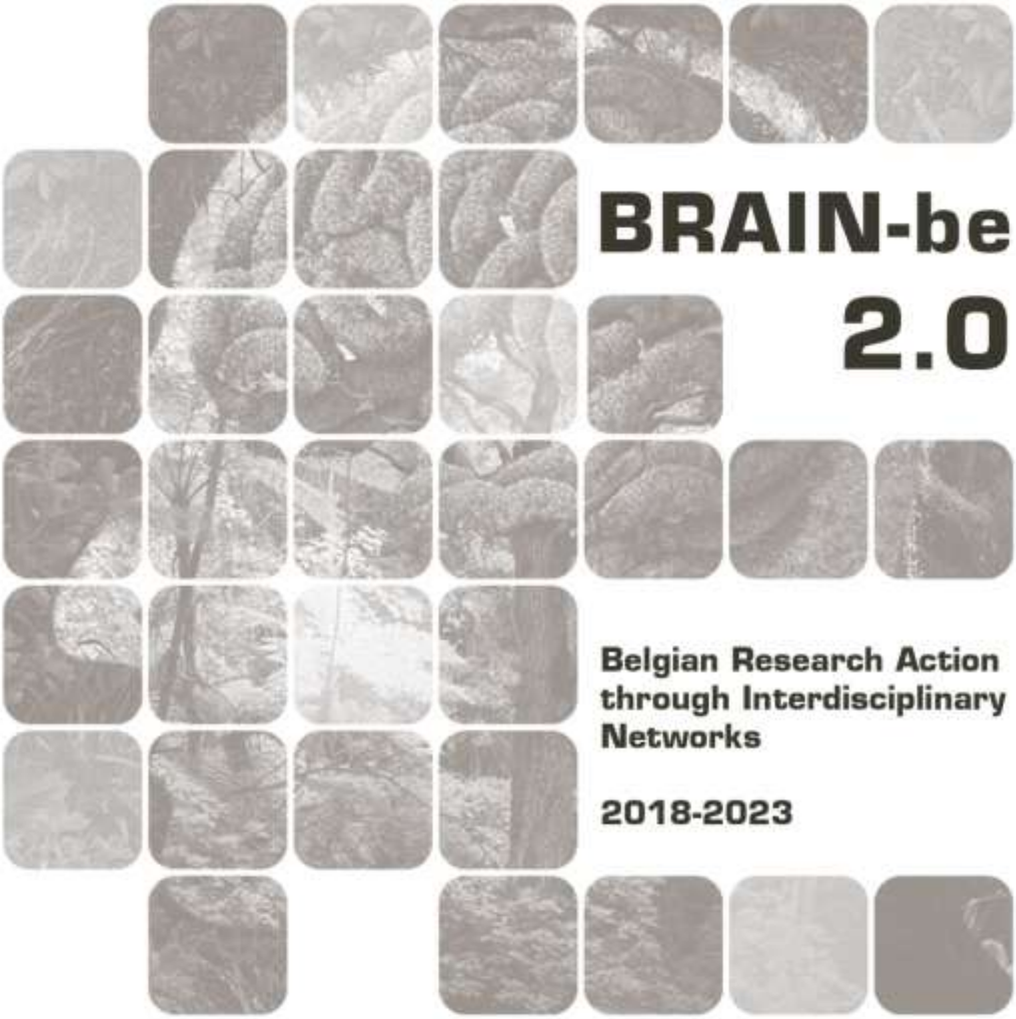

PORTAL

PhOtotrophy on Rocky habiTAble pLanets

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Pillar 1: Challenges and knowledge of the living and non-living world

NETWORK PROJECT

PORTAL

PhOtotrophy on Rocky habiTAble pLanets

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FINAL REPORT

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ABSTRACT

Context

Star light represents an unlimited and efficient source of energy that is abundantly used by life on Earth for billions of years and at the basis of trophic chains, so it could play also a key role in the development and sustainability of other biospheres elsewhere in the Universe. Tackling the questions of the universality and the diversity of phototrophic metabolisms is thus a critical step in our study of life on a cosmic scale -the purpose of the interdisciplinary field of astrobiology. Within the last three decades, thousands of exoplanets have been discovered, including a few dozen that are potentially habitable. The project "PhOtotrophy on Rocky habiTAble pLanets" (PORTAL) addresses the potential habitability of temperate rocky planets in orbit around very low-mass (<0.2 Msun; VLM) stars, and the possibility of detecting phototrophic life on such planets if it exists.

Objectives

The objectives are (1) to provide strong observational constraints on the physical and irradiative conditions at the surface of the planets orbiting in the habitable zone of the nearby dwarf star TRAPPIST-1, and (2) to use those constraints to investigate the possibilities of phototrophy in the infra-red range and the detectability of their signatures, in samples from the early Earth and modern extreme habitats, to simulated exoplanet conditions in a new TRAPPIST biodome, to rocky exoplanets orbiting VLM stars. Our approach is multidisciplinary, combining expertise in astrophysics, internal geophysics, atmosphere-interior dynamics, geology, paleobiology and microbiology from an international consortium of scientists in Belgium, France and Germany.

Conclusions

PORTAL improves our understanding of the TRAPPIST-1 exoplanetary system. It provides new constraints on the high-energy stellar environment impacting atmospheric escape and photochemistry on the TRAPPIST-1 planets, methods for dealing with stellar contamination in atmosphere retrieval, models of possible atmospheres and their evolution around exoplanets of the TRAPPIST-1 system, or absence of atmosphere around certain exoplanets, discussion on exoplanet habitability around VLM stars. PORTAL also made important advances in our understanding of phototrophy on modern and early Earth. Finally, PORTAL provides a new experimental platform (a biodome) to investigate the possibility of phototrophy in the infra-red range, a system where oxygenic photosynthesis by model Earth microorganisms is performed and measured under controlled Trappist-1-like atmospheric and light conditions, and the possible biosignatures to detect remotely. This platform will also be useful for investigating other extraterrestrial and Early Earth conditions and for outreach and education.

Keywords

Habitability, biosignatures, phototrophy, infra-red light, very low-mass stars, atmosphere, models, biodome, exoplanets, early Earth, microfossils, cyanobacteria, algae

1. INTRODUCTION

Star light represents an unlimited and efficient source of energy that is abundantly used by life on Earth and at the basis of trophic chains, so it is natural to assume it could play also a key role in the development and sustainability of other biospheres elsewhere in the Universe. Tackling the questions of the universality and the diversity of phototrophic metabolisms is thus a critical step in our study of Life on a cosmic scale -the purpose of the interdisciplinary field of astrobiology. Within the last three decades, thousands of exoplanets have been discovered, including a few dozen that are potentially habitable. For a handful of them, a detailed atmospheric characterization should be within reach of upcoming giant telescopes. A thorough assessment of the habitability of late-type M-dwarfs is critical for a deep understanding of the universality and limits of life. The emission of these cold star peaks in the near-infrared (around 1 micron). Given their faintness, rocky planets have to orbit very close to them to be habitable. Depending on the planets' atmospheric and magnetospheric properties, their proximity to the active host star could translate into fluxes of XUV photons and stellar winds on their surfaces dozens of times larger than for Earth. The capacity of these worlds to harbor Life should thus heavily rely on the efficiency of the mechanisms used by phototrophic organisms to harvest infrared photons and to protect from X-ray and UV photons and high-velocity charged particles.
On Earth, phototrophic organisms have evolved metabolisms to scavenge photons in the visible spectrum, but also to use the infra-red range. Several clades of anoxygenic and oxygenic phototrophs across the three domains of life have also developed additional strategies for protection against UV radiation, such as adaptation to shaded habitats and/or the synthesis of sunscreen pigments. Anoxygenic photosynthesis appeared more than 3.4 Ga, when Earth atmosphere was lacking free oxygen and an ozone layer, and its surface was exposed to strong UV radiations. Later oxygenic photosynthetic organisms, cyanobacteria, had a major impact on atmosphere composition and oceanic chemistry from at least 2.4 Ga, which contributed to the diversification of complex life (eukaryotes). Phototrophy thus can have a major impact on planets and life evolution and may produce atmospheric and surface biosignatures that can be detected remotely.

The project "PhOtotrophy on Rocky habiTAble pLanets" (PORTAL) addresses the potential habitability of temperate rocky planets in orbit around very low-mass (<0.2 Msun; VLM) stars, and the possibility to detect phototrophic life on such planets if it exists. The objectives are (1) to provide strong observational constraints on the physical and irradiative conditions at the surface of the planets orbiting in the habitable zone of the nearby dwarf star TRAPPIST-1, and (2) to use those constraints to investigate the potential for phototrophy in the infra-red range and the detectability of their signatures, in samples from the early Earth and modern extreme habitats, to simulated exoplanet conditions in a new TRAPPIST biodome, to rocky exoplanets in orbit around VLM stars.
Our approach is multidisciplinary, combining expertise in astrophysics, internal geophysics, atmosphere-interior dynamics, geology, paleobiology and microbiology from an international consortium of scientists in Belgium, France and Germany.

2. STATE OF THE ART AND OBJECTIVES

Objectives

The PORTAL project aimed to address the potential habitability of temperate rocky planets in orbit around very low-mass (<0.2 Msun; VLM) stars, and the possibility to detect life on such planets. More specifically, its **objectives** were (1) to provide strong observational constraints on the physical and irradiative conditions at the surface of the planets orbiting in the habitable zone of the nearby dwarf star TRAPPIST-1, and (2) to use those constraints to investigate the potential for phototrophy in the infra-red range and the detectability of their signatures, from the early Earth to modern extreme habitats, to rocky exoplanets in orbit around VLM stars.

State of the art before the start of the project PORTAL

Exoplanet habitability and the TRAPPIST-1 opportunity

Is there life around other stars than the Sun? Since the seminal discovery of 51 Pegasi b (Mayor and Queloz, 1995), more than four thousand exoplanets had been discovered at the start of this project. This impressive harvest includes a steeply growing fraction of smaller rocky planets, a few dozen of them being potentially habitable, i.e. small and temperate enough to possibly have a rocky surface partially or totally covered by liquid water, the most basic ingredient of life as we know it. In parallel to all these detections, more and more powerful instruments permit to study in detail some exoplanets in orbit around nearby stars, notably to measure precisely their physical and orbital parameters but also to constrain their atmospheric compositions (Crossfield, 2015). At the start of PORTAL, these detailed studies concerned planets much larger and hotter than Earth and inhospitable to life. Extending further such studies to rocky worlds orbiting within the circumstellar habitable zone (HZ) of their star (Kasting et al., 1993) would make it possible to probe the atmospheric and surface conditions of potentially habitable worlds, to explore their atmospheric compositions for chemical disequilibria of biological origins (Schwieterman et al., 2018), and, maybe, to reveal the existence of life beyond our solar system. All it takes is to find the right planets, i.e. potentially habitable planets whose detailed atmospheric characterization is within reach of our most powerful upcoming astronomical facilities like the James Webb Space Telescope (JWST) that NASA successfully launched at the end of 2021.

Such planets were detected a few years ago around TRAPPIST-1, a Jupiter-sized VLM star forty light-years away that was shown by several of PORTAL members (Gillon et al., 2016, 2017) to host seven temperate Earth-sized planets. At least three of these worlds orbit within the HZ of the star. With semi-major axes ranging from 1 to 6% of an astronomical unit, these planets form a super compact planetary system whose long-term stability is ensured by its resonant architecture (Luger et al., 2017). While transit photometry brought precise measurements of the planets' sizes (Delrez et al., 2018; Ducrot et al., 2020), their strong mutual interactions allowed precise determination of their densities, consistent with rocky compositions volatile-richer than the Earth's (Grimm et al., 2018; Agol et al. 2020). The discovery of TRAPPIST-1 was followed by several theoretical studies (Barstow and Irwin, 2016; Morley et al., 2017; Batalha et al., 2018; Krissansen-Totton et al., 2018 ; Wunderlich et al., 2019; Fauchez et al., 2019; Lustig-Yaeger et al., 2019) which concluded that an ambitious JWST program should be able to detect the planets' atmospheres and to constrain their compositions. A community initiative developed a well-defined sequential structure for the study of the system with JWST and to coordinate on every aspect of its preparation and implementation, both observationally and theoretically (Gillon et al., 2020).

VLM stars like TRAPPIST-1 are of paramount importance for the study of life at the cosmic scale. Indeed, they comprise at least half of the stars of the Milky Way (Bochanski et al., 2010), and they are known to host more rocky planets than more massive stars (Mulders et al., 2015). Furthermore, their lifetimes are orders of magnitude longer than those of Sun-like stars (Iben, 1967). Nevertheless, the actual habitability of planets orbiting in their HZs remains highly uncertain as it is complicated by several factors like the long pre-main-sequence phase of the star, their high magnetic activity (flares, erosion), and the close proximity of the HZ to the star (tidal locking, atmospheric erosion) (Shields, 2016). The key questions here are the existence or absence of atmospheres around the planets, and the resulting physical and irradiative conditions at the surface of planets. They both depend on the exchange of volatiles with the interior through the planet's surface and the interaction with the planetary environment and the central star.

As demonstrated by spectroscopic observations performed with the Hubble Space Telescope (de Wit et al., 2017, 2018; Wakeford et al., 2019), the planets do not possess primordial H-dominated atmospheres. Potential atmospheres are therefore likely of secondary origin with pressures and compositions depending on the properties of the planet's interior dynamics. Before this PORTAL project, most studies so far have focused on the capacity of the planets to retain an atmosphere (Airapetian et al. 2020), but much less attention was paid to the crucial interactions between the atmosphere and the interior. Indeed, the erosion of the atmospheres – expected to be strong for TRAPPIST-1 planets – could be compensated by their replenishments through outgassing (Grenfell, 2020), a process whose amplitude depends strongly on the existence and style of mantle convection (Dorn et al., 2018), something that could be thoroughly constrained by a bulk structure and tidal evolution modeling. The exquisite precisions on the planets' densities have reached a few % in 2020 (Agol, 2020) and have improved even further in the following years.

Since the start of PORTAL, new data were obtained thanks to JWST, some of them in the frame of this project. They will be summarized below in the results section.

Evolution and limits of phototrophy

Phototrophy is the process by which organisms convert electromagnetic radiation into bioavailable chemical energy. It appeared very early on Earth, more than 3.4 billion years ago, as evidenced by fossil microbial mats and stromatolites (Javaux, 2019). It forms the basis of trophic chains on Earth by supplying most of the energy used by living organisms, so it is natural to assume it could also play a key role in the development and sustainability of other biospheres elsewhere in the Universe. Phototrophy comprises two metabolic modes: rhodopsin-based and chlorophyll-based (Bryant and Frigaard, 2006). Rhodopsins comprise a large membrane protein family that are found in archaea, bacteria, and metazoan lineages (Ostrovsky et al., 2017). Photosynthesis is the chlorophyll-based phototrophic mode. Currently, photosynthesis is known to occur in 7 phyla of modern bacteria and in 4 eukaryotic supergroups (Cardona, 2016), and can be either anoxygenic (aerobic or anaerobic) or oxygenic. On Earth, through time and space, phototrophic organisms have evolved metabolisms to scavenge the visible spectrum (400 to 700 nm), as well as the far-red light (FRL, 700–749 nm) and IR (750–1100 nm) wavelengths. Tackling the questions of the universality and the diversity of phototrophic metabolisms is thus a critical step in our study of life on a cosmic scale.

A few studies have investigated the possibility of photosynthesis around different types of stars (K, M) (e.g., O'Malley-James et al., 2012) including around small stars such as Proxima Centauri and TRAPPIST-1, and modelled the visible and IR spectra of these stars (Lin and Kaltenegger, 2020). One study (Ritchie et al., 2017) used primary productivity modelling based on light absorption and photosynthetic performance to estimate the primary production for Chlorophyll a (Chl a) and Chl d-based oxygenic photosynthesis, as well as for bacteriochlorophyll (BChl)-based anoxygenic photosynthesis under visible and IR light on Proxima Centauri b. They concluded that both oxygenic and anoxygenic photosynthesis would be possible on surfaces or in very shallow water.

FRL/IR-adapted photosynthesis appears to be widespread among prokaryotes. For instance, the Chl f first discovered in modern stromatolites (Chen et al., 2010) enables a subset of cyanobacteria to photosynthesize under FRL and is spread among the five traditional phylogenetic/morphological sections within the cyanobacterial phylum (Antonaru et al., 2020). These cyanobacteria exhibit a complex photoacclimation response, known as FRL photoacclimation (FaRLiP) by modulating gene expression (Zhao, 2015). They can also produce both Chl f and Chl d (Gan et al., 2014, 2015). A marker gene (apcE2) for detecting potential Chl f producing cyanobacteria allows to detect the latter in a range of shaded environments including mats, intertidal rocks, beachrocks, stromatolites, desert rocks and soils, and in symbioses or close associations with eukaryotes such as red algae (Antonaru et al., 2020).

FRL photosynthesis may have originated early in the Proterozoic when stromatolites reached their greatest diversity and distribution (Antonaru et al., 2020). Interestingly, the earliest microfossils that can be assigned with confidence to cyanobacteria are preserved in ~2 Ga silicified stromatolites (review in Demoulin et al., 2019). The rise of eukaryotes and the emergence of modern-day terrestrial environments opened new niches where this adaptation has endured and it is possible that "FRL contributes more to primary production in tidal and terrestrial regions than previously assumed, both in moderate and extreme environments" (Antonaru et al., 2020). FLR photosynthesis in shaded habitats also protects against UV radiations, as well as the synthesis of sunscreen pigments, known in several clades of anoxygenic and oxygenic phototrophs within the three domains of life. The phylogenetic (and therefore evolutionary) diversity of photosynthetic eukaryotes is much greater in the oceans (diatoms, dinoflagellates, coccolithophores, etc.) than in land emerged areas (primary green plants, mainly) (Oborník, 2019). Our knowledge of photosynthesis under IR/FR light is however mostly limited to green plants (Pettai, 2005). Anoxygenic photosynthesis appeared in Bacteria, but its origin is still poorly understood (Hamilton, 2019). It appeared early, when the atmosphere was lacking free oxygen and an ozone layer, and its surface was exposed to strong UV radiation. An early Earth-like anoxic atmosphere based on volcanic and hydrothermal outgassing dominated by CO_2, N_2, CO, with traces of CH_4 and NH_3 (Kasting, 2014) would have very similar absorption properties as the current Earth atmosphere at UV-B, visible, far-IR and IR wavelength (Ritchie, 2017). Oxygenic photosynthesis has a poorly constrained evolutionary history as well. The photosystem II, the water-oxidizing and O2-evolving enzyme of photosynthesis, originated in the Archean (Cardona et al, 2019), long before the diversification of cyanobacteria (as recently suggested, Oliver et al, 2023) and the development of oxygenic photosynthesis. Later oxygenic photosynthetic organisms, cyanobacteria, had a major impact on atmosphere composition and oceanic chemistry from at least 2.4 Ga, which contributed, with other factors, to the diversification of complex life (eukaryotes) (Demoulin et al, 2019).

More than 1 Gyr ago, the fossil record of multicellular red and green algae evidences the acquisition of plastid by eukaryotes through the endosymbiosis of a cyanobacteria within a protist cell, perhaps more than 1.64 Ga (Javaux and Knoll, 2017). The following diversification of algal phytoplankton is thought to have played a major role in the subsequent evolution of metazoans and complexification of trophic chains and ecosystems (Brocks et al., 2017). Photosynthesis thus may profoundly modify planetary environments, atmospheric composition, and biosphere evolution, but the mode and tempo of its evolution remain to be further investigated.

Probing TRAPPIST-1 atmospheres will represent a key step in understanding the diversity and evolution mechanisms of terrestrial planets atmospheres/environments beyond the solar system but also in searching for other worlds able to host life and signatures of life (Des Marais et al., 2002; Grenfell, 2017; Rauer et al., 2011 ; Catling et al., 2018). To date, our knowledge of terrestrial planet environments being restricted to the few 4.5-Gyrs old cases around the Sun and our comprehension of life, metabolisms, biogeochemical cycles being limited to our biosphere, and the very concept of such remote biosignatures is exploratory. Reaching a scientific consensus on observables from an exoplanet that could only be explained by the presence of life implies major progress in the aforementioned topics. Real data from temperate planets and their atmospheres will allow us to assess different approaches: quantifying chemical (dis)equilibrium and understanding its origins [54], addressing their possible abiotic origins (Wogan et al., 2020), producing self-consistent abiotic models consistent with the observations. Most studies on exoplanet biosignatures have discussed the case of identifying O2-rich atmospheres built-up as on Earth by oxygenic photosynthesis by O2 or O3 features (Selsis et al., 2002; Domagal-Goldman et al., 2014 ; Meadows et al., 2018; Lisse et al., 2020) and their possible abiotic nature related with the erosion of a water reservoir or the photochemistry of CO2, in particular around M stars (Harman et al, 2018; Hu et al, 2020). Other authors have modeled possible biosignatures in reducing atmospheres (Seager et al, 2013), addressed the case of specific molecules (like N_2O, CH_3Cl, PH_3, e.g., Sousa-Silva et al, 2020) or worked out list of terrestrial biogenic molecules (Seager et al, 2016). However, the exclusive biological origin of such molecules is debated. These arguments imply that without phototrophy - in other words without transferring low-entropy stellar energy into the biomass - the presence of life could be extremely difficult to infer from remote observations of an exoplanet (Rosing, 2005). Therefore, the so-called habitable zone is actually the phototrophic zone, where stellar light and surface liquid water can be found simultaneously potentially with global observable consequences. Photosynthesis could take various forms, in particular in an evolutionary context driven by a very different and redder star. The present project aims at studying the "alternative" ways for this stellar input to result in observable biogenic features. Beyond the detection of atmospheric species, alternative biosignatures such as pigment reflectance or absorption are interesting to investigate, as well as ways to distinguish them from mineral/ground properties. On modern Earth, chlorophylls reflectance by blooming phytoplankton or plants (red edge) or carotenoids and bacteriorhodopsins reflectance by blooming halophilic archaea (green edge) can be detected by remote visible and infrared imaging spectrophotometer (Arnold, L., 2008 ; O'Malley-James, J. T., et al., 2018; Takizawa, K., et al., 2017; DasSarma S., et al., 2020). The use of circular spectropolarimetry to detect homochirality, an agnostic signature of life, is also a promising avenue to detect life remotely (Patty et al 2022). However, the possible in situ and remote signatures of a cryptic oxygenic and anoxygenic phototrophic biosphere living in shaded habitats are not constrained and need to be investigated further.

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3. METHODOLOGY

Overall methodology

As the PORTAL project focuses on exoplanet habitability and the possibility of phototrophic life, it is intrinsically multidisciplinary and must be addressed with a synergistic approach. The research project PORTAL includes 9 science work packages (Figure 1) (WP): WP 1-5 (habitability of TRAPPIST-1 exoplanets), WP6 (IR photosynthesis on modern Earth), WP 7 (photosynthesis on early Earth) are addressed in parallel to foster synergy, and to provide data for WP 8 (TRAPPIST biodome) and 9 (possibility of phototrophy on rocky habitable exoplanets around very low-mass stars). WP8 (TRAPPIST biodome) needs data from WP 1-7. WP 9 needs data from all science WP 1-8. WP 1 to 5 aim to provide first constraints for the biodome (WP8) while continuing to observe and study the TRAPPIST-1 planets through the project. Because there are several planets of astrobiological interest in the system, these WPs carry on the observations, retrieval and modeling throughout the whole project. Different methodologies were applied, by selecting the most appropriate for each WP and task. They are detailed below.

For each WP, risk assessments were conducted and regularly re-evaluated to track the global progress rate, even if some tasks were delayed or more intricate than expected. One of the possible risks was the launch and deployment of JWST in December 2021. The success of this space telescope is one of the greatest technological challenges and achievements in space sciences and the new data it provides are revolutionizing several domains in astrophysics, including the observations of exoplanets and the Trappist-1 system.

A Gantt chart summarized the deliverables of each WP and the time people hired by the project and spend on specific tasks. To guarantee our synergistic approach, each person hired on the project was assigned to a main supervisor and a co-supervisor from another team and scientific background.

Three other work packages include: WP 10 for coordination, project management and reporting, WP 11 for data management, and WP 12 for dissemination and exploitation of results, and were implemented throughout the project. Annual reports were sent to BELSPO and to the advisory committee. Frequent communication within the network (6 promotors) and their 3 international partners were set up, in addition to weekly discussions within teams/institutions. A data management officer (P5) was responsible for maintaining a website for the public and for data exchange and safeguard with private access to the network. Data management and gender balance were insured by officers among the PIs.

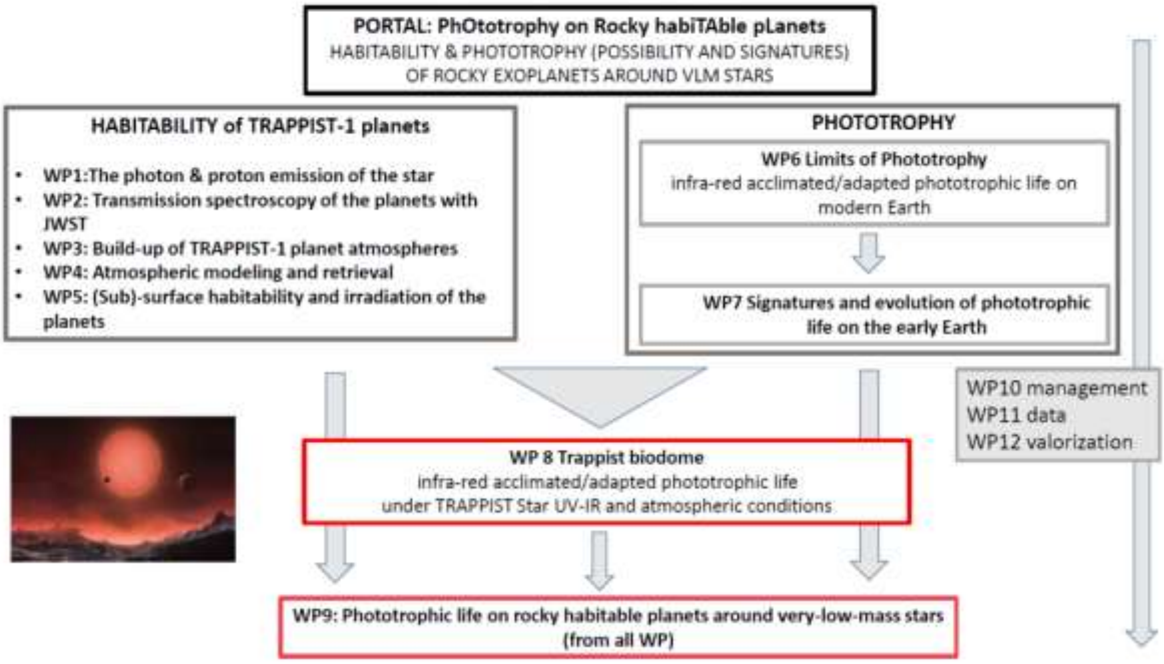

Figure 1: **summary of overall methodology for the PORTAL project**

Methodology of each WP

WP1 *The variable photon and proton emission of the star TRAPPIST-1* & WP2 *Transmission spectroscopy of TRAPPIST-1 planets with JWST*
Meaningful constraints on the conditions at the surface of the planets orbiting in the habitable zone of the nearby VLM star TRAPPIST-1 were obtained by combining state-of-the-art models to available and new data, requiring notably a large amount of observation time on the upcoming James Webb Space Telescope (JWST, see WP2) by astronomers. One of the PORTAL promotors, M Gillon (ULiège), leads a community initiative gathering more than 100 scientists aiming to support these observations and optimize their scientific return (Gillon et al. 2020). JWST is a fully-funded NASA/ESA/CSA space telescope that was launched in October 2021, and for which a large amount of TRAPPIST-1 observations has already been obtained, while many more expected by the astronomical community through observation proposals. The unique instrumental capacities of JWST enable the study of the atmospheric properties of the TRAPPIST-1 planets with the technique of transit transmission spectroscopy.
The other required astronomical data (WP1) – spectra of the star covering the X-ray to the IR range – existed in part at the start of PORTAL and were completed by JWST or by other space and ground-based telescopes through observation proposals. The reduction and analysis of these spectroscopic observations (WP1 + WP2) followed well-established methodologies (e.g., Bonfanti and Gillon, 2020; Bourrier et al., 2017a, 2017b; Burgasser et al., 2014; de Wit et al., 2017, 2018; Ducrot et al., 2018, 2020; Gillon et al., 2016, 2017a, 2017b; Knutson et al., 2014; Lendl et al., 2016; Triaud et al., 2020, Wheatley et al., 2017). One of the promotors, M Gillon notably developed a pipeline optimized for the

reduction and Bayesian analysis of data obtained by the JWST instrument NIRISS, NIRSPEC and MIRI). One postdoc Fatimeh Davoudi was hired to work on these WPs.

WP3 *Build-up of TRAPPIST-1 planet atmospheres*

WP3 is subdivided into several steps explained below. WP3 was performed by Promotors V. Dehant and T. Van Hoolst (ROB) in close collaboration with International Partner L. Noack (FU Berlin). A PhD student Lingshan Xiong was hired for this WP.

The main outputs are interior models of TRAPPIST-1 planets, their evolution, and the effects of tidal heating, which will lead to theoretical constraints on the efficiency of atmospheric replenishments by outgassing. By combining the inferred atmospheric properties (WP4) with these constraints on outgassing, we will also improve our understanding of the efficiency of atmospheric erosion processes. Furthermore, WP4 will provide observational constraints to WP3 models, as the observed atmospheric properties reflect the combined effects of source and sink processes.

WP3.1 - Interior structure and tidal effects

The Galilean satellite Io is the most volcanically active body of the Solar System due to tidal dissipation (Peale et al. 1979). The high tidal energy production, which dominates the heat budget in Io, raises temperatures in parts of Io's mantle to the melting point, leading to massive volcanism and heat being transported primarily by vertical magma motion. Tidal dissipation also contributes significantly to the total energy budget of the TRAPPIST-1 planets, with tidal heat fluxes being at least an order of magnitude larger than the Earth's mean heat flux (Turbet et al., 2018) and is expected to generate magma oceans in the innermost TRAPPIST-1 planets (Barr et al. 2018, Dobos et al. 2019). Because of related effects on the interior and the interior heat transport, tidal dissipation is a key ingredient to consider for the characterization of the atmospheres (Turbet et al., 2020). We explored tides and tidal dissipation in TRAPPIST-1 planets starting from the state-of-the art models developed for tidal calculations in Solar System bodies (Rivoldini et al., 2011; Beuthe, 2013) and in particular focused on the relative contribution of the different internal layers from the center to the surface, which is a substantial improvement to previously used methods, and on the angular distribution of tidal heating.

WP3.2 - Outgassing

Convection within the rocky mantle is a key process that governs the evolution of a planet's interior: it controls heat loss from the metallic core, which ultimately generates the magnetic field, and can drive plate tectonics, which on Earth governs the long-term volatile cycling between the atmosphere/ocean and the interior. Whether plate tectonics operates on TRAPPIST-1 planets is unknown, but planets with stagnant-lid convection can outgas volatiles, albeit to a lesser extent than planets with plate tectonics. The amount of outgassing depends on several factors, including planetary mass (Noack et al., 2017), bulk composition and differentiation (Noack et al., 2017; Dorn et al., 2018; Grenfell et al., 2020), and internal heat sources (Dorn et al., 2018). Outgassing requires that partial melting occurs in the silicate mantle during its evolution. Using 1D parametrized convection models and the 2D mantle convection code CHIC, developed at ROB and further extended at FU Berlin, we assessed the effect of tidal heating on mantle convection and volatile release in the TRAPPIST-1 planets. Outgassing contributes H_2O, CO_2, CO, H_2 and other species to the atmosphere (Grenfell et al., 2020) (depending on the solubilities of the volatiles in the melt, which are controlled by atmospheric chemistry and pressures, see WP 4). Gas speciation depends strongly on the redox state of the mantle (Ortenzi et al., 2020). Outgassing of water, essential for habitability, requires an oxidized or moderately reduced mantle, whereas a strongly reduced mantle will predominantly outgas H2, which is highly susceptible to atmospheric escape. We investigated the range of possible atmospheric compositions produced by redox-dependent outgassing modelling.

WP3.3 - Magnetic field

The magnetic field of a planet can have a large, although still poorly constrained, influence on the evolution of the planetary atmosphere, for example by inhibiting atmospheric escape (Tarduno et al., 2010; 2014), by modifying escape pathways in the absence or presence of a magnetic field (Gunell et al., 2018), or by shielding the atmosphere from magnetic heating induced by the host star (Kislyakova et al., 2017). A first-order estimate of whether a dynamo can operate within a planet can be obtained from the energy budgets and entropy balances in the core (e.g., Nimmo, 2015). We explored the possibility of dynamo action in TRAPPIST-1 planets across the range of interior models developed in this project, and investigated how tidal dissipation may influence core energetics and therefore dynamo generation. Those results, combined with observational signatures of the existence or absence of atmospheres, shed light on the still uncertain role of magnetic fields in governing atmospheric escape.

WP4: *Atmospheric forward and reverse modeling for TRAPPIST-1 planets* & WP5*: Exploration of the possible irradiation of the (sub)-surface of TRAPPIST-1 planets*

Analyses of the planets’ habitability also require accurate knowledge of their photon and proton irradiation environments (WP1), as well as theoretical constraints on their past and present atmospheric replenishment processes and tidal energy budgets (WP3), and the spectral energy distribution of the photons reaching their surfaces (WP5). Interpreting the JWST observations and deriving surface fluxes rely on state-of-the-art 1D and 3D atmospheric models (Turbet et al., 2018), combined with optimized spectral-retrieval procedures (WP4). Within PORTAL, International Partner M. Turbet (LMD/IPSL) provided retrieval tools developed specifically for the analysis of transit spectroscopy, namely TauREx (Waldmann et al., 2015) and Pythmosph3R (Caldas et al., 2019). He and International Partner F. Selsis (LAB/Univ. of Bordeaux) provided GCM (3-D Global Climate Models) simulations for both the preparation and interpretation of the observations. These simulations were applied to a wide range of atmospheric composition scenarios (WP4, based on the results of WP3) to compute the spatial distribution of the spectral flux received by an exoplanet at any point on its surface (WP5). These 3-D numerical simulations constitute a library of possible surface irradiation conditions, which serves as the basis for configuring the light environment of the TRAPPIST biodome (WP8).

Such an ambitious endeavor required a large scale of complementary expertise. Promotor M Gillon contributed stellar spectroscopy and JWST observations; Promotors V. Dehant and T. Van Hoolst, together with International Partner L. Noack, provided expertise in interior modeling and atmosphere-interior exchange; International Partners M. Turbet and F. Selsis brought atmospheric 1-D and 3-D modeling capabilities. Their teams as well as external collaborators J. Yazidi (LATMOS), E. Ducrot (CEA) and members of the TRAPPIST-1 JWST Community Initiative also played key roles in the project.

WP6: *Limits of Phototrophy: infra-red acclimated/adapted phototrophic life on modern Earth*

The astrophysical component of the project (WP1-5) provided strong constraints on the surface irradiation of the TRAPPIST-1 planets, which were then used to explore the possibilities of phototrophy in the infra-red range on these extrasolar worlds. This investigation examined a wide range of anoxygenic and oxygenic photosynthetic Earth microorganisms under “TRAPPIST-1–like” conditions, as well as under Early- and modern-Earth conditions. The selected organisms included strains from extreme environments already available in the laboratory of the coordinator E. Javaux (ULiege), as well as cultures already maintained in the laboratories of Coordinator E. Javaux, Promotor Y. Lara (ULiege), and Promotor P. Cardol (ULiege), supplemented by additional strains acquired during the project. This work focused on identifying the limits of the usable light spectrum towards the IR, and on characterizing the biochemical and ecological strategies developed by Earth life to harvest IR photons and to protect against intense UV radiation. It involved the study of microbial cultures selected for their shaded or low-light habitats (Task 6.1) and for their IR photosynthetic abilities, using biophysical, biochemical, and genetic analyses.

At the start of the project, seven Antarctic cyanobacterial strains were already available in the coordinator’s laboratory. Additionally, a selection of Antarctic or endolithic cyanobacterial strains were purchased from the BCCM/ULC collection (which maintains 140 Antarctic strains) and from the SAG culture collection. Furthermore, anoxygenic phototrophic bacteria were selected, along with photosynthetic microeukaryotes obtained from SAG and Roscoff Culture Collection (RCC), in order to cover both ecosystem diversity and phylogenetic diversity.

Cell cultivation under visible and IR light, and under IR-only illumination (Task 6.2) allowed the characterization of survival rates and pigment compositions of selected strains, while photosynthetic activity under IR irradiance (with and without visible light) was studied more deeply (Task 6.4). The approaches used included measurements of photosynthetic activity by fluorimetry and absorption spectroscopy, pigment content by HPLC, protein-pigment associations by native gel electrophoresis. In parallel, the genome of IR-adapted bacteria (Task 6.3) was sequenced to identify orthologous and paralogous protein sequences involved in the cores of their photosynthetic apparatus. The promotor Y. Lara was hired for the full duration of the project in the Coordinator E. Javaux’s laboratory, and a PhD student (T. Feller) joined Promotor P. Cardol’s laboratory, both contributing mostly to WP6, WP7 and WP8.

WP7: *Signatures and evolution of phototrophic life on the early Earth*

A selection of strains used in WP6, in addition to a subset of strains already cultivated in E Javaux’s laboratory, was characterized using FTIR (Fourier Transform Infrared) microspectroscopy, Raman microspectroscopy, and optical, confocal and electronic microscopy in order to define new biosignatures that could be preserved and detected in the fossil record (WP7). The biosignatures (such as UV-screen and photosynthetic pigments, walls or sheaths biopolymers and ultrastructures, morphology and distribution within the host rocks) were then sought in fossil material (WP7) originating from curated collections and from new field or drill core sampling in early Earth environments.

Promotor E. Javaux had access to an Archean geological site, the 3.22 Ga Moodies Group in the Barberton area of South Africa and to new drill cores that stored in Berlin and obtained through the International Continental Deep drilling Program (ICDP) BASE (Barberton Archean Surface Environment) project (for which E Javaux is one of the PIs). The Moodies Group is the earliest well-preserved marine to terrestrial siliciclastic succession, hosting the oldest undisputed microfossils (Javaux et al. 2010) and extensive microbial mats including mats in intertidal environments, cave dwelling mats (Heubeck et al., 2009) and mats in terrestrial fluvial environments (Homann et al., 2018). The new drill cores provided a unique pristine material to investigate traces of early phototrophs. A postdoc (B Johnson) supported by another project (FRS-FNSR PDR, E Javaux) worked also on this Archean material and contributed to WP7. A PhD student (FNRS-FRIA) M Coutant investigated the biogenicity of putative earliest microfossils or biomorphs from 3.45 Ga Strelley Pool Fm, Australia, using nanoscale microcopy and petrology.

Additional fossil material from the coordinator’s collection that was investigated as they included Proterozoic microbial mats and cells. One PhD student (C. Demoulin) and one postdoc (M.-C. Sforna), supported by another project (EOS ET-HOME, with Promotors E Javaux and V Dehant as two of the PIs) contributed to the analysis of the Proterozoic material, as well as the coordinator E Javaux who worked on the earliest Paleoproterozoic microbial ecosystem (McDermott Formation, Australia) preserving both cyanobacteria and early eukaryotes. The new data from the identification of microfossils as phototrophs of particular clades and from well-dated geological successions were integrated with published evidence of fossil phototrophy. Together, they improved our understanding of the timing and patterns of evolution and diversification of phototrophic metabolisms on early Earth and their impact on the emergence and evolution of complex life and on planetary evolution. These results will also support biosignatures detection strategies during the mission ExoMars 2028 in which Promotor E Javaux is involved, and for Mars sample return missions.

WP8: *TRAPPIST Biodome: infra-red acclimated/adapted phototrophic life under TRAPPIST UV, IR, atmospheric conditions*

Based on results from Tasks 6.2, 6.3, microbial strains were selected for cultivation under TRAPPIST star light and atmospheric conditions constrained by the results of astrophysical WP 1 to 5, for estimating the possibility of phototrophy in the infrared range by Earth microbial communities (WP6) and by hypothetical forms of life on exoplanets around VLM stars. Preliminary environmental parameters already available in the laboratories of Promotor M. Gillon and International Partners M. Turbet and F. Selsis were used to initiate the development of the biodome, with adjustments incorporated as new data became available.

The required equipment ("biodome") was designed starting in year 1 and consists of an incubator equipped with customed-made LEDs arrays mimicking the light spectrum of the VLM stars, and a controlled gas phase reproducing the atmospheric gaseous potential composition of the target exoplanet. Sensors connected to a computer allow continuous monitoring of the production of O_2 by oxygenic photosynthesis and CO2 concentration. In the future, beyond the duration of the project, a reflectivity detection system to measure light reflectance will be also included, as described in the original miniature system (Battistuzzi et al., 2020). The Biodome will also allow the cultivation of both liquid and solid biomass, from single strains to complex microbial communities.

WP9: *Phototrophic life on rocky habitable planets around very-low-mass stars*
Based on all data generated in WPs 1-8, WP 9 aims to provide an estimate of the possible biomass by hypothetical primary producers using IR photosynthesis on habitable planetary surfaces around TRAPPIST-1 at a planetary scale and to assess possible signatures that could be detected in exoplanet atmospheres or on surfaces around VLM stars. Using data from WP8 which include absorption spectra as in Ritchie and Sma-Air (2020), but also growth rates, and photosynthetic efficiencies under TRAPPIST-1 exoplanets conditions, we aim to estimate primary productivity at a planetary scale on rocky habitable planets around TRAPPIST-1. This will provide estimates for a biosphere active only on the illuminated side or only at the terminator based on constraints from data and atmospheric modelling from WP1 to 5. Modelling of possible effect on atmospheric composition of anoxygenic/oxygenic, aerobe/anaerobe phototrophs in the IR range will be carried out. In the future, detection of possible conventional (gaseous) biosignatures and alternative (pigment reflectance) biosignatures will be tested using modelling of absorption and reflectance spectra of TRAPPIST habitable exoplanets. All network members have contributed to this WP that is still ongoing beyond the project.

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4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

Scientific Results

WP1 *The variable photon and proton emission of the star TRAPPIST-1*

WP1 activity started with the analysis of time-series photometry of TRAPPIST-1 acquired with the Very Large Telescope (VLT) in g' band (400-550 nm) that show a very strong variability (frequent flares). Parallel observations with the SPECULOOS-South facility (also at Paranal in Chile) in the I+z band (700-1000 nm) do not show any of the flare-like patterns seen in the g'-band light curves, which suggest a chromospheric origin (H-beta line). The activity of the star was also assessed with a multi-year survey of the star with HST/STIS in Lyman-alpha. These observations confirmed a high frequency (sub-hour) of microflares (~10^{29} erg/flare), and the rotation period of the star to be ~3.3 days (Berardo et al. 2025).

Within WP1, the spectral activity of the ultracool dwarf TRAPPIST-1 was characterized using new JWST/NIRISS and NIRSpec observations together with archival optical and infrared spectra (UVES, MagE, SpeX). This work produced new multi-instrument stellar datasets and the most complete spectral energy distribution (0.6–5 µm) of TRAPPIST-1 to date, enabling refined measurements of its luminosity, effective temperature, and metallicity (Davoudi et al. 2024). Across this broad wavelength range, we identified photospheric and chromospheric features, including H_2O, CO, FeH, TiO, VO bands and key emission lines such as Hα, Ca II, and Na I D, which trace high-energy photon emission and the star's variable radiation environment.

The activity of TRAPPIST-1 was quantified through analysis of these emission lines and previously reported optical/XUV flares. Persistent Hα emission in all datasets, combined with evidence for miniflares in JWST observations, confirms significant magnetic activity and short-timescale variability relevant to the star's photon and proton output. These results provide new constraints on the high-energy stellar environment impacting atmospheric escape and photochemistry on the TRAPPIST-1 planets.

A detailed study of gravity-sensitive indices (FeH, VO, K I, H-band continuum) revealed that TRAPPIST-1 exhibits intermediate-gravity signatures despite its old age (Davoudi et al. 2025). This behavior likely reflects the effect of magnetic activity and other unresolved stellar properties and can have direct consequences for planetary transmission spectroscopy. WP1 therefore produced new protocols and methodologies for evaluating stellar contamination and characterizing the radiative behavior of active ultracool dwarfs.

WP1 contributed significantly to personnel training and skills development, including training in high-resolution spectroscopy, JWST spectral analysis, flare diagnostics, and modeling of ultracool dwarf atmospheres. Two peer-reviewed papers were published as PORTAL outputs, and the work strengthened international collaborations with MIT (B. Rackham, J. de Wit), UCSD (A. Burgasser), and the broader TRAPPIST-1 community. The datasets and analysis techniques developed in WP1 are now reusable for future JWST programs and exoplanet atmospheric characterization.

WP2 *Transmission spectroscopy of TRAPPIST-1 planets with JWST*
WP2 aimed to produce homogeneous, instrument-level transmission spectra for all JWST observations of the TRAPPIST-1 planets and to assess how stellar contamination, flares, and limb-darkening assumptions influence atmospheric inferences. The core deliverable is the complete reduction of all NIRSpec/Prism and NIRISS/SOSS datasets. All raw NIRSpec data were gathered from MAST and reduced at full spectral resolution using the Eureka! pipeline. High-resolution NIRISS/SOSS time-series from the Montreal collaboration are processed analogously. From these reductions, white-light and spectroscopic light curves are extracted at native wavelength resolution and in optimized bins.

The TRAFIT code was extended within WP2, including a new flare model in which flares are represented as blackbody emitters with free temperature, amplitude, and temporal profiles. WP2 also developed new protocols for automated TRAFIT input preparation and systematic testing of limb-darkening models (linear and quadratic) using wavelength-dependent stellar-atmosphere computations. Each transit is modeled with and without flares, and with or without external limb-darkening priors, to quantify how these choices affect the reconstructed transmission spectra.

A key scientific goal of WP2 is the quantification of stellar contamination in the planetary spectra. Early results confirm the findings of Lim et al. (2023), with one NIRISS transit of TRAPPIST-1 b showing a significant contamination component, while the first transit appears less affected.

Atmospheric retrievals are performed using the POSEIDON retrieval framework, which includes a dedicated stellar-contamination module. POSEIDON enables joint modeling of planetary atmospheres and heterogeneous stellar surfaces, retrieving molecular abundances, temperature structures, cloud parameters, and stellar contamination parameters such as spot/facula covering fractions and temperatures.

WP2 will deliver a publication presenting (1) raw and contamination-corrected transmission spectra for all seven TRAPPIST-1 planets, (2) stellar-contamination–aware atmospheric retrievals, and (3) combined spectra grouped by instrument and by planet. These results will constitute the first homogeneous JWST atmospheric atlas of a complete ultracool-dwarf exoplanet system.

The search for atmospheres around TRAPPIST-1 planets was completed by JWST GO Program 3077 (PI: M. Gillon) that observed the double phase curve of TRAPPIST-1b and c at 15 microns with the MIRI instrument aboard JWST. The large amplitudes of the planets' phase curves are consistent with an inefficient heat redistribution to the night side. Atmospheric models with surface pressures ≥1 bar and efficient greenhouse effects are strongly disfavoured for both planets. TRAPPIST-1 b is unlikely to possess any substantial atmosphere, while TRAPPIST-1 c may retain a tenuous, greenhouse-poor O_2-

dominated atmosphere or be similarly airless with a more reflective surface. These results suggest divergent evolutionary pathways or atmospheric loss processes despite similar compositions. These measurements tightly constrain atmosphere retention in the inner TRAPPIST-1 system (Gillon et al. 2025).

WP3 *Build-up of TRAPPIST-1 planet atmospheres*

Work Package 3 (WP3) focused on the fundamental question of whether the TRAPPIST-1 planets can build and maintain atmospheres through volatile outgassing from their interiors. This process is critical for habitability and is controlled by the planets' internal structure, composition, and thermal evolution, which are strongly influenced by tidal heating. Our research progressed from developing foundational models to running fully coupled simulations.

Developing Advanced Interior Models: We first developed and benchmarked a versatile code to describe the internal structure of the planets by a set of 1D depth-dependent physical quantities (such as density, pressure, temperature, composition) based on their observed mass and radius and taking into account compositionally distinct layers (iron core, silicate mantle, potential water/ice). We used a Markov Chain Monte Carlo (MCMC) sampler to determine probability density distributions for the main interior parameters, such as the mass fractions of the different layers. We demonstrated that including additional constraints, such as the stellar Fe/Si abundance ratio considerably reduces the ranges of the 1σ-confidence intervals for the water, mantle, and core mass fractions. However, for the host star TRAPPIST-1, Fe/Si is not yet reliably constrained.

Calculating Tidal Dissipation: We then developed and validated a computer code to calculate the tidal dissipation (heating) within the multi-layered structure of our interior models, benchmarking our results against published data for Io. A key finding was that simple, homogeneous models are inaccurate. Our detailed models showed that tidal heating is concentrated in specific zones, such as in the ice layer, at the core-mantle boundary, or within partially molten rock layers (so-called "mush layers") as shown in Figure 2 and Figure 3**a**. The calculated total dissipation could differ by 2-3 orders of magnitude from simpler models. The heat generated by tidal dissipation strongly depends on the local temperature, with warmer mantles producing thicker partially molten (mush) regions and large viscosity drops. As long as the mantle is not fully liquid, higher temperatures yield substantially larger total tidal power, with the mush layers contributing the dominant fraction of the total dissipation (Figure 3b).

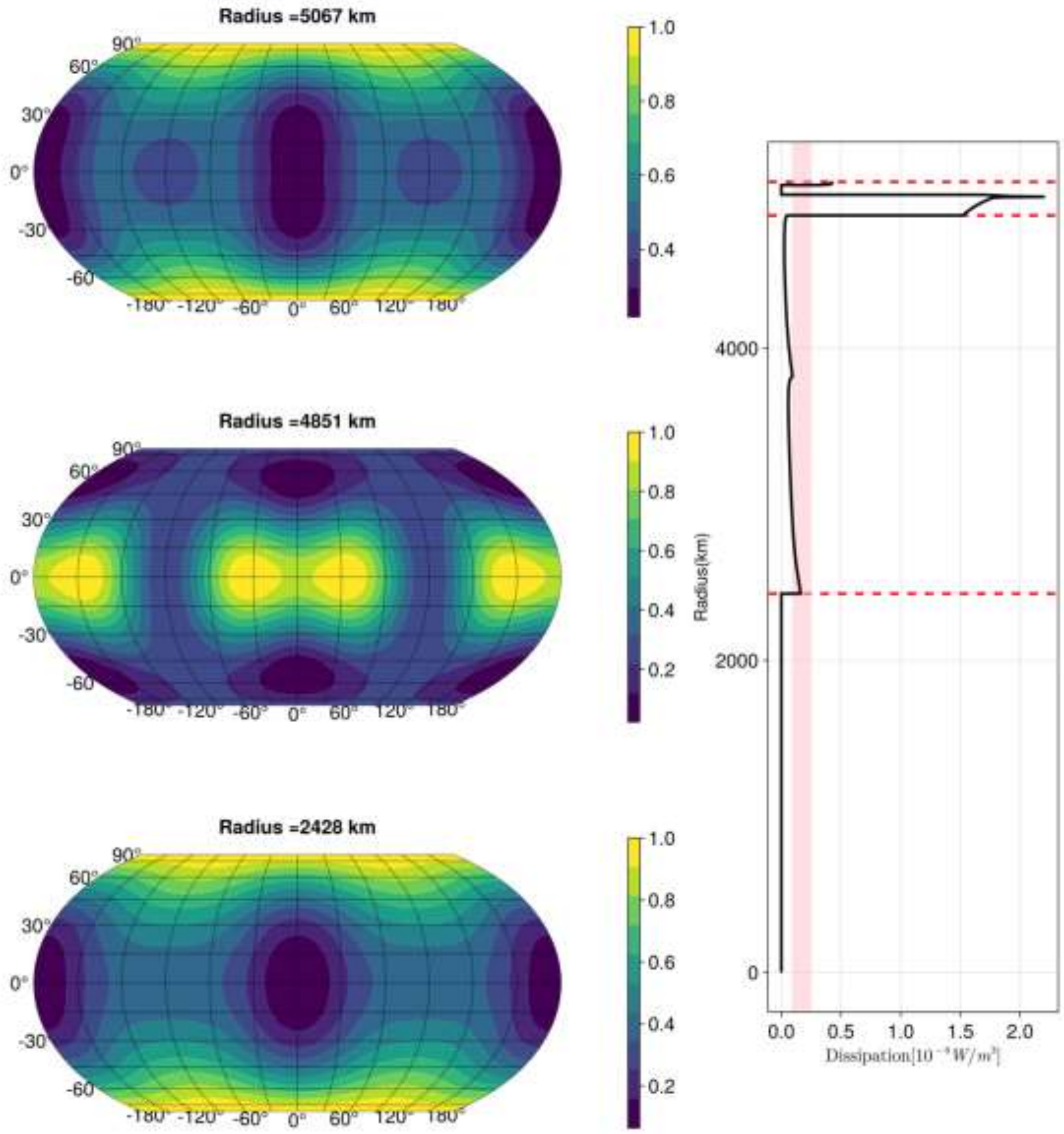

Figure 2: **Tidal dissipation**. Left Panel: Lateral distribution of the ratio of tidal dissipation within the interior of Trappist-1d relative to the maximum value at each depth. The three rows show this ratio at the surface (top), ice-mantle boundary (middle), and core-mantle boundary (bottom), with radii indicated by the red dashed lines in the Right Panel. Right Panel: Radially averaged power density profile from tidal dissipation within Trappist-1d. The pink shaded region represents the range of radiogenic heating rates, with the lower limit from a CI chondrite composition (Lodders & Fegley 1998) and the higher limit from a Bulk Silicate Earth model (McDonough & Sun 1995).

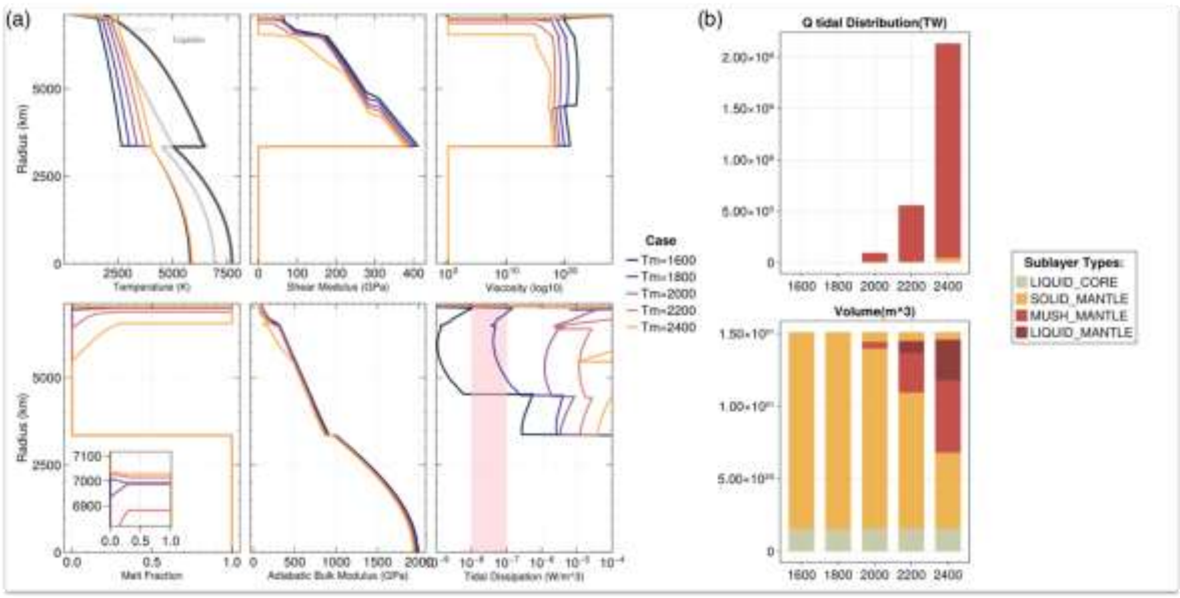

Figure 3: Effect of temperature profiles on interior structure and tidal heating for TRAPPIST-1b. (a) Top panels show radial profiles of temperature, shear modulus and viscosity, and bottom panels show radial profiles of melt fraction, adiabatic bulk modulus, and tidal dissipation for different mantle temperature cases. (b) Top panel shows the total tidal dissipation power and bottom panel shows the distribution among the different layer types (liquid core, solid mantle, partially molten mantle, and liquid mantle).

Coupling Thermal Evolution and Outgassing: Our main achievement was successfully coupling interior structure and tidal models with thermal evolution simulations, using both a 1D parameterized model (for efficient parameter space exploration), and the 2D mantle convection code CHIC (to model spatial distribution and volatile transport). This allowed us to simulate the planets' thermal evolution and, crucially, their outgassing history over billions of years.

For the hot inner planets (e.g., TRAPPIST-1b), we identified a strong positive feedback mechanism, which is absent in previous simplified models. As temperature increases, mantle viscosity decreases, shifting the peak viscoelastic response closer to the tidal forcing. This increases tidal dissipation and hence internal heating. If the generated heat is not balanced by efficient heat loss, the system could approach runaway melting, potentially resulting in a mostly molten mantle. The evolutionary pathway depends on the initial thermal state, mantle cooling efficiency, radioactive heating, and rheology.
For planets experiencing moderate tidal heating, like TRAPPIST-1d, our calculations show that tidal heating increases the mantle temperature by approximately 100 K. More importantly, our simulations demonstrate that this enhanced tidal heating accelerates volatile outgassing. A planet with tidal heating can develop its secondary atmosphere much more rapidly—within the first ~1 billion years—compared to a planet without tidal heating (Figure 4).

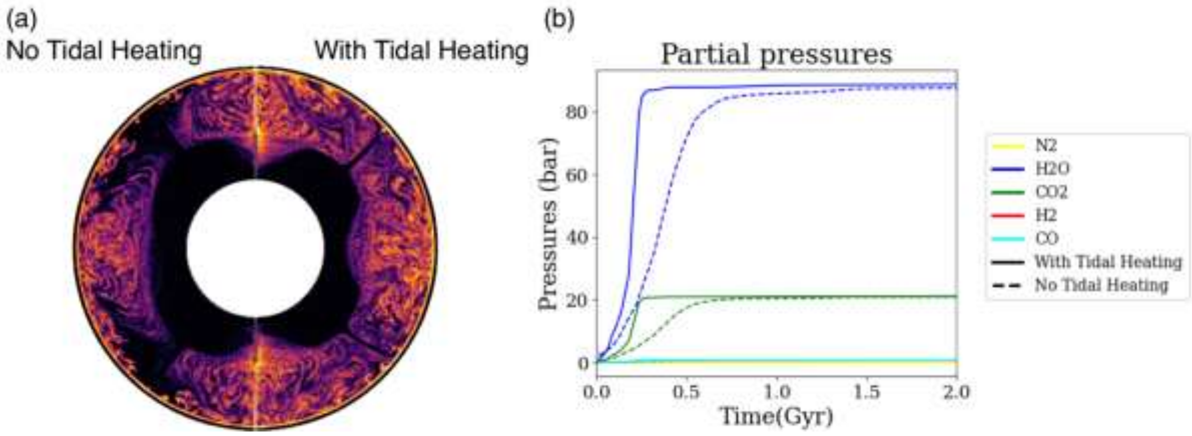

Figure 4: (a) Mantle volatile depletion in TRAPPIST-1d after 1 Gyr of evolution, comparing models without tidal heating (left) and with tidal heating (right). Yellow-pink regions indicate higher levels of volatile depletion. (b) Evolution of atmospheric partial pressures over time (0-2 Gyr) for N_2, H_2O, CO_2, H_2, and CO, under tidal heating (solid lines) and non-tidal heating (dashed lines) conditions.

WP4: *Atmospheric forward and reverse modeling for TRAPPIST-1 planets*

We continued the development of our 1D and 3D atmospheric modeling tools, which build upon the *Generic PCM* climate model (Turbet et al. 2018) and its associated observables modules (e.g., Pytmosph3R; Caldas et al. 2019). We applied these models to the interpretation of nearly all TRAPPIST-1 planets observed with JWST.
Our work focused first on the JWST MIRI observations of TRAPPIST-1b and TRAPPIST-1c (Maurel et al. 2025; Maurel et al., in prep.), carried out in the framework of Alice Maurel's PhD thesis supervised by M. Turbet (defended in September 2025). We then extended the modeling analysis to transmission spectroscopy with JWST NIRSpec data for the outer planets: TRAPPIST-1d (Piaulet-Ghorayeb et al. 2025), TRAPPIST-1f (Lim et al., submitted), and TRAPPIST-1g (Benneke et al., submitted).
Our 3D modeling results indicate that TRAPPIST-1b is unlikely to host an atmosphere (Gillon et al. 2025, Maurel et al. 2025), while TRAPPIST-1c may retain a thin one (Lagage et al., in prep.; Maurel et al., in prep.). For the other, outer TRAPPIST-1 planets, our modeling work shows that current JWST observations remain consistent with multiple scenarios: no atmosphere, tenuous atmospheres, or atmospheres with high-altitude cloud decks. In particular, our 3D simulations highlight the role of clouds in flattening transmission spectra (Fauchez et al. 2019), thereby requiring additional observational effort to identify molecular features.
These results informed several ambitious JWST Cycle 5 observing proposals submitted by our team, made possible by the predictive capabilities of our 1D and 3D climate models. Future and ongoing JWST programs will enable a more detailed exploration of the remaining atmospheric scenarios.

WP5: *Exploration of the possible irradiation of the (sub)-surface of TRAPPIST-1 planets*

Studies were conducted on the irradiation environment and atmospheric evolution of TRAPPIST-1e. As part of WP5, simulations investigated how the stellar UV flux propagates through oxidizing atmospheres and how this affects subsurface and surface conditions. These simulations showed that ozone production can be enhanced under oxidizing conditions, but that the resulting changes in surface UV flux remain small compared with the impact of clouds and the large variations in stellar zenith angle associated with synchronous rotation. Recent work (Cooke et al., 2023, 2024) demonstrated that uncertainties in the TRAPPIST-1 UV spectrum produce large variations in modeled ozone abundances, in some cases leading to potentially harmful ozone concentrations at the surface. These results indicate that any conclusions related to atmospheric chemistry or surface habitability remain strongly dependent on the poorly constrained UV output of the star.

In parallel, Jaziri et al. (in revision) explored the potential for atmospheric oxygenation on TRAPPIST-1e using a coupled photochemical–climate model (Generic-PCM). Their results suggest that, under certain UV conditions, M-dwarf irradiation may favor more efficient ozone formation and earlier atmospheric oxidation than on Earth, which could also enhance the detectability of ozone with JWST. Although these findings point to a potentially favorable pathway for oxygen-rich atmospheres around M dwarfs, they remain limited by the same uncertainties in stellar variability and UV spectral shape.

Overall, these studies converge on the need for improved characterization of the TRAPPIST-1 radiation environment. Better constraints on UV fluxes and temporal variability are essential to reliably model atmospheric chemistry, evaluate habitability, and discriminate between biotic and abiotic oxygenation scenarios on TRAPPIST-1e and similar planets.

WP6: *Limits of Phototrophy: infra-red acclimated/adapted phototrophic life on modern Earth*

During the first year of the project, 63 cyanobacterial strains, 37 Archaeplastida (primary eukaryotic algae), 59 complex algae (Crypstista/Discoba/Haptista/Rhodophyta/Sar) plus the strain five aerobic anoxygenic bacteria were collected and maintained, and cultivated under IR illumination. Strains were collected from public culture collections ULC/BCCM, SAG, CCALA, PCC, RCC and BLCC culture collections. Strains habitat range from Antarctic soil crust, to Florida's' mangrove, and Atacama Desert.

Spectroscopic screening of cyanobacterial strains resulted in the highlight of NIR absorption adapted strains from different lineages (Chroococcidiopsis, Leptolyngbya, Nostochopsis, Pleurocapsa and Stanieria). Three marine and one freshwater strain of Stanieria were characterized by absorption and fluorescence, the freshwater SAG33.87 strain, marine PCC7301 and marine PCC7304 showed FARLIP far-red light photoacclimation (FARLIP) adaptation (a mechanism that allows some cyanobacteria to utilize far-red light (FRL) for oxygenic photosynthesis (Figure 5). Absorption spectra of in vivo biomass of SAG33.87 suggested a change in chlorophyll composition with an absorption peak around 705-710 nm potentially related to Chl f and/or Chl d. The studied Stanieria strains belong to the same monophyletic cluster within the Pleurocapsales order. The freshwater strain SAG33.87 is the most basal of the studied Stanieria. The strain Pleurocapsa CCALA 161 showed FARLIP adaptation too. This suggests that FARLIP taxa may often occur in pleurocapsalean cyanobacteria. Finally, the strain CCALA 049 also showed FARLIP adaptation but was confirmed to be part of the Chroococcidiopsis cluster.

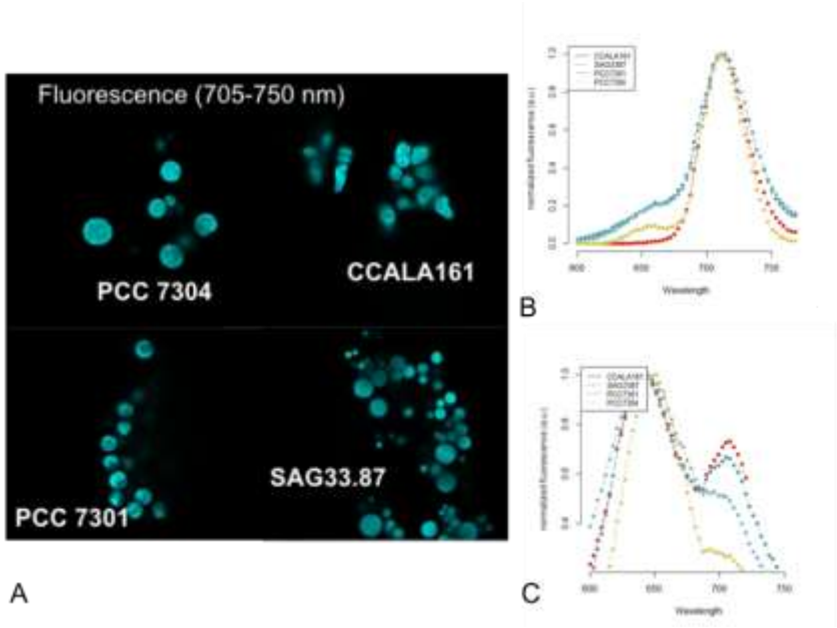

Figure 5: **Fluorescence microscopy picture of IR adapted Pleurocapsalean (*Stanieria* sp PCC7301/PCC7304/SAG33.87; *Pleurocapsa* CCALA161)** (A), single cell chlorophyll fluorescence spectra after 440 nm as excitation source of IR-adapted strains (B), single cell chlorophyll fluorescence spectra after 577 nm as excitation source of IR-adapted strains (B).

Photosynthetic organisms have evolved diverse strategies to adapt to fluctuating light conditions, balancing efficient light capture with photoprotection. Cyanobacteria are an ancient clade that developed remarkable adaptability to diverse light conditions through photoacclimation strategies, including Low-Light Photoacclimation (LoLiP), Far-Red Light Photoacclimation (FaRLiP), and Complementary Chromatic Acclimation (CCA). We investigated these mechanisms in *Stanieria cyanosphaera* SAG 33.87, a cyanobacterium from the Pleurocapsales order isolated from the reed beds of Neusiedler See, Austria. Using a combination of spectroscopic, biochemical, genomic, and fluorescence lifetime imaging analyses, we demonstrate that *S. cyanosphaera* employs CCA, LoLiP and FaRLiP to modulate its photosynthetic apparatus in response to low and far-red light environments (Figure 6). Genomic analysis revealed the presence of canonical LoLiP and FaRLiP clusters, including genes encoding specialized subunits of photosystems and phycobilisomes (Figure 7). This is the first report in the Pleurocapsales order. Under far-red light, significant structural remodeling of photosystems was observed, with incorporation in PSII and PSI of chlorophyll *f,* a pigment enabling light absorption beyond 700 nm, accounting for ~3-4% of total chlorophyll. In low-light conditions, *S. cyanosphaera* utilized LoLiP to enhance far-red light absorption. High-light stress responses were characterized by increased carotenoid production, although accompanied by reduced photosynthetic efficiency. Together, these findings highlight the ecological versatility of *S. cyanosphaera*, its dependence on far-red and low-light niches, and the evolutionary importance of FaRLiP and LoLiP in cyanobacterial success in light-limited environments.

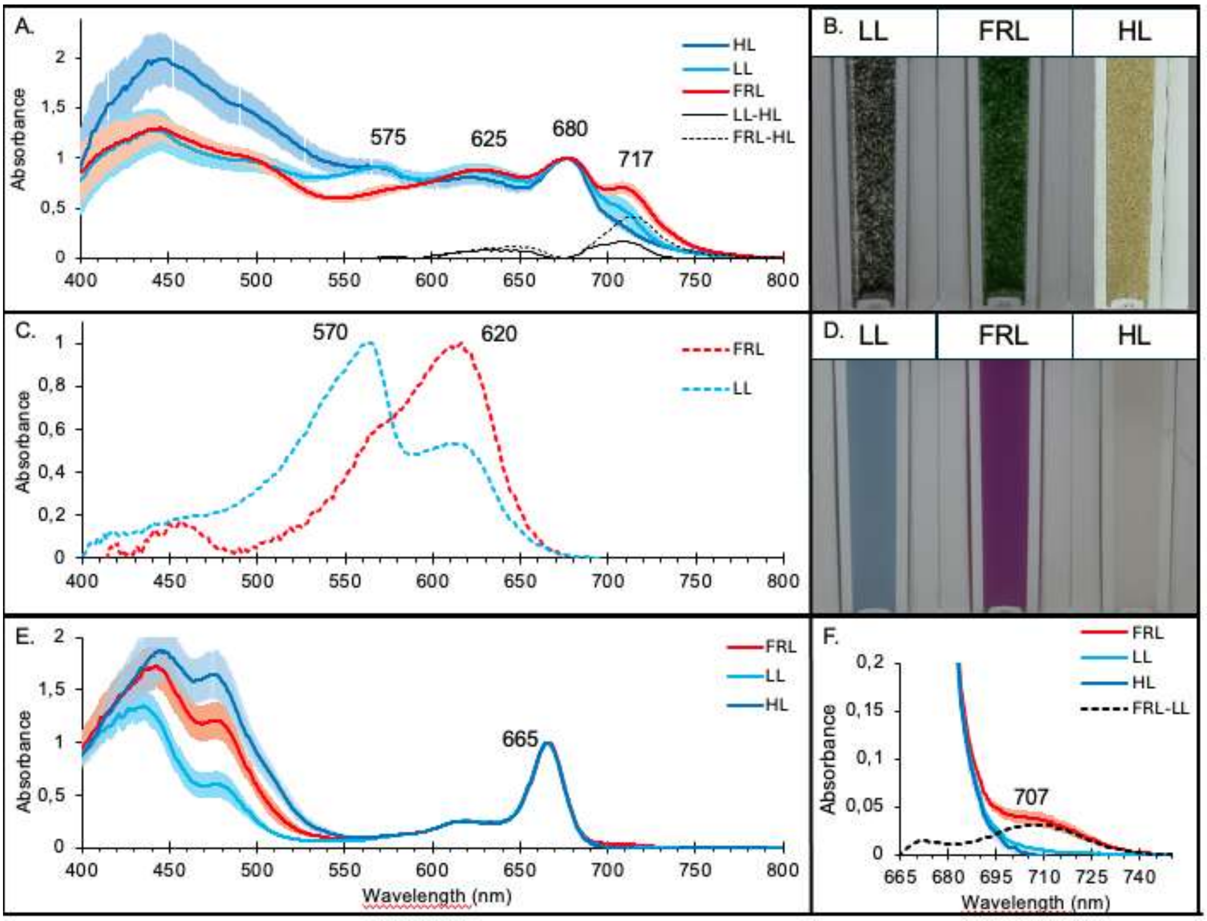

Figure 6 Absorbance Spectra of *S. cyanosphaera SAG 33.87* under different light conditions. (A) Average Absorbance spectra of cultures acclimated to low light (LL, light blue line), high light (HL, dark blue line) and far-red light (FRL, red line), following 17 days of exposure. Each spectrum is normalized to the peak at 675 nm (Error bars represent standard deviation for LL (light blue), and FRL (light red), with (n=10). The difference spectra between LL and HL, and between FRL and HL are represented by solid and dotted black lines, respectively. (B) Representative photograph of in vivo cultures under different light conditions. (C-D) Absorbance spectra and photograph, respectively, of membranes in HEPES mixture after methanol extraction. Spectra are normalized to their maximum absorption. (E-F) Absorbance spectra of methanol extracts from previous cultures. Spectra are normalized to the peak at 665nm, with n = 8 for LL and FRL, and n = 4 for HL.

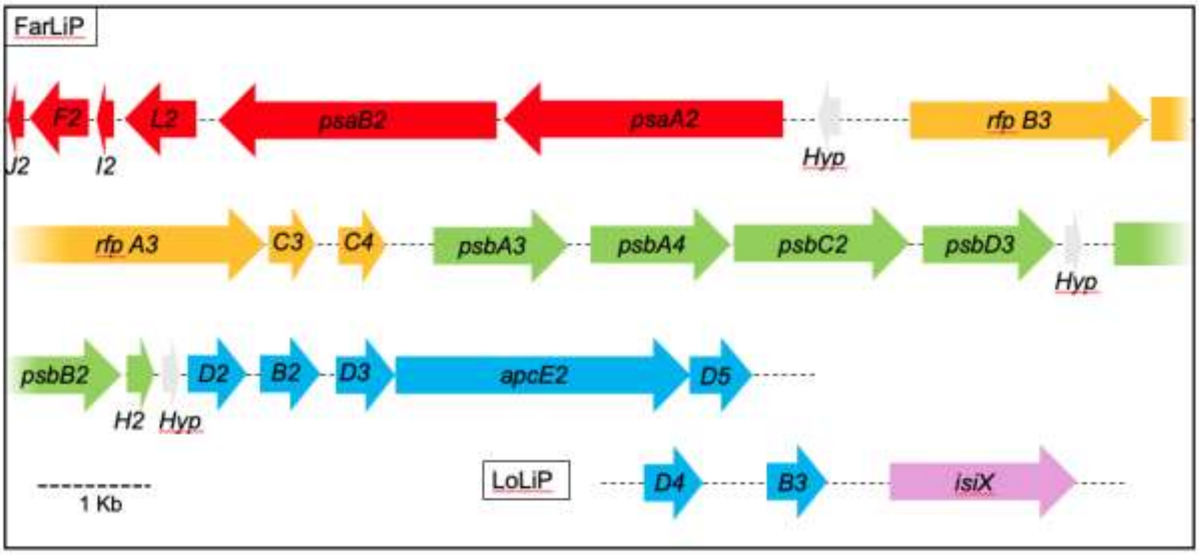

Figure 7. Physical map of FarLiP and LoLiP gene clusters in *"Stanieria cyanosphaera"* SAG 33.87. *FarLiP: Core subunits of PSI (psa, red), core subunits of PSII (psb, green), core subunits of PBS (apc, blue), knotless phytochrome photoreceptor (rfpA), response regulators rfpB and rfpC (Orange), and hypothetical proteins (grey). LoLiP: core subunits of PBS (apc, blue) and Chl a-binding protein (isiX, pale blue). Relative size of gene and position are represented in nt.*

In green algae and land plants, this involves specialized light-harvesting complexes (LHCs), non-photochemical quenching, and state transitions driven by dynamic remodeling of antenna proteins associated with PSI and PSII. Euglena gracilis, a flagellate with a secondary green plastid, represents a distantly related lineage whose light-harvesting regulation remains poorly understood. Although spectral shifts under different light regimes have been observed, their molecular basis has been unknown. Here, through integrated phylogenomic, proteomic, structural, and spectroscopic analyses, we identify a novel chlorophyll a far-red-absorbing antenna complex in E. gracilis, composed of a species-specific LHC E (Lhce) protein family (Figure 8). This antenna forms a pentameric complex under low light and transiently associates with PSII during far-red light exposure. It is structurally and functionally distinct from canonical LHCII trimers and absent in Viridiplantae. Additionally, PSI in E. gracilis is surrounded by an expanded belt of Lhce and LhcbM proteins surrounding a minimal core. These findings reveal a unique mechanism for regulating PS antenna size in E. gracilis that is distinct from known models in plants and green algae and highlights an alternative evolutionary strategy for light acclimation in organisms with secondary plastids (Figure 9).

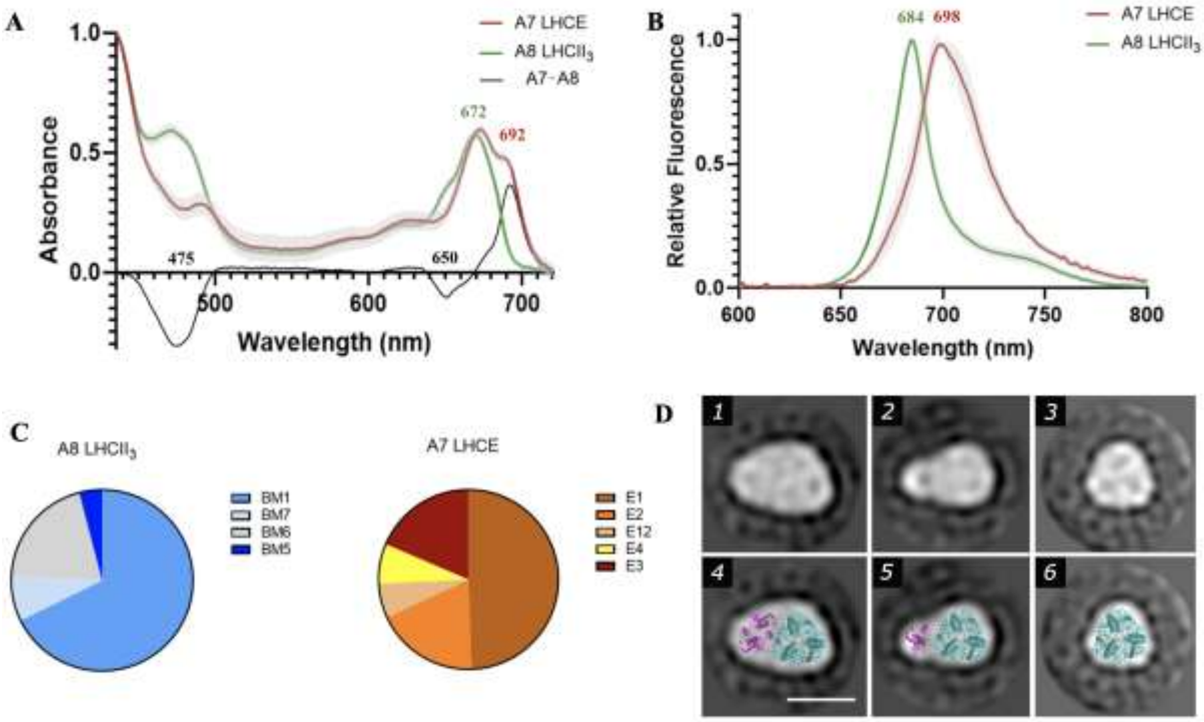

Figure 8. Analysis of the Euglena gracilis light-harvesting complex (LHC) E antenna complex. (A) Absorption spectra of isolated LhcE antenna complex and LHCII trimers (LHCII3), together with the difference between their absorbance. A7 and A8 refer to the bands shown in Fig. 2A. The lines represent means and the shaded areas are the SD, based on three independent biological replicates. (B) Room-temperature fluorescence spectra of isolated LhcE antenna complex and LHCII3. (C) Relative amounts of LHC proteins in the 110 kDa (LHCII3) and 180 kDa (LHCE5) antenna complexes. Data are based on three independent biological replicates. D. Averaged 2D projections of the LhcE antenna. Three major classes were identified, with a class sum of 4028, 2907, and 3840 particles, for A, B, and C, respectively. The larger LhcE complex comprises up to five LhcE monomers (A, D): one trimer (cyan) plus 2 monomers (violet). The smaller classes might correspond to LhcE antenna complexes with detached monomers (B, C, E, F). The scale bar is 10 nm.

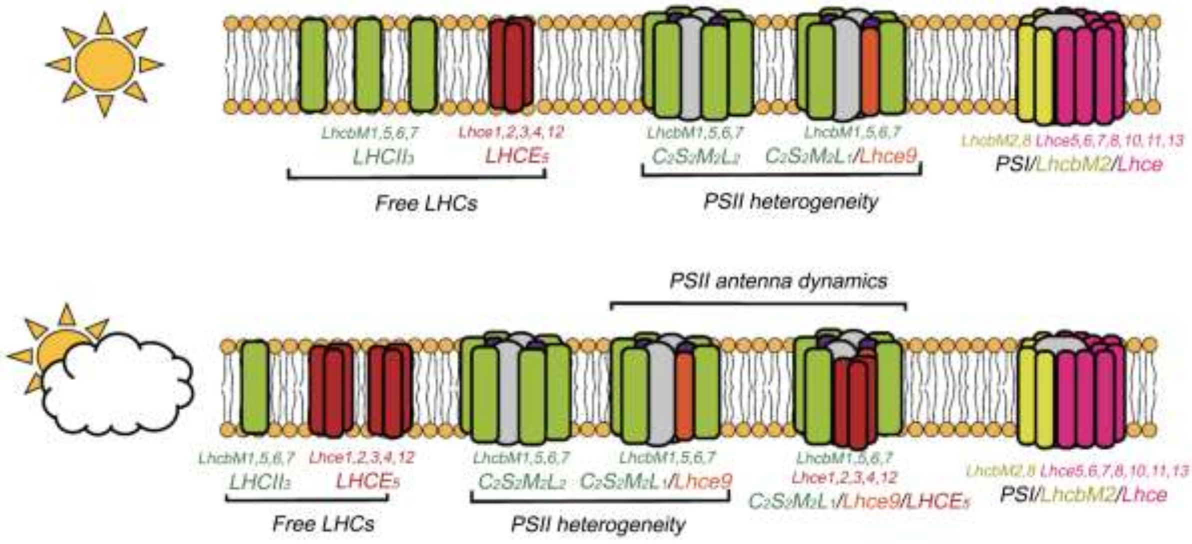

Figure 9. Proposed mechanism for light adaptation in Euglena gracilis, showing the differences in distribution of photosynthetic pigment–proteins complexes within the thylakoid membrane under medium light conditions (top) low light/far-red light conditions (bottom).

WP7: *Signatures and evolution of phototrophic life on the early Earth*

Starlight is a source both of strong lethal radiation (e.g., UV) and of unlimited and efficient energy. Therefore, life on Earth has developed strategies to protect itself from the harmful radiation and at the same time, to use photons from the visible to infrared wavelengths (i.e., phototrophy) very early on (more than 3.4 Ga). If life exists elsewhere, it might have evolved analogous strategies. On Earth, cyanobacteria developed multiple strategies to avoid lethal effects of UV radiation. One of these strategies is to synthesize extracellular UV-screening pigments which accumulate in an exopolysaccharide sheath. So far, two classes of pigments were identified: the scytonemins and the gloeocapsins. Scytonemins are the more extensively characterized extracellular cyanobacterial UV-screening pigments (Garcia-Pichel and Castenholz, 1991; Proteau et al., 1993). They are indole-alkaloid extracellular pigments associated with polysaccharide sheaths, which protect cyanobacterial cells from UVA exposure (Proteau et al., 1993). Unlike scytonemins, the structure and biosynthesis pathway of the gloeocapsins have yet to be characterized. This lack of knowledge is mainly explained by the absence of cultivated gloeocapsin-producing strains, and thus, the impossibility to produce large amounts of purified molecules (Grant and Louda, 2013). During PORTAL project, we reported the production of a halochromic pigment in a new order of cyanobacteria (Synechococcales), represented by the strain *Phormidesmis nigrescens* ULC007. After isolation and partial purification of this compound, we compare with the enigmatic halochromic gloeocapsin produced by *Gloeocapsa alpina* by Raman and FTIR spectroscopy. FT-IR and Raman spectra of *G. alpine* and *P. nigrescens* ULC007 pigment extracts strongly suggested a common backbone structure. The high-pressure liquid chromatography-UV-MS/MS analysis of the ULC007 pigment extract allowed to narrow down the molecular formula of gloeocapsin to potentially five candidates within three classes of halochromic molecules: anthraquinone derivatives, coumarin derivatives, and flavonoids. With the discovery of gloeocapsin in *P. nigrescens*, the production of this pigment is now established for three lineages of cyanobacteria (including *G. alpina*, *P. nigrescens*, and *Solentia paulocellulare*) that belong to three distinct orders (Chroococcales, Pleurocapsales, Synechoccocales), inhabiting very diverse environments. This suggests that gloeocapsin production was a trait of their common ancestor or was acquired by lateral gene transfer. In parallel, cyanobacteria from different habitats ranging from Belgian limestone wall to Antarctic microbial mats were analyzed by Raman mapping. Both carotenoid distribution and extracellular pigments signature were examined. Carotenoid signal was intense and showed that they were located inside the cells most likely associated with thylakoids as already observed in the literature (Storme et al., 2015; Lara et al., 2022) except for anabaena ULC080 for which carotenoid signal was more intense in the heterocyte. The yellowish-brown extracellular pigment observed in some of the Nostocales and Stigonematales presented Raman signatures of scytonemin, signature of gloeocapsin were found in *G. alpina* and *P. nigrescens*. An orange-brown pigment was observed in polysacharride sheath of *C. polonicus* (Figure 10). Raman signature of this pigment appeared significantly different from gloeocapsin and scytonemin, which suggest the presence of a potential uncharacterized molecule only observed in this species.

This work represents an important step toward the elucidation of the structure of this enigmatic pigment and its biosynthesis, and it potentially provides a new biosignature for ancient cyanobacteria. It also gives a glimpse on the evolution of UV protection strategies, which are relevant for early phototrophic life on Earth and possibly beyond.

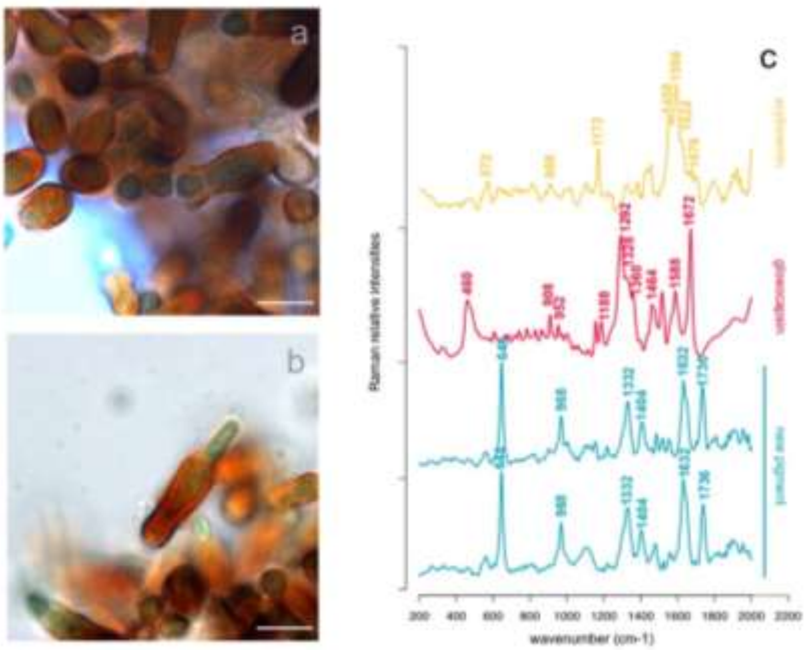

Figure 10, Raman signature of a so-far unknown pigment produced by *Chamaesiphon* sp.. a, b; Microphotography of the strain *Chamaesiphon* sp. using a light microscope**;** c Raman microspectrocopy of pigments scytonemin (in yellow), gloeocapsin (in red) and new pigment (in blue).

Pigments involved in phototrophy, produced by phototrophic organisms, or involved in UV protection were purchased from Sigma-Aldrich or obtained from cultivated and environmental microbes. These pigments were used as standard references for Raman analysis using 514, 633, and or 785 nm laser beams and to compute datasets for multivariate analysis. It included anthraquinone derivatives, carotenoids derivatives, coumarin derivatives, gloeocapsins, quercetin derivatives, scytonemins and unknown pigment signatures. Non-metric multidimensional scaling and hierarchical cluster analyses are being performed to evaluate its use for the quick characterization of groups of compounds (Figure 11).

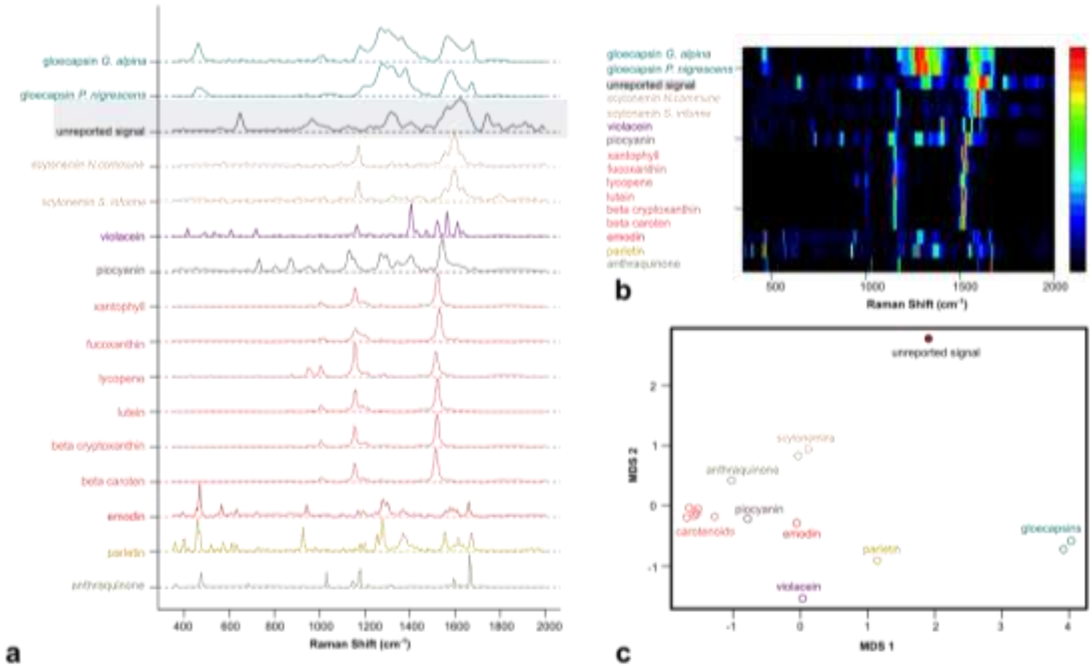

Figure 11: a, Reference pigments normalized Raman spectra; b, Heatmap representing band intensities of reference pigments; NMDS using spectral dataset.

Fossils of microorganisms are abundant in Precambrian rocks. However, their role in early Earth biogeochemical cycles and life evolution is not always established as most of their taxonomic affiliations and trophic modes remain unknown. Molecular clocks suggest an early origin of anoxygenic and oxygenic photosynthesis (Cardona et al, 2019; Demoulin et al, 2019; Sanchez-Baracaldo et al, 2022). Oxygenic photosynthesis is regarded as an essential process for the building of modern Earth atmosphere and the evolution of aerobic life on Earth. Constraining its timing of origin and its distribution among fossilized organisms is required for a better understanding of the evolution of ecosystems toward the modern biosphere. Therefore, the definition of criteria or biosignatures distinguishing early primary producers from heterotrophs is critical.

Chlorophylls and bacteriochlorophylls are key molecules for the completion of the photosynthesis reaction. Their degradation products may be preserved as geoporphyrins after diagenesis. Other biomolecules contain porphyrin nuclei such as numerous bacterial cofactors and hemes (e. g. cytochrome c oxidase, cytochrome P450, cobalamin B12) and can also be preserved as geoporphyrins.

The biosynthesis of porphyrins is considered an essential step in the evolution of early metabolisms, which probably diversified from chemolithotrophy and fermentation to methanogenesis and (anoxygenic then oxygenic) photosynthesis, both involving a variety of porphyrins (Lopez-Garcia et al 2006). Treibs in 1936 proposed that geoporphyrins preserved in the rock record (in fossil oils) most likely derived from (bacterio)chlorophylls.
Combination of morphological, chemical, and ultrastructural analyses and synchrotron-based X-ray Fluorescence (SR-XRF) and X-ray Absorption Spectroscopy (SR-XAS) of multicellular branching eukaryotic filamentous microfossils from the 1Ga Mbuyi-Mayi Supergroup (DRC) permitted the identification of tetrapyrrole moieties of Ni-porphyrins as chlorophyll derivatives (Figure 12), and *A. tetragonala* as one of the earliest multicellular eukaryotic algae. This new methodology, applicable to billion-year old, overmature rocks, provides new constraints on the evolution of eukaryotic oxygenic photosynthesis during the Precambrian and the diversification of primary producers in early ecosystems.

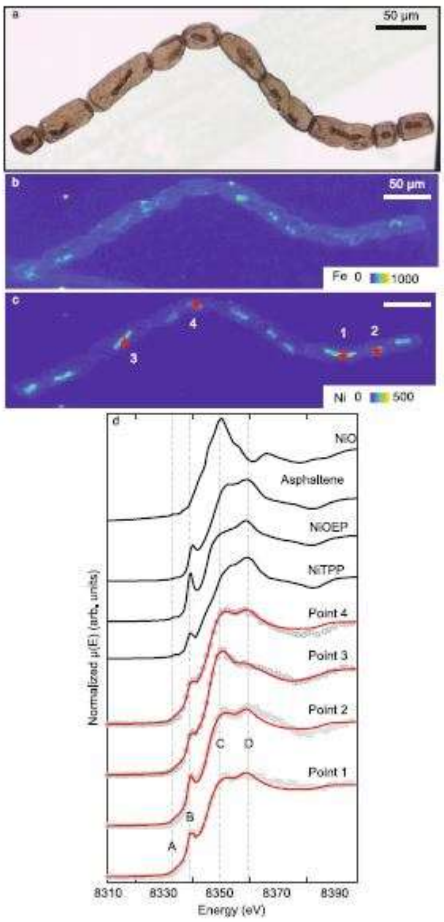

Figure 12, Presence of tetrapyrrole moieties highlighted by XANES analyses on intracellular inclusions in a 1 Ga eukaryotic multicellular microfossil *Arctacellularia*. a Microphotograph of the studied specimens. b, c Fe and Ni SR-µXRF maps obtained at SLS (pixel: 1.5 µm, 200 ms/px) showing the enrichment in Ni and Fe of the intracellular inclusions (ICI). Color scales correspond to normalized counts. d XANES spectra at the Ni K-edge of 4 ICIs performed in zones with low Fe content (gray circles) and their linear combination fitting (red lines) and XANES spectra of two Ni-porphyrin (NiTPP: Ni(II)-tetraphenylporphine, NiOEP: Ni(II)-octaethylporphine), asphaltene, and NiO standards. The shoulder and the spectral line shape are typical of Ni in coordination (IV) in bound Ni-porphyrinic species. Differences between the fitted spectra and the data come from the molecular heterogeneities between the standards used for the fitting and the incorporated tetrapyrroles moieties in the kerogen.

This approach was used to investigate the possible cyanobacteria *Polysphaeroides filiformis,* which is related to the multiseriate true-branching heterocytous clade represented by members of the modern genera *Stigonema* (Demoulin et al, 2024a). One billion years old specimens were isolated from the Mbuji Mayi Supergroup (DR Congo) and examined for the presence of remaining fossilized Chlorophylls using X-ray Fluorescence (XRF) and X-ray Absorption Near Edge Structure (XANES) synchrotron microspectroscopy. These techniques allowed evidence traces of Ni-tetrapyrrole derived from chlorophyll in fossilized intracellular inclusions. Together with the examination of the microfossil ultrastructure, and using the Fourier Transformed Infrared Spectroscopy (FTIR) fingerprinting it allowed the unambiguous interpretation of the fossil as a Stigonemataceaen.

Another microfossil, *Navifusa* gathers dozens of microfossils with similar morphology but may vary in size. Its taxonomic affinity remains ambiguous as its morphological traits may be found in distinct lineages of both prokaryotes and eukaryotes. We studied the ultrastructure of *Navifusa* specimens isolated from three different sedimentary successions of 1 to 1.75 billion years old. We highlighted the presence of preserved inner structures that were interpreted as fossil thylakoïds in the oldest specimens of *N. majensis* from McDermott Formation, Australia as well as in the 1 billion years old *N. majensis* from the Grassy Bay Formation, Canada (Demoulin et al, 2024b). Thylakoids represent direct ultrastructural evidence for oxygenic photosynthesis metabolism. Their preservation and characterization in microfossils allow the identification of oxygenic photosynthesizers in Precambrian rocks. Both studies gave two new unambiguous calibrations for the fossil calibration for the computing of molecular clocks for a better understanding of the evolution of cyanobacteria. A PhD thesis on the biosignatures of modern and fossil cyanobacteria was defended on June 26th 2024 by C. Demoulin.

Some of the earliest geological record was also investigated for possible traces of life and traces of photosynthesis. A PhD thesis on the microscopic to nanoscopic characterization of putative oldest microfossils from the 3.45 Ga Strelley Pool Chert and 3 Ga Farrel Quartzite, Australia, was defended by M Coutant in September 2024 and led to several articles (Coutant et al, 2022, in press, in prep). Organic-walled microfossils of unknown identity and microbial mats of possible phototrophs were rediscovered in the 3.22 Ga Moodies Group, South Africa and their morphological, ultrastructural and chemical analyses is ongoing to evidence their biogenicity, syngenicity and possible their identity (Johnson et al, in prep).

In order to evaluate the timing of evolution of oxygenic photosynthesis, evidence of its occurrence in the fossil record is mandatory. Oxygenic photosynthesis is also performed by a variety of eukaryotes (algae and plants) but their origin and evolution are still poorly constrained. A new Palaeoproterozoic assemblage of microfossils from the 1.78-1.75 Ga McDermott Formation, Australia, was described (Javaux, 2025). It includes the oldest eukaryotic microfossils known to date with complex ornamentation, cyst opening structures, multicellularity and budding structures, pushing back their fossil record by more than 100 Ma, as well as prokaryotes including thylakoid-bearing cyanobacteria (Demoulin et al, 2024b) and other probable filamentous cyanobacteria. The paper also reviews the origin of eukaryotes (eukaryogenesis) and the fossil record of algae born from the primary plastid endosymbiosis of a cyanobacteria by a heterotrophic protist (unicellular eukaryote).
Overall, these studies provided new constraints on the timing of evolution of life and of oxygenic photosynthesis on the early earth, combining the geological, fossil and molecular records as well as estimations from molecular phylogenies (figure 13).

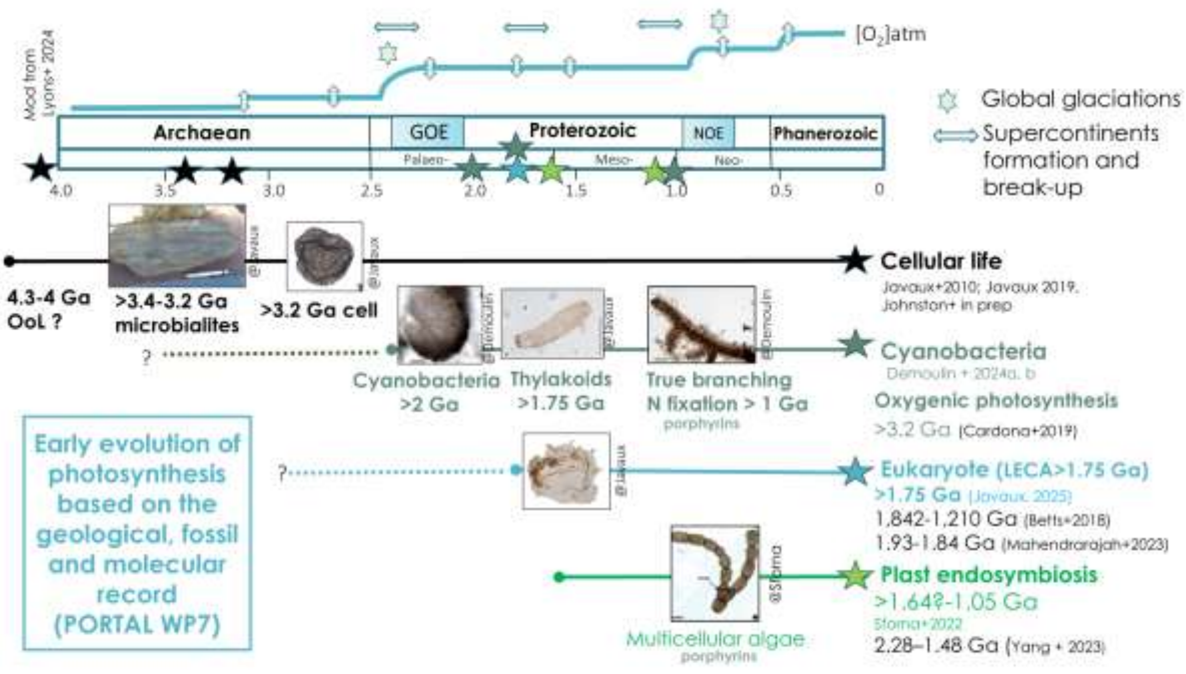

Figure 13. **Evolution of phototrophy on the early Earth: integrating the geological, fossil and molecular record**

WP8: *TRAPPIST Biodome: infra-red acclimated/adapted phototrophic life under TRAPPIST UV, IR, atmospheric conditions*

Recent works of La Rocca team have shown that IR adaptability of photosynthetic metabolism of cyanobacteria enhance the plausibility of finding oxygenic photosynthesis in M-dwarf planetary system (Battistuzzi et al., 2024), and evidenced cyanobacterial biomass production and oxygen release under M7-Dwarf star emission (Claudi et al., 2020; Battistuzzi et al., 2023). In addition, it was shown that cell growth and physiological response of the strain *Synechococcus* sp. PCC7335 in CO_2 enriched (8%) atmosphere under IR illumination are not affected (Liistro et al., 2024). In this context our set up was design to measure O_2 and CO_2 concentrations both in liquid and gaseous phase of anaerobic reactors. Atmospheric composition is controlled using a glove box purged with CO_2. Our custom-made IR lamps set gathers (730/750/780/810/910/1100/1200/1300 nm LED for red Dwarf-like illumination, and hyperspectral 400-900 nm LED for Sun-like illumination. LEDs at 730 nm 750 nm, 790 nm and 810 nm are mimicking Trappist-1 emission spectra between 700 and 850 nm which is critical for oxygenic photosynthesis.

Our first experiments were performed with the axenic strain PCC 6803 under Earth conditions (Sun and atmosphere) to test O2 sensor in both phase liquid and dry air. We were able to monitor O2 released by oxygenic photosynthesis in the liquid media and transferred to the gaz phase. Further analyses with FarLip adapted strains suggested to increase the period of preincubation under IR illumination for the strain SAG3387 to more than 14 days, as it was reported for PCC7335 (Liistro et al., 2024). Similarly, in a previous report of cultivation of freshwater cyanobacteria in CO2 enriched environment it was shown that modern cyanobacteria can survive in 100% CO_2 enriched atmosphere and can still produce biomass for some taxa, but required successive pre-incubation for acclimation (Thomas et al., 2005). Experiments are still on going and will continue beyond PORTAL project.

WP9: *Phototrophic life on rocky habitable planets around very-low-mass stars*

A review paper on the Trappist-1 system where up-to-date knowledge of the system and its possible habitability is discussed (Ducrot et al, in prep). A broader discussion on false negatives biosignatures is also in preparation (Ten kate et al, in prep). We plan a general paper on PORTAL with new data from JWST and our biodome experiments, to discuss the possibility of phototrophic life on rocky habitable planets around very-low-mass stars.

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Recommendation

Impact on Scientific knowledge, future capacities and skills

PORTAL has had a major impact on scientific knowledge by investigating the habitability of exoplanets and the potential for phototrophy in the TRAPPIST-1 system. The stellar radiation in this system is very different from that of the Sun; the planets' atmospheres, if they exist, could be very different from the Earth atmosphere; and any living organisms might have developed different phototrophic metabolisms. The network members of the project generated new data, published or in preparation in peer-reviewed scientific journals, contributing to the following major scientific results: the characterization of the habitability of TRAPPIST-1 exoplanets, new models of TRAPPIST-1 exoplanets' atmospheres, new biosignatures of phototrophic life to search for in the early Earth record and in the solar and extraterrestrial systems, new understanding of the evolution of phototrophy in prokaryotes and eukaryotes on the early Earth, of terrestrial life adaptations to extreme light conditions, and new basic knowledge in biology and biochemistry on the limits of photosynthesis by prokaryotes and eukaryotes in the IR range.

The PORTAL project also provided a new facility: a TRAPPIST biodome adaptable to other planetary conditions for future astrobiological projects.

The publications from PORTAL on these topics reached a broad audience, given their implications for habitability, the potential existence of life on other planets, and the evolution of the early biosphere on Earth. The results were presented at international congresses and meetings across planetary and Earth sciences (e.g., Lunar and Planetary Science Conference-LPSC, European Geoscience Union-EGU, Goldschmidt, American Geophysical Union – AGU), exoplanet meetings, and astrobiology (e.g., BEACON, ABSICON), photosynthesis (e.g., International or European Congress on Photosynthesis Research) and microbiology (e.g., International or European Phycological Congress). These outputs have already or will have a major impact on the entire cosmos/geochemical/planetary/astrobiology communities.

Compliance of the research with BELSPO BRAIN 2.0 research themes: habitability

As the central objectives of PORTAL were to examine the conditions of planetary habitability and to investigate the possibilities of various types of phototrophy and their associated signatures, from the early Earth to modern extreme habitats, to rocky exoplanets, the project aligns directly with the theme of habitability. PORTAL was a multiscale endeavor ranging from the molecular to cosmic scales through time. It addressed the detection, characterization, and environmental requirements of life on Earth as well as on exoplanets within the habitable zone. The PORTAL project focused on critical, yet previously underexplored, aspects of habitability. Its science results have large implications for interpretating data from both past and present Earth, as well as for guiding the preparation of exoplanet future missions. Overall, PORTAL represents a significant advance in our understanding of phototrophy and habitability.

Environment, health and quality of life

PORTAL addressed fundamental questions regarding environmental conditions and potential planetary habitability. Its research priorities focused specifically on: (1) understanding the essential requirements for habitability, (2) identifying factors likely to compromise habitability, and (3) exploring pathways to achieve sustainable habitability.

Studying habitability beyond Earth also provides valuable perspective on our own planet, which remains the only habitable world for *Homo sapiens* and requires careful stewardship to minimize the impacts of human activities on the entire biosphere, including our own species. PORTAL further highlighted the critical role of stellar/Sun radiation and its evolution on planetary habitability and the potential for life.

Policy and public services

The PORTAL objectives align closely with the long-term strategy of the European Space Agency ESA as well as with priority themes of the European Commission's (EC) Horizon 2020 program, which explicitly specifies search for life beyond Earth and the analysis of sample returned for the search for traces of life. Therefore, PORTAL fits strategically in and contributes to the planetary exploration programme of ESA and the Horizon 2020 programme of the EC. PORTAL addressed key questions highlighted in ESA COSMIC VISION 2015-2065 BR 247.

Civil society

Transferring knowledge to the public is essential to explain the importance of free (not oriented) curiosity-driven fundamental research and its long-term impacts on our understanding of life on Earth, possible life beyond Earth, and planetary systems in the universe. It also helps to reflect on our planet that is uniquely habitable for our species and needs respect and protection for the whole biosphere including us and from us. Whether there is life out there or not, there is no planet B for our species. Not only does our research provide novel knowledge, but it also contributes to defining new space missions and telescopes (and the required technology) and new approaches to understand modern life and life origin and early evolution and to define which traces of life we can detect and how to do it. Such a grand endeavor also illustrates challenges and richness in multidisciplinary collaborations,

and challenges in discriminating life-an anomaly- from background universal physical and chemical processes. Conveying these messages is not simple, but important to educate the public on these topics, to help take a step back on our place in the universe, and to illustrate how national and international cooperation may lead to exciting discoveries and new ideas for further research.
Our activities in transferring knowledge included conferences, cours-conferences, books, press inertveiws, and a TV documentary (see dissemination below).

Culture and heritage
The project used collections supported by BELSPO, such as the Belgian Coordinated Collections of Microorganisms (polar cyanobacteria), and other samples acquired using the Antarctica Belgian base infrastructure. Additional material studied in this project holds significant scientific value as evidence of major steps in Earth’s biosphere evolution. They include collection of fossil material in the Coordinator’s laboratory, comprising some of the oldest traces of life, including cyanobacteria and protists. Archean samples came from a field site and core samples in South Africa obtained through a ICDP project. This field site is a UNESCO world heritage site known as the “craddle of life”, where a geotrail is accessible to the public. Discoveries made through the PORTAL project increase its immaterial, cultural, and scientific value and contribute to public education.

5. DISSEMINATION AND VALORISATION

Target group of diffusion: scientific community

Our results were disseminated through publications, a PORTAL project website, and through participation in scientific meetings.
We took advantage of our annual Belgian astrobiology meeting (FRS-FNRS Belgian contact group Astrobiology-Coordinator E Javaux, president and Promotor V Dehant, secretary) organized yearly since 2006, to present our project to the community and invite international experts.
Each partner has a large network of collaborators who were interested to discuss our results and to participate in these initiatives, including the scientific communities involved in ESA and NASA space missions such as ExoMars 2022, JUICE, JWST initiative, CHEOPS, ARIEL, and the ground telescopes TRAPPIST and SPECULOOS.
Results of PORTAL were presented at various international meetings by PORTAL team members (see abstracts below).

Regarding the signatures and evolution of phototrophic life on the early Earth, several oral presentations and posters were presented at international meetings (BEACON 2023, 2025, EPSC 2025, EANA 2024), and invited talks at workshops of the Royal Society, London (Nov 2024), Heidelberg University (May 2025), McGill Univ, Montreal (May 2025), UBC Vancouver (June 2025).

Results regarding the internal structure and thermal evolution of TRAPPIST-1 planets (WP3) were presented by Lingshan Xiong at several key international and national venues. This included a poster presentation on "Tidal dissipation in TRAPPIST-1 planets" at the doctoral school on solid earth sciences in Les Houches (France) on September 30th, 2024, and another poster titled "Thermal Evolution of TRAPPIST-1 Planets via Multilayer Tidal Dissipation Models" for the European Planetary Science Congress (EPSC) 2025. At the national level, Lingshan Xiong shared results via a poster for the FNRS Contact Group "Astronomie & Astrophysique" & Astronomy Day of the Royal Observatory of Belgium, and through an oral presentation at the Royal Observatory of Belgium (ROB) OD1 seminar focusing on "Dynamic Interior and tidal dissipation of exoplanets".

In the frame of the PORTAL activities at ROB, Prof. René Doyon was invited to Belgium, where he discussed with the ROB scientists on April 2nd 2024. Professor Doyon is the Director of the Trottier Institute for Research on Exoplanets and the Observatoire du Mont-Mégantic, Canada. His research activities are focused on the development of state-of-the-art astronomical instrumentation for various ground- and space-based observatories. He is also actively involved in various observational programs for detecting and characterizing brown dwarfs, exoplanets and young low-mass stars. On the instrumentation front, he leads several infrared instrumentation projects (camera and spectrograph) for the Observatoire du Mont-Mégantic. He is co-investigator of the Gemini Planet Imager, co-principal investigator of SPIRou installed on the Canada-France-Hawaii Telescope, principal investigator of NIRISS, one of the four scientific instruments on the James Webb Space Telescope. He is awarded the first "Chaire du Québec" of the Académie royale de Belgique. Lingshan Xiong presented her work connected to the PORTAL project during the full-day meeting. On April 2d and 4th 2024, Prof Doyon visited the PORTAL partners at the Royal Observatory of Belgium and at ULiège and several presentations were made by members of the ROB, EXOTIC and Early Life teams, and by Prof Doyon himself with plenty of time for discussion.

We used online databases dedicated to astrophysics data, orbi and dataverse ULiege for fossil datasets and Staniera genomic data.

PORTAL has a legacy that continues beyond the completion of the project, both for scientific, programmatic and outreach perspectives (see below).

For the scientific community, we plan to organize an international and interdisciplinary workshop on phototrophy on rocky exoplanets around VLM stars (several partners were SOC members of the successful TRAPPIST meeting in ULiège in 2019, or other national and international meetings) in 2026. After completion of the PORTAL project, our new TRAPPIST biodome l contributes to a Research Infrastructure for future astrobiological projects in the European community, and to projects beyond Europe.
The research themes of PORTAL are also part of the new ULiège Origins Center themes (www. Origins.uliege.be) where synergistic projects are developed on habitability, exoplanets, origin and evolution of phototrophy by large interdisciplinary community of scientists, engineers and sociologists/anthropologists, among which some of the PORTAL promotors as PIs or collaborators or as members of advisory committee.

Target group: students and ECR Early Career Researchers (PhD students and postdoctoral researchers)

Master students
Some of the partners participated to teaching at the annual astrobiology course at ULiège organized by the coordinator, and where the new project and possible research topics were presented to master students in science, engineering and humanities.
Two Master theses were defended in the frame of PORTAL. Following their training in PORTAL labs, both students have been accepted to conduct a PhD thesis after international selection in the Marx Planck Institute, Munich, Germany and EPFL Doctoral Program in Computational and Quantitative Biology, University of Lausanne, Switzerland.
Bredel Agathe.2023. *Evolution des premiers eucaryotes: analyse du microfossile Jacutianema solubila*. (Promotor: E Javaux), ENS Paris MsC1 Biology student, ULiège
Peyroche Giuseppe. 2023 *Metagenomic characterization of Antarctic endolithic photosynthesizers and implications for the Evolution of photosynthesis and Astrobiology* (Promotor: Y Lara) MSc2 MEME Erasmus + student, ULiège

PhD students

Five PhD students were supervised and defended a PhD thesis during PORTAL (3 were hired on PORTAL budget), and another PhD thesis is ongoing.

Coutant Maxime, 2024. Testing the biogenicity of putative organic microfossils from the Archean era using petrographic and chemical analysis with high spatial resolution (Promotor: E Javaux; Co-Promotor: K Lepot, ULille)

Demoulin Catherine, 2024. Biosignatures of modern and fossil cyanobacteria (Promotor: E Javaux, thesis committee: Y Lara), ULiège.

Feller Tom, 2025. Living Under Far-red light: Adaptation Of Photosynthetic Machinery Of Stanieria cyanosphaera, Vitrella brassicaformis, And Euglena gracilis. (Promotor: P Cardol, Co-Promotor: E Javaux), ULiège.

Forêt Hadrien, ongoing (FRIA fellowship). Contribution of unique light harvesting antenna system to far red absorption in Euglena gracilis (Promotor: P Cardol, thesis committee: E Javaux), ULiège.

Lingshan Xiong, ongoing. Dynamic interiors and tidal dissipation: modelling thermal-orbital evolution of rocky and ice-rich exoplanets (Promoter: Anne-Sophie Libert, Co-Promoter Attilio Rivoldini, Tim Van Hoolst), UNamur, ROB.

Four Postdocs

B. Johnson (ULiège, hired on another project) worked on some of the Early Earth (Archean) samples

Fatimeh Davoudi (ULiège) worked on the characterization of the star TRAPPIST-1 and stelar contamination.

Enrique Sanchis Melchor, Mathilde Kervarzo (FU Berlin) worked on the relationships between planetary interiors on atmospheres, tidal dissipation, outgassing and modelling.

Senior researcher (hired on PORTAL budget)

Y. Lara, Promotor worked on microbiological aspects of photosynthesis in IR and the biodome.

In addition, the TRAPPIST biodome designed and constructed for PORTAL is also useful to illustrate academic teaching and student events, and for further student theses and research projects.

Some of the promotors gave lectures to the annual class Astrobiology for Master students in science, engineering and humanities at ULiège

Target group of diffusion: public

Communication took place through news media and many science-related activities as all network members are already well-experienced.

Public outreach of this project was done by exhibitions, lectures, discussions and workshops in schools or in front of public audiences (see annex).

Every institute has an outreach-office to ensure that clearly written press releases are sent to the media in particular, we organized a series of course-conferences at the Royal Academy of Science of

Belgian (see annex). The coordinator E Javaux organized a Cycle of 4 courses on the origin of life in April 2023 "lorigine de la vie, des questions qui fascinent » Cour-conférence Collège Belgique Académie Royale de Belgique.

In the frame of the international workshop planned for 2026, activities will be planned to promote PORTAL with artists (Promotor M. Gillon has such experience and contacts with artists for the TRAPPIST project).
A project website was built for science and data sharing, but also with a public page.
Beyond PORTAL, in the following years, in the frame of the new ULIEGE ORIGINS CENTER (www.origins.uliege.be), dissemination will continue with SCI-FY evenings with discussion on movies, poster competition for students, a public exhibition around "the TRAPPIST biodome" and a "river of time" exhibition presenting the evolution of Earth and life, modified with a special focus on photosynthesis.
In addition, a documentary on Life in the Universe by Dominique Reguenne is in preparation for ARTE, where several of the promotors (M. Gillon, E. Javaux, Y. Lara) and International Partners (F. Selsis, M. Turbet) participate, and that includes a sequence on the TRAPPIST biodome. It will be diffused in September 2026, and a public event will be organized at ULiège for the public with a debate with scientists, journalists and the movie director.

Target group of diffusion: EC policy, Space agencies

After completion of the PORTAL project, our new TRAPPIST biodome can contribute to a European Research Infrastructure for future astrobiological projects in the European community, and to projects beyond Europe.
The data generated in the PORTAL project will be extremely useful in ongoing and future space missions in the solar system for the detection of traces of life in situ or in returned samples, and in exoplanetary systems for characterizing the habitability and possibility of life of rocky planets around VLM stars. Several network members are already involved in ESA and NASA space missions such as ExoMars 2028, JUICE, JWST initiative, CHEOPS, ARIEL, and the ground telescopes TRAPPIST and SPECULOOS.
As mentioned above, this is part of the long-term strategy of the European Space Agency ESA as well as priority themes of the European Commission's (EC) Horizon 2020 which explicitly specifies the search for life beyond Earth and the analysis of sample returned for the search of life.

6. PUBLICATIONS

Peer-reviewed publications

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Xiong, L. (2024). Tidal dissipation in TRAPPIST-1 planets, Poster presentation at the doctoral school on solid earth sciences in Les Houches

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Xiong, L. (2025). Thermal Evolution of TRAPPIST-1 Planets via Multilayer Tidal Dissipation Models, Poster presentation for FNRS Contact Group "Astronomie & Astrophysique" & Astronomy Day of the Royal Observatory of Belgium https://doi.org/10.5194/epsc-dps2025-605

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ANNEXES

Public events (examples)

EJ Javaux participated to the public exhibitions in Bordeaux « Le petit chemin de l'évolution » (Gargaud et al, Bordeaux 2024), Le grand chemin de l'évolution (Gargaud et al, Bordeaux 2025)

Interview of EJ Javaux in Ciel et Espace 2024 HS48, p86-91 « sur la Terre comme sur Mars, à la recherche des premières traces de vie » ;

Creation of Podcast Venu d'Ailleurs "La Planète des Signes" https://youtu.be/fWD5TPdhlrM 2024 by F Selsis, interviews of EJ Javaux, M Turbet

Interviews in the context of JWST launch and PORTAL at ULiège (M Gillon, E Javaux) https://www.thema.uliege.be/JWST, https://www.youtube.com/watch?v=RpaR3qwz9xI

T. Van Hoolst: Verkenning van oceanen in Jupiters ijsmanen met de JUICE-sonde, lecture in the frame of the "Lessen voor de XXIe eeuw: Wetenschap voor een nieuwe wereld" for about about 500 registered KU Leuven students and interested people, Leuven, 11 March 2024

T. Van Hoolst, "Verkenning van oceanen in Jupiters ijsmanen met de JUICE-sonde", in: "Lessen voor de XXIe eeuw: Wetenschap voor een nieuwe wereld", Universitaire Pers Leuven, pp. 267-290, 2024

M Turbet Rencontres ciel & espace 2022 : https://youtu.be/y52r3jpBnlk?si=yyCSWLj2XeihNmMk

M Turbet Festival de Fleurance 2024 : https://youtu.be/QoXwMOKYjpk?si=PSLjo5e9cv9IwdsH

<u>Public conferences-seminars</u>

Fortier V., and **Dehant V.**, 2020, Serpentinisation on Mars. ELIC/TECLIM séminaire, UCLouvain, Louvain-la-Neuve, 25 May 2020.

Dehant V., 2020, Habitabilité de Mars et ailleurs. Connaissance et Vie Waterloo, 19 November 2020.

Dehant V., 2021, L'habitabilité de Mars et ailleurs. Conférence publique pour la faculté des Sciences de l'UCLouvain, 29 March 2021.

Dehant V., 2021, Habitabilité de Mars et ailleurs. Conférence pour le KotAstro et MARS UCLouvain, virtual, 28 April 2021.

Dehant V., 2021, Habitability in the Solar System. Cambridge University Seminar, virtual, 5 May 2021.

Dehant V., 2021, Habitabilité de Mars et ailleurs. Académie royale de Belgique et la Délégation générale Wallonie-Bruxelles en France, Cycle sur l'Homme et son environnement, virtual, 5 May 2021.

Dehant V., 2021, Habitabilité de Mars et ailleurs. Conférence pour le KotAstro et MARS UCLouvain, virtual, 28 April 2021.

Dehant V., 2021, Habitability in the Solar System. Cambridge University Seminar, virtual, 5 May 2021.

Dehant V., 2021, Habitabilité de Mars et ailleurs. Académie royale de Belgique et la Délégation générale Wallonie-Bruxelles en France, Cycle sur l'Homme et son environnement, virtual, 5 May 2021.

Dehant V., 2021, Habitability of Mars and elsewhere in the solar system. Conference for ULB Colloque Solvay, Brussels, 28 September 2021.

Dehant V., 2021, Rotation and interior of terrestrial planets and moons - an ingredient for habitability. invited talk, The third China-Belgium Symposium Science and Technology exchange symposium, Virtual, 30 October 2021.

Dehant V., 2021, Geodesy at Mars and Mars' habitability. invited talk, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, Virtual, 18 November 2021.

Dehant V., 2021, Mission vers la planète Mars. Conférence pour la Société Européenne des Ingénieurs et Industriels (SEII), Château Ste-Anne, Auderghem, 26 November 2021.

Dehant V., 2022, Habitabilité de Mars et ailleurs. Conférence pour l'Université des Ainés de l'UCLouvain, 24 February 2022.

Dehant V., 2022, Habitabilité de Mars et ailleurs. Conférence pour le Printemps des Sciences, UCLouvain, 22 March 2022.

Dehant V., 2022, Mars était-elle habitable dans le passé ? Conférence pour les astronomes amateurs, Woluwe, 2 April 2022.

Dehant V., 2022, Planète Mars : résultats des dernières missions spatiales. Collège Belgique, Charleroi, 21 April 2022.

Dehant V., 2022, Mars new results for constraining its interior and habitability. colloquium Berlin Technical University, Berlin, Germany, 12 May 2022.

Dehant V., 2022, Habiter sur Mars ou sur une lune du système solaire ? séminaire invité, Les Rencontres de LouvainHouse, UCLouvain, Louvain-la-Neuve, 6 December 2022.

Dehant V., 2022, Missions vers Mars. Séance publique de la classe des Sciences, Académie, Brussels, 17 December 2022.

Dehant V., 2022, Belgian Space Strategy. Panel discussion, Residence Palace, Brussels, 22 December 2022.

Dehant V., 2023, Connaissances actuelles de la planète Mars et conséquences sur son habitabilité. Forum des Savoirs de l'ULiège, Virtual, 9 March 2023.

Dehant V., 2023, Connaissance de l'Univers. Journée Prix Lemaître, Palais des Beaux-Arts, Charleroi, 28 March 2023.

Dehant V., 2023, La planète Mars. Conférence pour MARS-UCLouvain, Louvain-La-Neuve, 2 October 2023.

Dehant V., 2023, Objectif Mars ! La Planète rouge a-t-elle un cœur ? Conférence pour le festival 'I love science', Brussels, 14 October 2023.

Dehant V., 2023, Exploration spatiale de Mars. Conférence pour le Kot-Astro, Louvain-La-Neuve, 17 October 2023.

Dehant V., 2024, Le NewSpace. Conférence pour le Cercle des Nations, conférence-débat avec Benoit Deper et Vladimir Pletser, coordonnée par Patrice Goldberg, Brussels, 31 January 2024.

Dehant V., 2024, Habitabilité des corps du système solaire. Printemps des Sciences, UCLouvain, Louvain-la-Neuve, 18 March 2024.

Dehant V., Rekier J., 2024, Fluid dynamics to serve planetary space missions. Seminar at UCLouvain-EPL (IMMC), Louvain-la-Neuve, 11 October 2024.

Dehant V., Mandea M., Cazenave A., 2025, Le champ magnétique, la rotation et la gravité de notre planète Terre : qu'ont-ils en commun ? Conférence grand-public, Planétarium de Bruxelles, Brussels, Belgium, 22 May 2025.

Javaux, EJ, 2020 Les plus vieilles traces de vie : preuves et défis. Académie Royale de Belgique, classse des sciences. RB 7 mars 2020
Javaux EJ 2022 Comment reconstruire les trois premiers milliards d'années d'évolution de la vie? Timeworld « constructions" Paris 29th June 2022
Javaux EJ 2022 A la recherche des plus ancienne straces de vie sur la terre et sur Mars. Altaïr ULB 12th March 2022
Javaux EJ 2023 A la recherche des premières traces du vivant dans l'Univers. Cycle Origine de la vie 2023 Cour-conférence Collège Belgique Académie Royale de Belgique 26 April 2023
Javaux EJ 2023 Comment reconstruire les trois premiers milliards d'années d'évolution de la vie? Forum des savoirs ULiege 2 Mars 2023
Javaux EJ, 2023. Life, here and there? ISSI gala dinner Bern Switzerland Nov 10th 2023
Viso M., Gargaud M., et al. (including **V. Dehant, E. Javaux**), 2025, Presentation of the book 'Mars and the earthlings'. Second Biennial European Astrobiology Conference (BEACON), Harpa Conference Centre, Reykjavik, Iceland, 1-5 July 2025.