Invited Paper

Mitigation of Environmental Extremes as a Possible Indicator of Extended Habitat Sustainability for Lakes on Early Mars

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ABSTRACT

The impact of individual extremes on life, such as UV radiation (UVR), temperatures, and salinity is well documented. However, their combined effect in nature is not well-understood while it is a fundamental issue controlling the evolution of habitat sustainability within individual bodies of water. Environmental variables combine in the Bolivian Altiplano to produce some of the highest, least explored and most poorly understood lakes on Earth. Their physical environment of thin atmosphere, high ultraviolet radiation, high daily temperature amplitude, ice, sulfur-rich volcanism, and hydrothermal springs, combined with the changing climate in the Andes and the rapid loss of aqueous habitat provide parallels to ancient Martian lakes at the Noachian/Hesperian transition 3.7-3.5 Ga ago. Documenting this analogy is one of the focuses of the High-Lakes Project (HLP). The geophysical data we collected on three of them located up to 5,916 m elevation suggests that a combination of extreme factors does not necessarily translate into a harsher environment for life. Large and diverse ecosystems adapt to UVR reaching 200%-216% that of sea level in bodies of water sometimes no deeper than 50 cm, massive seasonal freeze-over, and unpredictable daily evolution of UVR and temperature. The HLP project has undertaken the first complete geophysical and biological characterization of these lakes and documents how habitability is sustained and prolonged in declining lakes despite a highly dynamical environment. The same process may have helped life transition through climate crises over time on both Earth and Mars.

Keywords: High-Lakes Project, Mars, Mars analog, habitability, habitat sustainability, life potential on Mars, environmental extremes, high-altitude lakes.

1. INTRODUCTION

The exploration of Mars habitability and life potential is guided by our knowledge of the environments occupied by terrestrial biota and by the data returned by Mars Global Surveyor (MGS), Mars Odyssey (MO), the Mars Exploration Rovers (MER), Mars Express (MEx), and the Mars Reconnaissance Orbiter (MRO). They converge to show that Mars was habitable for life as we know it[1-5] but favorable conditions disappeared rapidly 3.7-3.2 Ga ago[6]. OMEGA has identified phyllosilicates and sulfates in the oldest rocks[7]; THEMIS shows anhydrated ferric oxides (olivine) in early Hesperian[8-9]. This mineralogical succession is consistent with a wet-to-dry environment and alkaline-to-acidic conditions and suggests no large-scale weathering for 75% of Mars history but still transient and localized aqueous processes most likely associated with high-obliquity cycles.

Within that context, and using an analogy to Earth, lakes on early Mars would have been favorable sites for the inception and development of life[10-16]. As a result, they are high on the list of priority sites sought for by the planetary science community in the search for life on Mars. Evidence of their presence abounds planetwide with the highest density in the southern uplands where the most ancient terrains are located. Dry basins at the termini of fluvial valley networks were the first indicators of the presence of ancient lakes. Other evidence includes the existence of delta-like landforms[15, 17-21] whose morphology testifies of surface water stability over periods that could have spanned tens of thousands of years. The morphological evidence is supported by the presence of hydrated minerals showing the existence of abundant surface water during the same geological periods[7].

Pursuing the analogy with Earth further, habitat sustainability in a Martian lake would have been dependent on both the lake's own characteristics and external factors, such as environment and climate. At the tail end of Mars' wet period,

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climate change would have triggered profound modifications in lakes with implications on their habitability whose decline was related to evaporation and increasing negative pressure of environmental parameters, such as enhanced ultraviolet radiation (UVR) in an ever reducing water column. Figure 1 summarizes the commonly accepted view on the evolution of aqueous environments during the wet period compared to the period of climate transition (3.7-3.2 Ga).

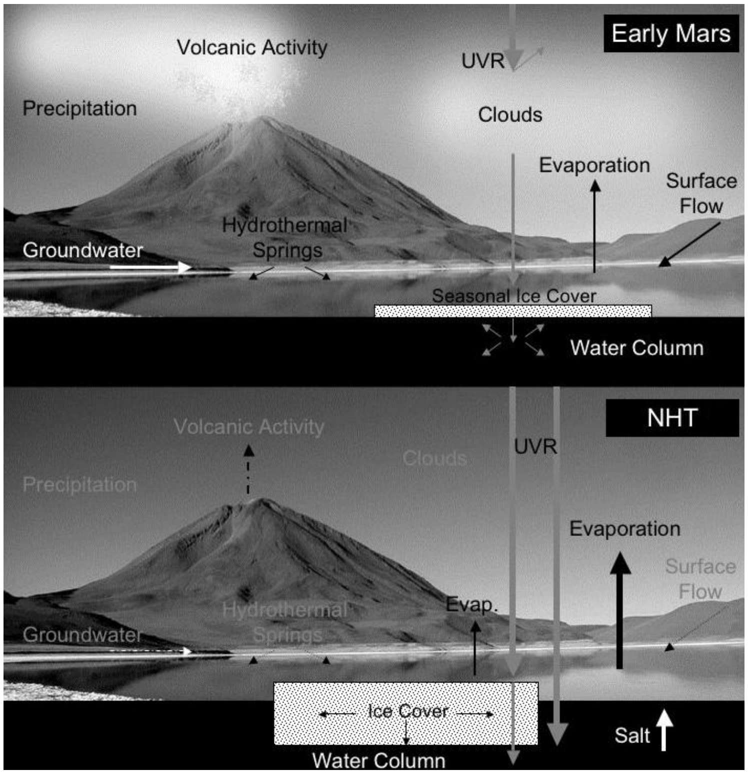

Figure 1 – Top: Mission data support the presence of a hydrological cycle comparable to Earth on early Mars. Ice cover on lakes was possibly limited to cooler seasons and latitude-dependent. The effect of UVR was likely mitigated by clouds and a deep water column; Bottom: Mars at the Noachian/Hesperian Transition (NHT, 3.7-3.2 Ga ago). This transition period must have been associated with the thinning of the atmosphere, less cloud protection, increased evaporation and water salinity, reduction of the water column and ultimately loss of surface water. The direct impact of UVR at the surface was enhanced due to the thinning of the atmosphere. However, similarly to the Andean lakes, it is possible that this impact might have been mitigated in the water by ice cover formation which became perennial through time and the increase of water salinity associated to evaporation. The NHT was also marked by cooling average temperatures and the onset of larger daily temperature fluctuations. Surface flow became episodic and ice permanent until it completely sublimated in the low and middle latitudes. In later times, the presence of water and ice at those latitudes was related mostly to high-obliquity cycles, catastrophic ruptures of subsurface aquifers and, to a lesser extant, precipitation.

While Martian lakes ultimately disappeared, how long those bodies of water remained habitable as their water column shrunk may have controlled life's ability to transition to new environments, *i.e.*, by adapting/migrating to more protected habitats that offered radiation refuge and moisture retention, such as within sediments, rocks (endolithic), or potentially underground. Documenting this question is essential to the planning of future missions "*following the water"* that will search for traces of life on Mars starting with the Mars Science Laboratory (MSL) mission in 2009. Understanding the threshold of habitat sustainability in declining lakes is therefore a fundamental part of (a) our vision of Mars past habitability and life potential and (b) our ability to select relevant landing sites for missions. However, while global models of past Martian climate and hydrosphere do exist[22] no attempt has been made yet at modeling ancient Martian lakes' behavior.

Usually, the question of life survival on Mars is addressed by listing individual environmental extremes plausibly present when the climate changed and qualitatively summing their negative influence. However, a natural system is not a sum but a *combination* of environmental factors with complex loops and feedback mechanisms. While the impact of individual extremes on life such as UVR, temperatures, or salinity is well-documented[23-27] their combined effect and relative dominance in a natural system are not well-understood or quantified although it is a fundamental issue controlling the evolution of habitability. How those combinations operated in Martian lakes determined how, and how fast, the sustainability threshold for life was reached. The way they interacted depended not only on the environmental factors external to the body of water (*e.g.,* obliquity, seasons, atmospheric pressure, temperature, UVR) but also on the physical and chemical characteristics of the lakes themselves (*e.g.,* salinity, *p*H, chemistry, initial depth, total dissolved solids (TDS), mixing, stratification), their geographical location (elevation, latitude), and water supply. As a result, the lakes' response to environmental change should be looked at as heterogeneous at planet-scale since each one was potentially unique due to its own individual characteristics. However, for modeling purposes, interactions and feedbacks between physical, chemical, environmental, and biological parameters can be simplified on a first order to three types that were common to all lakes. This is illustrated by the following examples:

(a) Negative – high-UVR combined with abrupt swings in temperatures generates an environment where it becomes difficult for life to repair its DNA[28-30]. This results in a reduction of habitability conditions;

(b) Counteractive – Hypersalinity delays the formation of ice by depressing the freezing point of water, preserving the photic zone, which otherwise is reduced by ice-cover;

(c) Positive – Ice-cover regulates water temperature by insulating it from large external temperature variations.

The complexity of natural systems is that all variables are interacting simultaneously with each other and their combination in nature generates a *multiple-interaction system* leading to loops and feedback mechanisms impacting habitability. For instance, although salinity preserves liquid habitat longer by depressing the freezing point of water, it allows UVR to penetrate the water column and exposes life to deadly radiation as evaporation reduces the water column. On the other hand, as water evaporates, increased TDS in the water may amplify UVR scattering, somewhat diminishing its impact. Another example could be that while ice protects life by screening UVR, it also decreases critical photosynthetic active radiation (PAR) for photosynthetic microbial organisms. Figure 2 illustrates some simple loops and feedbacks in a system using selected variables.

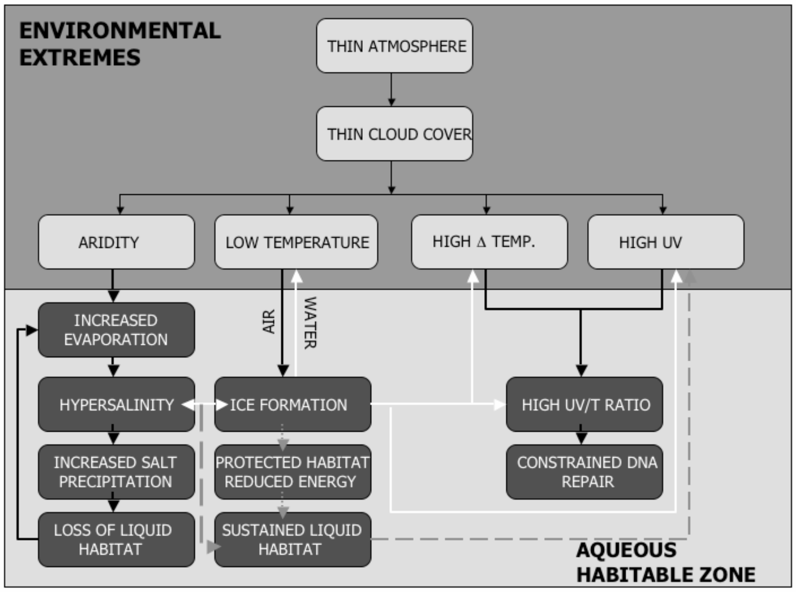

Figure 2: Selected and simple interactions between the environment and the aqueous habitable zone (aHZ). Within the aHZ, dark arrows show negative effects; White arrows are positive feedback that could allow sustained habitability; Grey dotted arrows are temporary positive impact that may come at a cost for life (*e.g.,* exposure to new environmental extremes). For instance: Hypersalinity inhibits ice formation by maintaining liquid habitats longer. As a result, life may be exposed to UVR as evaporation reduces the water column. Ice formation protects life from UVR but reduces the amount of energy received. It also maintains water temperature stability and low UVR/T ratio, favoring DNA repair. This example is a snapshot in time and does not compute the evolution of the system.

An obvious caveat to such modeling for Mars is that the model is necessarily based on our knowledge of terrestrial aqueous microbial organisms' ability (or lack thereof) to adapt to changing conditions. It may be speculated that this ability was different for putative Martian aqueous microorganisms[31-34]. Modeling also relies on the accuracy of other models *i.e.,* the evolution of the Martian atmosphere and its impact on the stability of surface liquid water[35-45]. Another limiting factor is the degree of analogy between the natural systems used as a base for the model and ancient Martian lakes environment.

2. MARS ANALOGS

Because lakes are favorable environments for the inception and evolution of life, and for the preservation of its record (*e.g.,* fossils) various aspects of extreme lake environments have been studied as Mars analogs, including: The physical and biological constraints on the structure and function of ecosystems in the Dry Valleys of Antarctica[46]; the nature of lake sedimentary environment[47]; the geomorphology of high latitude lakes[48]; the formation of tufa[49]; the conditions of evaporite formation[50] and their remote sensing signatures[51]; the biology of impact crater lakes in the High-Arctic[52]; and the physical environment of subglacial lakes in Antarctica[53, 54]. Each study provides critical information about the individual impact of selected parameters on putative life in early Martian lakes. However, a *systemic* understanding of early Martian lakes ideally requires an environment where many of the parameters analogous to past Mars are present together, including: low average temperature, high-daily temperature amplitude, thin atmosphere, high-UV radiation, ice, reduced yearly precipitation, volcanic and hydrothermal environment. Those conditions are met at high-altitude in the Andes where evaporation in lakes was initiated by climate change ~18,000 years ago[55, 56] and is currently accelerated by Global Warming.

2.1 Environmental analogy

No terrestrial site will ever be a perfect analog to Mars but many of the important parameters sought for to model early Mars are present in the Bolivian Altiplano where some of the closest environmental analogy to Mars at the end of the wet period is encountered, *i.e.,* thin atmosphere, high-UVR, seasonal ice-cover, sulfur-rich, volcanic and hydrothermal environment. UVR, particularly the shorter, biologically relevant wavelengths, is elevated compared to sea level due to the elevation; P_{ATM} is 550-480 mb; $\Delta T \sim 30\text{-}40\,^{o}C$ for altitudes ranging from 4,300-6,000 m, respectively. While UVR and temperature generally evolve in parallel, abrupt and significant fluctuations in temperatures (*e.g*., loss of $10^{o}C$ in a few seconds due to wind or clouds, *field observations*) can generate high UVR/T ratio with damaging impact on life and DNA repair abilities.

The climate evolution provides another level of analogy to Mars. Lakes were formed ~18,000-14,000 years ago when the Altiplano received 500 $mm \cdot y^{-1}$ precipitation[55]. Aridity set in at the Holocene transition and current precipitation of ≤ 100 $mm \cdot y^{1}$ generates a strong negative water balance[57-59].

2.2 Study sites

The three investigated lakes are in the Potosi region of Bolivia in a basaltic-andesite environment with local sulfur enrichment due to volcanic activity. They are representative of some of the plausible diversity of Martian lakes during the climatic transition (ranging from close to alkaline to acidic). They are the Licancabur lake (5,916 m), Laguna Blanca and Laguna Verde (4,340 m).

The Licancabur lake is nested ~90 m below the summit crater of a dormant volcano (Figure 3). Its latest eruption is assumed to have occurred at the Pleistocene/Holocene transition ~10,000 years ago[60] although no detailed study exists on the volcano's activity. Geological transects and ^{14}C performed by the HLP team on the paleoterraces of Laguna Verde at the contact with some of Licancabur's lava flows could indicate a period of activity around 13,240 BP ± 100 yr[61]. Comparing photographs dating back from the 1980s, it is estimated that the lake was ~10 m deep and 120 m across. We established the first bathymetry of this lake in November 2006 which shows that the current maximum depth is 5.2 m. Its shorelines receded in the past three years at a rate which, if sustained, will result in the complete evaporation of the lake within 15-20 years.

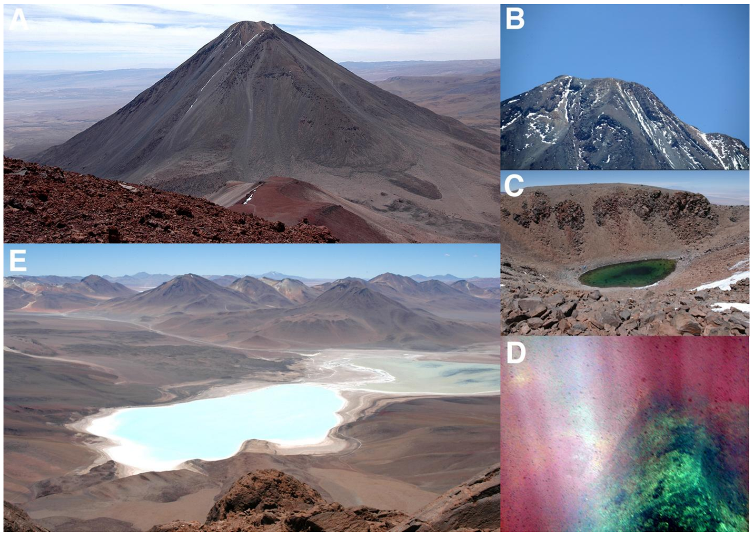

Figure 3 – A: Licancabur volcano (18°44'32"S/68°58'46"); B: Summit crater; C: Summit lake in the crater; D: A boulder attracts a large colony of red copepods (5.2 m depth); E: Laguna Verde (left) and Laguna Blanca (background) from Licancabur (22°47.32'S/67°49.16'W). *HLP 2004 expedition, NAI/SETI/NASA Ames.*

Lagunas Blanca and Verde are located in a tectonic basin at the foot of the Licancabur volcano. They were part of a single (~21 x 7) km large x 50 m deep lake which experienced its peak volume at the end of the Holocene ~10,800-9,200 BP[61]. Because of climate change[55, 62], evaporation, and topography, these two lakes are now separating and are only connected by a small (20 m x 5 m) channel. They already display very different ecosystems[63, 64] and physico/chemical characteristics (Table 1). Laguna Blanca and Laguna Verde have maximum depths of 0.5 m and 5 m, respectively.

Table 1: Lakes Physical and Chemical Characteristics

Physical Parameter	Laguna Blanca	Laguna Verde	Licancabur Summit Lake
Lake surface area (km^2)	3.5	7.5	0.01
Maximum depth (m)	0.5	5.5	5.2
Atm. Pressure (mb)	550-600	550-600	480
Air Temp. (°C)	-28 /+10	-28/+10	-40/+5
RH (%)	9-25	9-25	2-70
Average Water Temperature (°C)	12 (a)	13 (1)	4.9
Hydrothermal Input	12-36°C	12-15°C	Unlikely
pH	8.1	8.1	6.9
TDS (mg/L)	23,050	199,000	1,307
Ice Cover	Variable year round	Rare	April-September
UVR (% sea level)	200	200	216
UVA (W/m^2)(b)	56.1 (80.5)(c)	56.1 (80.5)	67.5 (95.6)
UVB (W/m^2)	2.7 (16.1)	2.7 (16.1)	3.2 (17.2)
PAR (W/m^2)	373 (555)	373 (555)	379 (556)
Erythemal (W/m^2)	0.3 (1.6)	0.3 (1.6)	0.4 (1.7)
UVA (J/m^2)(d)	1367 (1988)(c)	1367 (1988)	1613 (2481)
UVB (J/m^2)	41.7 (75.6)	41.7 (75.6)	50.2 (95.4)
PAR (J/m^2)	9832 (15061)	9832 (15061)	9935 (23925)
Erythemal (J/m^2)	4.8 (8.5)	4.8 (8.5)	5.8 (10.8)
τ UVB (m) (e)	0.077	n/d	0.53
τ UVA (m)	0.28	n/d	1.1
τ PAR (m)	0.88	n/d	10.1

(a). Water temperature measurements from shoreline geothermal springs; (b). Mean daily average; (c). Number in parenthesis are maximum daily peaks; (d). Mean daily fluence; (e). UVR optical depth (attenuation) in water. Note: The pH of these lakes has varied every year since 2002. The values reported in this table are averages from the 2006 data.

3. INSTRUMENTS AND METHODS

We surveyed the physical environment between 2002 and 2006 using European Light Dosimeter Network[65] (ELDONET) type UVR dosimeters, meteorological stations, water and rock sampling, underwater temperature probes, and boat-mounted thermal sensors. Zooplankton and microbiological sampling was performed by plankton netting (10µm and 50 µm mesh) and scuba diving.

The geophysical environment was characterized through direct measure of air, soil and water temperature as a function of depth, relative humidity, and UVR flux at the surface and as a function of water depth. Lightweight, handheld probes were used to record conductive heat flux from the lakebeds, Onset Computer Corporation dataloggers for long-term integration (yearly data) of air and water temperature. UVR was measured with ELDONET UVR dosimeters at each site. These instruments are 3-channel (UVB: 280-315 nm, UVA: 315-400 nm, and PAR: 400-700 nm) submersible, logging ultraviolet dosimeter units, which monitor automatically UVR on all three data channels as well as external temperature and pressure (depth). In 2006, the team used a SolarLight company UVR detector with 4 sensors covering UVA, UVB, UVC (280-100 nm), and PAR. The instrument was used to perform daily monitoring during the expedition at the refuge's station (4,370 m), at the summit of Licancabur, and during the ascent to study the UVR gradient as a function of elevation.

Yearly meteorological data was recorded since 2003 using HOBO mast mounted micro-meteorological and soil stations equipped with temperature, relative humidity, soil moisture, wind speed and direction sensors. The first bathymetric map of the Licancabur lake was completed in 2006 using a portable teleoperated boat developed by the team. It carried a Global Positioning System (GPS), sonar, temperature sensors, and a Eagle Fish Elite 480 Computer. Water analysis was performed by ActLabs: Anion concentration was determined by ion chromatography, cation concentration by inductively coupled plasma mass spectrometry and optical emission spectrometry (ICP-MS, ICP-OES); pH and TDS measurements were made in the field with handheld digital meters and replicated in laboratory.

4. OBSERVATIONS AND PRELIMINARY RESULTS

Compared to Lagunas Blanca and Verde, the summit lake is subject to greater solar UVR irradiance, colder average air temperature and greater air temperature. While the two lower lakes are relicts of the same body of water, varying water temperatures, pH, alkalinity, transparency, and hydrothermal input (see Table 1) lead to drastically different individual dynamics, which impact local ecosystems. Noticeably, the resulting effects on life are somewhat opposite to what is theoretically predicted for UVR and water column. At constant UVR, the lake with the deepest water column should provide the best protection against solar radiation. Compared to Laguna Verde (5 m), the 0.50 m deep Laguna Blanca offers theoretically less shielding to life, which is confirmed by a high rate of deformities in diatoms[63]. However, the greatest abundance and biodiversity is found in Laguna Blanca, whereas Laguna Verde produces a simple and primitive foodchain (Table 2).

Table 2: Lakes Biodiversity (*)

Lake	Foodchain	Description
Laguna Blanca	Flamingoes, zooplankton, diatoms, cyanobacteria, heterotrophic bacteria	Cyanobacteria, bacillariophycae (diatoms), dinophyta and charophyceae (macro alga), filamentous green algae, ciliata, gastroptrycha, testacea, mollusca, copepoda, ostracoda, amphipoda, oligochaeta, chironomida, heteroptera.
Laguna Verde	Cyanobacteria, diatoms	Cyanobacteria, bacillariophycae (diatoms)
Licancabur	Zooplankton, diatoms, cyanobacteria, heterotrophic bacteria	Copepods, ostracods, rotifers, chironimids, cladoceran, cyanobacteria, bacteria, archaea, sulfate reducing bacteria

* This table presents a preliminary assessment of the lakes biodiversity. Samples from the 2006 expedition are still being analyzed.

This observation suggests that in a natural system where several extremes interact, the critical factor for life is their relative individual influence and how they combine with each other. This is a fundamental issue for the survival of a putative life on early Mars since UVR is generally considered to have been the most severe threat as climate and atmosphere changed, although this view is evolving[66, 67]. In mostly the same physical conditions as early Mars, the shallow, evaporating Laguna Blanca provides an environment where high UVR flux is mitigated, which prolongs habitat sustainability.

To test further the hypothesis that the combination of extremes can maintain habitat sustainability in some cases, we collected data on temperatures, UVR/T ratio, and salinity and evaluated their plausible interactions and feedback mechanisms. The Andean high-lakes have in common with ancient Mars a high UVR coupled with high daily ΔT, thin atmosphere (480 mb at the Licancabur lake) and low relative humidity, which increases evaporation. As extremes combine, their effects modify the aqueous habitable zone as shown by the simplified model in Figure 1. Temperature and UVR vary along the same gradients. However, the changes are not parallel over space and time. Common inverse relationships between UVR and temperature as observed in the Andes subject aqueous ecosystems to high UVR/T ratios (Figure 4). Cloud cover can reduce total UVR exposure but the proximity of the Atacama desert makes overcast rare and mostly confined to winter time. Moreover, breaks in clouds, high-wind gusts. and rapidly changing weather generate other risks for life as the UV/T ratio evolution becomes unpredictable.

The coupling of UVR and temperature is significant: It drives in part the ability of organisms in high-altitude shallow lakes to repair DNA damage. Microbial organisms are dose rate sensitive: Photosynthesis and DNA synthesis are partly regulated by UVR flux[68-74] and many aquatic organisms depend on photoenzymatic repair (PER) for protection. UV damage is mostly temperature independent, however, molecular repair is temperature dependent and microbial life is less tolerant to UVR at lower temperatures[29]. Thus, the mostly negative temperatures, high ΔT, and UVR of the Andes should be a deadly combination for life, while it colonizes all lakes and in the greatest abundance and diversity in the shallowest water column. Here, Laguna Blanca provides a clear example that the amount of UVR reaching the surface is not as important as how radiation is mitigated by the environment. Despite the shallow depth, high UVR, and UVR/T ratio, the waters attenuate harmful solar UVB rays (equivalent to half of that received on Mars at the equator) in the upper centimeters of the water column, while longer-wavelength PAR can penetrate all the way to the lake floor. Therein, Laguna Blanca's water column can be thought of as the zone where UVB is significantly attenuated yet PAR is still accessible to allow a safe environment for primary producers. The unique optical properties of Laguna Blanca's waters is due to the salt concentration and presumably higher dissolved organic carbon concentration from higher biodiversity and density. Thus, the lake's water chemistry, albeit extreme by its salinity, is a critical component to its habitability and deflects most of the harmful effects of high UVR and UVR/T ratio.

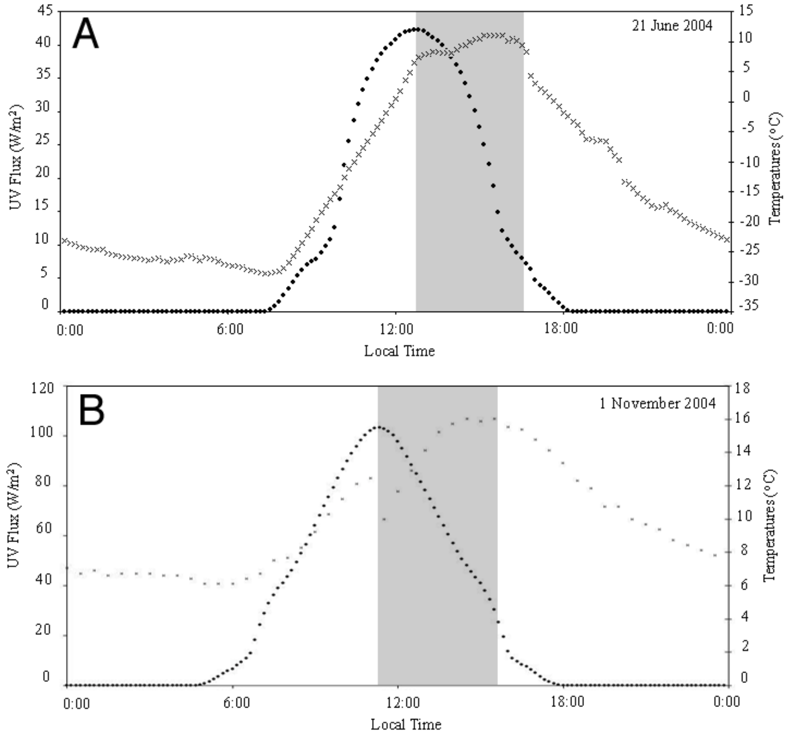

Figure 4 – A: Air temperature (black dots) and UVR (grey dots) measured at the surface of Laguna Blanca (ELDONET); B: Water temperature and UVR. For both graphs, grey areas show daytime (lake unfrozen) when UVR and T diverge generating challenging conditions for life (high UVR/T ratio).

Increased salinity also depresses the freezing point of water, allowing water to stay liquid longer at negative ambient temperatures, as shown by the freezing points of the various lakes: The Licancabur lake freezes at ~0°C; Laguna Blanca freezes at –5°C. This temperature is reached regularly at night even in summer leading to a surficial overnight icing followed by thawing in the early morning hours. The lake has a permanent winter ice cover over ~20% of its water column; the Na-Cl-(SO_4) brines of Laguna Verde should freeze at –25°C[74] but high-winds prevent ice formation even in winter when the temperature falls to -30°C except on a small fraction of its shoreline. The lake froze only once in the past 30 years (*unpublished observation from local inhabitants*).

Hypersalinity in Laguna Verde has complex consequences for life: No ice cover is formed that could reduce DNA weighted irradiance and the water column remains liquid year-round. While the water column is deep enough to mitigate UVR, the lower number of species suggests that high-salt content and close-to-alkaline pH prohibit the colonization of water by many organisms while there is no natural obstacle to prevent migration from Laguna Blanca. For instance, the rare copepods found in Laguna Verde were dead specimens which probably migrated through the small channel from Laguna Blanca were colonies are thriving. Environmental segregation was initiated recently at geological scale: ^{14}C analysis of the paleoterraces indicates a major drop in level between 8,440 ±80 and 6,300 ±70 BP, the lake loosing ~20 m in 2,000 years. Micrographs of Holocene fossils show comparable species and abundance for both lakes when they were still merged. Biological separation could be as recent as the 1990s when Laguna Blanca and Laguna Verde were still mentioned as a single body of water[75].

Conversely, substantial freezing occurs at the summit lake trapping 15% of its water column (0.8 m) in winter. In addition to providing shielding against UVR, the ice cover stabilizes the fluctuation of daily water temperatures, promoting a more stable thermal and UVR/T environment. One-year water temperature data logging showed daily $\Delta T_{Water} = 8^{o}$ without ice and 1^{o} with ice. The downside for life is light attenuation to complete darkness, which impacts photosynthesis. However, variable extinction coefficients of snow and ice generate density gradients in waters that life is known to use for metabolic activity during winter[76] resulting in a great survival dependency over the lake's dynamics (*e.g.,* convection). When ice thaws in spring, the distribution of some species follows closely UV attenuation in the water column (Figure 5).

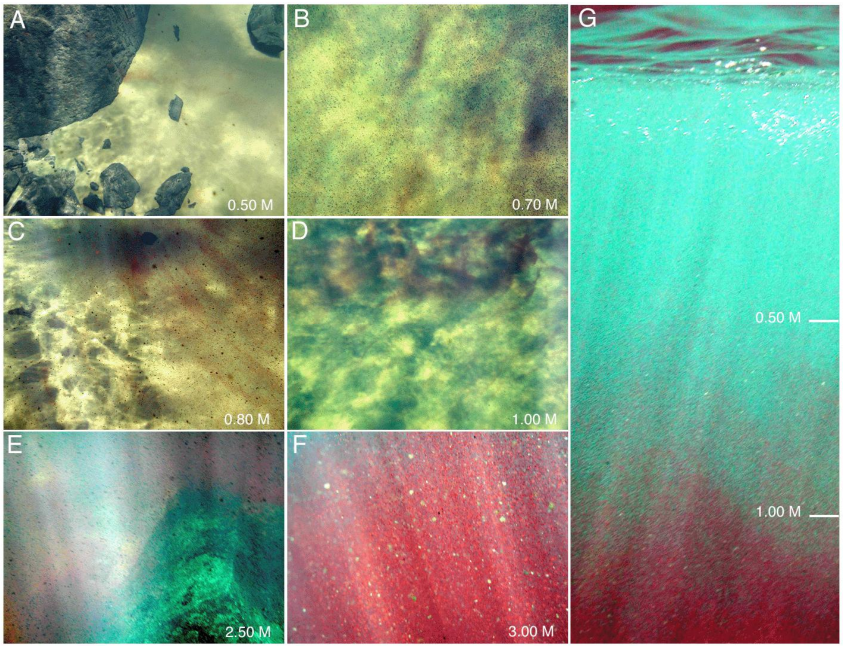

Figure 5: Licancabur lake (5,916 m). A-F. Submillimetric red copepods (average 700 µm) observed by the diving team at various depths (shown in lower right). G: Distribution of microorganisms density in the water column correlating with in situ measurements of UVB and UVA attenuation at 53 cm and 1.08 m respectively. *Credit photos: HLP 2004 Expedition. (NAI/SETI/NASA Ames).*

5. CONCLUSION

Complex interactions of extreme factors in early Mars analog environment provide some evidence to suggest that habitability in evaporating Martian lakes was not a simple sum of negative factors. Rather, the various ways extremes dominate and combine is paramount for habitat sustainability. Our observations raise the possibility that habitability in Martian lakes at the dawn of Hesperian might have been preserved in some cases well into declining climate conditions. Our findings show that the amount of UVR reaching the surface is not as significant as how radiation can be mitigated in the water, even in very shallow aqueous environments. While UVB and UVC are greater on Mars and generally more detrimental to biology, both are strongly attenuated high in the water column in salty aqueous environments.

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REFERENCES

1. S. W., Squyres R. E. Arvidson, J. F. Bell III, J. Brückner, N. A. Cabrol, and the Athena Science team, "The Opportunity rover's Athena science investigation at Meridiani Planum, Mars", Science **306(3)**, 1698-1703, 2004
2. S. W. Squyres, A. H. Knoll, R. E. Arvidson, B. C. Clark, J. P. Grotzinger, B. L. Jolliff, S. M. McLennan, N. Tosca, J. F. Bell, III, W. M. Calvin, W. H. Farrand, T. D. Glotch, M. P. Golombek, K. E. Herkenhoff, J. R. Johnson, G. Klingelhöfer, H. Y. McSween, A. S. Yen, "Two years at Meridiani Planum: Results from the Opportunity Rover", Science **313(5792)**, 1403-1407, 2006.
3. A. H. Knoll, M. Carr, B. Clark, D. J. Des Marais, J. D. Farmer and 8 authors, "An astrobiological perspective on Meridiani planum. Earth Planet", Sci. Let. **240**, 179-189, 2005.
4. S. M., McLennan, J. F. Bell III, W. M. Calvin, P. R. Christensen, and B. C. Black, "Provenance and diagenesis of the evaporite-bearing Burns formation, Meridiani Planum, Mars", Earth Planet, Sci. Let. **240**, 95-121, 2005
5. D. J., Des Marais, " Did habitable environments once exist in Gusev crater? Astrobiology and the Mars Exploration Rover Spirit", AGU Fall Meeting, Abstract P22B-07, 2006.
6. M. Golombek, L. S. Crumpler, J. A. Grant, R. Greeley, N. A. Cabrol and 12 authors, "Geology of the Gusev cratered plains from the Spirit rover traverse", JGR, **111**, doi: 10.1029/2005JE002503, 2006.
7. J. P., Bibring, Y. Langevin, A. Gendrin, B. Gondet, F. Poulet, M. Berthé, A. Soufflot, R. Arvidson, N. Mangold, J. Mustard, P. Drossart, and the OMEGA team, "Mars surface diversity as revealed by the OMEGA/Mars Express observations", Science **307(5715)**, 1576-1581, 2005.
8. P. R. Christensen, J. L. Bandfield, J. F. Bell III, N. Gorelick, V. E. Hamilton, A. Ivanov, B. M. Jakosky, H. H. Kieffer, M. D. Lane, M. C. Malin, T. McConnochie, A. S. McEwen, H. Y. McSween, Jr., G. L. Mehall, J. E. Moersch, K. H. Nealson, J. W. Rice, Jr., M. I. Richardson, S. W. Ruff, M. D. Smith, T. N. Titus, M. B. Wyatt, "Morphology and composition of the surface of Mars: Mars Odyssey THEMIS results", Science **300(5628)**, 2056-2061, 2003.
9. J. F. Mustard, F. Poulet, A. Gendrin, J. P. Bibring, Y. Langevin, B. Gondet, N. Mangold, G. Bellucci, F. Altieri, "Olivine and pyroxine diversity in the crust of Mars", Science **307**, 1594-1597, 2005.

10. J. D. Farmer, In *Landing Site Catalog*, NASA RP **1238**, 2nd Ed. (Greeley R., and P. L. Thomas Eds), 363-366, 1994.
11. J. D. Farmer, "Mars Exopaleontology". Palaios, **10(3)**, 197-198.
12. J. D. Farmer, "Strategies for the astrobiological exploration of Mars", In: *Concepts and approaches for Mars exploration*, part 1, Lunar and Planetary Institute Contribution No. **1062**, 110-112, 2000.
13. D. J. Des Marais and J. D. Farmer. "The Search for Extinct Life". In: M. Meyer and J. Kerridge, Eds. *An Exobiological Strategy for Mars Exploration*. 21-25, 1995.
14. J. D. Farmer and D. J. Des Marais, "Exploring for a record of ancient martian life", JGR **104 (E11)**, 26,977-26,995, 1999.
15. N. A. Cabrol and E. A. Grin, "Evolution of Lacustrine Environments on Mars (Is Mars Only Hydrologically Dormant?)", Icarus, **149**, 291-328, 2001.
16. N. A. Cabrol and E. A. Grin, "Ancient and recent lakes on Mars", In: *Water and Life on Mars*, Springler-Verlag, 181-205, 2004.
17. R. De Hon, "Classification of Martian lacustrine basins", 22nd Lunar Planet Sci. Conf. XXII, 293-294 (abstract).
18. R. De Hon, "Martian lake basins and lacustrine plains", Earth, Moon, Plan. **56(2)**, 95-122, 1992.
19. R. De Hon, "Sedimentary provinces of Mars", 32nd Lunar Planet. Sci. Conf., **1361** (abstract).
20. M. C. Malin and K. S. Edgett. "Evidence for persistent flow and aqueous sedimentation on early Mars", Science **302 (5652)**, 1931-1934, 2003.
21. J. L. Wood, "Geomorphology and stratigraphic architecture of the Mars NE Holden delta", Proceed. Am. Pet. Geol. (GSA Bull, in press), 2007.
22. S. M. Clifford, "A model for the hydrologic and climatic behavior of water on Mars", JGR **98**, 10973-11016, 1993.
23. R. Zepp T. V. Callahan, and D. J. Erickson III, "Effects of enhanced solar ultraviolet radiation on biogeochemical cycles," Ambio **24(3)**, 181-187, 1995.
24. H. E. Zagarese and C. E. Williamson, "Impact of solar UV radiation on zooplankton and ichthyoplankton", In: De Mora, S. J. et al. (Eds.) *Effects of UV radiation on marine ecosystems*; Cambridge University Press, New York, NY, 279-309, 1999.
25. A. Oren, *Halophilic Microorganisms and their Environments*, Kluwer, 575 pp, 2002.
26. P. Rettberg and L. J. Rothschild, "Ultraviolet radiation in planetary atmospheres and biological implications", In: *Astrobiology: the Quest for the Conditions of Life*, Ed. Horneck, G. & Baumstark-Khan, C., pp. 232–243. Springer, Berlin, 2002.
27. C. S. Cockell, "The origin and emergence of life under impact bombardment", Phil Trans Royal Soc., 1845-1855, 2006.
28. C. E. Williamson, P. J., Neale, G. Grad, H. J., De Lange, B. R. Hargreaves, "Beneficial and detrimental effects of UV on aquatic organisms: implications of spectral variation", Ecol Appl **11**, 1843–1857, 2001.
29. C. E. Williamson, G., Grad, H. J., De Lange, S. Gilroy, D. M. Karapelou, "Temperature-dependent ultraviolet responses in zooplankton: implications of climate change", Limnol Oceanogr. **47**, 1844–1848, 2002.
30. R. W. Sanders, A. L. Macaluso, T. J. Sardina, and D. L. Mitchell, "Photoreactivation in two freshwater ciliates: Differential responses to variations in UV-B flux and temperature", Aquatic Microb Ecol **40**, 283-292, 2005.
31. C. Ponnamperuma, C., and H. P. Klein, "The Coming Search for Life on Mars", Quarterly Review of Biology, **45(3)**, 234-258, 1970.
32. K. Dose, C. Stridde, R. Dillmann, S. Risi and A. Bieger-Dose, "Biochemical constraints for survival under Martian conditions", Adv. Space Res. **15**, 203-210, 1995.
33. M. Allen, C. Miller, C. Webster, and P. Wennbe, *Exploration for Habitability and Life in the Solar System and Beyond: an Earth Analogue*, White paper, 2 pages, 2005.
34. M. D. Wagner, "Tolerance limits of methanogenic life in terrestrial permafrost", DFG Colloquium: *Mars and the Terrestrial Planets*, Berlin, 29-30, 2005.
35. J. F. Kasting, "CO2 condensation and the climate of early Mars", Icarus **94(1)**, 1-13, 1991.

36. M. T. Mellon and B. M. Jakosky, "The distribution and behavior of Martian ground ice during past and present epochs", JGR **100**, 11781, 1995.
37. R. M. Haberle, "Interannual Variability of Global Dust Storms on Mars", Science, **234**, 459-461, 1986.
38. R, M. Haberle, "Early Mars Climate Models", JGR **103**, 28,467-28,479, 1998.
39. F. Forget, and R. T. Pierrehumbert, "Warming early Mars with carbon dioxide clouds that scatter infrared radiation", Science 14**, 278(5341)**, 1273–1276, 1997.
40. B. M. Jakosky, B. M., Haberle, and R. E. Arvidson, "The changing picture of volatiles and climate on Mars", Science **310(5753)**, 1439-1440, 2003.
41. S. W. Squyres and J. F. Kasting, "Early Mars: How warm and how wet?", Science **265**, 744-749, 1994.
42. F. Forget, " Alien weather at the poles of Mars. Science **306(1298)**, 2004.
43. J. I. Sackmann, and A. I. Boothroyd, "Bright young sun consistent with helioseismology and warm temperatures on ancient Earth and Mars", Astrophys. Journal **583(1)**, 1024–1039, 2003.
44. J. Laskar, A. C. M. Correia, M. Gastineau, F. Joutel, B. Levrard and P. Robutel, "Long term evolution and chaotic diffusion of the insolation quantities of Mars", Icarus **170(2)**, 343-364, 2004.
45. D. C. Catling, D. C., and C. Leovy, "Mars atmosphere and volatile history", In: L. McFadden, P. Weissman (eds.) *Encyclopedia of the Solar System*, Academic Press (in press).
46. P. T. Doran, R.A. Wharton Jr., D. Des Marais, and C.P. McKay, "Antarctic paleolake sediments and the search for extinct life on Mars", JGR **103(E12)**, 28481-28493, 1998.
47. K. C. Benison and B. B. Bower, "Acidic saline lake systems give clues about past environments and the search for life on Mars", Icarus **183(1)**, 225-229, 2006.
48. J. W. Rice, "High latitude terrestrial lacustrine and fluvial field analogs for Martian highlands", In: *Workshop on the Martian Highlands and Mojave Desert Analogs*. Paper No. 4010, 2001.
49. C. R. Stoker, D. Barch, J. Farmer, M. Flagg, T. Healy, T. Tengdin, H. Thomas, K. Schwer and D. Stakes, "Exploration of Mono Lake with an ROV: A prototype experiment for the MAPS AUV program", In: *IEEE Symposium on Autonomous Underwater Vehicle Technology*, June 3-6, Monterrey, CA, 1996
50. S. J. Wentworth, and P. A. Morris, "The geology, paleontology, and biology of evaporite and near-evaporite system in both terrestrial and extraterrestrial environments", In: *Topical Session 27*, Geological Society of America, Boston, November 1-10, 2001.
51. A. M. Baldridge, A.M., J.D. Farmer, J.E. Moersch, "Remote sensing of terrestrial analogs for evaporite basins on Mars: Analysis of ground truth", Eos Trans. AGU, **82**, 3, 2001.
52. C. S. Cockell, Osinski, G.R., and P. Lee, "The impact crater as a habitat : Effects of impact-processing of target materials", Astrobiology, **3**, 181-191, 2003.
53. G. K. A. Oswald and G. Robin, "Lakes beneath the Antarctic ice sheet", Nature **245(5423)**, 251-254, 1973.
54. M. J. Siegert, J. A. Dowdeswell, M. R. Gorman, and N. F. McIntyre. "An Inventory of Antarctic sub-glacial lakes". Antarctic Science **8 (31)**, 281-286, 1996.
55. B. Messerli, M. Grosjean, G. Bonani, A. Bürgi, M. A. Geyh, K. Graf, K. Ramseyer, H. Romero, U. Schotterer, H. Schreier, M. and Vuille, "Climate change and dynamics of natural resources in the Altiplano of northern Chile during late glacial and Holocene time. First fynthesis". Mount. Res. Dev. **13(2)**, 117-127, 1993.
56. M. Grosjean, "Mid-Holocene climate in the South-Central Andes: Humid or dry?", Science **292**, 2391-2392, 2001.
57. A. N. Hock, N. A. Cabrol, E. A. Grin, and L. Rothschild, "Ultraviolet radiation and life at high-altitude: Licancabur 2004", NAI 2005 Biennal Meeting, University of Colorado, Boulder, Center for Astrobiology, (abstract # 1043), 2005.
58. A. N. Hock, N. A. Cabrol, E. A. Grin, G. T. Kovacs, R. L. Rothschild, S. E. Parazynski, L. Prufert-Bebout, and the Mars Underwater Science Team, "Mars-relevant conditions at the lakes of Licancabur volcano, Bolivia", 2005 AGU Fall Meeting, San Francisco. (Abstract # P41D-06), 2005.
59. N. A. Cabrol, E. A. Grin, K. T. Kiss, E. Ács, I. Grigorszky, K. Szabò, B. Tóth, D.A. Fike, A. N. Hock, C. Demergasso, L. Escudero, G. Chong, P. Galleguillos, B.H Grigsby, J. Zambrana Román, C. P. McKay, and C.

Tambley, “Signatures of habitats and life in Earth’s high-altitude lakes: Clues to Noachian aqueous environments on Mars”, In: *The Geology of Mars, Chapter 14: Evidence from Earth-Based Analogs*, ed. Mary Chapman, Cambridge University Press, 349-370, 2007.

60. N. Marinovic and A. Lahsen, *Hoja Calama*. Carta Geologica de Chile, 58. SNGM, Santiago.
61. N. A. Cabrol, A. N. Hock, M. Sunagua, and E. A. Grin, “Evolution of aqueous habitat and life in high-altitude lakes during rapid climate change: Astrobiological methods & geo and biosignatures”, *37th LPSC*, (abstract #1016), 2006.
62. F. Sylvestre, M. Servant, S. Servant-Vildary, C. Causse, C. Fournier, “Lake-level chronology on the southern Bolivian Altiplano (18 degrees -23 degrees S) during late-glacial time and the early Holocene”, *Quat. Res.*, **51**, 54-66, 1999.
63. E. Acs, N. A. Cabrol, I. Grigorszky, I. Friedmann, A. Kiss, K. Szabó , and K. T. Kiss, “Similarities and dissimilarities in biodiversity of three high-altitude mountain lakes (Andes, Bolivia)”, In: *6th Hungarian Ecological Congress*, (Dombos M and G. Lakner, Eds.). St. Stephan University, Publishers. Godollo **305**, 2003.
64. K. T. Kiss, E. Acs, G. Boris, N. Cabrol, I. Grigorsky, E. Grin, A. Kiss, K. Szabo, and B. Toth 2004. “Habitats extrêmes pour les communautés de diatomées dans les lacs de haute altitude (Laguna Blanca et lac de cratère du volcan Licancabur, Bolivie)”, *23ème Colloque de l’ADLaF*. Orléans, France, 2004.
65. H. P Häder, D. D. Kumar, R. C. Smith, and R. C. Worrest, “ UV-B Effects on aquatic ecosystems”, J. Photochem. & Photobiol. B: Biology **46**, 53-68, 1998.
66. C. S. Cockell, A. Schuerger, I. Friedmann, D. Billi, C. Panitz, “Effects of a simulated Martian UV flux on the cyanobacterium Chroococcidiopsis sp. 029”, Astrobiology, **5**, 127-140, 2005.
67. C. S. Cockell and J. A. Raven, “ Zones of photosynthetic potential on Mars and the early Earth”, Icarus **169(2)**, 300-310, 2004.
68. F. Garcia-Pichel, “A model of self-shading in planktonic organisms and its implications for the usefulness of ultraviolet sunscreens”, Limnol. Oceanog. **39**, 1704, 1717.
69. D. Karentz and H. J. Spero, “Response of natural Phaeocystis population to ambient fluctuations of UVB radiation caused by antarctic ozone depletion”, J. Plankton Res. **17**, 1771-1789, 1995.
70. F. L. Figueroa, C. Jiménez, L. M. Lubián, O. Montero, M. Lebert, and D. P. Häder, “Effects of high irradiance and temperature on photosynthesis and photoinhibition in Nannochloropsis gaditana Lubián (Eustigmatophyceae)”, J. Plant Physiol. **151**, 6-15, 1997.
71. R. G. Wetzel, P.G. Hatcher, and T. S. Bianchi, “Natural photolysis by ultraviolet irradiance of recalcitrant dissolved organic matter to simple substrates for rapid bacterial metabolism”, Limnol. and Oceanography **40**, 1369-1380, 1995.
72. R. Santas, A. Koussoulaki, D. P. Häder, “In assessing biological UV-B effects, natural fluctuations of solar radiation should be taken into account”, Plant Ecology **128**, 93-97, 1997.
73. R. V. Miller, W. Jeffrey, D. Mitchell, and M. Elasri, “Bacterial responses to Solar Ultraviolet light”, ASM News. **65**, 535-541, 1999.
74. L. J. Rothschild, and C.S. Cockell, “Radiation, microbial evolution and ecology, and its relevance to Mars missions”, Mutation Research/fundamental and Molecular Mechanisms Mutagenesis **(430)2**, 281-291, 1999.
75. H. P. Eugster, and L. A. Hardie, “Saline lakes”, In: Lerman, A. (ed.) *Chemistry, Geology and Physics of Lakes*, Springer-Verlag, New York, 237–293, 1978.
76. F. Risacher and B. Fritz, “Geochemistry of Bolivian salars, Lipez, southern Altiplano: Origin of solutes and brine evolution”, Geochem. Cosmochem. Act. **55(3)**, 687-705, 1991.
77. A. McMinn C. Ashworth, and K. Ryan, “Growth and productivity of Antarctic sea ice algae under PAR and UV irradiances”, Bot. Mar, **42**, 401-407, 1999.