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ASTROBIOLOGY

Photosynthesis in watercolours

John Raven

The spectrum of stellar radiation available to an organism is altered by the atmosphere and water on the planet it inhabits. Study of this relationship can outline the limits to photosynthesis.

Water is essential for life 'as we know it', and the search for life 'as we don't know it' elsewhere in the Universe centres on the search for evidence of water¹. But the properties of water that make it essential for organisms and their environments can also restrict organisms' activities. An example that has now been re-investigated by Kiang *et al.*^{2,3} and by Stomp *et al.*⁴ is the wavelength dependence of the absorption of electromagnetic radiation by water, and also by permanent atmospheric gases. Such studies can inform our understanding of the distribution and pigmentation of photosynthetic organisms on Earth^{2–4}, and on any life-supporting Earth-like planets in other solar systems.

This biological dark side of water — its absorption of solar electromagnetic radiation — creates habitats that restrict or eliminate the roles of solar radiation in supplying energy for photosynthesis and information to sensory systems. The effective absence of solar radiation deep in large bodies of water such as lakes and oceans has long been recognized, and limits photosynthesis with this energy source to at most the top few hundred metres of water bodies, and to the land surface. The significance of water's wavelength-dependent attenuation of solar radiation for photosynthesis by aquatic organisms has been recognized since the late nineteenth century. Engelmann⁵, with his theory of complementary chromatic adaptation, suggested in 1883 that the depth at which seaweeds with different pigments grow might be related to the spectrum of incident radiation they receive.

Later work showed that Engelmann had underestimated the role of dissolved and suspended material in modifying the radiation attenuation due to water alone, and that, even when this was taken into account, the quantitative significance of complementary chromatic adaptation of seaweeds in nature was small⁶. But Engelmann's perception was a great stimulus to study of the photosynthetic pigmentation and the radiation environment of organisms in relation to the absorption of radiation by water. That work has extended to anoxygenic organisms (photosynthetic bacteria)^{2–4} — that

is, those whose photosynthesis does not generate oxygen — as well as being carried out on the oxygenic organisms considered by Engelmann, and also to other planets that might support life⁴. On Earth, the advent of anoxygenic organisms preceded that of oxygenic ones.

Kiang *et al.*² surveyed the diversity of photosynthetic organisms, and propose constraints on the evolution of the pigments that harvest and transform radiation. One is the wavelength of the peak photon flux in the environment. Another is the longest wavelength that has sufficient energy per photon to bring about the appropriate photochemical reaction (in which photon energy is converted into chemical energy). Organisms that produce oxygen from water, a very energy-intensive reaction, are constrained to using shorter wavelengths than are those that do not produce oxygen. This is the case despite the oxygen producers using two photochemical reactions in series, rather than a single reaction, as seen in anoxygenic organisms. The sorts of photochemistry that can occur, and the pigmentation of the organisms, are greatly influenced by the absorption of solar radiation by water (and oxygen) in the atmosphere and, for aquatic organisms, in the water body in which they live².

Independent work by Stomp *et al.*⁴ emphasizes the photon-absorbing properties of bulk water. Their analysis concentrates on photosynthetic microorganisms living in various bodies of water whose photon-attenuation properties differ because of dissolved and suspended material. Stomp *et al.* also examined the details of the photon absorption of water in the visible and infrared parts of the spectrum, concentrating on the harmonics of the molecular vibrations resulting in the main absorption features.

A major outcome of this work is in defining spectral niches for photosynthetic organisms in different aquatic habitats. Such conclusions for photosynthetic microorganisms do not necessarily conflict with those of Dring⁶ for seaweeds. Dring showed that the differences in pigmentation among seaweeds are less quantitatively significant for photosynthetic performance in their natural

habitats than many had previously believed.

Kiang and colleagues' analyses² of constraints on pigmentation of photosynthetic organisms on Earth provide the basis for their discussion³ of astrobiological aspects of photosynthesis. Putative planets associated with stars of the M spectral type are commonly taken to be locations where life might occur, given the abundance of these stars and their longevity. Photosynthetic organisms on an Earth-like planet orbiting an M star would experience stellar radiation with maximum photon fluxes at wavelengths in the infrared spectrum. The 'average' photon would have a lower energy content, and there would also be a much greater absorption by water, than for solar radiation on Earth^{2–4,7}.

Significant photosynthesis could nonetheless occur on such a planet^{4,7}. But there would be energetic problems in using the relatively low-energy photons to reduce carbon dioxide with electrons from water, with production of oxygen. The mechanism on Earth relies on two photochemical reactions in series; on planets orbiting an M star more than two reactions in series would be required^{2,7}. On any such planet, the longer wavelengths at which photosynthetic pigments would absorb would have implications for the remote sensing of pigments by reflectance spectroscopy as an indicator (with appropriate caveats) of photosynthesis, and hence life.

Kiang *et al.*^{2,3} and Stomp *et al.*⁴ use physics and chemistry to set limits on the mechanisms of photosynthesis that are possible in different habitats on Earth and on any Earth-like planets orbiting other stars. The authors' analyses outline the sorts of photosynthetic mechanism that are possible in a given radiation environment, without defining the chemical nature of the pigments or other components of the photosynthetic system.

Although the evolution of oxygen-producing photosynthesis is a likely outcome of the biogeochemical changes that accompany photosynthesis not involving oxygen production on a planet, this cannot be taken for granted. Accordingly, in the search for life outside our Solar System, an astrobiological niche presents itself. This is the spectroscopic remote-sensing not only of photosynthetically produced oxygen and its derivative ozone⁸, but also of a diversity of photosynthetic pigments^{3,7}, on any Earth-like planets that may be detected. ■

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