BRAIN-be 2.0 PORTAL Contract - B2/212/P1/PORTAL PhOtotrophy on Rocky habiTAble pLanets

INTRODUCTION. Star light represents an efficient source of energy that is abundantly used by life on Earth and is 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. Among the thousands of detected exoplanets, a few dozen are potentially habitable and a detailed atmospheric characterization should be within reach of upcoming telescopes. A thorough assessment of the habitability of exoplanet around late-type M-dwarfs is critical for a deep understanding of the universality and limits of Life. Because the luminosity of these cold stars is much smaller than that of the sun, rocky planets have to orbit very close to them to be habitable. Since the spectrum of M-dwarfs peaks in the infrared, phototrophic life on the surface of their planets needs to be able to harvest infrared photons while protecting itself against very strong fluxes of XUV photons and stellar winds. On Earth, phototrophic organisms have evolved metabolisms to scavenge photons in the spectrum of visible light, but also in the infra-red range, and strategies for protection against UV radiations. Phototrophy appeared more than 3.4 Ga ago, when the anoxic Earth atmosphere was lacking an ozone layer, and its surface was exposed to strong UV radiations. Later oxygenic photosynthesis had a major impact on atmosphere composition and oceanic chemistry from at least 2.4 Ga ago, which contributed to the diversification of complex life (eukaryotes). Phototrophy thus can have a major impact on planets and life evolution. **The project PORTAL addressed the potential habitability of rocky planets in orbit around very low-mass stars, and the possibility to detect life on such planets**.

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.

METHODOLOGY. As the PORTAL project focused on exoplanet habitability and the possibility of phototrophic life, it is intrinsically multidisciplinary and must be addressed with a synergistic approach. PORTAL combined expertise in astrophysics, geophysics, geology, paleobiology and microbiology. WP1-5 (habitability of TRAPPIST-1 exoplanets), WP6 (IR photosynthesis on modern Earth), and WP7 (photosynthesis on early Earth) were addressed in parallel to foster synergy, and provided data for WP 8 (TRAPPIST biodome) and WP9 (possibility of phototrophy on rocky habitable exoplanets around very low-mass stars).

RESULTS

PORTAL improves our understanding of the TRAPPIST-1 exoplanetary system. WP1 provides new constraints on the high-energy stellar environment impacting atmospheric escape and photochemistry on the TRAPPIST-1 planets. It evidences various properties such as refined measurements of its luminosity, effective temperature, and metallicity and photospheric and chromospheric features, high frequency (sub-hour) of microflares (~10^{29} erg/flare), and the rotation period of the star to be ~3.3 days, (of the TRAPPIST-1 star, and it confirms significant magnetic activity and short-timescale variability relevant to the star's photon and proton output. This work also shows that TRAPPIST-1 exhibits intermediate-gravity signatures despite its old age methods, reflecting the effect of magnetic activity and other unresolved stellar properties that can have direct consequences for planetary transmission spectroscopy. Consequently, this work also produced new protocols and methodologies for evaluating stellar contamination and characterizing the radiative behavior of active ultracool dwarfs.

In WP2, Atmospheric models with surface pressures ≥1 bar and efficient greenhouse effects suggest that 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.

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. The 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 to simulate the planets' thermal evolution and, crucially, their outgassing history over billions of years. For the hot inner planets (e.g., TRAPPIST-1b), the evolutionary pathway depends on the initial thermal state, mantle cooling efficiency, radioactive heating, and rheology. Planets experiencing moderate tidal heating, (like TRAPPIST-1d) can develop a secondary atmosphere much more rapidly (within the first ~1 billion years) compared to a planet without tidal heating.

In WP4, 3D modeling results indicate that TRAPPIST-1b is unlikely to host an atmosphere, while TRAPPIST-1c may retain a thin one. 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, 3D simulations highlight the role of clouds in flattening transmission spectra, thereby requiring additional observational effort to identify molecular features.

As part of WP5, simulations investigated how the stellar UV flux propagates through oxidizing atmospheres and how this affects subsurface and surface conditions. using a coupled photochemical–climate model (Generic-PCM). 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 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 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. A wide range of anoxygenic and oxygenic photosynthetic Earth microorganisms were examined under visible and IR light, and under IR-only illumination 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. The approaches used included measurements of photosynthetic activity by fluorimetry and absorption spectroscopy, pigment content by HPLC, protein-pigment associations by native gel electrophoresis, and specific genetic markers by PCR. In parallel, the genome of IR-adapted bacteria was sequenced to identify orthologous and paralogous protein sequences involved in the cores of their photosynthetic apparatus. The evolutionary histories of their gene sequences were studied by phylogeny.

In WP7, PORTAL also made important advances in our understanding of phototrophy on modern and early Earth, confirming its long history. Discoveries include clades of cyanobacteria and microalgae that are able to perform photosynthesis in the IR range by adapting their photosystems or using different chlorophylls. PORTAL also provides new constraints on important evolutionary steps in the early evolution of life and photosynthesis on the early Earth, with the oldest intracellular remains of thylakoids-the membranes where oxygenic photosynthesis takes place in cyanobacteria (1.75 Ga), intracellular porphyrins as remains of chlorophylls in 1 Ga multicellular cyanobacteria and algae, and the oldest eukaryotic cells (1.75 Ga), pushing back their record by hundreds of millions years. It also contributes to the study of some of the oldest fossil cells and microbial mats (?3.45Ga-3.2 Ga).

Combining multidisciplinary knowledge generated in WP1 to 7, WP8 provides a new tool (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 is also useful for investigating other extraterrestrial and Early Earth conditions and for outreach and education. In WP9, PORTAL led to the discussion of exoplanet habitability around VLM stars, and the need for further research to detect possible biosignatures of phototrophy in diverse exoplanetary systems as well as to investigate the origin and early evolution of this successful metabolism on early Earth.

CONCLUSIONS: PORTAL improved our understanding of the TRAPPIST-1 exoplanetary system. The new strong constraints on the surface irradiation of the TRAPPIST-1 planets were then used to explore the possibilities of phototrophy in the infra-red range on these extrasolar worlds. PORTAL also made important advances in our understanding of phototrophy on modern Earth and on important evolutionary steps in the early evolution of life and photosynthesis on the early Earth. Finally, PORTAL led to discussion of exoplanet habitability around VLM stars, and the production of a new experimental platform (a biodome) to investigate the possibility of phototrophy in the infra-red range and the possible biosignatures to detect remotely.

Keywords Habitability, biosignatures, phototrophy, infra-red light, TRAPPISt-1, atmosphere, models, biodome, exoplanets, early Earth, microfossils, cyanobacteria, algae