Photosynthetic Constraints on the Habitable Zone

M. C. Storrie-Lombardi, A. I. Tsapin, G. D. McDonald, and M. L. Coleman
Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, M/S 183-301, Pasadena, California 91109

The habitable zone (HZ) around a star has been previously defined as the region in which an Earth-like planet could maintain liquid water (Kasting, et al., 1993). Earth, our only known example of an inhabited planet, orbits a middle-aged G2 dwarf star with an estimated lifespan of 10 Gy. While G stellar types are numerous, they are not the "average" classification of the H-R diagram main sequence stars. Figure 1 depicts the distribution of main sequence types found within 25 pc of Earth (data adapted from Ames NASA/NSF Near Star catalog).

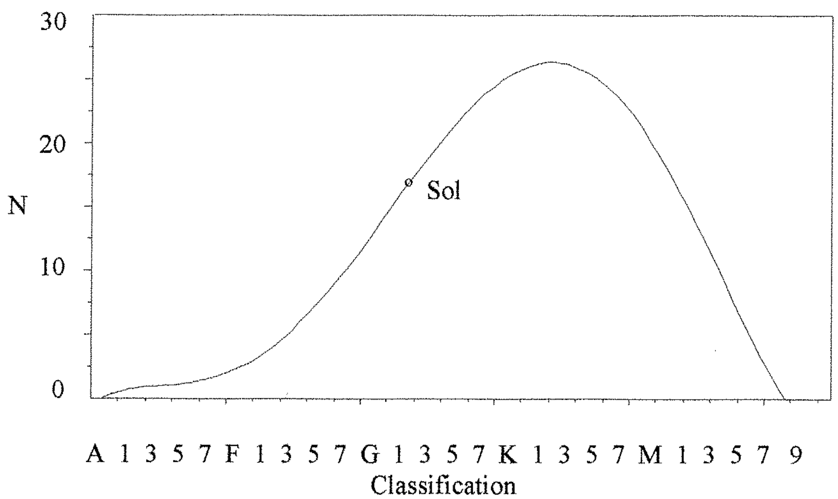

Figure 1. Number of stars (N) as a function of stellar types in 663 main sequence stars less than 25 parsecs from Sol (data from the Ames NASA/NSF Near Star catalog, http://nstars.arc.nasa.gov). More than 55% of stars are classified as types G3 to K7.

The majority of objects appear as cooler stars than Sol, with temperatures ranging between 5800 and 5300°K for G3 to G9 stars and between 5300 and 4000°K for K0 to K7 stars. Stars classified red-ward of our sun as G3 to K7 account for more than 55% of observed objects. Within the next decade the active search for terrestrial planets orbiting within HZ will require observation of relatively near targets. If we confine our search to "Sol-like" stars, e.g. G1 and G2 stellar types, we have a total of 32 targets within 25 pc of Earth. In contrast, if the existence of HZ appears possible for G3-K7 stars, inclusion of these objects would add 362 nearby targets for Terrestrial Planet Finder (TPF).

Unfortunately, a number of unresolved issues accompany the shift in focus to redder main sequence stars (Kasting, et al., 1993). Spectral reddening, diminished mass, and increased longevity of the star accompany the decrease in stellar surface temperature and luminosity. The primary relationships between mass, longevity, luminosity, and the orbital change required to compensate for diminished luminosity are depicted in Figure 2 below. Moving from stellar type G2 to K5 is accompanied by a 1/3 diminution mass and a decrease in luminosity to ~10% that available to Earth. To obtain Earth-equivalent flux a decrease in orbit to 0.4 AU is required.

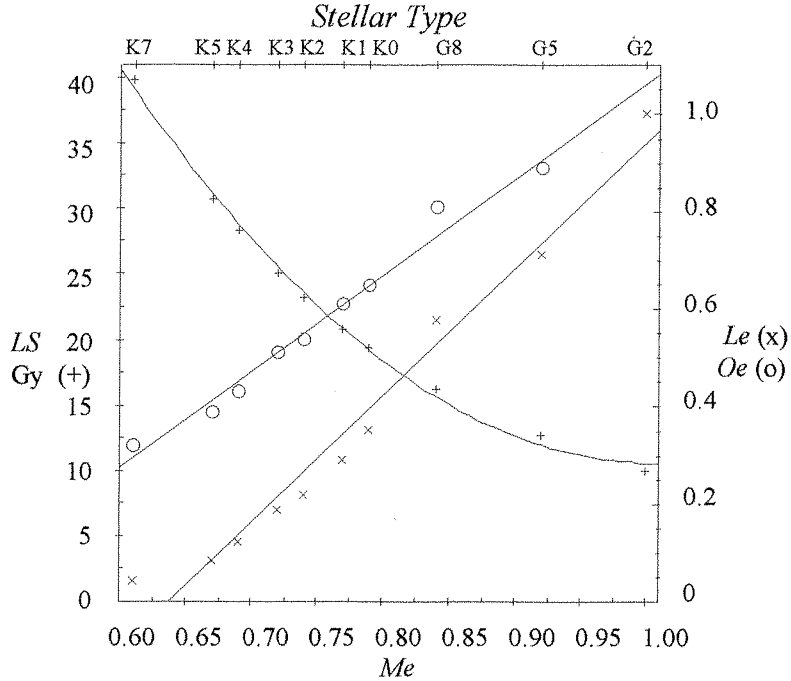

Figure 2. Stellar spectra from main sequence stars <25 pc from Earth exhibit a decrease in luminosity as a function of diminished mass. At an Earth equivalent mass (*Me*) of 0.64 a K5 star has an Earth equivalent luminosity (*Le*) of 0.10. Compensation for the loss in solar flux requires an Earth equivalent orbit for a terrestrial planet of 0.4 AU. Estimated life span (*LS*) of the K5 star would be ~30 Gy.

The impact of these environmental changes on the probability of terrestrial planet formation and the subsequent origin and evolution of life on a terrestrial planet in these systems is unknown. To fine tune the constraints on the habitable zone during the next five years in preparation for terrestrial planet finder efforts will require investigation into the effect of diminished planetary mass and ultraviolet flux on atmosphere evolution and retention; the probable evolution of vulcanism and geochemical weathering in low mass environments; and the probability of decreased material for planetary formation in low mass stellar systems to mention only a few of the parameters. In this work we address only one of the myriad of effects: the impact of spectral reddening on photosynthesis.

Moving down the main sequence of stars from F-, through G-, to K-stellar types produces the spectral shifts depicted in Figure 3. The overall effect is an increase flux in the red end of the spectra and a decrease in the blue, i.e. a "reddening" of the spectra. It is this shift in available photon energy that is central to our understanding of the photosynthetic constraints on the habitable zone, not the total flux available. Moving required orbital radius for the habitable zone towards the parent low mass star provides compensation for total flux but does not effect the changes induced by the spectral shift.

Photosynthesis in an organism begins with the efficient capture of solar photons. To accomplish this plants, bacteria, and algae have produced a variety of pigments optimized for the absorption of particular wavelengths of light. Often, a single organism will contain multiple pigments and proteins working together in what is called a light

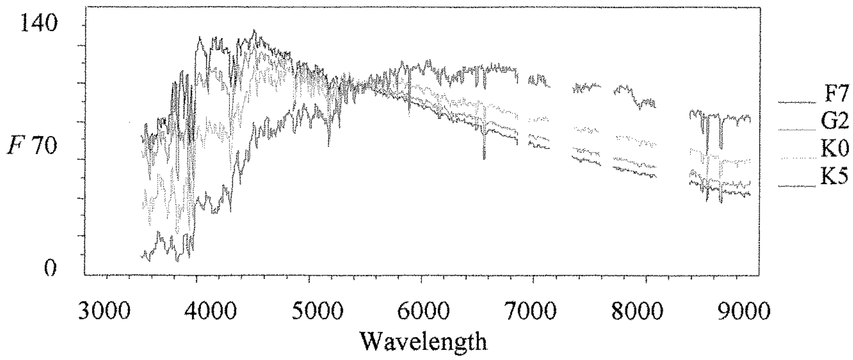

Figure 3. Stellar spectra from main sequence stars exhibit a red-ward shift in the shape of the continuum across F7 to K5 stellar types. The shift is a result of decreasing stellar surface temperature, a parameter controlled primarily by stellar mass.

harvesting complex (LHC). LHCs in terrestrial organisms include photon-absorbing pigments optimized for a wide variety of light conditions. Shifts in the spectral distribution of the solar flux received on Earth can be expected to play a critical role in the evolution of the constituent molecules of these complexes. The faint young sun hypothesis suggests that our own sun was significantly cooler and redder early in the life of our planet. This raises the possibility that understanding the light harvesting characteristics of the early inhabitants of Earth might be of assistance in predicting photosynthetic constraints on the HZ of low mass stars.. Current estimates place the earliest appearance of microbial life at ~3.3 Gy (Schopf, 1999). This is early enough for microorganisms to experience growth and evolution under a cooler, redder sun. Two of the most ancient lineages, the purple bacteria and cyanobacteria, appear to have LHCs capable of performing in such an environment.

While the stellar spectral shift seen in low mass stars would be disadvantageous to organisms employing pigments with absorption maxima in the blue, LHCs that include pigments operating efficiently in the red and near-IR would be relatively unaffected. Chlorophyll a and b exhibit dual absorption maxima at 4300|6620Å and 4530|6420Å, respectively. While the blue pigments would be of diminished utility in a low mass star environment, the red-absorbing pigments would remain effective. Cyanobacteria contain phycobiliproteins with absorption maxima ranging between 5450Å (B-phycoerythrin) and 6150Å (C-phycocyanin). Purple bacteria contain LHCs comprised of multiple pigments and proteins. Carotenoids frequently are included in these complexes to provide absorption in the blue and green regions. Other pigments have absorption maxima shifted far into the red such as the LHCs absorbing at 8000-8500Å found in *R. acidophilus* seen above in Figure 4 (Freer, et al., 1996). A novel LH2 complex has been isolated from *Rps. palustris* that absorbs at 8000Å (Tharia, et al., 1999). The complex is expressed in large amounts under low light growth conditions and is the major LH2 complex under such conditions.

The relative shift in spectral power density that occurs as we move red-ward along the main sequence is depicted in Figure 3 and compared to the absorption spectra of LHCs from a purple bacterium and from the cyanobacterium phycobiliprotein, phycocyanin-C. The relative spectral shift is demonstrated by a simple ratio of the K5 and G2 spectra presented in Figure 2 above. The shift is characterized by a marked decrease in ultraviolet and blue flux, and a relative increase in red and infrared power. Relative stellar flux data have been superimposed on the absorption spectrum of light harvesting complex II (LH2) from the purple bacterium *Rhodopseudomonas acidophila.* A low light harvesting portion of the LH2 complex produces the absorption (R) at 8000 and 8500Å. The phycocyanin-C absorption maximum occurs at 6400Å.

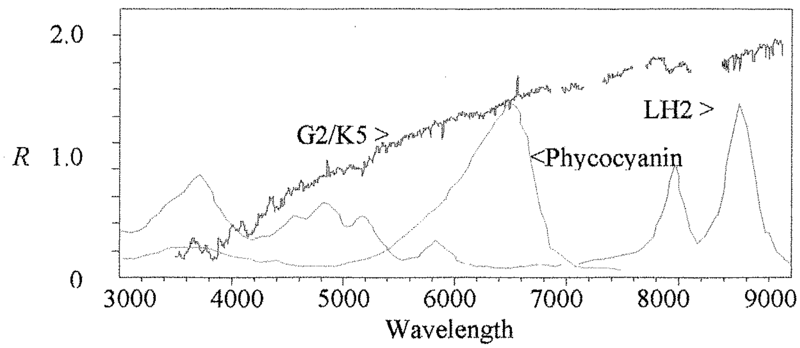

Figure 4. The spectral shift represented by the normalized ratio (*R*) of a typical K5 spectrum to a G2 spectrum I superimposed on the absorption spectrum of Light Harvesting Complex II (LH2 from a purple bacteria and the cyanobacterium phycobiliprotein, phycocyanin-C.

Certainly for organisms such as these, the shift to a faint red sun would have relatively minimal impact on light harvesting ability. As a result of these preliminary observations we have initiated an investigation into molecular phylogenetic and light harvesting characteristics a diverse set of photosynthetic microorganisms. The long-range goal of the effort is to constrain (1) habitable zone estimates of nearby stellar systems to aid terrestrial planet finder efforts and (2) the faint young sun hypothesis for our own solar system. It is important to state again that this is only one of many parameters required to adequately constrain HZ estimates prior to initiating TPF observational work. Observing time requirements for each observation will be significant and proper prioritization of nearby targets critical for successful conduct of this search.

References

Kasting, J.F., Whitmire, D.P. and Reynolds, R.T. (1993) Habitable zones around main sequence stars. Icarus 101, 108-128.
Schopf, J. W. 1(999) Cradle of Life: The Discovery of earth's Earliest Fossils. Princeton U. Press, 367.
Freer, A., Prince, S. Sauer, K., Papiz, M., Hawthornthwaite-Lawless, A. M., McDermott, G., Cogdell, R., and Isaacs, N.W. (1996) Pigment-pigment interactions and energy-transfer in the antenna complex of the photosynthetic bacterium *Rhodopseudomonas acidophila*, Structure 4(4) 449-462.
Tharia, H.A., Nightingale, T.D., Papiz, M.Z. and Lawles, A.M. (1999) Characterization of hydrophobic peptides by RP-HPLC from different spectral forms of LH2 isolated from *Rps. Palustris*, Photosyn. Res. 61, 157-167.