Colors of extreme exoEarth environments

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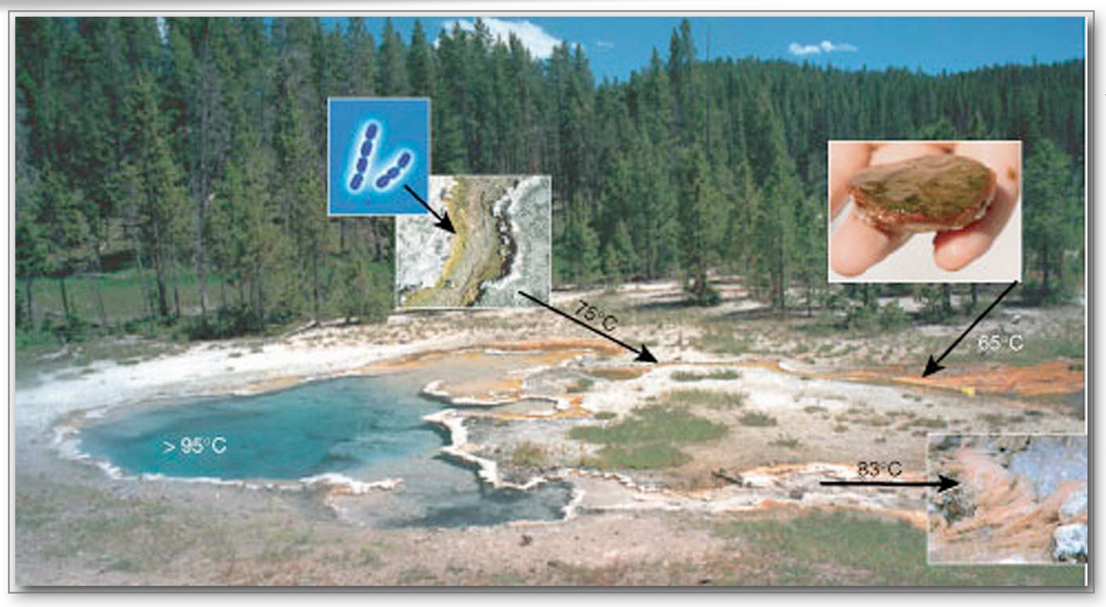

Abstract: Several rocky planets and planetary candidates have been detected with minimum masses consistent with rocky planets in the Habitable Zone of their host stars. Detailed information in regard to the habitability of Earth-sized extrasolar planets or "exoEarths" can be achieved by studying the atmospheric and surface properties of the planet in contention. A low-resolution spectrum in the form of a color-color diagram of a planet is likely to be one of the first post-detection quantities to be measured for the case of direct detection. A color-color diagram, distinguishes giant planets from rocky ones for solar system objects (see, Traub, 2003). Using a similar strategy, we explore potentially detectable surface features and their connection to and importance as a habitat for extremophiles as known on Earth, thereby providing a link between geomicrobiology and observational astronomy. We use filter (or 3-color) photometry in the visible as a first step in the characterization of rocky exoplanets to prioritize targets for follow up spectroscopy.

Extremophiles on Earth

- Extremophiles (literally "lovers of extreme environments") are organisms that live and thrive in very harsh environments and provide us with the minimum known envelope of environmental limits for life on our planet.
- To explore a wide definition for the limits of life on exoplanets, we focus on extremophiles. Environmental "extremes" are defined in terms of physical and geochemical parameters (*see*, Table 1).
- Similar environmental factors should be dominant on rocky exoplanets.
- We explore the detectability of such extreme environments as well as known extremophiles using a color-color diagram (*Fig.1*).

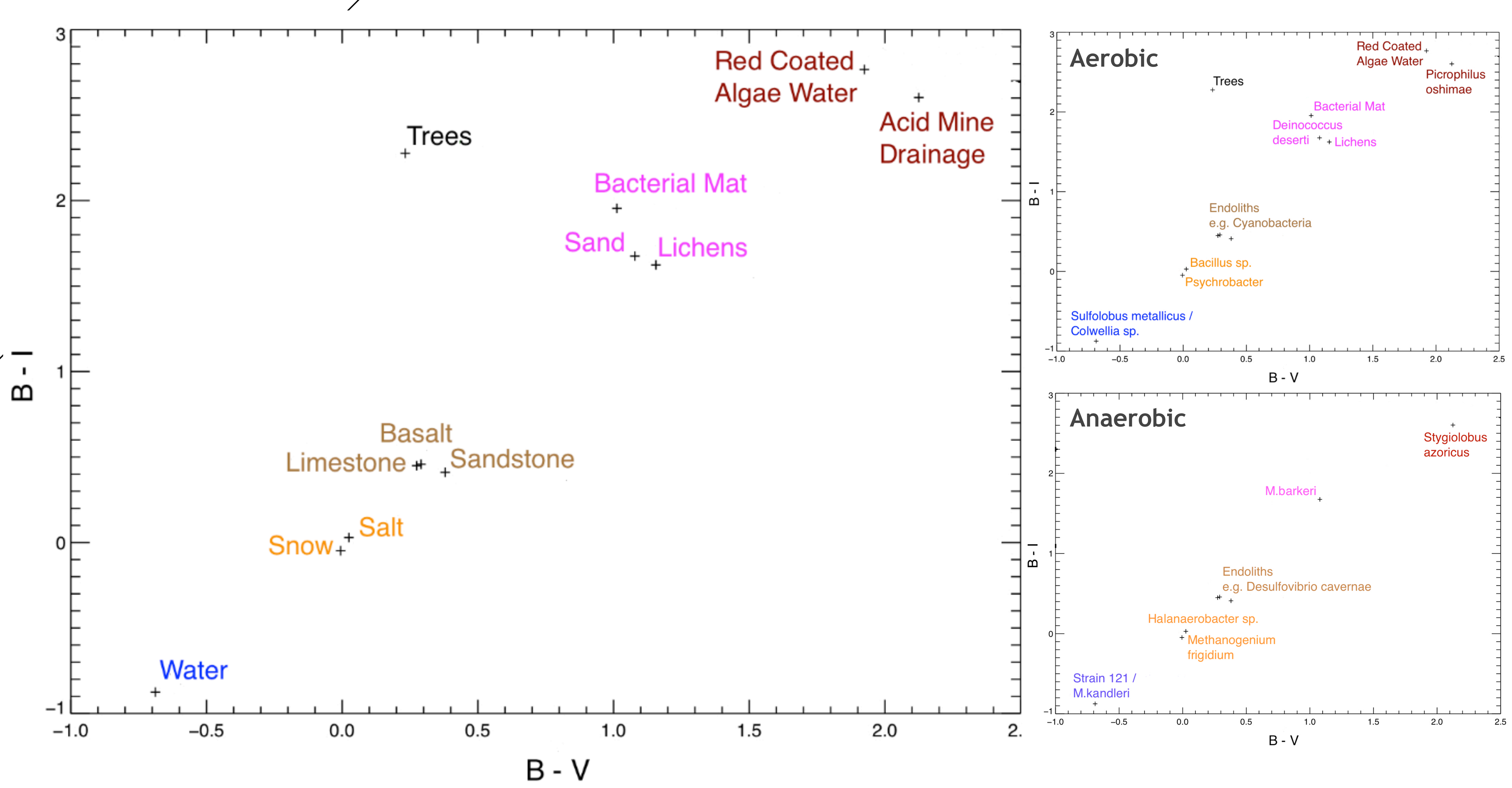

Fig. 1. Color-color diagram based on observed reflectivity of characteristic surfaces (like oceans, snow, rocks, etc) that support extremophiles on Earth. The figures on the inset show which classes of extremophiles can be potentially distinguished for aerobic and anaerobic atmospheres.

Environmental Parameter	Class	Defining Growth Condition	Environment / Source	Remotely Detectable Observable	Example Organisms
High Temperature	Hyperthermophile Thermophile	> 80 °C 60 - 80 °C	Submarine Hydrothermal Vents Hot Spring	Water	*Pyrolobus fumarii, Strain 121* *Synechococcus lividis, Sulfolobus* sp.
Low Temperature	Psychrophile	< 15 °C	Ice, Snow	Ice, Snow	*Psychrobacter, Methanogenium* spp.
High pH	Alkaliphile	ph > 9	Soda Lakes	Salt	*Bacillus firmus OF4, Haloanaerobium alcaliphilum*
Low pH	Acidophile	ph < 5 (typically much less)	Acid Mine Drainage, Volcanic Springs	Acid Mine Drainage	*Picrophilus oshimae/torridus, Stygiolobus azoricus*
High Pressure	Piezophile	High pressure	Deep Ocean eg. Mariana Trench	Water	*M.kandleri, Pyrococcus* sp., *Colwellia* sp.
Radiation	-	Tolerates high levels of radiation	Sunlight eg. High UV radiation	Sand, Rocks	*Deinococcus radiodurans, Thermococcus gammatolerans*
Salinity	Halophile	2 - 5 M NaCl	Salt Lakes, Salt Mines	Salt	*Halobacteriaceae, Dunaliella salina, Halanaerobacter* sp.
Desiccation	Xerophile	Anhydrobiotic	Desert, Rock surfaces	Sand, Rocks	*Artemia salina, Deinococcus* sp., *Lichens, Methanosarcina barkeri*
Rock-dwelling	Endolith	Resident in rock	Upper subsurface to deep subterranean	Rocks	*Lichens, Cyanobacteria, Desulfovibrio cavernae*

Table 1. Classification of extremophiles.

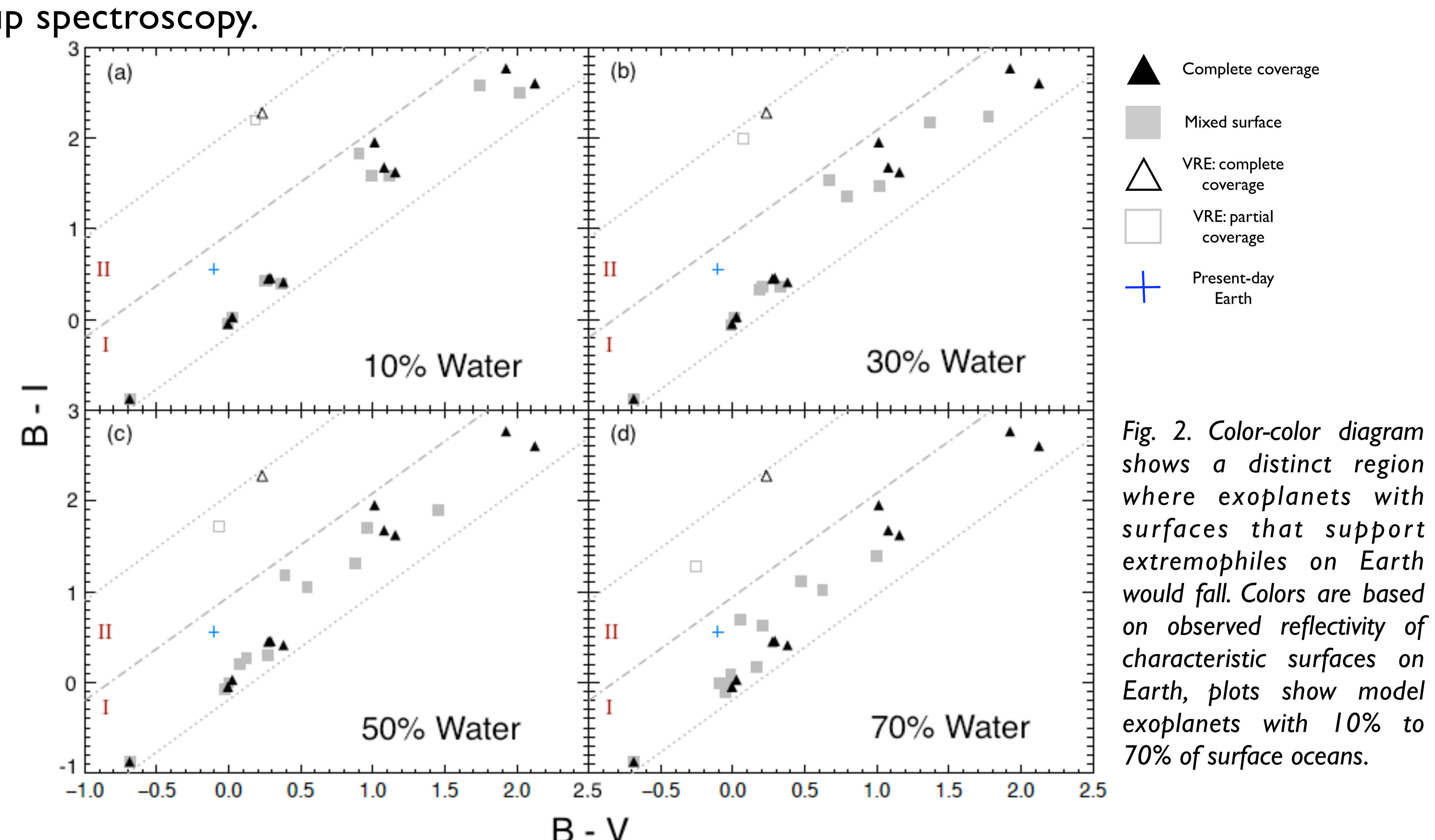

Fig. 2. Color-color diagram shows a distinct region where exoplanets with surfaces that support extremophiles on Earth would fall. Colors are based on observed reflectivity of characteristic surfaces on Earth, plots show model exoplanets with 10% to 70% of surface oceans.

Discussion

- Exploring surface features of exoplanets only becomes possible if either no cloud cover exists on an exoplanet or the SNR of each observation is sufficiently high to remove the cloud contribution from the overall detected signal.
- Further in-depth characterization can be obtained by modifying the bandpass definitions to distinguish certain surfaces or use narrow-band filters to distinguish known near-similar environmental signals as well, provided a high enough SNR is available.
- The characterization of surface features for Earth-type rocky planet environments using a color-color plot alone is not a reliable detection of life on an exoplanet, but can prioritize targets for follow up spectroscopy.

Conclusions

- Many surface environments on Earth have characteristic albedos and occupy a different color space in the visible waveband (0.4 μm - 0.9 μm) that can be distinguished remotely using standard Johnson-Cousins broadband filters.
- A simple low-resolution color-color diagram can be used to remotely characterize different types of rocky planet environments (*Fig.1*) that support extremophiles on Earth (Table 1).
- Different surface environments group in the color-color diagram e.g. salt and snow (*Fig.1*). Bacterial mats, lichens and red algae in acid mine drainage are shown as examples of extremophiles, that have measured surface reflectance. Trees are shown as reference to relate our work to the Vegetation Red Edge feature of terrestrial land plants. The figures in the inset (*Fig.1*) show which classes of extremophiles can be potentially distinguished in a simple color-color diagram.
- The method can be used in prioritizing targets for follow up spectroscopy. An Earth-type rocky planet placed outside the contour region (*Fig.2*) should receive lower priority for follow up. The priority should increase towards the lower left corner in the color-color diagram due to higher probability of liquid water being indicated on the surface.
- Detailed spectroscopic studies will be needed to learn more on the potential habitability of rocky exoplanets.

References: Canganella and Wiegel, Extremophiles: from abyssal to terrestrial ecosystems and possibly beyond, 2011; Cavicchioli, R. 2002, "Extremophiles and the search for extraterrestrial life", Astrobiology, vol. 2, no. 3, pp. 281-292; Clark, R. N., et al., USGS digital spectral library splib06a. 2007. U.S. Geological Survey, Digital Data Series 231; Hegde and Kaltenegger, Colors of extreme exoEarth environments, Astrobiology, 2012, *in print*; Rothschild, L.J., and Mancinelli, R.L. 2001. Life in extreme environments. Nature. 409, 1092–1101; Traub, W. A. 2003, "Extrasolar planet characteristics in the visible wavelength range", In: Proceedings of the Conference on Towards Other Earths: DARWIN/TPF and the Search for Extrasolar Terrestrial Planets, 22-25 April 2003, Heidelberg, Germany. pp. 231-239.

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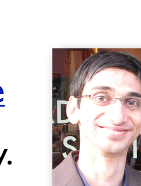

Acknowledgement: The authors acknowledge support from DFG funding ENP Ka 3142/1-1. S.H. also acknowledges support from the International Max Planck Research School for Astronomy and Cosmic Physics at the University of Heidelberg (IMPRS-HD), of which he is a fellow.

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