Response by Lars Olof Björn to bg-2021-135-CC4-supplement

This is a revision of an earlier manuscript.
In the new manuscript new sections are shaded in grey

Major changes from previous manuscript:
The following references have been deleted:
Foote Smith, E, (2019), Meireles, J.E. et al. (2020), Rautiainen, M. et al, (2018)
The following of the former Figures have been deleted: Figure 1, Figure 2, Figure 3, Figure 5
The following Figures are new: Figure 2, Figure 3, Figure 5, Figure 6
Figure 4 was modified (correction of comma to dot, change from color to grey tone).

One of the reviewers had no complaints about the manuscript. Here follow remarks by the other reviewer (in blue) and my response (in black).

Kleidon

1. Is the claim by Michaelian & Simeonov (2015) valid or useful? Here I side with the skeptical attitude of the author of the commentary and with William Martin. I do not believe MS2015, and doubt that it has much value. So there would be quite a bit that can be criticisized, but this criticism in its own needs to be well justified and substantiated.
2. Is the commentary by Björn well justified and substantiated? As I expressed in my review, it is not. For a commentary, I would expect something stronger and better argued, and I gave an example of how such a commentary could look like in the review. In the case of MS2015, I think that such a more substantial commentary would be easy to do.

Specifically, the comment questions the statement that "Living systems reduce the albedo of Earth" and elaborates whether this statement is correct. The manuscript uses the example of the Moon and compares it to the Earth, and provides some anecdotal evidence where life is not darker than its surroundings. Yet, this comparison is flawed, because what we would need to compare is an Earth without life to an Earth with life, not with another planetary body (Simulations of such conditions have been made, e.g., Kleidon et al. (2000) "A green planet versus a desert world", Clim Change, 44: 471-493.). Furthermore, it is textbook knowledge that the surface albedo of forests is in most cases darker than bare ground, even though there may be some isolated exceptions.

Björn reply: I have cut down on comparison with the Moon, added some remarks about Mars, but extended the article with comparisons between areas on Earth with and without organisms, and one comparison that shows that a type of prokaryote (cyanobacteria) reflects more sunlight that eukaryotes in the same habitat. For terrestrial (land) areas I have focused on bacteria and biocrusts, and deleted the parts about trees, since we should discuss the early stages of biological evolution. Therefore I have also added more information about aquatic life, since I believe that life arose in water.

Also the original authors criticized my comments to their article. Their main views are shown below (in blue) followed by my response (in black).

Michaelian & Simeonov

Michaelian and Simeonov (2015a) do not "call everything that absorbs photons a pigment". (See point 4 of the comment by Michaelian and Simeonov (2015b) on our original article for validation of the use of the word "pigment" in our paper.) We suggest that those organic molecules now known as the fundamental molecules of life (i.e. those in the 3 domains of life) that strongly absorb light within the 210-285 nm (UVC) region and have a conical intersection to rapidly dissipate the electronic excitation energy into heat (Michaelian2011;2017;2021) were originally (at the origin of life) organic pigments which were dissipatively structured from simpler and more common precursor molecules under this UVC light to perform the thermodynamic function of dissipating this light into heat.

Björn bases his critique on the suggestion that non-living material can be more photon absorbing than living material. He gives a number of examples in which he shows that the albedo of material devoid of life is lower than that of 5 biotic material and concludes that these examples counter our assertion. However, Björn makes the erroneous assumption that albedo (reflection) is the only important factor related to photon dissipation (entropy production) occurring in the light-pigment interaction in living systems. He ignores the other contributions to entropy production due to the photon interaction which were listed in our article;
1) the shift towards the infrared of the emitted spectrum,
2) the diffuse emission and reflection of light into a greater outgoing solid angle,
3) the coupling of photon-induced evapotranspiration in the pigmented leaf to further photon dissipating processes such as the water cycle, which further allows dissipating biopigments to flourish over all of Earth's surface.

Björn reply:
1) I try to make more clear that I include the shift towards the infrared of the emitted spectrum. The more of the incident radiation that is absorbed, the more is eventually emitted as infrared radiation (p. 6, lines 111–113).
2) I do not believe that there is any difference in principle between living and dead matter as to the angular distribution of reflected radiation (see p. 1, lines 20–22). Except for smooth wet surfaces and calm water surfaces, most natural surfaces reflect light in a diffuse way.
3) Yes, this is a point, in particular as regards life on land. Therefore I have deleted leaves and put more emphasis on aquatic life, which is also more relevant, because the earliest life is thought to have been aquatic. Also aquatic life can in some cases have an effect on evaporation, as can life in the atmosphere have an effect on precipitation by serving as condensation nuclei. Thus Mati Kahru, Juha-Markku Leppänen & Ove Rud (Cyanobacterial blooms cause heating of the sea surface, Marine Ecol. Progr. Ser. 101, 1–7, 1993) noted that cyanobacteria can cause increased surface temperature, and presumably increased

evaporation, from the water surface. I have included a reference to this work, but have assumed that this is a minor and not very common effect. I have now mentioned this on p. 4, lines 82–84.

Michaelian & Simeonov also have more detailed criticism in a supplement (bg-2021-135-CC4-supplement.pdf). Here follows my response to that:

Reply to bg-2021-135-CC4-supplement by Karo Michaelian and Aleksandar Simeonov

Abstract (of KM's and AS's supplement)
KM and AS write (lines 5–6) "Björn makes the erroneous assumption that albedo (reflection) is the only important factor related to photon dissipation (entropy production) occurring in the light-pigment interaction in living systems." This is a misunderstanding. I fully understand that the change in angular distribution and change of the radiation to longer waves are also important.
Forests (e.g., Rengarajan & Schott (2017) as well as moss and lichen (e.g., Solheim et al. 2000) exhibit large deviations from Lambertian scattering, but so do some, but not all, unvegetated natural ground surfaces (Watson 1972, Pommerol et al. 2013, Hapke 2021). The general tendency seems to be that vegetated surfaces have more reflection concentrated in the direction opposing the incident light, than do unvegetated surfaces. This would contribute to less entropy generation by vegetated surfaces.
Literature cited above:
Hapke, B. (2021) Bidirectional reflectance spectroscopy 8. The angular width of the opposition effect in regolith-like media. Icarus 354: 114105 (13 pp.). https://doi.org/10.1016/j.icarus.2020.114105
Rengarajan, R. & **Schott**, J.R. (2017) Modeling and simulation of deciduous forest canopy and its anisotropic reflectance properties using the Digital Image and Remote Sensing Image Generation (DIRSIG) tool. IEEE J. Selected Topics Appl. Earth Observ. Remote Sens. (14 pp.).DOI: 10.1109/JSTARS.2017.2751539
Pommerol, A., Thomas, N., Jost, B., Beck, P., Okubo, C. & McEwen, A.S. (2013) Photometric properties of Mars soils analogs. Geophys. Res. Planets 118, 2045–2072, doi:10.1002/jgre.20158
Solheim, I., Engelsen, O., Hosgood, B. & Andreoli, G. (2000) Measurement and modeling of the spectral and directional reflection properties of lichen and moss canopies. Remote Sens. Environ. 72, 78–94.
Watson, R.D. (1972) Spectral Reflectance and Photometric Properties of Selected Rocks. Remote Sens. Environ. 2, 95–100.

The heat radiation emitted (and fluorescence, usually a minor part of the emitted radiation) over wider angles than the incoming light depends on the amount of radiation absorbed, and thus on albedo (although for fluorescence also other circumstances are important). KM and AS further write: "The coupling of photon-induced evapotranspiration in the pigmented leaf to further photon dissipating processes such as the water cycle, which further allows dissipating biopigments to flourish over all of Earth's surface." It is true that phase transitions can also be important, but since the title of the original publication is "Fundamental molecules of life are **pigments which arose** and co-evolved as a response to the thermodynamic imperative of dissipating the prevailing solar spectrum" we should not be concerned with leaves and land plants, since no new photosynthetic pigments have evolved after the transition of life from the aquatic environment to land. I have removed reference to land plants from the revised manuscript. My intended main emphasis is on aquatic organisms, since life with all probability started in an aquatic environment. As for life on land, I concentrate on "simple" organisms (if we can rightly label any organisms as simple). My Figure 3 is intended to demonstrate that cyanobacteria have higher albedo than eukaryotes inhabiting the same environment. This could, with good will, be interpreted as if organisms evolve toward increased absorption.

KM and AS further criticize my sentence: “Thus, it appears that if Michaelian and Simeonov are correct, one would expect organisms, in particular phototrophic organisms, or the biosphere to be less reflecting and more absorbing than dead matter.“ I have removed this offending sentence from the new version.

Albedo of the Moon, a world without life

On line 66 KM and AS write “a wavelength dependent albedo will not change the result”. This is surprising. I thought that high albedo at large wavelength would result in more entropy production. Low albedo at low wavelengths will, in principle result in as much thermal radiation per incident flux as low albedo at large wavelengths, while long-wave reflected light would carry more entropy than short-wave reflected light. KM and AS write on lines 88–89 “it is also important to consider the temperature data of the emitted spectrum”.

Comparison of planets

On lines 40–42 KM and AS write: “We found that Earth’s entropy production per unit area is almost twice that of either of its neighbors, and this may be attributed to the presence of life on Earth [Michaelian (2012b)].” I think that it rather may be related to the different influx of solar energy, i.e. to the different distances from the Sun. If we adjust their values for this, we find (using the values in their Table 1 and leaving out the units):

For the Earth $1.247 \times (1.4960 \times 10^{11})^2 = 2.791 \times 10^{22}$

and for Mars $0.689 \times (2.2792 \times 10^{11})^2 = 3.619 \times 10^{22}$, i.e. a ca 30% higher value for Mars, despite the fact that the Earth has oceans and a thicker atmosphere.

The temporal aspect

KM and AS write (line 101): “The forests, as Björn correctly indicates, are sometimes buried and later burned as fossil fuel by humans. However, they produced at least 1000 times more entropy during their lifetime than that obtained by burning the same trees as fossil fuel today.” I do not see that they have got my point. A tree lives, say 100 years. Assuming the “1000 times more entropy during their lifetime than that obtained by burning the same trees as fossil fuel today” is correct, the fraction 0.001 of the entropy not produced during the lifetime is “saved” during 325 million years and emitted now. 325 000000 million years is 325 000 times the life-time of the tree, thus causing a substantial delay (lowered rate) of the production of the 0.001 of the entropy, thus causing a substantial decrease of the entropy production rate.

On line 116 KM and AS correctly point out that “fluorescence reduces entropy production”, followed on lines 118–119 “ecosystems still have room to evolve under the thermodynamic imperative towards becoming even better dissipating systems”. However, it appears that the fluorescence yield of the photosynthetic system of plants and algae is already optimized for efficient photosynthesis. The chemical potential that can be achieved by a pigment in photosynthesis is a positive function of the fluorescence yield. See, e.g., equation (6) in

“Thermodynamics of light emission and free energy storage in photosynthesis” by Robert T. Ross and Melvin Calvin, Biophys. J. 7, 595–614, 1964. On the other hand, only energy that is not emitted as fluorescence can be used to “split water”.