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Icy ocean worlds - astrobiology research in Germany

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Icy bodies with subsurface oceans are a prime target for astrobiology investigations, with an increasing number of scientists participating in the planning, development, and realization of space missions to these worlds. Within Germany, the Ocean Worlds and Icy Moons working group of the German Astrobiology Society provides an invaluable platform for scientists and engineers from universities and other organizations with a passion for icy ocean worlds to share knowledge and start collaborations. We here present an overview about astrobiology research activities related to icy ocean worlds conducted either in Germany or in strong collaboration with scientists in Germany. With recent developments, Germany offers itself as a partner to contribute to icy ocean world missions.

KEYWORDS

subsurface oceans, space missions, habitability, icy moons, solar system exploration, Deutsche Astrobiologische Gesellschaft (DAbG), ocean worlds, German Aerospace Center (DLR)

1 Introduction: past and future exploration of icy ocean worlds

The German space science community and particularly the German Astrobiology Society (Deutsche Astrobiologische Gesellschaft; DAbG) has a deep scientific interest in space exploration. In 2023, the German Government published its space program strategy (BMWK, 2023) by explicitly mentioning the value of space research, technology developments and exploration for the society in general. The strategic view formulated in this document is to support synergy of different competences, expertise and resources to allow on the one hand space research and space exploration leading to international space missions and on the other hand the use of space related technology via technology transfer also in society relevant topics such as climate and environmental protection as well as discovering and using sustainable resources. We will here start with an overview on the general scientific interest and space missions as well as showing the German participation and/or interest in the present and future exploration missions particularly to the icy moons of Jupiter and Saturn. We further describe the technology developments and scientific strategy including planetary analog field research, laboratory experiments, numerical simulation investigations and even space experiments in Earth's orbit. At the end, the context of German space exploration activities to the German political strategy in reference to the exploration of the icy ocean worlds will be highlighted. Technology developed for future missions will be able to be transferred to disciplines related to polar-, ocean-, deep sea- and climate change-research to address fundamental scientific questions related to our home planet Earth.

The first enlightening visits of the giant planets and their moons by spacecraft (Pioneer 10/11 in 1973–1990, Voyager 1/2 in 1979–1989) led to an increasing interest to further investigate those planetary systems as key elements for understanding the Solar System as a whole. Measurements by Galileo in the Jovian (in 1995–2003) and Cassini-Huygens in the Saturnian system (in 2004–2017) revealed the existence of subsurface oceans under the ice shells of, for example, Jupiter's moons Europa and Ganymede as well as Saturn's moon Enceladus (e.g., Nimmo and Pappalardo, 2016). The Cassini-Huygens mission discovered a plume emanating from the south pole of Saturn's moon Enceladus (Porco et al., 2006). This plume emerges from cracks in the ice shell and consequent studies revealed its composition to be mainly water vapor and ice particles originating from a subsurface ocean, with a salinity slightly lower than Earth's oceans (Postberg et al., 2009). Finding analogue sites for extraterrestrial icy vents and plumes here on Earth is challenging due to the triple point conditions present inside the icy vents of Enceladus (Schmidt et al., 2008), derived from the drastic difference in pressure between the interior and exterior of the moon. Analogies to the environment near terrestrial, submarine hydrothermal vents, a potential site for the origin of life on the early Earth were striking and the icy moons became promising candidates for habitable worlds and prime targets for astrobiology investigations.

Alike Enceladus, Europa harbors a global subsurface liquid water ocean that is in contact with a rocky core (e.g., Kivelson et al., 2000). Ganymede's subsurface ocean is probably sandwiched between two layers of ice (Vance et al., 2014; Saur et al., 2015), making material exchange between the liquid ocean and the core less likely. The same applies to Jupiter's moon Callisto (Hartkorn and Saur, 2017). Saturn's moon Titan has a liquid, likely stratified (Idini and Nimmo, 2024), water ocean underneath its organic-covered ice shell (Goossens et al., 2024). Neptune's moon Triton is another, yet widely unexplored, ocean world and a compelling destination for future space mission (Frazier et al., 2020; Hansen et al., 2021).

Our current understanding of the oceans of the icy moons and the fascinating discoveries by spacecraft in the recent past (e.g., Enceladus's plume) will be discussed in some detail in the following chapters. However, many questions could not be answered so far, which led to the development of numerous mission proposals to further investigate the oceans of the icy moons (e.g., Howell and Pappalardo, 2020; Barnes et al., 2021; Mousis et al., 2022).

After the end of the Cassini-Huygens mission in 2017, the flybys of Ganymede and Europa of the Juno spacecraft in 2022 and 2023, as part of its extended mission, are the only occasions of a spacecraft visiting ocean moons in the 2020s. This lack is partially mitigated by the spectacular observations of the James Webb Space Telescope of the moons Europa (Villanueva et al., 2023a; Trumbo and Brown, 2023) and Enceladus (Villanueva et al., 2023b). Although these observations yield better data than any other telescopic observation, the spatial resolution of the James Webb Space Telescope, even for the Jovian moons, is still four to five orders of magnitude below what can be achieved with a close flyby.

However, starting in 2030, ocean moons will become more important targets of both NASA's and ESA's space programs. In 2030 and 2031 respectively, two flagship missions - Europa Clipper (NASA) and the JUpiter Icy Moons Explorer (JUICE; ESA) - will arrive in the Jovian System to observe Europa, Ganymede, and Callisto as their prime targets. Both missions Europa Clipper (Howell and Pappalardo, 2020) and JUICE (Grasset et al., 2013) have significant German contributions, advancing the research in this field at German research facilities (Figure 1).

Europa Clipper is scheduled for launch in October 2024 and has the overarching goal to constrain the habitability of Europa's subsurface ocean with about 50 close flybys within the 4 years of its prime mission while in orbit around Jupiter (Vance et al., 2023). The locations of these flybys are all fixed in form of a flyby sequence, but a potential extended mission could allow for targeted flybys over regions that have turned out to be of specific interest for Europa's habitability.

JUICE (launched 14 April 2023) has a somewhat broader scope. During the first part of the mission the spacecraft will stay in a Jovian orbit with two flybys of Europa and tens of flybys of each Callisto and Ganymede. In December 2034, ESA plans to go into Ganymede orbit for a detailed investigation of the largest moon in the Solar System. After up to 1 year in Ganymede orbit a crash onto the moon's surface will then end the JUICE mission.

Titan will be visited by the spectacular Dragonfly mission in the mid 2030s. Currently, the launch of this NASA New Frontier class mission is foreseen in 2028 with an arrival in 2034. The spacecraft is a rotorcraft lander weighing about 450 kg, that - driven by radioisotope thermoelectric generators (RTG) – will sample the moon's atmosphere and surface composition at different landing sites to assess Titan's potentially prebiotic organic chemistry. The combination of low gravity and dense atmosphere allow the drone-like lander to investigate various sites and altitudes during its

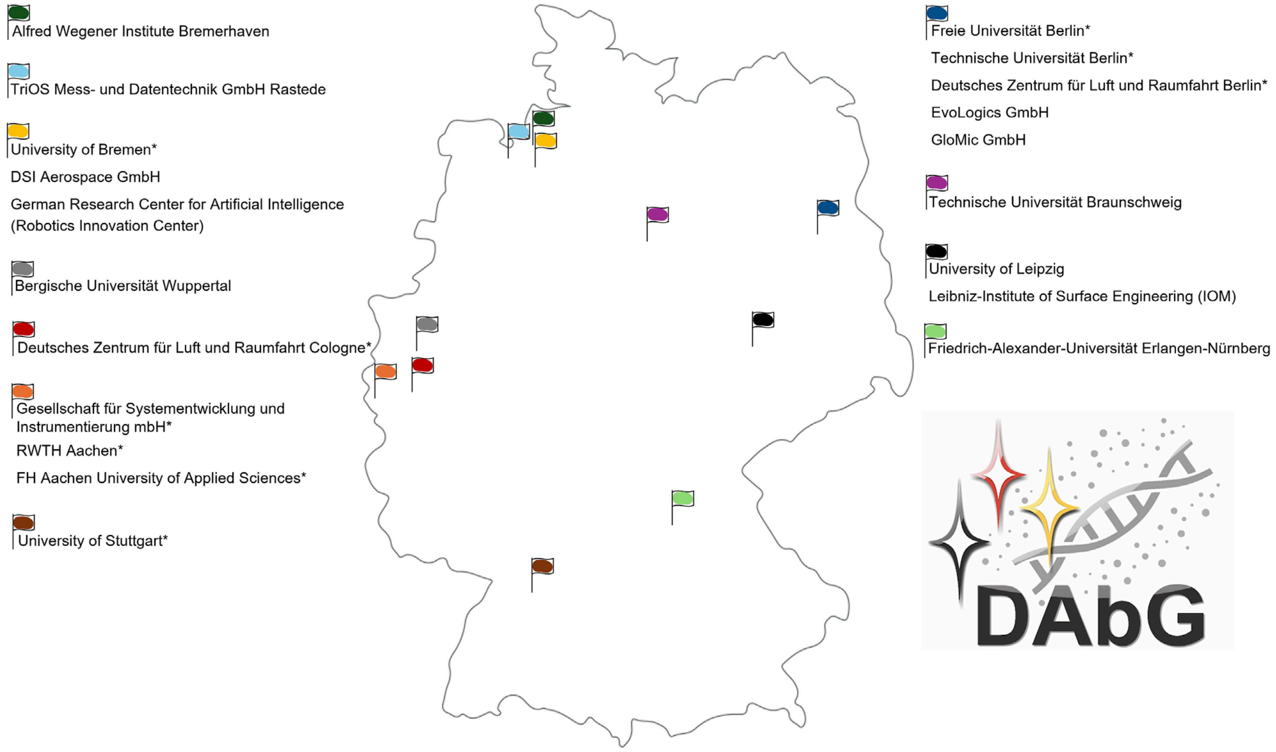

FIGURE 1
Locations of research groups in Germany with ongoing astrobiology research and collaborations related to icy ocean worlds. Research themes are summarized in Table 1. The German Astrobiology Society (Deutsche Astrobiologische Gesellschaft; DAbG) logo is shown on the bottom right. Institutions where DAbG members are currently located are marked with an asterisk.

3.5-year prime mission by flying distances of up to 100 km while climbing to altitudes of up to several kilometers (Barnes et al., 2023).

Beyond these approved missions, there are long term strategies of space agencies, most notably NASA, ESA and the China National Space Administration (CNSA), to investigate the giant planets and their icy moons. On the U.S. side, this is outlined in the Planetary Science and Astrobiology Decadal Survey 2023–2032 (National Academies of Sciences, Engineering, and Medicine, 2023) as well as in reports written by the Outer Planets Assessment Group (OPAG), established in 2004 (Beauchamp et al., 2009). The NASA competitive programs, Discovery and New Frontiers (NF), include the possibility to propose missions to icy ocean worlds. New Horizons (NF1) performed a flyby of dwarf planet Pluto. JUNO (NF2) is in orbit around Jupiter. The aforementioned Dragonfly has been selected as the fourth New Frontiers mission (Barnes et al., 2021). All those missions have relevance to icy ocean worlds exploration.

The Planetary Science and Astrobiology Decadal Survey 2023–2032 foresees up to three major missions in the near future. Firstly, the next New Frontiers mission (NF5) lists Enceladus as a potential target. Moreover, the next two flagship missions should be a Uranus orbiter and an Enceladus lander. Following the Orbilander concept (MacKenzie et al., 2021), the latter would be a mission that looks for life on Saturn's active ocean moon with a planned arrival in the early 2050s. Already sometime earlier the Uranus orbiter would arrive and the exploration of the Uranian moons, some of which are potential ocean worlds, will certainly be part of the mission goals. ESA considers contributing to this Uranus mission in a similar fashion as it has been successfully implemented for the joint Cassini-Huygens mission where ESA provided the Huygens probe that landed on Titan in 2005 (Lebreton et al., 2005).

At ESA, the long-term priorities in space sciences are described in the Voyage 2050 report (Tacconi et al., 2021), which identifies a mission to "moons of the giant planets" as the fourth large mission (L4) in the science program (following JUICE, Athena and LISA) as well as a so-called "Inspirator Mission", aiming for sample return from one of the icy moons (Rapley et al., 2022). With a launch date in the early 2040s, Enceladus is the most likely target for this L4 mission, as recently announced by ESA (Martins et al., 2024).

China is also planning to investigate the Jovian system with the Tianwen-4 mission (also referred to as Gan De, after a Chinese astronomer of the 4th century). As a possible launch date, 2029 has been announced (Lei et al., 2021). It is worth noting that currently there are no concrete plans to land on a Jovian satellite, and even less so to physically penetrate the ice crust. Although many ideas were addressed and the concept of a Europa lander mission was studied (Hand et al., 2022), this concept was not rated as a high-priority mission. Nevertheless, some astrobiological questions will only be answered by lander missions or melting/drilling probes. For example, limiting elements of life, such as iron, may be remotely detectable on the surface in flybys, but *in situ* analyses with a lander provides spatially better resolved and much more detailed and sensitive measurements. Other space agencies, e.g., Russia, Japan, or India, currently do not have plans for ocean moon exploration.

2 Activities in Germany - general overview

In the last decades there has been increasing activities in Germany to investigate icy ocean moons to realize future space missions to these worlds. DAbG Members (Figure 1; Table 1) are heavily involved in both missions to the Jovian system JUICE and Europa Clipper. Involvements include participations in various instrument teams, such as the Particle Environment Package-Neutral Ion Mass Spectrometer (PEP-NIM; Barabash et al., 2013), the JANUS multispectral camera (Della Corte et al., 2014) and the Ganymede Laser Altimeter GALA (Enya et al., 2022) for JUICE as well as the SUrface Dust Analyzer (SUDA) for Europa Clipper (Kempf et al., 2024).

2.1 Explorer Initiatives at the German Aerospace Center

Since 2012, the Explorer Initiatives at the German Aerospace Center (DLR) have been supporting universities, research institutions and commercial companies from all over Germany in specially created project lines. The aim of these project lines is to develop innovative technologies to enable future space missions to astrobiologically interesting celestial bodies in our Solar System (Funke and Horneck, 2018). Each project line is based on a central, albeit currently fictitious, mission scenario:

In the EnEx initiative (“EnEx - Enceladus Explorer”; Kowalski et al., 2016), technologies are being developed for taking a H_2O sample from a vent on Saturn’s moon Enceladus. The sample can be taken without completely melting through the moon’s outer ice shield, which is several kilometers thick.

Jupiter’s moon Europa is also receiving special attention, here in the project lines “EurEx - Europa Explorer”, and “TRIPLE - Technologies for Rapid Ice Penetration and subglacial Lake Exploration”:

In EurEx, an autonomous underwater vehicle (AUV) is being developed to explore the seabed of the deep global ocean on Europa completely independently (Hildebrandt et al., 2022). The challenges are enormous, particularly in terms of the AI required for this task, and successful implementation is not expected before the middle of this century.

While EurEx has a long-term focus, the TRIPLE project line has a medium-term objective (Waldmann and Funke, 2020): The plan is to develop an AUV that is even more miniaturized than the EurEx AUV. This nanoAUV is designed as a payload for a melting probe, which is designed to penetrate the ice sheet of Europa into the global ocean below (see also Section 3). The melting probe will be anchored in the ice at the point of entry into the ocean and will serve as a base to ensure communication to the surface and from there to Earth. The nanoAUV payload will then be deployed into the ocean as a mobile unit and will be used for exploration within a radius of approximately 100 m around the base. The nanoAUV will also be used to take samples from the bottom side of the ice and bring these samples to the melting probe for further analysis within the AstroBioLab, which is another payload of the probe. It is planned to demonstrate the technological readiness of the complete TRIPLE system consisting of three major parts: The melting probe TRIPLE-IceCraft (Figure 2), the mobile exploration unit TRIPLE-nanoAUV and the TRIPLE-AstroBioLab.

These three main components are designed to work together as consecutive stages of the TRIPLE comprehensive exploration strategy. With its state-of-the-art instrumentation, the AstroBioLab serves as the portable analytical field hub for analyzing samples previously collected under the ice and transported to the surface.

2.2 The AstroBioLab

The AstroBioLab analytical pipeline consists of four modalities: (a) fluorescence spectroscopy, (b) fluorescence microscopy, (c) DNA sequencing and (d) mass spectrometry interconnected by a sophisticated microfluidics system.

Fluorescence spectroscopy (a), especially when coupled with Chromophoric Dissolved Organic Matter (CDOM) analysis principles, emerges as a powerful tool in astrobiology, particularly for scrutinizing extraterrestrial environments or seeking signs of life (Barker et al., 2009; Smith et al., 2018). Unique combinations of fluorescence intensity, peak shapes and exact positions produce characteristic spectral patterns that shed light on CDOM’s composition, concentration and even its origin. Extensive testing in Arctic ice, Antarctic lakes and deep-sea hydrothermal vents has demonstrated the effectiveness of fluorescence spectroscopy in studying complex aquatic ecosystems and in detecting organic compounds under conditions analogous to those found on other planets (Storrie-Lombardi and Sattler, 2009). For instance, fluorescence analysis of water samples from Antarctic lakes revealed significant photosynthetic and biodegradation activities, (De Laurentiis et al., 2013). To meet the future mission requirements regarding miniaturization, energy consumption, robustness and easy handling, a semi-automatic fluorimeter module has been designed and manufactured by the FH Aachen University of Applied Sciences and GSI mbH (Figure 3).

Fluorescence microscopy (b) will enable direct visualization of particulate matter, ranging from submicron to submillimeter size (e.g., Mulyukin et al., 2014). Studies in Earth’s polyextreme environments like the Atacama Desert have shown the potential of this technology in visualizing and identifying microbial life forms in various microhabitats (Wierzchos et al., 2018). In future field missions, miniaturized automated fluorescence microscopy systems such as OpenFlexure (which can be 3D printed), can be deployed for *in situ* exploration, thereby diminishing the necessity for sample return. Furthermore, employing advanced fluorescence techniques, such as lifetime imaging microscopy, may provide additional insights into the microenvironment of (extra) terrestrial water samples (Nadeau et al., 2016).

DNA sequencing (c) is yet another valuable tool for exploring icy ocean habitats (e.g., Carré et al., 2024). Field tests in locations like Antarctica’s subglacial lakes and Canadian high arctic permafrost ice wedge have validated the feasibility of

TABLE 1 Institutes in Germany (see Figure 1) and their icy ocean world research themes.

Institute	Research themes	Web links (on 01 August 2024)
Alfred Wegener Institute Bremerhaven	Arctic research, nanoAUV sample return system, Life detection	https://www.awi.de/en/focus/mosaic-expedition.html
Bergische Universität Wuppertal	TRIPLE Forefield Reconnaissance System (FRS)	https://www.uni-wuppertal.de/en
DSI Aerospace GmbH	nanoAUV avionics	https://www.dsi.space/
Deutsches Zentrum für Luft und Raumfahrt (DLR), Institute of Aerospace Medicine, Cologne	Laboratory experiments, Space simulation facilities, Life detection efforts, Participation in ESA's space experiment IceCold (PI Elke Rabbow)	https://www.dlr.de/en/dlr/locations-and-offices/cologne https://www.dlr.de/me/en/desktopdefault.aspx/tabid-7207/
Deutsches Zentrum für Luft und Raumfahrt (DLR), Space Operations and Astronaut Training, Microgravity User Support Center (MUSC), Cologne	Operations of experiments during field studies, in Low Earth Orbit (ISS), on the Moon (LUNA connected with the DLR Human Exploration Control Centre), in the Solar System and on ground; hardware tests, evaluation of operation procedures; integrated astrobiology and planetary science topics, leading ESA's next space experiment on board the ISS: BioSigN (PI Jean-Pierre de Vera)	https://www.dlr.de/en/rb/about-us/departments/microgravity-user-support-center-musc
Deutsches Zentrum für Luft und Raumfahrt (DLR, Institute of Planetary Research, Berlin	Laboratory and numerical simulations of subsurface processes, Environmental chambers and measurements in the Planetary Spectroscopy Laboratory (PSL) as well as the astrobiological Planetary Analog Simulation Laboratories (PASLAB) and Raman Mineral and Biosignature detection (RMBD) laboratory, Instrument participation in ESA's JUICE mission (Laser Altimeter GALA: PI Hauke Hussmann; Camera JANUS: Co-PI Ganna Portyankina); BioSigN Co-PI Mickael Baqué	https://www.dlr.de/en/pf
EvoLogics GmbH	TRIPLE nanoAUV development	https://evologics.de/
FH Aachen University of Applied Sciences	Exploration of icy vent systems, *In-situ* decontamination procedures, Life detection systems, Melting probe technology	https://www.fh-aachen.de/en/
Freie Universität Berlin	Laboratory and numerical investigations of subsurface oceans and plumes, Analysis of spacecraft data, Research on natural analogues from polar locations	https://www.geo.fu-berlin.de/en/geol/fachrichtungen/planet/index.html https://www.elsaesserlab.space
Friedrich-Alexander-Universität Erlangen-Nürnberg	TRIPLE FRS	https://www.fau.eu
German Research Center for Artificial Intelligence	Under ice navigation, TRIPLE Launch and Recovery System (LRS)	https://www.dfki.de/en/web
Gesellschaft für Systementwicklung und Instrumentierung mbH	TRIPLE IceCraft melting probe development	https://www.gsi-systems.de/
GloMic GmbH	TRIPLE FRS	https://www.labo.de/firma/glomic-gmbh.htm
Leibniz-Institute of Surface Engineering (IOM)	Development of chemical sensors for space applications	https://www.iom-leipzig.de/en
RWTH Aachen University	TRIPLE IceCraft melting probe development, TRIPLE Guidance, Navigation and Control (GNC) of the nanoAUV, TRIPLE scientific payload AstroBioLab, Ice Data Hub	https://www.rwth-aachen.de/go/id/a/?lidx=1
TriOS Mess- und Datentechnik GmbH Rastede	TRIPLE *in situ* sensor technology as nanoAUV payload	https://www.trios.de/en/
Technische Universität Berlin	Investigation of the habitability of subsurface environments including oceans, Instrumentation to detect life	https://www.tu.berlin/en

(Continued on the following page)

TABLE 1 (*Continued*) Institutes in Germany (see Figure 1) and their icy ocean world research themes.

Institute	Research themes	Web links
Technische Universität Braunschweig	JUICE magnetometer, TRIPLE LRS	https://www.tu-braunschweig.de/en
University of Bremen	Investigation of subsurface oceans, TRIPLE nanoAUV development	https://www.uni-bremen.de/en/
University of Leipzig	Development of chemical sensors for space applications	https://www.chemie.uni-leipzig.de/en/institute-of-chemical-technology
University of Stuttgart	Calibration of hypervelocity impact detectors, such as Cassini's Cosmic Dust Analyzer: PI Ralf Srama	https://www.irs.uni-stuttgart.de/en/

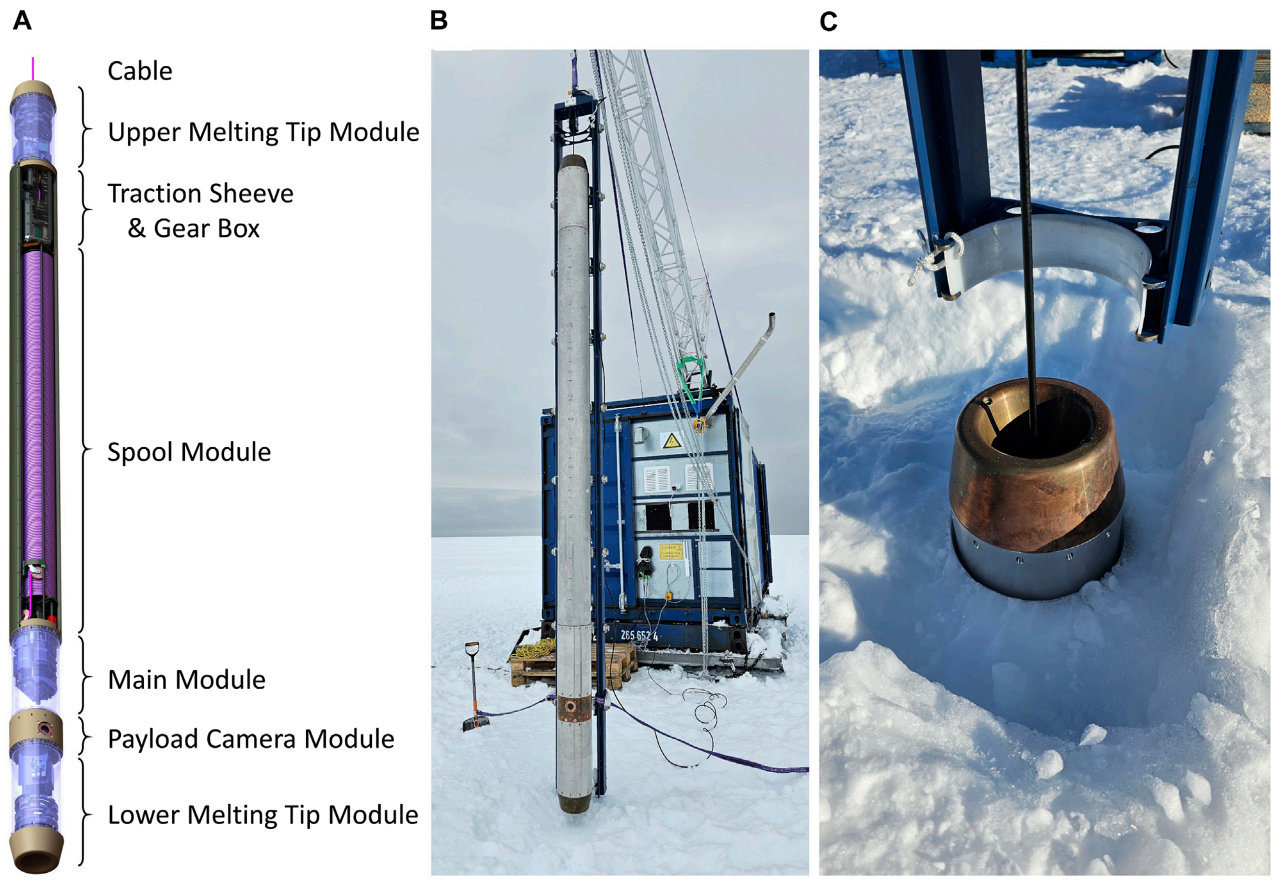

FIGURE 2
TRIPLE-IceCraft melting probe. **(A)** Technical drawing showing the different parts of the melting probe, which is 4 m in length and 20 cm in diameter. **(B)** and **(C)** Photographs of the melting probe during a test campaign on the Ekström Ice Shelf, Antarctica in 2023/2024. **(C)** shows the Upper Melting Tip Module and the cable after the probe melted through the ice.

using portable sequencers in remote and harsh environments (Goordial et al., 2017). Nanopore sequencers, exemplified by the Oxford Nanopore MinION, are available as extremely compact devices for environmental water sampling (Li et al., 2023). However, further progress must be made in automatization of real-time DNA sequencing where a critical step remains in the preparation of a DNA library, which currently needs to be performed manually.

The mass spectrometry unit (d) will provide crucial information of elemental and molecular composition of the sample (O'Donnell et al., 2016). Criteria related to compactness, energy efficiency and robustness define the range of the available options. Currently we consider the portable field mass spectrometer EcoSys-P (ESS Ltd., Ireland) to be a promising system.

Obvious challenges to address include extremely low temperatures, broad magnitudes of pressures, limited available

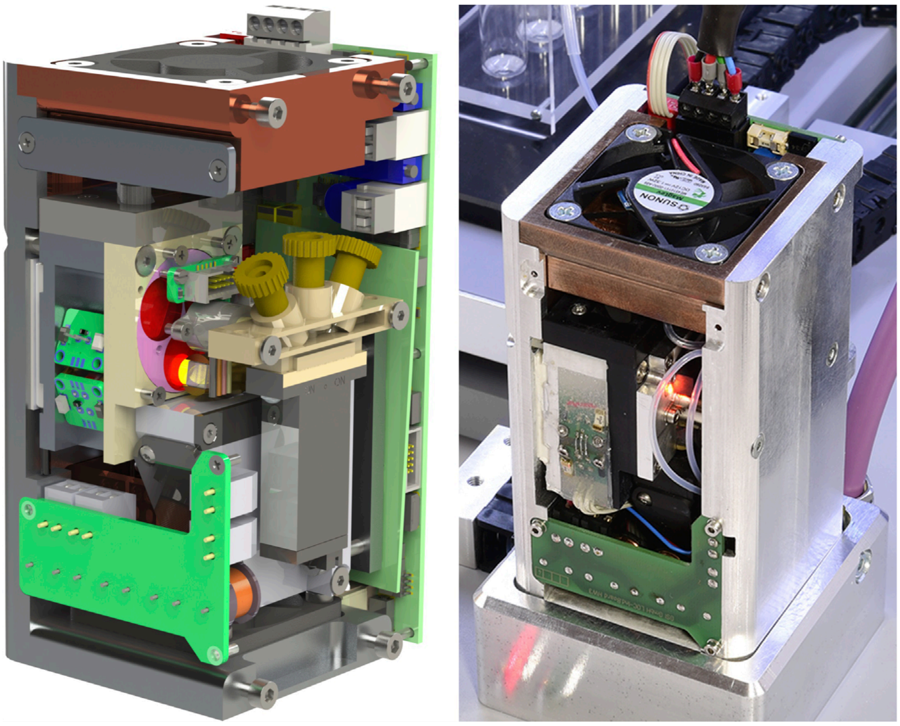

FIGURE 3
Computer Aided Design (CAD; left) and photograph (right) of a miniaturized UV-fluorescence spectrometer.

power, as well as limitations in space and weight. All this demands comprehensive interdisciplinary collaboration, coupled with advanced engineering and AI solutions.

The scientific payload is planned to be tested by the end of this decade in a major terrestrial analog scenario field campaign at the Dome C region in Antarctica: There, the IceCraft (Figure 2) has to melt through ~3.3 km of ice, avoiding any possible obstacles within its vertical trajectory by a specially designed forefield reconnaissance system (implemented into the melting head), and to finally get access to a subglacial lake that has been hermetically sealed from the environment for about 1 million years.

2.3 Beyond the Explorer Initiatives

In addition to these specific technological developments, laboratory setups and sophisticated computer simulations are being designed in Germany to help understand processes on icy ocean worlds and inform instruments on board space missions (Section 4). Other projects in Germany include, for example, at DLR and the Berlin universities, research on organics, biosignature detection and extremophiles (Sections 5, 6). Instruments on board space missions are calibrated in laboratory experiments at, for example,, Freie Universität Berlin and University of Stuttgart.

Another Recent development is the formation of the international team "Bridging the Gap: From Terrestrial to Icy Moons Cryospheres" sponsored by the International Space Science Institute (ISSI) in Bern. The team is led by researchers from German institutions and investigates active processes on icy moons with the aim of bridging the temporal and spatial scales between terrestrial and extraterrestrial cryospheres (Kowalski et al., 2024).

3 Technology and sensor developments

Accessing ocean worlds is not trivial but crucial for *in situ* astrobiological investigations. The water reservoirs of the currently known ocean worlds like Europa or Enceladus are situated below thick icy crusts. In fact, a recent study suggests that Europa's ice shell may still be growing (Shibley and Goodman, 2024).

While Ground-Penetrating-Radar is useful to better understand the icy shell and underlying oceans of Solar System bodies (e.g., Heggy et al., 2017), yet nobody drilled or melted through an icy moon's shell to gather *in situ* information from the ocean water. Technology to penetrate the ice is, hence, a key technology for future missions. Thermal melting seems to be a promising technology to achieve this task due to its mechanical simplicity and robustness (Dachwald et al., 2023). Also, thermal melting probes can be operated autonomously, and the removed ice is transported as meltwater to the back of the thermal drill. In contrast, mechanical drilling requires less energy (Rinaldi et al., 1990), but it faces the issue that cut ice chips must be mechanically transported to the back of a mechanical drill. Whatever penetration method would be used, considerable infrastructure on the surface and high energy supply will be required (Dachwald et al., 2020).

The discovery of a plume at the south pole of Enceladus that is sourced from a liquid water ocean in the early 2000s

(Hansen et al., 2006; Porco et al., 2006) inspired the development of space mission concepts that include thermal melting probes (Konstantinidis et al., 2015) and the development of new types of melting probes (Dachwald et al., 2020). Activities in Germany are mainly organized within the Explorer Initiatives led by the DLR (Section 2.1) and include the EnEx-IceMole concept that is maneuverable due to its ice screw and differential heating (Dachwald et al., 2014; Kowalski et al., 2016; Baader et al., 2024), tiny laboratory scale probes (Baader et al., 2016), and small helper probes for localization (Weinstock et al., 2021). Another probe is the large TRIPLE-IceCraft (Heinen et al., 2021; see Section 2.1) that will allow to carry small autonomous underwater vehicles (TRIPLE-nanoAUV) as a payload (Waldmann and Funke, 2020). To describe the trajectories of such probes, modeling efforts are ongoing (Schüller and Kowalski, 2019; Boxberg et al., 2023). A major success was the use of the EnEx-IceMole to retrieve clean samples from a water reservoir that feeds the Blood Falls at Taylor Glacier in Antarctica in November 2014 (Kowalski et al., 2016; Lyons et al., 2019; Mikucki et al., 2023). However, the probe only melted through about 17 m of ice to reach the subglacial water. Although the thicknesses of the ice layers on top of the icy ocean worlds are not yet well constrained, it is very likely that melting probes must overcome ice layers of several kilometers. Therefore, current developments like the TRIPLE-IceCraft are focusing on increasing the range and the level of autonomy of such melting probes and establishing a standardized interface to enable an easy integration of arbitrary scientific payloads or sensors. A first polar test of the TRIPLE-IceCraft was performed on the shelf-ice close to the German Neumayer Station III in Antarctica in 2023. One of the main goals of the current TRIPLE project (Figure 2) is to develop a melting probe that is able to penetrate ice with a thickness of 3–4 km, which is the maximum thickness available in analogue missions on Earth, at Dome C in Antarctica. Within the same project, the nanoAUV is developed for autonomous investigation of subglacial water reservoirs (Waldmann and Funke, 2020). Tests in partly frozen lakes and below shelf-ice are planned.

Recent improvements in onboard computing capacities and power storage used within AUVs is allowing far more detailed studies of environmental conditions and flora and fauna distributions within the oceans of Earth and beneath the permanent ice caps of both poles. Societal interest in global environmental changes is driving some of these developments (Benway et al., 2019).

There is also industrial interest in studying remote, high pressure and variable temperature locations such as deep-sea polymetallic nodule fields and hydrothermal provinces. The application of these sensor systems into high pressure platforms (both automated and tethered) for use in the underice environments is ongoing. Permanent underice monitoring systems such as the F/Photometric Robotic Atmospheric Monitor (FRAM) observatory network combines traditional "Conductivity, Temperature and Depth" sensors, cameras and direct sampling with these new systems to inform on life below the ice – from the microscopic bacterial life to megafauna – as well as to monitor the ongoing effects of climate change in these underice environments.

Promising techniques for *in situ* analysis of the water ice and accompanying compounds include spectroscopic techniques, such as Laser Induced Breakdown Spectroscopy (LIBS) and Raman spectroscopy. Both methods rely on the use of a laser and detect the light of a laser-induced micro plasma for elemental analysis (LIBS) or inelastically backscattered laser light for information about molecules and lattices (Raman). They are thus greatly complementary in giving information about the elemental and molecular compositions of targeted samples. Both methods have the advantage of requiring only optical access to the target of interest with rapid data acquisition and are developed at DLR with a focus on extraterrestrial applications including the analysis of ices (e.g., Pavlov et al., 2011; Schröder et al., 2013; Böttger et al., 2017; Hagelschuer et al., 2022). Salts as well as other inorganic compounds, minerals, but also organics and complex biomolecules can be detected and identified, even after space exposure (Baqué et al., 2022). The instruments could serve as payload for robots investigating the surface of an icy moon or be integrated into systems exploring the subsurface. For example, the Raman spectrometer RAX that was developed for the small Martian Moons eXploration (MMX) rover weighs only 1.5 kg in a volume of about 10 dm^3 (Hagelschuer et al., 2022) and LIBS instruments of similar weight are currently under development (Rapin et al., 2023).

4 Analogues, experimental and numerical simulations in the field, laboratory, and space

4.1 Field analogues

Cassini's measurements revealed geochemical evidence for hydrothermal vents at Enceladus's ocean floor (Hsu et al., 2015; Waite et al., 2017). Terrestrial analogues sites for extraterrestrial hydrothermal systems include deep sea vents around mid-ocean ridges (e.g., Lost City in the Atlantic Ocean; Kelley et al., 2005), arcs (e.g., Tonga-Kermadec and Le Havre-Lau back arc system; Smith and Price, 2006), and hot spots in volcanic active areas (e.g., Iceland).

The icy shells of several icy satellites, such as Europa, Enceladus and Ganymede are heavily affected by brittle and ductile deformation (e.g., Collins et al., 2010). The analysis of the resulting structural patterns is essential for understanding the driving forces, such as tidally-induced stresses (Tufts et al., 1991; Hoppa et al., 2000). Terrestrial analogues for tectonic deformation of ice volumes support the study of icy satellites and include mountain glaciers, ice caps, and marine ice shelves (e.g., Blankenship and Morse, 2004). Of particular interest are faults and fractures as pathways for ascending fluids which could deliver biosignatures from liquid water reservoirs within the icy shells to the surface to make these signatures available for spacecraft analysis.

The surfaces of icy ocean worlds are exposed to high doses of radiation (Cassidy et al., 2021). The epitome of this is the tidally locked moon Europa, where the leading and trailing hemispheres of the moon present stark contrast due to the differences in surface irradiation. Terrestrial analogues to icy moon's surfaces include the Greenland Ice Sheet, maritime and continental Antarctica (e.g., McMurdo Ice Shelf, Deception island and the South Pole) and altitude glaciers found in several mountain ranges (e.g., Southern Ice Field in Patagonia and Andean or Himalayan glaciers).

The interaction between ice and the waterbed can be studied through terrestrial analogue sites. Subglacial lakes such as Lake

Untersee (Eastern Antarctica) present anoxic, methane rich, stratified waters. Similar lakes, such as Lake Vida (McMurdo Dry Valleys) or Lake Vostok (East Antarctic ice sheet) are also considered important analogues. Lastly, Gypsum Hill Springs in Axel Heiberg Island (Canadian Arctic) is adjacent to highly saline ice, rich in perennial saline springs (Heldmann et al., 2005), and is relevant for studying both Enceladus and Europa.

Field tests are not only valuable for testing drilling and melting probes, such as the TRIPLE-IceCraft (see Sections 2.1, 3), but also for studying the compositions, including organics and microbes, of sites analogous to icy ocean worlds. The Planetary Sciences & Remote Sensing group at Freie Universität Berlin recently conducted icy moon analogue research in coastal Antarctica, with a field campaign at the beginning of 2024 (Hortal Sánchez et al., 2024) carried out in collaboration with the Centro de Astrobiología in Spain and the Instituto Antártico Uruguayo. The goal was to retrieve icy samples in King George Island, in the South Shetlands islands in the Antarctica peninsula. Samples were collected in the Southwestern region of Collins Glacier (a.k.a Bellingshausen Glacier), at four sampling points: by the seaside, at the dome, by the land front and in cryoconite pockets. Cryoconite pockets are of special interest due to their high organic content. They usually form during summer due to the lower albedo of the accumulated dark dust (i.e., soot, ash and rock particles), and the resulting higher temperature that melts the glacier ice directly under it. Alpine and McMurdo Dry Valley glaciers with cryoconite surfaces and holes have proven to be unique niches for psychrophiles (Porazinska et al., 2004; Margesin et al., 2012). Deposition of micrometeorites on the surface of icy moons may create similar conditions for putative life-forms ejected from the subsurface oceans of these moons.

At the sampling site by the seaside, deposition of ocean-borne aerosols is expected. The action of wind on the sea around polar regions on Earth creates sub-micron aerosols: ice particles that are organic-rich and salt-poor (Burrows et al., 2014). These organic-laden ice particles are similar in composition to the organic rich Type II ice grains found in Enceladus plume (Postberg et al., 2018). The deposition of these ice particles on the glacier's surface and subsequent sampling presents an excellent analogue for the study of ice grains from icy ocean worlds.

Sampling carried out at the dome of the glacier as well as by the land front could present interesting cases for organic-poor ices and organic-rich ices, respectively, the latter having a bigger organic input from non-microbial species (e.g., algae). This expected difference in concentration of the target analyte allows further assessment on the limitations and capabilities of spaceborne instruments on board future space missions to icy ocean moons.

The collected samples include both deep ice cores (Figure 4) and surface ice. They will be analyzed with a range of analytical techniques to evaluate the organic content and presence of biosignatures that could be detected with spaceborne instrumentation on board missions to icy moons (e.g., Klenner et al., 2019). A detailed comparison of the data obtained by the different analytical techniques will provide analogue data for the detections of biosignatures by combining several instruments onboard spacecraft.

FIGURE 4
Ice core collected at the dome of Collins glacier by the Planetary Sciences & Remote Sensing group at Freie Universität Berlin at the beginning of 2024.

4.2 Experimental studies

Laboratory-based simulations complement our understanding of icy ocean worlds, their interaction with different radiation fields and allow us to examine specific chemical reaction pathways in much more detail. Some experimental setups are based on an ultra-high vacuum (UHV) chamber that is equipped with a cryostat and linked to radiation sources that provide X-rays, UV photons, or particle radiation. Ice analog samples are created via background condensation of gas-phase molecules on suitable substrates. For example, one such facility is operated at Freie Universität Berlin, where various ice mixtures on top of organic layers are irradiated using either an electron gun, a solar simulator, or both simultaneously. Detailed analysis of the samples is performed using Fourier-transform infrared (FT-IR) transmission spectroscopy and mass spectrometry, which are available both during the irradiation process and the warming-up process.

Another setup, newly built at the Planetary Spectroscopy Laboratory at DLR Berlin, aims at performing bi-directional reflectance measurements under cryogenic conditions to support current and upcoming missions to the outer Solar System, including ESA's JUICE and NASA's Lucy. The setup allows for measurements from UV to far infrared for up to four samples at temperatures lower than −150°C under vacuum down to 10^{-6} hPa (Helbert et al., 2023).

A setup (PI Nozair Khawaja) is being designed that can simulate the conditions in the only known extraterrestrial hydrothermal vent system, i.e., Enceladus seafloor (Figure 5). A detailed hydrothermal experimental plan is made to process several species in this reactor to investigate the effects of hydrothermal processing of compounds before incorporation in ice grains (Khawaja et al., 2024a). DAbG members at US institutions are involved in experimental studies that address the formation of these ice grains (Klenner et al., 2024a) as well as fractionation processes occurring upon eruption of an ocean world plume (Fifer et al., 2024).

The analysis of ice grains in space can be achieved by impact ionization mass spectrometers, such as SUDA on board Europa Clipper (Kempf et al., 2024). However, a detailed analysis of ice

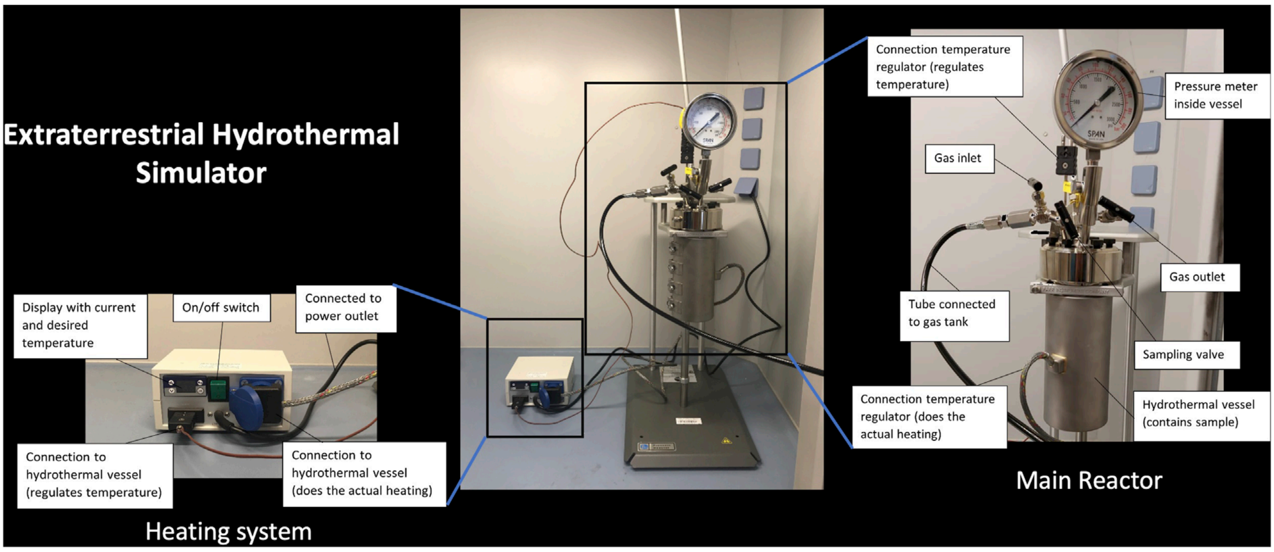

FIGURE 5
Experimental hydrothermal reactor used to simulate the conditions in Enceladus's interior. More information about this setup can be found in Khawaja et al. (2024a)

grain mass spectra requires laser-based analogue experiments conducted at Freie Universität Berlin (Klenner et al., 2019; 2022; Sanderink et al., 2023). This approach has successfully been used to analyze ice grain mass spectra recorded by Cassini (e.g., Postberg et al., 2018; Postberg et al., 2023) and predict mass spectra of ice grains containing molecules essential for the emergence of water- and carbon-based life, such as amino acids (Klenner et al., 2020a). Mass spectral data from impact ionization instruments can also be simulated using dust accelerators in a laboratory environment or quantum chemistry techniques in computer simulations (O'Sullivan et al., 2024).

However, the duration of particle exposure to the space environment before being analyzed can have an influence on their composition and on the preservation and detectability of complex organic molecules as potential traces of life. Laboratory-based simulations of certain space factors are necessary but generally not enough to fully recreate a complex space environment, especially in terms of radiation. Thus, several exposure experiments involving space platforms have been conducted by space agencies since humanity's presence in Low Earth Orbit (LEO) and beyond (Horneck et al., 2010). Among the latest ones, ESA's EXPOSE platform allowed a long-term exposure (12–18 months) in LEO of biological and chemical samples outside the International Space Station (ISS). It completed its third and final mission called EXPOSE-R2 in 2016 (Rabbow et al., 2017). New active and passive exposure experiments in LEO are currently being developed and prepared for flight by ESA and partners: the new payload EXPO on the Bartholomeo platform will include several experiments dedicated in part to the exposure of ice particles and their components: BioSigN (BioSignatures and habitable Niches), IceCold, OREOcube (ORganics Exposure in Orbit cube) and ExoCube (Exposure of organics/organisms cube). On these platforms, *in situ* analytical methods (including spectroscopy) are crucial tools for understanding photochemical and radiation-biological processes for studying organics and potential biosignatures. Simulating icy moon conditions through space experiments presents a challenge, particularly in maintaining low temperatures throughout the space exposure phase. New concepts for low-temperature platforms that enable irradiation and exposure of samples to space conditions exist (Cottin et al., 2022) but face implementation challenges.

4.3 Numerical simulations

Another important aspect in assessing the habitability of icy ocean worlds is to gain further understanding of the subsurface environment on a large scale. The cryo-subsurface environment includes the uppermost ice crust, the ocean as well as high-pressure ice layers. Whether an ocean or high-pressure ice layers are likely to occur depends on the individual icy moon (see review in Soderlund et al., 2020). Numerical models predicting the interior structure (e.g., Sohl et al., 2002) are based on observational constraints (e.g., the bodies mass, the moment of inertia factor or the tidal love number) and high-pressure experiments to investigate the material properties at high pressures and temperatures. The presence of liquids in these layers and the exchange of heat and material between them to address the overall habitability is subject to ongoing studies.

The uppermost ice crust may contain salt-rich liquids (brine) in the form of, for example, small subsurface lakes (e.g., Schmidt et al., 2011), cracks (e.g., Rudolph et al., 2022) or interstitial water at grain boundaries (e.g., Wolfenbarger et al., 2022). Salt is an essential ingredient in these cryo-environments as it efficiently decreases the melting temperature and thus prevents liquids from freezing in these otherwise extremely cold conditions. Liquid inclusions may originate from the ocean beneath the ice crust (e.g., Soderlund et al., 2020).

Recent modeling attempts address the uptake of salt-enriched liquids at the ice-ocean interface by investigating the physics of a mushy layer between the (mainly) solid ice crust and the ocean (Buffo et al., 2020; Buffo et al., 2021). A connected and emerging field of research is the interplay of the dynamics of the meso-scale mushy layer and the large-scale ice crust. Coupled models, developed by DLR scientists, are able to tell whether liquids trapped at the ice-ocean interface can move within the ice crust and remain liquid over longer periods of time (Myrs to Gyrs; Rückriemen-Bez et al., 2023). Other ways to create liquids are local melting of the ice crust due to heat sources such as tidal heating in the case of Europa (Sotin et al., 2009) and Enceladus (Spencer and Nimmo, 2013) or heating by impacts (Cox and Bauer, 2015). In both cases, large-scale models of the ice shell - being developed now - can investigate how the associated heat anomalies and liquid fractions are evolving, which ultimately provides an estimate of the lifecycle of habitable niches in the ice shell.

The ocean is of particular interest when the ocean floor is expected to be in direct contact with rocks (see Sections 4.1, 5). The suspected aqueous alteration of silicates is thought to be responsible for most of the ocean's salinity and organic molecules (Zolotov and Shock, 2001; Zolotov and Kargel, 2009). Fluid motions in the ocean influence the degree of mixing of these salty and organic compounds, and thus the distribution of chemical and thermal gradients. Numerical studies of ocean dynamics cover topics such as global circulation (e.g., Soderlund, 2019; Terra-Nova et al., 2023) and ocean tides (e.g., Matsuyama et al., 2018; Rovira-Navarro et al., 2019).

Especially for larger icy moons such as Ganymede, Callisto or Titan, high-pressure ice layers may occur above the rocky core of the moons effectively shielding any potential ocean from being in direct contact with rocks (Journaux et al., 2020). In these scenarios it is not immediately clear if the ocean can be continuously fueled with salts and organics, which is crucial for creating a habitable environment. A primary interest is thus studying the transport of heat and material across the high-pressure ice layers. Recent models have investigated whether (and at which rate) liquids emerging at the interface between the high-pressure ice and the rocky core are released into the overlying ocean (Choblet et al., 2017; Kalousová and Sotin, 2018; Lebec et al., 2024). Phenomena like magmatic volcanism originating from the rocky core and its effect on the ocean as well as the high-pressure ice layers have only recently come into focus (Bland and Elder, 2022; Kervazo et al., 2022).

Currently, in Germany, individual modeling efforts focus mostly on Europa and Enceladus. These efforts are being undertaken at the Freie Universität Berlin (e.g., Matteoni et al., 2023; Schmidt et al., 2024), University of Münster (e.g., Wong et al., 2022), University of Braunschweig (e.g., Gundlach et al., 2018), and at the DLR in Berlin (e.g., Plesa et al., 2024) in collaboration with RWTH Aachen (Rückriemen-Bez et al., 2022) and with the University of Münster (Holm et al., 2024). Future research needs to combine different modeling strategies to tackle overarching research topics that may be addressed in large collaborative projects. A crucial part of future planetary ocean models should be the influence of boundaries (ice shell at the top, rocky core/high-pressure ice at the bottom) on the ocean and *vice versa*.

5 Organics and detection of biosignatures

Besides the presence of liquid water, chemical disequilibria, available energy and organic molecules are important conditions and ingredients of life as we know it. Water is an excellent medium to initiate and facilitate biochemical reactions as well as nutrient transport, important for originating and sustaining life. Therefore, the discovery of subsurface liquid water oceans on icy moons triggered the search for organics and biosignatures in recent decades. DAbG members are involved in these efforts through various international projects and play a significant role in developing a systematic way to life detection by combining laboratory and field work with Low Earth Orbit (LEO) experiments (de Vera, 2019; de Vera et al., 2019; Baqué et al., 2022).

Organic and inorganic material can be leached from a rocky core into the subsurface ocean through water-mineral interactions at the seafloor. On Enceladus, such interactions may even take place throughout the whole rocky interior because of the relatively high porosity of the core (Kisvárdai et al., 2023). Further heat and chemical diversity could be provided through serpentinization reactions at the seafloor (e.g., Farkas-Takács et al., 2022).

Active cryovolcanism on Enceladus (Porco et al., 2006), and potentially Europa (e.g., Sparks et al., 2017; Bradák et al., 2023), provide a means of making material from the subsurface water ocean accessible for *in situ* analyses by spacecraft. On Titan, organic surface material may be delivered to the subsurface water ocean through impact cratering (Neish et al., 2024).

With the instruments already sent to icy moons (e.g., Srama et al., 2004), a large variety of organic compounds could be found in Enceladus's ocean by the analysis of mass spectra of emitted ice grains (Postberg et al., 2018; Khawaja et al., 2019). Some of these organics could potentially act as amino acid precursors. Cassini's data recently revealed more organics emerging from the subsurface ocean of Enceladus. These organics suggest an alternative pathway for organic synthesis that could lead to the formation of more complex organics, such as Polycyclic Aromatic Hydrocarbons (PAHSs) (Khawaja et al., 2024b). Because of these discoveries, many laboratory efforts are ongoing to better understand the processing and detectability of organics, including potential biosignatures (Malaterre et al., 2023), on icy ocean worlds (e.g., Klenner et al., 2020a; Klenner et al., 2020b; Napoleoni et al., 2023a; Napoleoni et al., 2023b; Dannenmann et al., 2023; Khawaja et al., 2023). The results of these experiments show that many organics and biosignatures, including biotic fatty acid abundance patterns or DNA molecules, will be identifiable with future spaceborne instruments, such as SUDA (Kempf et al., 2024) or the High Ice Flux Instrument (Mousis et al., 2022), thereby advancing the search for life in the Solar System. Moreover, methods are being developed to combine data from different analytical techniques in a complementary way to elucidate the composition of unknown organic species emerging from extraterrestrial oceans (Khawaja et al., 2022). Such laboratory investigations are primordial to guide future space missions and make recommendations for the detection of organic molecules or even life. These recommendations are particularly relevant to Europa Clipper (Pappalardo et al., 2024) or potential future Enceladus missions (Cable et al., 2021; Mousis et al., 2022).

In addition to terrestrial laboratory calibrations, experiments conducted on the International Space Station (ISS) involve organic molecules that are exposed to cosmic radiation. Several DAbG members are actively planning these experiments to support the exploration of Enceladus, Europa, Mars and beyond (e.g., Elsaesser et al., 2023).

6 Extremophile research

Icy ocean worlds present a potential abode for habitability, but their environments are challenging for the origin and persistence of life. Jupiter's icy moons, such as Europa and Ganymede but also Saturn's satellite Enceladus are subject to huge amounts of radiation on their surface, which could alter potential biomolecules that originate from their interiors. Not much is known about the environment within the subsurfaces of icy moons, but sub-zero temperatures, high pressure, low light levels, and probably high salt concentration beneath the ice crusts could be inferred (e.g., Marusiak et al., 2021). The thriving microbial life discovered in some of the most extreme environments on Earth serves as a potential analogue for habitats on these moons, particularly deep-sea hydrothermal vents (McCliment et al., 2006) and zones of accumulated sea water beneath and within Antarctic ice (Garrison, 1991), suggesting that life may also be able to exist under similar conditions in the subsurface oceans of some of the icy moons (Russel et al., 2017; Martin and McMinn, 2018; Weber et al., 2023). Hypothetical models of organisms that might live under the ice crusts of the icy moons have been advanced (e.g., Schulze-Makuch and Irwin, 2002). However, a special emphasis has been the study of polyextremophiles, which are adapted to thrive under multiple environmental stresses and serve as useful models for studying the limits of life. They provide valuable insights into the potential habitability of extreme environments, on both Earth and beyond (Thombre et al., 2020). These environments are also of special interest to the study of the origin of life. Can life originate under a hydrothermal vent scenario as has been suggested by multiple authors for Earth (e.g., Martin et al., 2008) or are land areas required for an origin of life as suggested by other authors (e.g., Schulze-Makuch and Irwin, 2018; Damer and Deamer, 2020; Toner and Catling, 2020; Haas et al., 2024)? Extremophile research is a rapidly growing field involving DAbG members from diverse disciplines, including microbiology, biochemistry, geology, and planetary sciences (e.g., Klenner et al., 2024b).

Recent advancements in technology have significantly improved our ability to study extremophiles (e.g., Caro-Astorga et al., 2024). Innovations in deep-sea robotics, high-pressure cultivation techniques, and advanced/new molecular biology tools are changing how we approach this research. These technologies not only allow for a deeper understanding of extremophiles but also equip us with tools for the search for potential life in space, especially on icy ocean moons.

The study of extremophiles is essential in astrobiology. By studying and comprehending how life adapts and thrives in Earth's most extreme conditions, we can better speculate about life's potential beyond Earth. This knowledge influences the design of future space missions, including the development of instruments capable of detecting life (e.g., Klenner et al., 2024b) and understanding its biochemistry.

7 Cleanliness and decontamination controls

In exploring icy ocean moons, we also face ethical issues and challenges. One major concern is the possibility of contaminating other celestial bodies with Earth's life forms (forward contamination) or bringing extraterrestrial organisms to Earth (backward contamination; e.g., Rettberg et al., 2019). This situation requires strict procedures to ensure a balance between scientific exploration and protecting potential ecosystems. The equipment that may touch pristine icy moon environments must be cleaned and verified. Applying a rigorous witness plan, for example, by using witness plates, provides a possibility to passively record the contamination level during the fabrication or testing of spacecraft instrumentation (e.g., Weissbrodt et al., 1994).

Novel thermoelectric melt probes such as the EnEx-IceMole, developed with funding from the German Federal Ministry for Economic Affairs and Energy (BMWi) can be specifically designed and optimized for (self)cleaning (Dachwald et al., 2014; Kowalski et al., 2016). They utilize no fuel, have a significantly smaller logistical footprint, and therefore offer potentially cleaner means of accessing the subglacial environment than many alternative ice penetration approaches.

The measures required for mitigation of contamination risks can be broadly divided into two groups, that should go hand-in-hand: (I) a complex of assays for contamination monitoring and assessment and (II) a set of procedures aimed at biological and chemical burden reduction. In terms of biological or organic contamination, celestial environments are under protection by the guiding principles of the Planetary Protection Policy (Kminek et al., 2020).

Many aspects and components of the Planetary Protection Policy are reflected in further official standards regulating exploration of polar terrestrial regions. This includes the Protocol on Environmental Protection within the Antarctic Treaty, and the Code of Conduct (CoC) for the Exploration and Research of Subglacial Aquatic Environments (Doran und Vincent, 2011; Siegert und Kennicutt, 2018). The principles set in both these documents also were applied in the Clean Access Plan for the EnEx field tests performed in Antarctica (Mikucki et al., 2023).

The tasks and recommendations regarding contamination management and control, published in the abovementioned documents, are derived from the necessity to reduce the number of cells and biological molecules on the instruments that enter (sub)glacial environments. Efficient biological and chemical burden reduction has required developments of multiple-step procedures for each hardware component. Usually, sampling equipment is sterilized before its transportation to the application site. However, this approach does not prevent contamination appearing shortly after the mission begins, for instance, if the ice-melting probe must penetrate contaminated upper ice layers on its way to the subglacial locations of interest. In this situation, two action classes must be defined: (a) pre- and inter-mission hardware decontamination in the stationary laboratory conditions and (b) *in situ* measures and protocols applied during the (sub)glacial exploration. The actions in the first group (a) can be designed very flexibly and use numerous classical disinfection and decontamination methods, combined and applied in a consecutive way. In addition to cleaning with various detergents and organic solvents, physical removal of bioburden can be assisted by autoclaving, dry heat, exposure of surfaces to ozone, ethylene oxide, ultraviolet or gamma radiation, gas plasmas or hydrogen peroxide (Rummel and Pugel, 2019).

The *in situ* decontamination (b) is especially important when multiple independent sampling acts have to be performed within the same deployment, without return to the laboratory. Main requirements for efficient *in situ* chemical decontamination in glacial environments are: high killing rate and activity against a broad range of microorganisms (spores, fungi, viruses, small insects, etc.), fast decomposing, environmentally friendly end products, easy handling, good solubility in water at any temperatures, good penetration ability, activity in cold environments, easy storage and easy application. Several successful decontamination protocols are developed and validated, for example, in the laboratories at FH Aachen University of Applied Sciences, using specially designed compositions based on 3%–5% (v/v) hydrogen peroxide and 3% (v/v) sodium hypochlorite (Leimea et al., 2010).

8 Relevance to systems on Earth

Considering the challenging work for realizing missions to the outer Solar System and to investigate particularly the habitable and potentially inhabited icy ocean worlds around Jupiter and Saturn, it is clear that the technology developments and realization of such missions have also a significant impact on the realization of tools necessary to explore environments on Earth (see also Section 4.1). An excellent side effect of this fact is the collaboration of engineers, natural scientists and information scientists from the three main research fields, such as polar research, ocean/deep sea research and space research, who finally are able to use different facilities and develop instruments for society relevant topics such as climate change studies, economic energy use, exploration of the ocean, exploration of the remote polar areas and also the exploration of space for finding new resources.

The oceans of Earth are far more dynamic and varied than is commonly assumed (Olbers et al., 2012), with the ice-covered regions doubly so. Taking the Arctic and Antarctic in turn, the Arctic ocean is in general an area with reasonably thin ice cover (several meters thick the general maximum thickness) that waxes and wanes in coverage throughout the year, with the central high Arctic permanently covered in moving sea ice (Kwok, 2018). The recent Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition locked the German Polarstern research icebreaker of the Alfred Wegener Institute for Polar and Marine Research (AWI) in Bremerhaven into this moving ice to monitor firsthand the highly variable under and above ice environmental conditions taking place throughout the polar summer and polar night (Nicolaus et al., 2022). Below the ice, the water depth of the Arctic varies from a few centimeters at the coast to 5,500 m in the Molloy Deep. Topography is also highly variable, with flat plains interspersed with steep hills, cliffs, seamount chains, isolated seamounts, ridges and rises (Jakobsson et al., 2012). Of particular interest to icy moon research may be the Gakkel Ridge, a 4,000 m and ultraslow constructive plate margin running across the central Arctic, touching 85°N, and supporting a variety of active hydrothermal vents at depth, each with a unique community of life (Ramirez-Llodra et al., 2023). Shallow 1,000 m–2,000 m seamounts adjacent to the ridge are 100% covered by thick, extremely slow growing and long living sponge communities (Stratmann et al., 2022). Other sponge communities seem to bloom in the deeps, downstream of hydrothermal sources. Other Arctic areas include the extended Lomonsov Ridge and numerous isolated basins.

The Antarctic ocean contrasts with the Arctic in that it has a continental landmass center, covered with kilometers of glacial ice, containing many hundreds of isolated lakes of briny waters that cannot be reached by the sunlight (Dorschel et al., 2022). The waters around the Antarctic continent also differ from those surrounding the Arctic. According to current knowledge, they lack active hydrothermalism and are covered by glacial ice of hundreds of meters thickness, which has broken from the continent and may stay floating or grounded in the open ocean for decades (Wesche and Dierking, 2016). Beneath this ice, which can form hundreds of kilometers of ice tongues out over the ocean, no life penetrates but advected nutrients support diverse ecosystems, as new sensor equipped robotic platforms are starting to discover (Griffiths et al., 2021).

The great variety of polar life, food sources and environmental niches is still largely unknown. In 2021, the vast, several hundred km square array of actively nesting icefish was discovered in one of the more studied regions of the Weddell Sea (Purser et al., 2022). How these complex and diverse ecosystems interact in the underice environment can only inform icy ocean world research.

9 Conclusion and outlook: near future strategies

We here presented an overview about astrobiology research related to icy ocean worlds conducted in Germany. Due to involvements in ESA's JUICE and NASA's Europa Clipper, astrobiology investigations of icy ocean worlds are getting more and more attention within Germany and beyond. Through various institutions, such as the German Aerospace Center or German universities, Germany offers itself as a partner for international collaborations in icy ocean world research and space missions. The German Astrobiology Society represents a valuable platform for scientists and engineers to exchange ideas and start collaborations in icy moon research, involving international institutions, from space mission participations to individual research at universities and other institutions. Efforts include the development of melting probes to melt through the outer layer of an icy ocean world as well as instrumentation for life detection on these worlds. These projects feed upcoming missions, such as Europa Clipper, JUICE and potential future missions to Enceladus, Europa or any other icy ocean world.

One important aspect of icy moon research is the impact on society through themes like climate change, biodiversity and the exploration of new resources, as it is also supported by the general space program strategy of the German Government. In the near future the synergistic strategy in space exploration will be a significant gain for science as well as for innovative inventions for terrestrial applications and technology developments, particularly in increasing the benefit for the human society and the environment on our home planet Earth. Future missions to the icy ocean worlds with their resulting exploration technologies will provide opportunities to further support the exploration of Earth's oceans and polar regions and to understand the role of these environments for the climate and the biosphere of the whole planet.

A new way of common cooperation should be consolidated on the long term because of its multi-useable technology and scientific outcome. Collaborations with international institutions are key to realizing space missions and exploiting the full potential of icy ocean world research. Field studies beyond Germany are easier to realize when researchers from other locations, meaning from the field site, are involved. Biosignature detection represents another realm in which various international institutions, particularly US institutions, are collaborating with researchers from Germany. In the near future, one particular focus should lie on modeling efforts to investigate the interactions between a subsurface ocean and a rocky core or an ice shell.

It is clear that the sequence of field investigations, lab research and space tests should be maintained and further supported. Synergy is key and will lead to collaborative actions as well as to visible solutions of common problems. To get there, politicians, national and international foundations, entrepreneurs and stakeholders should foster this promising collaborative interdisciplinary approach by significantly increasing their budgets for supporting such cooperative synergistic activities, technology developments and transfers.

Author contributions

FK: Conceptualization, Project administration, Resources, Supervision, Visualization, Writing–original draft, Writing–review and editing. MB: Resources, Writing–original draft, Writing–review and editing. KB-V: Resources, Writing–original draft, Writing–review and editing. JB: Resources, Writing–original draft, Writing–review and editing. MB: Resources, Writing–original draft, Writing–review and editing. BD: Resources, Writing–original draft, Writing–review and editing. ID: Resources, Writing–original draft, Writing–review and editing. AE: Resources, Writing–original draft, Writing–review and editing. CE: Resources, Writing–original draft, Writing–review and editing. OF: Resources, Writing–original draft, Writing–review and editing. EH: Resources, Writing–original draft, Writing–review and editing. DH: Resources, Writing–original draft, Writing–review and editing. FH: Resources, Writing–original draft, Writing–review and editing. LHS: Resources, Writing–original draft, Writing–review and editing. NK: Resources, Writing–original draft, Writing–review and editing. MN: Resources, Writing–original draft, Writing–review and editing. A-CP: Resources, Writing–original draft, Writing–review and editing. FP: Resources, Writing–original draft, Writing–review and editing. AP: Resources, Writing–original draft, Writing–review and editing. TR-B: Resources, Writing–original draft, Writing–review and editing. SS: Resources, Writing–original draft, Writing–review and editing. DS-M: Resources, Writing–original draft, Writing–review and editing. SU: Resources, Writing–original draft, Writing–review and editing. J-PdV: Conceptualization, Project administration, Resources, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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