or tube secreting organisms.

8. Conclusions

We emphasise that this has been a somewhat speculative but preliminary study of the potential habitability of SRP's and that the conclusions presented here will be modified in the course of future work. It must not be forgotten that we do not yet have observational confirmation of the existence of Earth-mass planets orbiting main sequence stars, although their presence is anticipated. Moons orbiting close to major Solar System planets have observationally confirmed capture rotations, but SRP's remain unconfirmed as yet. If such planets do exist, Kasting *et al*. (1993) may be correct in their opinion that dM stars will offer less attractive opportunities for life than more massive stars. However, higher plant habitability is nevertheless compatible with modelled temperature regimes for plausible SRP's. Substellar PAR should be sufficient for photosynthesis, although we acknowledge that the greater thickness of atmosphere to be traversed, including clouds, and also increased reflectivity of water surfaces at lower sun altitudes, could seriously diminish the availability of PAR with distance from the substellar point. Perpetual illumination would partly compensate for PAR reduction. Stellar flaring does not present insurmountable problems. Even major flare activity cannot be expected to completely sterilize the surface and near-surface environment of an entire planet. We recognise, of course, that key problems, such as the geophysical condition of Earth-mass planets subject to intense tidal deformation, remain to be explored. Notwithstanding, since such a large percentage of stars are dM stars, there are grounds for cautious optimism that the number of potentially forest-habitable planets in our Galaxy is larger than may have been considered previously.

Acknowledgements

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