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The search for Life on Mars and in the Solar System - Strategies, Logistics and Infrastructures

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Abstract

The question "Are we alone in the Universe?" is perhaps the most fundamental one that affects mankind. How can we address the search for life in our Solar System? Mars, Enceladus and Europa are the focus of the search for life outside the terrestrial biosphere. While it is more likely to find remnants of life (fossils of extinct life) on Mars because of its past short time window of the surface habitability, it is probably more likely to find traces of extant life on the icy moons and ocean worlds of Jupiter and Saturn. Nevertheless, even on Mars there could still be a chance to find extant life in niches near to the surface or in just discovered subglacial lakes beneath the South Pole ice cap. Here, the different approaches for the detection of traces of life in the form of biosignatures including pre-biotic molecules will be presented. We will outline the required infrastructure for this enterprise and give examples of future mission concepts to investigate the presence of life on other planets and moons. Finally, we will provide suggestions on methods, techniques, operations and strategies for preparation and realization of future life detection missions.

Keywords: life detection; Mars; icy moons, habitability; space missions

Acronyms/Abbreviations

Committee on Space Research (COSPAR), German Aerospace Center (DLR), European Space Agency (ESA), European (-E) and Russian (-R) Exposure Platform on the ISS (EXPOSE), Instituto Nacional de Técnica Aeroespacial (INTA), Infrared Radiation (IR), Japan Aerospace Exploration Agency (JAXA), Jupiter Icy Moon Explorer (JUICE), National Aeronautics and Space Administration (NASA), A Japanese orbital Astrobiology experiment (Tanpopo), Technical Readiness Level (TRL).

1. Introduction

Mars and the icy ocean moons around Jupiter and Saturn (in particular Europa and Enceladus) are prime goals in the astrobiological search for life within the Solar System [1]. The rationale for expecting life on other Solar System bodies is the simultaneous presence of carbon molecules, an energy source, bio-essential elements and liquid water, either during the past or present day, for instance periodically on Mars [2] or continuously on Europa and Enceladus [3]. Some scientists even suggest the presence of constant liquid water below the South Pole Ice cap of Mars [4].

1.1 State of the art

In-situ investigations of Mars by Viking, Pathfinder, Spirit, Opportunity and Curiosity, as well as orbital observations from Mars Odyssey, Mars Express, Mars Reconnaissance Orbiter, have documented a diverse landscape with a variety of geomorphological features, geological structures and mineralogy. To date, the search for life on Mars has concentrated on looking for signatures of past life, i.e. fossil biosignatures and prebiotically-relevant systems, because habitable conditions at the surface of the planet existed early in its history. Nevertheless, life could still exist in subsurface environments protected against harmful radiation, some of which may be connected to the surface environment. If viable organisms could be transported to micro-caves, fissures and cracks in rocks or in the martian regolith, or also into areas characterised by frost driven patterns, like polygons, or water tracks [5] and slope lineae [2], such environments would be of high interest to search for extant life. ExoMars will be accessing the subsurface or near-subsurface areas through drilling (see *e.g.* ExoMars 2020) but here we propose an alternative, low energy cost solutions, to achieve environmental measurements (humidity, temperature, etc.) and investigations of these environments to search for life or remnants of life.

Galileo and Cassini have provided important information regarding the Jupiter and Saturn system and, in particular, the icy moons orbiting these giant gas planets. Specifically, the Jovian moon Europa and the Saturn moon Enceladus show cryo-plate tectonics and cryo-volcanism suggesting an interaction between the surface and postulated subsurface oceans [6,7]. For example, the Cassini spacecraft has observed gigantic jets of cryo-geysers (plumes) consisting of salt, water and gases, such as CO_2, N_2 and methane (CH_4) that could serve as major components to form and sustain microbial life [8,9]. Even organic substances have been detected [10], but it was not possible to determine their origin or possible biogenic relation because of instrumental limitations. Therefore, we suggest following two strategies to investigate the potential presence of life on the icy worlds. One is based on using a probe within a flyby mission to collect material ejected by the plume. The collected material could then be analysed directly (i.e. quasi-*in situ*) by a set of spectroscopic methods (Raman, IR, mass spectroscopy). The second proposed method is a lander mission using an ice mole concept to reach cracks and fissures as well as possible water pockets within the icy crusts. This would search for pre-biotic material or even life, or remnants of life, ejected by the plumes or accumulated in the micro-ice-caves through the jets connected to these fissure caves, cracks and water pockets.

1.2 Exploration strategies

Our exploration strategy focuses on using very specific payloads to address the search for life. On Mars, a soil/rock-endoscope-wheel (SoRo-EW) equipped with multiple sensors and connected to spectroscopic analysers in a rover would be able to analyse fissures, cracks and micro caves near ancient hydrothermal environments, or recent water-driven active surface areas. On Enceladus, a flyby orbiter mission is proposed to be equipped with a payload collecting plume material in a wheel-collector and analysing it by a multi-spectroscope including Raman, IR, fluorescence and mass spectroscopy. In addition, an ice mole for a lander mission to Enceladus or Europa could be equipped with miniaturized Raman and IR-spectroscopes.

For the efficiency to interpret the resulting spectroscopic data of future astrobiology exploration missions to the icy worlds of our Solar System the installation of a unified European and finally world-wide “biosignature data base” is a prerequisite. This means, there is an urgent need to create an international acknowledged and valid reference data base of biosignatures and analogue environments for future space exploration programmes whose objective is the search for extra-terrestrial life. This is still the case for Mars, for which existing databases are incomplete, and especially true for the icy moons within our Solar System with their potential subsurface habitats for which no database exists.

2. *Science Case*

Liquid water, classified as one requirement for habitability, can only exist within the subsurface, a subglacier environment or, protected by a suitable atmosphere, on the surface of planetary bodies. In our Solar System subsurface environments containing liquid water are supposed to be more widespread than surface hydrospheres. For example, there is evidence that below Mars' cryosphere a global aquifer resides [11] and even subglacial lakes [4] are postulated, or that the small icy satellites Europa and Enceladus, harbour liquid oceans or lakes beneath their water-ice crust. These bodies, however, do not lie within the habitable zone, lack a significant magnetic field, and have no atmosphere. Nevertheless, such subsurface aqueous environments could coexist with nutrients and energy which are provided *e.g.* through hydrothermal activity (*e.g.* subsurface hydrothermal fluids or hydrothermal vents) or geochemical reactions (*e.g.* serpentinization, *i.e.* reactions between hot hydrothermal fluids and basaltic rocks) for instance, and therefore could support chemotrophic life [12].

Excluding the possibility of probing the subsurface directly by energy consuming drilling procedures, the ability to detect biosignatures of such a putative biosphere, although limited,, can be improved by invasive endoscopic or, in the case of the icy moons, by melting methods [13,14]. Nevertheless, in the case of Enceladus, relatively complex organic compounds were detected by the Cassini mission in the South Polar Plume [3,8,9]. For Europa, it has been suggested that the remote detection of biosignatures might be possible through spectroscopy of ocean material that reaches the surface through fractures or via brine diapirs [15]. However, the high radiation environment induced by Jupiter would rapidly degrade any organic biosignature at the surface. On the other hand, possible inclusion of biosignatures within the icy crust could be detected by a penetrator or drill. Any detection of biosignatures within the icy crust would indicate life below, in the ocean or even in water pockets or channels in the ice. *In situ* analysis of hydrocarbons in eruption plumes emanating from the surface of active satellites (e.g., Enceladus's South Pole terrain; [3,8,9]) could be performed during close spacecraft encounters to determine the ratio of non-methane hydrocarbons to methane (which is extremely low for biological sources and higher for non-biological sources [16]). These analyses further gave reason to suggest that several methanogenic subsurface ecosystems on Earth could serve as analogues for possible habitats on Enceladus and Europa. Extraterrestrial habitats which might harbour life forms or contain traces of past life (as can be supposed for the planet Mars), or niches (e.g. cracks and fissures in the outermost crust layers of the icy moons) which store possible ingredients or deposits of the geysers and fountains of the icy moons, should be detectable in future space exploration missions.

In this particular context, it is essential to determine and prepare the most suitable set of instruments for detecting life as well as a database collecting all relevant information regarding the biosignatures that would be produced by life and that could be detected, *e.g.* generic organic biomarkers, chirality, molecular patterns, isotopic ratios, as well as morphological structures, *e.g.* nanovesicles and bio-minerals. This is especially important, if we take into account evolutionary processes on planets such as (i) Mars, where surface liquid water and a significant part of the atmosphere basically disappeared early in the evolution of the planet, or (ii) in the liquid-water oceans beneath the ice crusts of outer planet satellites, where liquid water charged with unknown organic material is ejected in large plumes into space [3,17]. In the case of Mars, the environment has been particularly altered by radiation and lack of water would have had a severe effect on early life forms and their organic remains. Irradiation and vacuum would also affect the stability of organics or even possibly ejected life forms in space eventually released by the venting plumes discovered on Enceladus [3] and possibly on Europa [18]. The best target for classification of stable biosignatures that could serve as usable fingerprints are those that are relatively resistant to high radiation and diagenesis, *i.e.* fossilised structures or robust organic components or their degraded refractive derivatives. These stability investigations can be undertaken, for example, by using planetary simulation facilities and exposure platforms on the ISS, such as EXPOSE (Europe, ESA), Tanpopo (Japan, JAXA), and the future CubeSat generation. These facilities are available in Low Earth Orbit (LEO) and tests for improving operations of life detection instruments directly in an open space environment can easily be realized with very small time delay before sending them further into the deep Solar System. The observations made in LEO result finally in a space-proved biosignature data base.

3. **Material and methods**

A multispectral analysis (Raman-, IR- or mass-spectroscopy) and imaging systems, and possibly other analytical tools like a "lab on a chip" device (immune-assay for potential biomolecules) will be required in order to perform biochemical analysis in micro-niches, melted ice, subglacial water reservoirs or in collected ice cores on planetary surfaces including analyses of ejected material during plume sampling. Moreover, the majority of such techniques has been previously selected or deployed on planetary missions and so are available at TRL 8-9 (see Curiosity or ExoMars 2020 for microscopes, GC-MS, or the Cassini mission for the ion and neutral mass spectrometer; [19]). For the characterization of micro-niches, in particular on Mars, an environmental analyser measuring radiation, humidity, temperature, pressure and, if possible, gas composition, is needed. Some of these sensors were used in previous missions to Mars (see Curiosity) but some still need to be developed or have a low TRL level (TRL 5 to TRL 8-9). Furthermore, as noted above, it is necessary to create a biosignature database for life detection instruments, such as Raman- and IR-spectroscopy.

4. Results and Discussion

This work is a study on what is necessary for the future exploration missions to investigate the solar system and its potential habitable worlds on the absence or existence of extant or extinct life. According to the scientific requirements, a brief list of potential probes and hardware as well as the necessary methods to explore Mars, Europa and Enceladus and to detect possible traces of extinct or extant life will be presented here as results, before presenting in detail, which instruments could be an excellent support for future life-detection missions and on which field sites on Mars and the icy moons the operations have to be done.

3.1 Needed operations and instruments on Mars

- Precision landing of a spacecraft at a location where traces of past hydrothermal activity or still recent water-driven processes on the surface of Mars are suspected to exist based on earlier remote-sensing measurements;
- Development of an endoscopic / invasive system to investigate potential habitats at the subsurface or near surface, such as fissures and micro-caves in rocks, in the regolith, as well as permafrost patterns like polygons and in surficial water tracks.

3.2 Operations and instruments on icy moons

- Precision flybys of Enceladus at a location where earlier remote-sensing measurements have previously observed plumes;
- Precision landing of spacecraft at locations on Europa or Enceladus near ice cracks and fissures in proximity to plumes (on Enceladus and if they exist, on Europa);
- A flyby orbiter (Plume catcher) has to be equipped by a payload capable of sampling and making "semi *in situ*" measurements of the trapped plume material.
- A lander would need to be equipped with an ice mole containing a life detection payload (Raman, IR-Spectroscope, Mass-Spectroscope or a "Lab on a chip" technology) for direct "*in situ*" measurements.

3.3 Mars - Locating areas with water driven surface changes or former hydrothermal activity

Water driven geomorphological changes have been observed on the present Martian surface. In some areas, high-resolution orbital images, such as those obtained with the Mars Reconnaissance Orbiter [20] have already identified slope lineae indicating recent water driven surface activity. Craters on Mars with indications of subsurface water ice, as well as polygon rich areas [2,5] are of interest because of the potential for past impact-driven hydrothermal activity within the craters [21].

3.4 Europa / Enceladus – Locating areas with access to subsurface water

On Europa it is a very challenging enterprise to find adequate landing sites for depositing a landing device with an ice mole [22] to investigate directly the subsurface icy crust and its fissures and cracks or potential water pockets below the surface. Images obtained from the Galileo mission will be complemented by those to be taken by the future missions JUICE and Europa Clipper that will enable detection of potentially suitable landing sites. Continued mapping of Enceladus by the Cassini mission provided more data about potential landing sites [8] although a better resolution is needed for determining the most suitable sites. This can be done by a mission combining mapping of plumes and tiger stripes with sampling of the plumes in orbit for analysis of their particulate content.

3.5 Endoscopic analysis of Martian niches.

Environmental conditions within fissures, cracks and micro-caves (Fig. 1) are different to those outside [23]. These niches are protected against intense radiation fluxes and generally have much higher levels of humidity as well as constant temperatures without too much fluctuation between night and day.

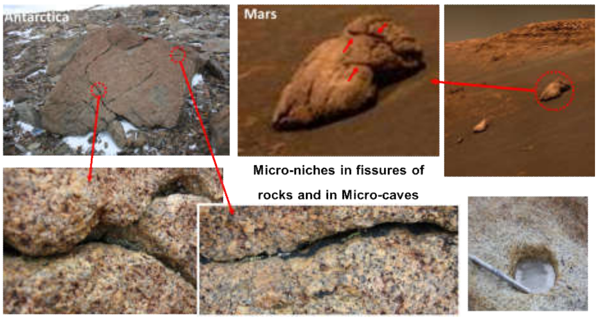

Fig.1. Potential micro-habitats, fissures/cracks in rocks

Such protected areas, if situated near slope lineae where water activity would be higher, might also be habitable environments for extant life on Mars or could harbour remnants of life (traces within the mineral structure or micro-fossils) which are protected against the harsh environmental conditions.

The same is valid for the subsurface of polygons rich areas (Fig. 2), where fissures and cracks in the Martian regolith can be accessible with suitable techniques. In the past, such micro-niches were ignored and, thus, no instrument analysis of them was made to determine their degree of habitability or whether they contained traces of life.

Fig. 2. Polygon rich areas in Antarctica and on Mars. Fissures and cracks within the regolith should be investigated because these structures indicate water driven permafrost activity, which also can increase or decrease the humidity of the soil.

We propose a technical solution to investigate these Martian locations of interest, *i.e.* a rover equipped with a robotic arm with a wheel or hand like extremity containing various flexible probes and analytical instruments for endoscopic operations and microscopic analysis. It will thus be possible to make *in situ* investigations of fissures and cracks within rocks or the regolith by extruding the glass fibre sensor into the micro-niche and to make environmental measurements (temperature, radiation, humidity), as well as spectroscopic analyses (Raman, Mid-IR, NIR-IR, fluorescence), and observations (microscope) (Fig. 3).

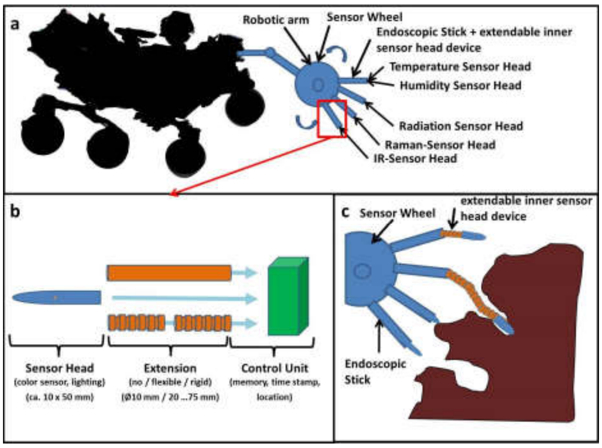

Fig 3. (a) A rover equipped with a robotic arm and sensor wheel. (b) Endoscopic probe with an extendable protected glass fiber sensor head device. (c) Operation of the payload instruments within micro-caves of a rock.

3.6 *Plume catcher in orbit of Enceladus*

The plumes observed by Cassini on the southern hemisphere of Saturn's moon, Enceladus, are of high interest because they demonstrate exchange between a water-rich interior and the exterior of the moon through cryovolcanism. Landing on such potentially habitable worlds is challenging because of their rough icy surfaces and because of the need to avoid contamination by terrestrial material (see COSPAR Planetary Protection guidelines). Thus, a plume catcher mission could be an elegant solution avoiding such kind of contamination or the uncertainties of safe landing. The ejected material from Enceladus' ocean can be collected by a multiple flyby orbiter in a resonant orbit with the aim of sampling as close to the surface as possible in order to collect the larger particulate sizes. Such a concept is presented in Fig. 4.

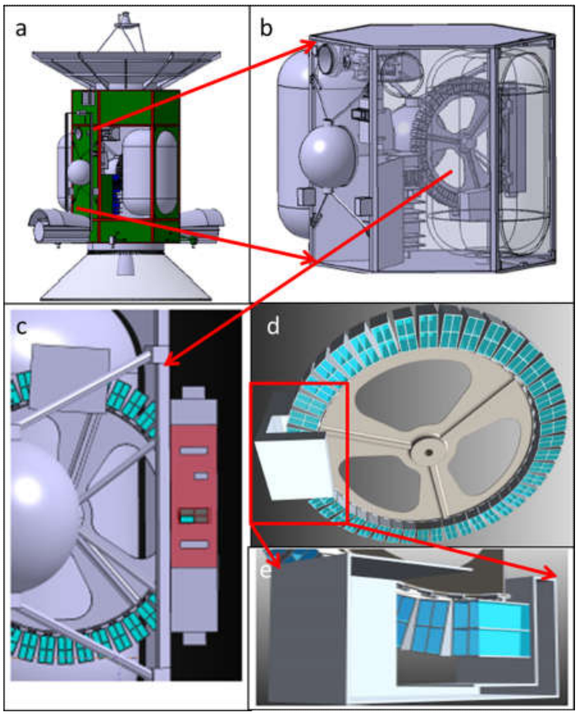

Fig. 4. Plume Catcher details: (a) Orbiter with payload arrangement. (b) Segment with Aerogel-sample-collector-wheel. (c) Detail of sample collector and collector window. (d) Detail of sample wheel and analytical box (red box). (e) Detail of the analyzer box: samples are passing through the spectrometer laser within the box (student study at FH Aachen, 2016).

A wheel equipped with a large number of aerogel-traps will be maneuvered through the plumes with changes of the aero-gel boxes for sampling for each flyby. The trapped material within the aerogel, including their trajectories and with potentially defragmented components (because of the velocities), will be analysed by the analytical box containing IR, Raman spectrometers, microscope, etc. inside the orbiter. This could be a useful "semi *in-situ*" measurement that avoids potentially contaminating landing operations. Such a mission would significantly advance our understanding of the habitability of the Solar System by studying the habitability of Enceladus and the possible existence of biosignatures, such as cells nanostructures or biomolecules in ejected plume material.

3.7 IceMole operations on Europa or Enceladus

Taking into account suitable planetary protection measures, the *in situ* investigation of the icy surfaces of Europa or Enceladus near cracks or plumes (the latter on Enceladus) in search for near-surface ice caves or even pockets of trapped ocean water, a lander or rover operating an ice mole is needed. We propose to develop such an instrument equipped with still well-defined biosignature detection payloads, including a microscope and Raman- and IR-spectroscope. Studies available in icy moon analogue field sites in Antarctica or Alpine glaciers [13,14] have shown that such kind of operations can also avoid contamination and take into account the planetary protection guidelines. Further studies and improvements of such kinds of system are needed to adapt the payload to this kind of probe. We suggest doing this by using heritage from the instruments developed for the ExoMars 2020 and Mars 2020 missions.

The ice mole equipped with a microscope and Raman and IR-spectroscopy-payload will need to investigate by melting the ice sampled within the probe or in the ice channels produced by the mole. Salts, water ice and also inclusions of ejected back fall from plumes can be analysed. Potentially ejected bio-relevant molecules might also be detected in such an environment (see Fig. 5).

3.8 Biosignature database

The creation of a biosignature data base based on combined microscope and spectrometer analyses and by taking into account all field, laboratory and space data (see Fig. 6) will be of invaluable use to future space exploration missions to Mars and the ice moons (e.g. ExoMars 2020, JUICE and beyond). In the same way a data base of rocks and minerals, such as the International Space Analogue Rockstore (www.isar.cnrs-orleans.fr), is essential for surface missions to rocky bodies. Such a database should take into account details regarding environmental conditions, measurement regimes, obtained spectra and observations etc. in the form of diagrams, tables and images (meta data: see Fig. 6). This will realize a systematic investigation and support future space missions with the primary goal to find life in the solar system.

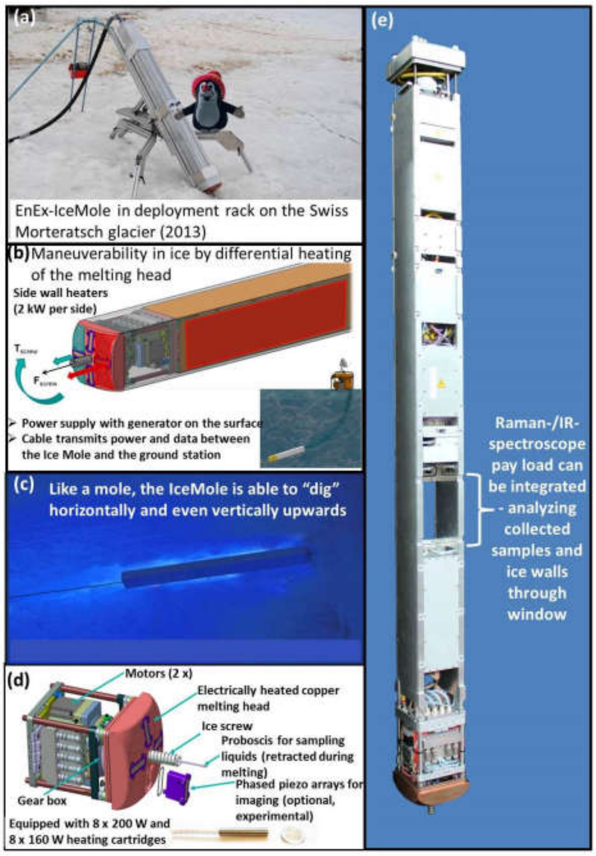

Fig 5. (a) Operating IceMole on the Swiss Morteratsch Glacier. (b) Melting by the probe in diverse directions within glacier ice. (c) Melting principle for changing directions within the ice. (d) Detail of the melting head. (e) Overview on ice mole with space for spectroscopic payload devices like Raman and IR-spectroscopes.

3.9 Planetary Analogue field research and planetary simulations

Instruments need to be tested in planetary analogue field sites, such as on and in glaciers in the Arctic or Antarctic (Mars and icy moon relevant) or even in the deep sea and in subglacial lakes like Lake Vostoc beneath the 4 km ice shield (Mars subglacial lake and icy moon relevant), as well as in planetary simulation facilities, such as those existing in different planetary simulation teams (e.g. DLR Berlin, DLR Cologne, Open University Milton Keynes, FH Aachen, INTA Madrid). Access to relevant planetary field sites could be achieved through different expedition operating institutions such as the BGR (Federal Institute for Geosciences and Natural Resources, Germany), the AWI (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Germany), University of

Viterbo, University Tor Vergata, Italy or through the Russian Antarctic Expedition and NRC KI-PNPI (with relevance to Mars and icy moons) and GEOMAR (deep sea, icy moon relevance).

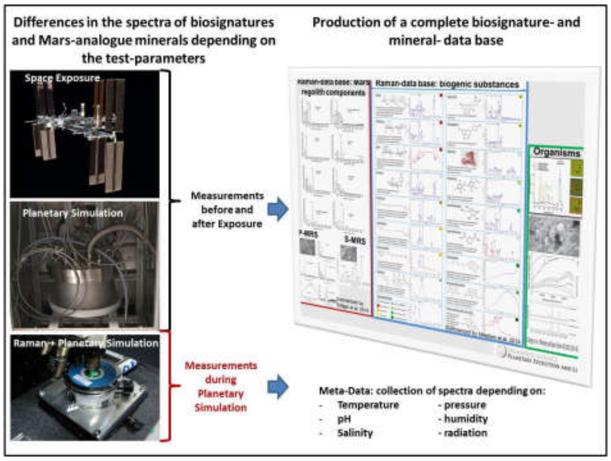

Fig 6. Schematic overview on a concept of a data base collecting microscopic observations and spectroscopic results of biomolecules (biosignatures) and planetary analogue minerals in reference to planetary environmental conditions (meta data). Data are collected through planetary simulations in specific facilities on the ground and in space (*e.g.* exposure platforms on satellites and the ISS).

5. Conclusions, Strategic Considerations and Fit to the Exploration Programme

- Mars is still the primary target for the search for life beyond Earth with the future ESA-Roscosmos ExoMars 2020 and NASA Mars2020 missions.
- NASA launched the "new frontiers call" by mentioning as one of the important upcoming missions to investigate the icy ocean worlds in our solar system.
- Moreover ESA is very interested in this topic and announced the high relevance of the environment for searching for life.
- The exploration of potentially habitable worlds with the primary goal of searching for life in the solar system is also in full agreement with AstRoMap, the European Astrobiology Roadmap which was supported by the FP7 framework of the European Union [1].

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