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habitability

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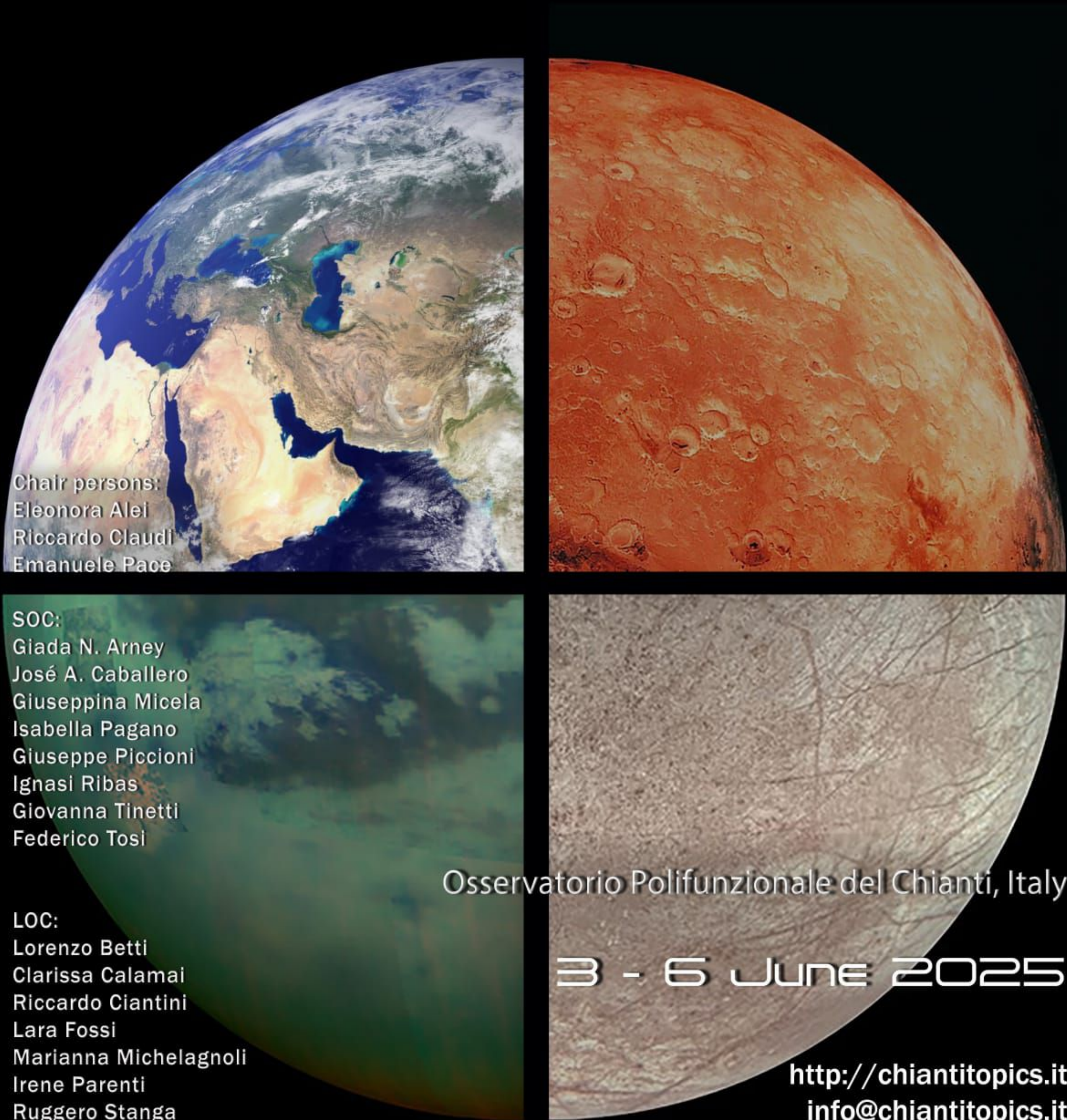

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Habitable Zone and Beyond

R. Kopparapu[1]
[1]NASA Goddard Space Flight Center.

Keywords: Habitability, exoplanets, runaway, moist green house, habitable zone

Introduction: This talk will discuss a review of the habitable zone concept, the utility of the concept in finding potential habitable planets, the current knowledge of the habitable zone boundaries and wys to estimate the boundaries with future missions.

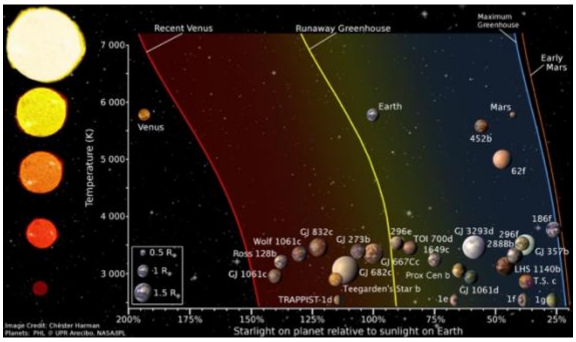
The concept of the *habitable zone* (HZ)—the circumstellar region where liquid water can persist on a planetary surface of an Earth-like planet—remains central to the search for life beyond Earth. It is the first step that is needed to identify habitable, and inhabited, worlds beyond our solar system.

Over the past decade, advances in atmospheric modeling, stellar characterization and the discoveries of exoplanets, have significantly impacted our understanding of the HZ's boundaries and limitations. Climate models that estimate the HZ boundaries explore the interaction of stellar spectral energy distribution, meaning different types of stars and their radiation, with the radiative transfer properties of different greenhouse gases in a planetary atmosphere. These models estimate that the Sun's inner edge of the HZ is at around ~ 0.95 AU, and the outer edge of the HZ is close to ~1.67 AU. For comparison, present Venus is at 0.72 AU and present Mars is at 1.54 AU. While the current Venus is not in the HZ, current Mars is indeed inside the Sun's HZ, though it is not a habitable planet due to its small size.

Modeling efforts also investigated the effects of varying stellar spectra, especially for cooler M and K spectral type stars, which emit more radiation in the infrared. This has implications for the absorption of stellar flux by atmospheric constituents and alters the climate feedbacks relevant to habitability. The impact of cloud coverage, surface albedo, and atmospheric composition was also explored with multi-dimensional climate models to develop more flexible definitions of the HZ to accommodate uncertainties in planetary and stellar properties.

We are now at a point where we could obtain empirical estimate of the HZ boundaries statistically with either existing or upcoming missions like TESS, PLATO and ROMAN. The abundance of exoplanet discoveries will help in fine tune our modeling efforts to assess the HZ boundaries.

Fig.1: Habitable zone estimates around different stars as a function of incident stellar flux on a planet normalized to current Earth Flux. All the currently known exoplanets that are between 0.5 to 1.5 Earth radii are also shown. Most of them are around M-dwarf stars due to the high sensitivity of existing instruments to close-in small planets around M-dwarf stars.



POTENTIAL CLIMATES AND HABITABILITY ON ECCENTRIC WORLDS: THE CASE OF Gl 514 b AND HD 20794 d

L. Biasiotti[1], P. Simonetti[1], S.L. Ivanovski[1], M. Damasso[2], A.Sozzetti[2], R. Spinelli[3], L. Calderone[1], F. Dogo[1], S. Monai[1], G. Vladilo[1]
[1]INAF-OATs (lorenzo.biasiotti@inaf.it), [2]INAF-OATo, [3]INAF-OAPa.

Keywords: exoplanets, habitability, astrobiology, Sun-like star, M-type star.

Introduction: High-eccentricity planets are not rare among confirmed exoplanets. Despite their dramatic seasonal changes in insolation between periastron and apoastron, several studies agree on assuming such worlds are habitable (e.g., [1,2,3,4,5,6]). However, they also agree that planets located near the outer regions of the habitable zone may enter a globally frozen 'snowball' state, posing a threat to their ability to support water-based life [2]. Therefore, detailed climate studies of highly eccentric planets are essential for testing these predictions. In this context, Gl 514 b [7,8] and HD 20794 d [9,10] offer the best chance for such investigations because, among the confirmed exoplanets orbiting around M-dwarfs and Sun-like stars, they have the exoplanets with the highest eccentricity, with $e = 0.45^{+0.15}_{-0.14}$ and $e = 0.45^{+0.10}_{-0.11}$, respectively. In the present work, we used a seasonal-latitudinal energy balance model, EOS-ESTM [11], to explore the potential impact of both constrained and unconstrained planetary, orbital, and atmospheric parameters on their habitability, mapped in terms of surface temperature.

Results: To explore the surface habitability, we calculated a temperature-dependent habitability index, *h*, which represents the fraction of planetary surface with temperature within the liquid-water range. The climate simulations were constrained using measured quantities (e.g., insolation and planet mass) and parametrizing unknown planetary (e.g., geography, rotation period, axis obliquity), orbital (e.g., eccentricity, argument of periastron), and atmospheric (e.g., surface pressure, chemical composition) quantities. Since measurements of the radius are not available for the two planets, we assumed an internal composition similar to that of Earth.

Regarding the planetary atmosphere, in the case of Gl 514 b, we tested three sets of CO_2-dominated atmospheres, each with its own CH4 concentration (xCH4: 0 percent, 0.1 percent, and 1 percent), varying the total surface pressure in the range $p_{tot} \in (1, 13)$ bar. In contrast, for HD 20794 d, we narrowed the ranges of surface pressures and CO_2 fractions that enable potentially habitable conditions (Figure 1).

As a general trend, the higher the global coverage of oceans is, the more habitable the planet is (Figure 2). This behaviour is due to the combination of two factors (i) the land has a lower thermal capacity than the water and (ii) oceans are darker than bare soil.

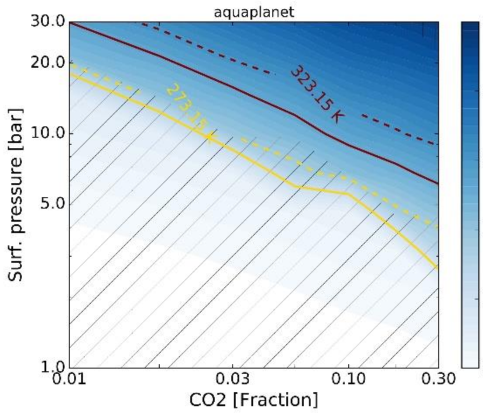


Figure 1. Predicted values of the average surface temperature, T , as a function of CO_2 and total surface pressure for an aquaplanet scenario. For the remaining parameters we adopt $\epsilon = 0^{\circ}$, P_{rot} = 1 day, e = 0.45 and $\omega_{peri} = 0^{\circ}$. The dashed areas indicate the parameter space in which atmospheric CO_2 condensates (oblique bars) and H_2O on the surface evaporates (horizontal bars). Yellow and red contour lines highlight the regions of the parameter space for which pure water can be maintained in liquid form and the biological limit, respectively. Dashed lines represent the average temperature along the orbit whilst solid lines represent the maximum temperature. Credits: [10].

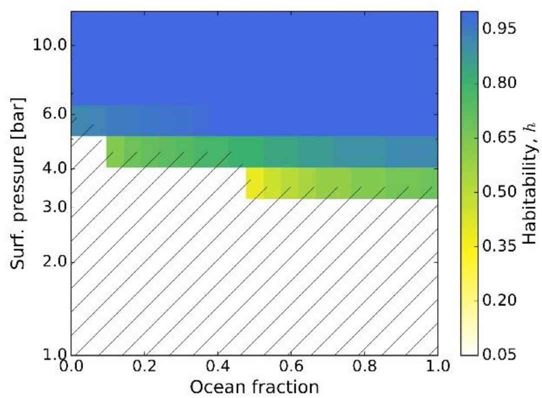


Figure 2. Predicted values of the habitability index, *h*, as a function of the ocean cover fraction and total surface pressure for an atmospheric composition with CO_2+1 per cent CH_4. For the remaining parameters we adopt $\epsilon = 23.44^{\circ}$, P_{rot} = 1 d and $\omega_{peri} = 0^{\circ}$. The

dashed areas indicate the parameter space in which atmospheric CO_2 condensates. Credits: [8].

When the obliquity increases, the planet experiences stronger seasonal excursions of surface temperature. This means a larger fraction of polar regions undergo periods of high daily-averaged insolation, reducing the ice caps and increasing habitability (Figure 3). However, the impact of higher obliquity tends to disappear as surface pressure increases due to the high efficiency of horizontal energy transport, which removes temperature gradients on the planet's surface.

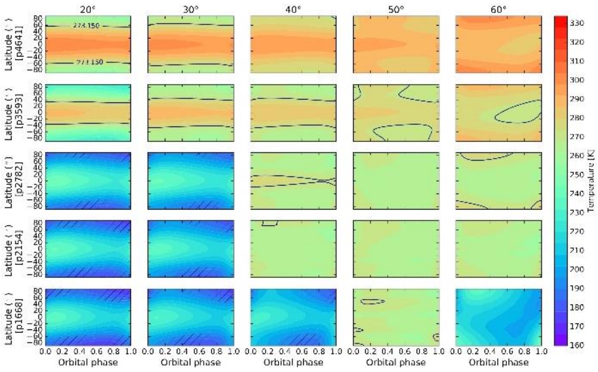


Figure 3. Seasonal and latitudinal maps of surface temperature obtained by extracting the results of Fig. 9c (case with 1% CH_4) at constant values of axis obliquity (from left to right: ϵ = 20°, 30°, 40°, 50°, and 60°) and total pressure (from top to bottom: p_{tot} = 4 641, 3 593, 2 782, 2 154, and 1 668 mbar). The solid line indicate the limit within which water can be maintained in liquid form. Credits: [8].

In the range of orbital eccentricity consistent with the observations ($e = 0.30 - 0.60$), the impact of the eccentricity on habitability is important. The higher e, the wider the range of atmospheric pressure favourable to habitability becomes, down to a moderate pressure (p_{tot} ∼1 bar). We find that the impact on habitability of eccentricity variations is higher than that induced by variations of other key planetary quantities, such as obliquity.

More in general, we underline that remarkable differences exist between the low- and high-concentration of CO_2 and CH_4, as well as between the low- and high-pressure regimes. These results are due to the higher greenhouse effect of the thick, CO_2/CH_4-rich atmospheres and to the higher efficiency of the horizontal transport at high atmospheric pressure.

Future perspectives: Future observations may help constrain the actual range of stellar, orbital, and planetary properties that affect the habitability of Gl 514 b and HD 20794 d. Asteroseismology obtained through extensive monitoring of nearby bright stars with PLATO may help measure stellar ages and internal structures. The large uncertainty in eccentricity can be reduced by a long-term sequence of radial-velocity measurements.

Regarding Gl 514 b, searches for transits might be performed with PLATO during the 'Step and Stare' Observation Phase. Moreover, high-contrast imaging is expected to become feasible with the Extremely Large Telescope (ELT) (see [7] for more details). These observational developments suggest that we will be able to assess the actual habitability of planets similar to Gl 514 b, as long as they transit in front of their host star.

Concerning HD 20794 d, high-contrast imaging with next-generation facilities such as ANDES at the ELT and dedicated missions like LIFE and HWO will enable direct atmospheric characterization in both the thermal and visible/near-infrared regimes. Given HD 20794's proximity (6.04 pc) and its inclusion in target lists for PLATO and HWO, HD 20794 d is poised to become a flagship object in our quest to understand the complex interplay between orbital dynamics, atmospheric processes, and habitability in super-Earths.

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Beyond habitability:
How extremophiles shape our understanding of life's potential

M. Marcellino[1,2], D. Locci[1], R. Aslam[1,2], A. Ciaravella[1], A. Jime´nez-Escobar[1],
A. Mangione[1], G. Micela[1], and C. Cecchi Pestellini[1]

[1]INAF - Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, 90134 Palermo, Italy,
[2]Universita` degli Studi di Palermo, Dipartimento di Fisica e Chimica, Via Archirafi 36, 90123 Palermo, Italy

Keywords: extremophiles, planetary atmospheres, habitability framework, Multiparametric Life Score

The search for potentially habitable exoplanets is a central pursuit in astrobiology. Traditional habitability criteria have largely focused on Earth-like conditions, emphasizing the role of the habitable zone (HZ), the region where liquid water can exist. However, this approach may be overly restrictive and anthropocentric, potentially overlooking environments where life, in forms vastly different from terrestrial life, could prosper. Extremophiles (e.g., thermophiles, halophiles, acidophiles, and psychrophiles) thrive in environments with extreme temperatures, salinity, acidity, and pressure conditions far from those traditionally considered habitable. Recent studies [1,2] have emphasized not only the resilience and adaptability of extremophiles, but also their active role in geochemical processes on a planetary scale.

The extraordinary diversity of planetary environments challenges the idea of a uniform model for habitability, necessitating a shift toward a broader framework. Our focus is on atmospheres judged to be the exoplanetary zone directly explorable by current observational techniques, moreover planetary atmospheres represent potential biomes, as evidenced by Earth's "aerial biosphere" hosting diverse microorganisms from troposphere to stratosphere. Venus demonstrates atmospheric habitability potential in its middle cloud layer (48-60 km altitude) with more temperate conditions (200-350 K), while gas giant exoplanets may harbor atmospheric zones suitable for airborne microbial ecosystems.

Our research proposes a novel methodological approach centered on the analysis of exoplanet data retrieved from the NASA exoplanetary archive. We have developed a computational code to estimate pressure, temperature, and radiation profiles within exoplanetary atmospheres. The core of our methodology is the definition and application of the concept of a "life-compatible shell"—an atmospheric layer where pressure conditions fall within the vital tolerance range of terrestrial extremophiles, defined between 10^{-6} Pa and 130 MPa. For each exoplanet, we model a pressure gradient considering planetary parameters such as mass, radius, estimated atmospheric composition, and temperature profile.

To quantify the potential of these "life-compatible shells", we have introduced the Normalized Shell Volume (F_V), comparing the volume of an exoplanet's "life-compatible shell" with Earth's, providing a relative measure of potential atmospheric habitat size. This parameter, along with compatibility scores for temperature and radiation based on extremophile tolerances on an database of 200 extremophile species tanks to a matching code will estimate the Multiparametric Life Score (MLS) to provide a quantitative assessment of an exoplanet's atmospheric habitability.

This study will establish a framework for evaluating exoplanetary atmospheres as potential habitats based on extremophiles' environmental tolerances. We anticipate that our approach will identify promising candidates for future observation, including planets currently excluded by conventional habitability metrics. The MLS methodology is expected to reveal that planets with diverse atmospheric conditions could support multiple ecological niches, potentially increasing the likelihood of life's emergence and adaptation. With upcoming instruments, we expect to refine our model with more accurate atmospheric composition data, enhancing the relevance and applicability of our approach to prioritizing targets in astrobiological exploration.

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A NEW ENERGY BALANCE MODEL TO MAP THE HABITABILITY OF ROCKY, TIDALLY LOCKED PLANETS: APPLICATION TO THE ARIEL TARGET LIST

P. Simonetti[1,2,3], S. Ivanovski[1,2,3], L. Biasiotti[1], G. Vladilo[1], S. Monai[1], F. Dogo[4], L. Calderone[1], R. Politi[2,5], D. Turrini[2,6]

[1]INAF-OATs (paolo.simonetti@inaf.it), via G. B. Tiepolo 11, Trieste, [2]Centro Nazionale di HPC, Big Data & Quantum Computing, via Magnanelli 2, Casalecchio di Reno (BO), [3]Institute for the Fundamental Physics of the Universe, via Beirut 2, Trieste, [4]Università degli Studi di Trieste, via A. Valerio 2, Trieste, [5]INAF-IAPS, via del Fosso del Cavaliere 100, Roma, [6]INAF-OATo, via Osservatorio 20, Pino Torinese (TO).

Keywords: astrobiology, planets and satellites: climates, planet and satellites: atmospheres, planet and satellites: terrestrial planets

Introduction: The search for biosignatures in the atmospheres of exoplanets is a central goal of many state-of-the-art instruments currently in operation [1], under construction [2] or otherwise proposed [3,4]. Biosignatures that can be recognized as such are inevitably produced by a type of life not too dissimilar than our own, which in turn allows us to define a variety of environmental limits for its existence. The most used in astrobiology are those related to the presence of liquid water on the surface of a rocky planet (e.g. [5]).

More than two thirds of the 72 known low mass (<10 Earth masses) rocky exoplanets in the Habitable Zone (HZ) of their stars orbit M-type dwarfs [6]. The HZ of this class of stars is well within the tidal lock radius [7], which define the region of the system where the gravitational interaction of the central body force the planet into a 1:1 spin-orbit ratio on a timescale shorter than the permanence in the Main Sequence of the star. The climate of these planets cannot be studied using standard 1-D Energy Balance Models (EBM, [8]) and most investigators rely on computationally expensive 3-D General Circulation Models (GCM, e.g. [9]). This severely limits the number of combinations of unconstrained or poorly constrained planetary parameters that can be tested to determine how much robust the habitability of these planets actually is. Since observing the comparatively thin atmosphere of a rocky planet requires long integration times, a reliable framework for the selection of the best targets is needed.

Model: Here, we present a new 1-D EBM specifically tailored for the study of tidally locked rocky temperate exoplanets. This model discretizes the surface of the planet in a number of zones defined with respect to the instellation pole (i.e. the substellar point). The surface temperature profile as a function of the angular distance with the terminator is determined by the equilibrium between the absorbed stellar radiation, the outgoing longwave radiation and the horizontally transferred heat, treated as diffusive. By defining an interval of temperatures suitable for the survival of life (here, 0-100°C, [10]), it is possible to derive the fraction of the planetary surface that is habitable. Vertical radiative transfer is taken into account using a set of lookup tables produced by a GPU-accelerated radiative transfer model (EOS, [11]). The contribution of clouds and the surface albedo to the energy balance are taken into account via parameterized, independently calibrated relations [12,13]. The potential precipitation of atmospheric CO2 on the nightside is taken into consideration. Finally, the emission temperature of the planet at different points of the surface can be used to produce synthetic infrared phase curves.

Free parameters, such as the normalization of the diffusion coefficient, have been calibrated on specific benchmark cases to reproduce the average, substellar and antistellar temperatures as found by both 3-D GCMs [14] and a priori theoretical calculations [15].

While the use of 1-D EBM on tidally locked planets is not entirely new (see e.g. [16,17,18]), previous models were consistently simpler and generally focused on a single, specific climatological aspect.

Results: We have applied our new EBM for tidally locked planets to the eight temperate Earths and Super-Earths of the Ariel Target List (TRAPPIST-1c, -1d, -1e, -1f and -1g, LHS 1140b, K2-18b and TOI-1468c), all of which orbit M-type stars. In particular, we mapped the fractional habitability as a function of the surface pressure, in the [0.1, 10] bar range, and the CO2 mixing ratio, in the [-4, 0] dex range for a N2-CO2-H2O atmosphere. Both line and collisional induced absorption of the involved gases were taken from the HITRAN2020 repository [19]. All the targets were modeled as aquaplanets. Our preliminary analysis showed that: (i) TRAPPIST-1c and TOI-1468c are not habitable under any of the tested combinations of atmospheric parameters and likely in a runaway greenhouse state; (ii) TRAPPIST-1f, -1g and LHS 1140 b are habitable only in presence of dense (> 10 bar) and CO2-rich (> 1-10 %) atmospheres. For LHS 1140 b, habitable conditions are incompatible with the observationally derived upper limit on the CO2 mixing ratio of its atmosphere, as shown in Fig.1; (iii) TRAPPIST-1d is habitable only for either low total pressure or low

CO2 mixing ratio, i.e. when the partial pressure of CO2 is < -4 dex. This might limit the action of Earth-like photosynthetic organisms and thus the production of detectable, Earth-like biosignatures [20]; (iv) TRAPPIST-1e and K2-18b have the largest number of combinations that can potentially give rise to habitable conditions and are thus ideal targets for astrobiolgical studies. However, in both cases there exist a limiting pressure above which these planets likely enter a runaway greenhouse state. For K2-18b this limiting pressure is ~3 bars for a ≥1% CO2 concentration, which might clash with interior structure models of the planet that predict a deep (albeit H2-dominated) atmosphere [21].

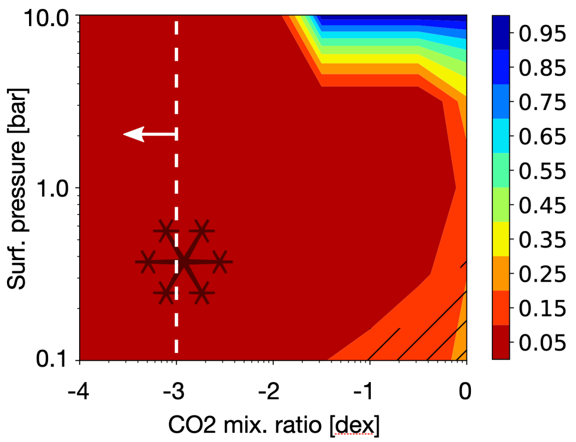

Fig.1: The fraction of the surface within the 0-100 °C interval (i.e. habitable) as a function of the surface pressure and the atmospheric CO2 mixing ratio, for the planet LHS 1140 b. The white dashed line represents the upper limit on the CO2 mixing ratio as derived from observational data by [22]. The hatched region represents the portion of the parameter space in which the atmosphere is unstable against (partial) collapse, caused by the condensation of CO2 on the planetary nightside. The snowflake symbol identifies the region of no habitability as caused by the onset of a planetary Snowball state.

Future prospects: We plan to expand the atmospheric pressure range and to test different atmospheric compositions, including H2-dominated cases (for K2-18b) and atmospheres with a varying amount of CH4. Our results can be compared with observational data, as done e.g. in Fig. 1 (the white dashed curve represent two observationally derived upper limit on the CO2 mixing ratio).

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A reanalysis of the LHS 1140 b atmosphere observed with the Hubble Space Telescope

A. Biagini, G. Cracchiolo, A. Petralia, J. Maldonado, C. Di Maio, G. Micela[1]
[1] INAF – Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, I-90134 Palermo, Italy, alfredo.biagini@inaf.it

Keywords: exoplanets – planets atmospheres – stellar abundances – stellar activity

Introduction: The super-Earth LHS 1140 b is an interesting target for atmospheric observations since it is close to the habitable zone of its star and falls in the gap of the radius distribution of small exoplanets, in the region thought to correspond to the transition between planets with and without atmospheres. Observations of the primary transit with WFC3 on board of the Hubble Space Telescope (HST) revealed a modulation in the planet transmission spectrum compatible with the presence of water; however this modulation may be also due to stellar activity-related phenomena. Here we present a detailed analysis of the WFC3/HST observations to probe the nature of this modulation and to understand if it can be attributable to the presence of unocculted spots on the stellar surface. Our analysis strongly suggests that LHS1140 is a rather quiet star with subsolar [Fe/H] and enriched in alpha elements. Therefore, we rule out the possibility that the planetary spectrum is affected by the presence of spots and faculae. This analysis shows the importance of a proper modelling of the stellar spectrum when analyzing transit observations. Finally, we modelled the planetary atmosphere of LHS1140 b to retrieve its atmospheric composition. However, the low resolution and the narrow spectral range of HST observations prevented us from definitively determining whether the spectral features are attributable to the presence of water or of other molecules in the planetary atmosphere.

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Additional Information: If you have any questions or need more information about preparing your abstract, please email **info@chiantitopics.it**.

Advancing the Concept Maturity and Technology of the Habitable Words Observatory (HWO)

L. Feinberg[1]
[1]HWO Principal Architect, NASA Goddart Space Flight Center

Keywords: -

Abstract: This talk will review the overall approach to maturing the architecture, science and technology for the Habitable Worlds Observatory. It will provide overall status of the new HWO Technology Maturation Project Office (TMPO) and cover the overall approach to iterating architectures, technology and science. It will discuss progress and plans in key areas like technology, testbeds and modeling. The talk will discuss results and lessons learned from three Exploratory Analytic Cases (EAC 1,2,3) developed this past year and the associated servicing considerations. It will conclude with the overall plan ahead towards Mission Concept Review.

References: -

THE LARGE INTERFEROMETER FOR EXOPLANETS (LIFE) - A SPACE MISSION DESIGNED TO SEARCH FOR LIFE OUTSIDE THE SOLAR SYSTEM

Sascha P. Quanz[1,2] and the LIFE collaboration[3]
[1]ETH Zurich, Institute for Particle Physics & Astrophysics, Wolfgang-Pauli-Str. 27, 8093 Zurich, Switzerland
[2]ETH Zurich, Department of Earth Sciences, Sonneggstrasse 5, 8092 Zurich, Switzerland
[3]www.life-space-mission.com

Until today, Earth remains the only known place in the cosmos that supports life. However, over the last 30 years, we have learned that, statistically, nearly all stars host planetary systems. Notably, a significant fraction of these planets is similar in mass, size, and temperature to Earth, raising the question of whether some have developed extraterrestrial biospheres. These biospheres can be inferred through the detection of atmospheric absorption lines of so-called biosignatures—molecules present only due to biological activity that accumulated to detectable levels. Unfortunately, current ground- and space-based instruments cannot readily detect these signatures.

In this talk, I will introduce the Large Interferometer For Exoplanets (LIFE), a space mission project, rooted in Europe and led by our research group at ETH Zurich, which has been gaining significant international support and traction over the last few years. As a space-based nulling interferometer operating at mid-infrared wavelengths, LIFE will be able to directly detect hundreds of exoplanets, with an expected 30 to 50 of which of size and temperature similar to Earth, and measure their intrinsic thermal emission spectroscopically. The wavelength range and mission design of LIFE offers unique and distinct advantages compared to other future missions and projects. This allows LIFE to search for atmospheric biosignatures in Earth-twin exoplanets, but LIFE can also find atmospheric biosignatures from biospheres that differ significantly from that of Earth in their composition or stellar environment. Also, LIFE has the capabilities to search for imprints of technology in exoplanet atmospheres, so-called technosignatures. This versatility allows LIFE to become the world's leading mission in the search for life beyond the Solar System. With a target launch no later than 2040, LIFE's vision and ambition go beyond standard agency-led development processes, driving us to explore new private-public partnerships.

In this talk I will outline LIFE's unique science potential, provide an update on ongoing technology development activities, and discuss how LIFE will help us address one of humanity's oldest questions: Are we alone?

A general introduction to LIFE and estimates about the expected detection yield can be found, for instance in [1,2,5,8]. The characterization potential of LIFE regarding the atmospheres of terrestrial exoplanets is discussed in [3,4,6,7,9,11]. The power of combining LIFE data with data from NASA's future flagship mission HWO is discussed in [10].

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Arguments and proposition for a joint HWO-LIFE data challenge and the nulling interferometry data standard to support it

R. Laugier[1], D. Defrère[1], J. Kammerer[2], P. Huber[3], F. Dannert[3], J. Hansen[3], M.-A. Martinod[1]
[1]Institute of Astronomy, KU Leuven, Celestijnenlaan 200D bus 2401, 3001 Leuven, Belgium (romain.laugier@kuleuven.be), [2]European Southern Observatory, Karl-Schwarzschild-Straße 2, 85748 Garching, Germany, [3]ETH Zurich, Institute for Particle Physics and Astrophysics, Wolfgang-Pauli-Str. 27, 8093 Zurich, Switzerland.

Keywords: High-contrast, coronagraph, nulling, data reduction.

Introduction: High-contrast imaging, whether with single dish coronagraphs or with long-baseline nulling interferometry makes use of carefully designed and adjusted optics to set-aside the on-axis light of the star and prevent its contamination of the off-axis light present in its scientific channels. The leftovers of this operations constitute so-called leakage light and speckle residuals, which carry uncertainties typically more than an order of magnitude larger than the target performance of the instrument. The observer must rely on data reduction and post-processing techniques to obtain the extra x10 gain required for astrophysical interpretation.

In both cases, these techniques face similar challenges of non-Gaussian distributed, correlated errors and mixed multi-planet signals for which the community is offering innovative tools and forward modeling is a crucial part of this approach. For nulling interferometry, an new data standard NIFITS developed by our consortium is meant to support these new techniques and their deployment to real datasets.

A thorough understanding of the capabilities of these techniques in realistic conditions now, during the concept phase of this new generation of coronagraphs (HWO) and nullers (LIFE) is pivotal in order to convert the scientific requirements into meaningful technical requirements, and keep costs under control. This can be investigated through a data challenge. While similar challenges already exist for coronagraphs ([1], [2]) and classical interferometry (i.e. beauty contest), a joint challenge dedicated to HWO and LIFE is relevant to fast-track the exploration and testing of this new generation of advanced methods in realistic conditions. In this talk, we will present some of these cutting-edge techniques, the new data standard NIFITS to support them, as well as propose a preliminary draft of a contest including the whole chain from nearly raw data (L1) to the scientific conclusions.

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RADIOMETRIC PERFORMANCE MODEL FOR A NOTIONAL IMAGING SPECTROMETER AS PART OF THE URANUS FLAGSHIP MISSION

B. Gorga[1,2], F. Tosi[2], and G. Piccioni[2]
[1]Sapienza, University of Rome, Italy (beatrice.gorga@uniroma1.it), [2]INAF-IAPS, Rome, Italy.

Keywords: Uranus system, icy moons, radiometric model.

Introduction: While all planets of our Solar System, including the outer planets with their satellites and ring system, have been visited at least once by spacecraft, not all of them had dedicated, orbital missions. The two ice giants Uranus and Neptune have only been flown by the Voyager 2 spacecraft in 1986 and 1989, respectively. Among the Flagship mission concepts to be funded by NASA in the next decade, the Uranus Orbiter and Probe (UOP) has been given top priority, as it addresses most of the key questions outlined in the 2023–2032 Planetary Decadal Survey [1, 2]. This mission will provide answers to fundamental questions about the origin and evolution of our Solar System, as well as potentially provide a paradigm for ice giants beyond our system.

The Uranian system is particularly intriguing due to the extreme axial tilt of the planet (98°), apparent lack of internal heat, complex magnetic field, and well-structured ring and satellite system, which may include ocean worlds. Recent data, obtained from both ground-based and space-based telescopic observatories, show that the five classical regular moons (Miranda, Ariel, Umbriel, Titania, and Oberon) exhibit neutral to slightly reddish spectral slopes in the ~0.3-1.3 μm range [3]. In the ~1.4-2.5 μm range, the spectra shift toward a bluish slope, indicating the presence of water ice mixed in varying proportions with other non-ice, optical dark materials, such as organics and silicates.

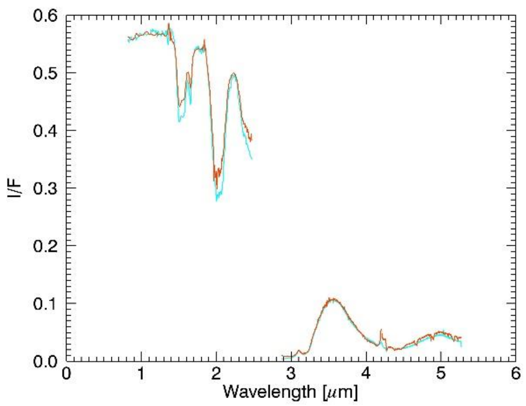

Figure 1: Reflectance factor of Ariel's leading (cyan) and trailing (orange) hemispheres.

For example, the spectrum of Ariel's trailing hemisphere shows CO_2 ice combination and overtone bands between 1.9 and 2.2 μm, which are not evident in the leading hemisphere [4]. The bombardment by charged particles within Uranus' magnetic field could be the cause of this reddening [5]. The possible presence of nitrogen-bearing species is suggested by a feature centered near 2.2 μm, indicating relatively young surface regions [5, 6]. Spectral features detected on Ariel's surface in the 2.8–5.1 μm range may be associated with the presence of hydrocarbons, nitriles, and carbonates [7].
These spectral characteristics are illustrated in Figure 1. The reflectance spectra of Ariel's leading and trailing hemispheres were obtained by combining two different datasets: IRTF/SpeX (~0.8–2.5 μm) and JWST/NIRSpec (2.87–5.2 μm).

Radiometric model: To identify and map the surface composition of Uranus' classical moons from a close distance, and to correlate it with geological features, one needs to design an imaging spectrometer. Based on the knowledge of the surface composition of the icy satellites, the near-infrared (NIR) spectral range 0.8-5.0 μm has the highest priority. This spectral range overlaps well with high-level scientific requirements for analyzing Uranus' atmosphere, with the visible range 0.4-1.0 μm providing complementary information. In the NIR range, a spectral sampling step equal to or smaller (i.e., better) than 10 nm, is required to resolve all the main chemical compounds known and expected to occur on the icy moons of Uranus.

The goal of a radiometric performance model is to simulate the instrument's response by computing the expected signal, noise, and hence signal-to-noise ratio, for the selected targets.

One key input for a radiometric performance model is a radiance spectrum of the target. Here, we achieve this goal by using a spectrum of Ariel obtained by combining IRTF/Spex and JWST/NIRSPec data (Fig. 1) and converting it into units of spectral radiance W/m^2/μm/sr by means of a solar spectrum scaled for the heliocentric distance of Uranus.

Other key instrumental parameters, such as field of view and angular resolution, are driven by the scientific objectives to be achieved at the moons.

While this is ongoing work, here we summarize the main parameters that make up a radiometric performance model, with particular reference to the hypothetical case of an imaging spectrometer to be housed on board the Uranus Flagship mission.

Conclusion: New data sets collected by a dedicated Uranus Orbiter will be essential for improving our understanding of the icy satellites of the Uranian system and clarify whether Uranus's five classical moons are, or were once ocean worlds.

In particular, thanks to high-resolution imaging spectroscopy, it will be possible to link surface composition and satellite morphology with the exogenic and endogenic processes that affect the complex Uranian system.

Acknowledgments: We acknowledge support from the "*Studio preliminare dei payloads per la missione URANUS flagship di NASA*", funded by the Italian Space Agency (ASI) under contract n. n. 2024-5-HH.0 - CUP n. F33C24000160005.

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EVALUATING LUNAR SURFACE CHEMISTRY WITH A PYTHON ROUTINE: MAIRAN CRATER AS A TEST CASE FOR ISRU IN FUTURE ARTEMIS MISSIONS

F. Colaiuta[1,2], F.Tosi[2], and F. Zambon[2]

[1]Department of Physics, University of Rome "La Sapienza", Piazzale Aldo Moro 2, 00185 Rome, Italy (federico.colaiuta@uniroma1.it, federico.colaiuta@inaf.it), [2]INAF – Istituto di Astrofisica e Planetologia Spaziali (INAF-IAPS), Via del Fosso del Cavaliere 100, I-00133, Rome.

Keywords: Moon, Hydroxyls, Unmixing, ISRU.

Introduction: Understanding the mineralogical composition of the lunar surface is essential for planning future robotic and crewed missions to the Moon. In particular, it supports the assessment of terrain characteristics at candidate landing sites and enables the identification of regions with high potential for *In-Situ Resource Utilization* (ISRU). Imaging spectroscopy plays a central role in this effort, and the *Moon Mineralogy Mapper* (M^3) [1,2,10], onboard India's Chandrayaan-1 mission, has been a key instrument in advancing our knowledge of the Moon's surface composition.

M^3 acquired data across a wide spectral range (0.43–3.00 µm) in two operational modes: a global survey with ~140 m/pixel resolution and coarser spectral sampling (20–40 nm), and a target mode offering ~70 m/pixel spatial resolution with finer spectral detail (10 nm). While global data allow broad compositional studies across the lunar surface, target mode is better suited for localized analyses, despite its limited coverage.

One of the most significant achievements of M^3 was the confirmation of widespread water/hydroxyl absorption features, especially near the lunar poles [4]. The key diagnostic for hydroxyl-bearing minerals is the 2.8-µm absorption band, whose depth and minimum position provide critical insight into surface hydration [3,4,5,6,7].

To enable efficient detection and mapping of such features, we developed a Python-based routine for the spectral analysis of M^3 data. This tool is designed to extract key indicators of surface hydration and composition and to support the selection and prioritization of sites for ISRU-focused exploration. Before applying the method to Artemis III candidate landing sites (Fig. 1), we validated it on a region characterized by hydrogen enrichment (as revealed by nuclear spectroscopy data [9]) and favorable observation conditions: the Mairan Crater area, located at (41°36′N, 43°24′W), in the lunar nearside.

ISRU for human settlement: Due to the generally high surface temperatures across much of the lunar terrain, water cannot exist in a stable state in most regions. However, the Moon's minimal axial tilt (~1.5°), combined with the presence of deep craters near the poles, allows for the formation of *Permanently Shadowed Regions* (PSRs) at polar latitudes. In these areas, temperatures remain consistently below the sublimation point of water, making them promising candidates for the presence of stable and potentially extractable ice deposits.

Despite this potential, resource extraction within PSRs poses significant technical challenges, primarily due to the extreme environmental conditions, including prolonged darkness and cryogenic temperatures, which complicate rover or lander operations.

Consequently, evaluating the distribution and abundance of hydroxyl in Artemis III candidate landing sites is of paramount importance. These investigations could inform the development of advanced resource extraction technologies, enabling access to critical volatiles—such as water—not only from PSRs at polar latitudes but also from regions with more favorable illumination, thereby enhancing the feasibility of sustainable ISRU.

In addition to water, essential resources—including breathable oxygen—may be extracted from lunar minerals through specialized thermochemical processes. Examples include the reduction of ilmenite ($FeTiO_3$) using hydrogen to produce water [8], molten electrolysis of anorthite-rich regolith for direct oxygen extraction, and solar thermal reduction of metal oxides. These approaches offer promising pathways to support extended lunar exploration and the establishment of a long-term human presence.

Identifying the most effective extraction strategies and associated technologies requires a detailed understanding of the lunar surface composition and the relative abundance of key materials. Therefore, comprehensive compositional analyses of the Artemis III landing sites represent a critical step toward enabling human settlement on the Moon.

Limitations of M^3 data: Imaging spectroscopy from orbit at polar latitudes is particularly challenging due to the very large incidence angles and the low amount of light detected by the instrument. These issues make the photometric correction of data particularly difficult, resulting in a very low *signal-to-noise ratio* (SNR) [10] and rendering the data less reliable at high latitudes. To overcome the lower SNR, it is possible to study the general features of the average spectrum of each landing site. This method would reduce instrumental noise, at the cost of losing spatial information about the distribution of the different compounds.

The current approach provides a comprehensive overview of the average surface chemical composition within the potential landing zones; however, it does not allow for a detailed analysis of the spatial distribution of spectral indices or the best-fit endmembers identified through linear unmixing. To evaluate the performance and full capabilities of the developed routine, it has been applied to Mairan crater datasets, where the SNR is higher [10] and the photometric correction is more reliable.

Mairan crater as test case: To evaluate the effectiveness of our spectral analysis routine, we applied it to M^3 data from the Mairan Crater surrounding regions. Previous data from the Lunar Prospector mission revealed hydrogen enrichment in this region [9], highlighting its relevance as an analog for ISRU-driven exploration.

Our analysis began with the computation of key spectral indices across the region. By measuring the depths of the 1-µm and 2-µm absorption bands, we identified compositional variations tied to pyroxene-rich minerals. Notably, high-Ca pyroxenes appear to be more concentrated in the southern portion near Oceanus Procellarum, in contrast to the more evolved terrains of the Mairan peninsula.

To assess the presence of hydroxyl-bearing minerals, we examined both the depth and area of the 2.8-µm absorption band. These parameters show a clear correlation with the spectral slope index (see Fig. 2), supporting the hypothesis that hydroxyl formation is largely driven by solar wind interactions, particularly in older lunar terrains. Additionally, variations in the band center indicate diversity of hydroxyl-bearing minerals across different terrain units, with lower center values in maria-like areas.

We complemented this analysis with a linear spectral unmixing approach, which revealed the presence of ilmenite and FeO—both of which are crucial for resource extraction strategies aimed at producing breathable oxygen and water [8]. However, due to known instrument limitations affecting the 2.8-µm region [6], hydroxyl detection through unmixing remains unreliable and must rely on index-based methods.

Conclusions and future applications: The Mairan Crater case study demonstrates the capability of our Python-based routine to identify and map ISRU-relevant materials using M^3 spectral data. By integrating spectral indices with unmixing techniques, we successfully highlighted the presence of key surface compounds, including pyroxenes, iron oxides, and ilmenite, as well as spectral evidence of hydroxyl-bearing minerals.

Having validated the routine in a high-SNR context, the next step is to apply this method to the average spectra of Artemis III candidate landing sites. This will enable two main objectives: prioritizing the candidate landing sites with the highest ISRU potential and supporting the design of scientific payloads optimized for in-situ resource prospecting.

This approach contributes directly to the broader goal of sustainable human exploration of the Moon, by enabling a data-driven strategy for resource identification and utilization.

Acknowledgments: This abstract derives from the *Space It Up* project, funded by the *Italian Space Agency*, ASI, and the *Ministry of University and Research*, MUR, under contract n. 2024-5-E.0 - CUP n. I53D24000060005.

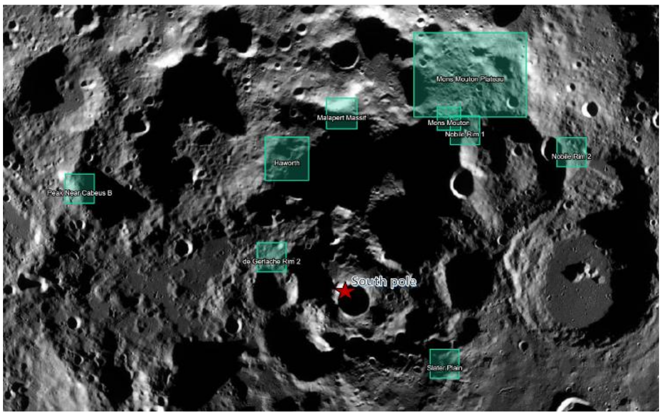

Figure 1 Artemis III candidate landing sites, updated as of October 2024.

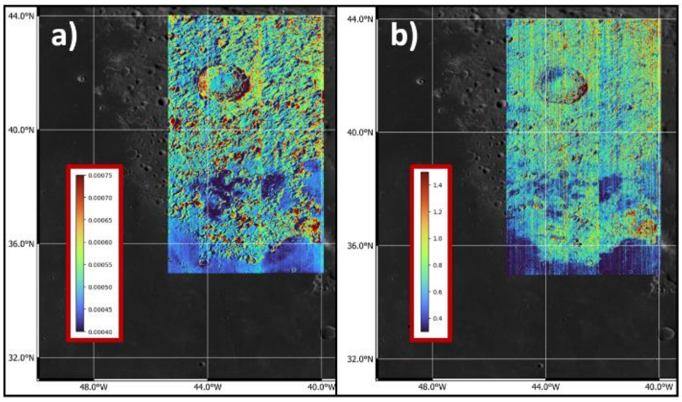

Figure 2 (**a**) Spectral slope mapped across our region of interest. Ancient terrains are associated with higher slope values. (**b**) 2.8-µm band area. The variability is related to potential changes in the abundance.

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Ariel-IT end-to-end exercise from the astrophysical scene to planetary spectra: simulations and retrieval

A. Bocchieri[1], A. Lorenzani[2], A. Petralia[3], G. Micela[3], and the Ariel-IT community
[1]Dipartimento di Fisica, La Sapienza Università di Roma, Piazzale Aldo Moro 5, Roma, 00185, Italy (e-mail: andrea.bocchieri@uniroma1.it); [2]INAF - Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, 50125, Firenze, Italy; [3]INAF - Osservatorio Astrofisico di Palermo, Piazza del Parlamento 1, I-90134, Palermo, Italy.

Keywords: Ariel, ExoSim2, stellar activity, data analysis, atmospheric spectra.

Abstract: The forthcoming Ariel space mission will conduct the first spectroscopic survey of the atmospheres of hundreds of exoplanets in the visible and infrared bands of the electromagnetic spectrum. The mission is currently in Phase C and a Dry-Run exercise is ongoing to assess early preparedness and highlight key areas for further work ahead of launch in 2029. The Ariel-IT community has set up an end-to-end procedure from target identification to simulated primary transit observations and retrieval. The current focus is on a sample of hot Jupiters and planets orbiting active stars, with key activities including determination of stellar and planetary properties, planetary formation and evolution models, star-planet interaction, atmospheric evolution, and spectral synthesis. These simulations are passed as inputs to the latest version of the exoplanet observation simulator, ExoSim2 [1], alongside the Ariel payload description and the PSFs vs wavelength for each instrument and focal plane generated with PAOS [2], a generic open-source physical optics simulator. ExoSim2 produces photometric and spectroscopic timelines of a simulated Ariel observation in the time domain, including the effects of stellar activity and jitter in the spacecraft's line of sight [3], a source of disturbance when measuring the spectra of exoplanet atmospheres. Our preliminary results for WASP-69b showcase the ability to achieve photon noise-limited observations across the entire Ariel spectrum post-processing and the possibility to discriminate between different input atmospheric compositions in the studied cases. Current limitations will be discussed along with the next steps needed to complete the analysis of our sample.

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Experimental study of the interference dips observed on the Collison-induced Absorption fundamental band of H_2: their relevance to planetary atmosphere characterization

F. Vitali[1,2], S. Stefani[1], G. Piccioni[1] , M. Snels[3], D. Grassi[1], D. Biondi[1] and A. Boccaccini[1]
[1]IAPS-INAF, Via del fosso del cavaliere 100, 00133 Rome, Italy, [2]Università degli studi di Roma “Tor Vergata”, Via Cracovia 50, 00133, Rome, Italy, [3]ISAC-CNR Via del fosso del cavaliere 100, 00133, Rome, Italy francesca.vitali@inaf.it

Keywords: CIA, H_2, dips, quadrupole, retrival

Introduction: The habitability concept represents a synergy between diverse aspects, including the presence and composition of an atmosphere (or exosphere), the radiation coming from the host star or, when we talk of moons, the host planet, the presence of a magnetic field, and many others. A modern concept of habitability also includes the so-called "ocean worlds," which are important for understanding how the giant planet systems in the outer Solar System and beyond work. In particular, the Jupiter system will be visited in a few years by the JUICE mission. It will study the complex environment of Jupiter and how it affects the habitability of its icy moons.

Focusing on the Jovian system, it is very important to have an overview as accurate as possible of how the gas giant affects the environment, starting from the composition and opacity of its dense and composite atmosphere. The latter is mainly composed of H_2 and He, making the Collision-Induced Absorption (CIA) one of the main sources of opacity. Theoretical models have been previously calculated in a wide temperature range [1][2] from hundreds to thousands Kelvin, but not so many experimental measurements have been provided, most of all at high temperatures. For this reason, we concentrated our activity on the experimental study of the H_2 CIA in the [3600, 5500] cm^{-1} spectral range at high resolution.

Experimental setup: The experimental setup employed here is called PASSxS (Planetary Atmosphere System Simulation x Spectroscopy). It consists of a simulation chamber that contains a Multi-Pass cell coupled with an IR Fourier spectrometer (FTIR) and aligned to reach an optical path of 3.28 m. The chamber can be heated to 550 K, cooled to 100 K, and sustain pressures up to 70 bar. The FTIR has a maximum resolution of 0.002 cm^{-1}.
A photo of the setup can be visualized in Figure 1.

Experimental results: We recently measured the binary absorption coefficients due to both the H_2-H_2 and H_2-He collisions in the [3600, 5500] cm^{-1} spectral range for temperatures going from 120 to 500 K [1]. Superimposed on the CIA absorption, some narrow features have been observed at all the temperatures. Those are called *interference dips* and

Figure 1*: Experimental setup, consisting of a Fourier Spectrometer coupled with a simulation chamber (in grey behind the FTIR)*

represent a lack of absorption at specific frequencies not taken into account by the existing models.
They have been previously observed in other experimental works [4-8] at temperatures equal to and less than 300 K.
In order to study the behavior of those features with density and temperature, we performed measurements of the CIA H_2 fundamental band at a resolution of 0.05 cm^{-1}, temperatures from 300 to 500 K, and different pressures.
Figure 2 shows the comparison between the experimental absorption coefficients measured at 12 bar and 400 K and Abel’s model.

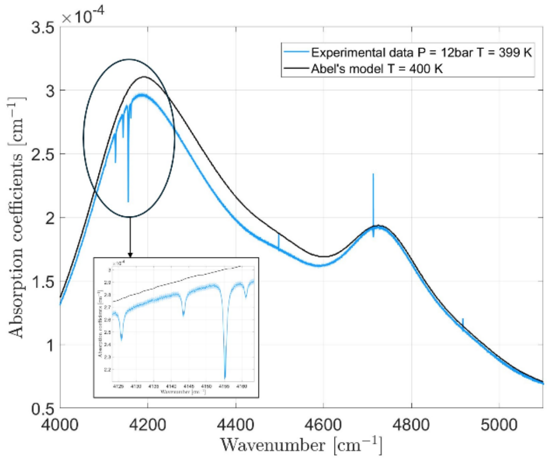

Figure 2*: Comparison between experimental absorption coefficients measured at 12 bar and 400 K (blue line) and Abel's model (black line). In the bottom left panel, a blow-up of the main peak of the band can be observed, where four interference dips are visible.*

Along the band profile, some sharp features with different origins can be observed. First, we have the so-called *interference dips*, well visible on the main peak of the band. Those can be visualized in the bottom left corner of Figure 2. Furthermore, they are also present around 4500 cm^{-1}, 4700 cm^{-1}, and 4900 cm^{-1}, but are difficult to see because of the superimposition of some sharp absorption lines due to the H_2 quadrupolar transitions, present in proximity of all the dips except that at 4161 cm^{-1}.

Since we performed measurements at three different pressures for both 400 K and 500 K, we managed to study the behavior of the FWHM with the density of each observable dip.

Figure 3 shows the FWHM measured for the dip around 4155 cm^{-1} in function of the density for both the temperatures considered.

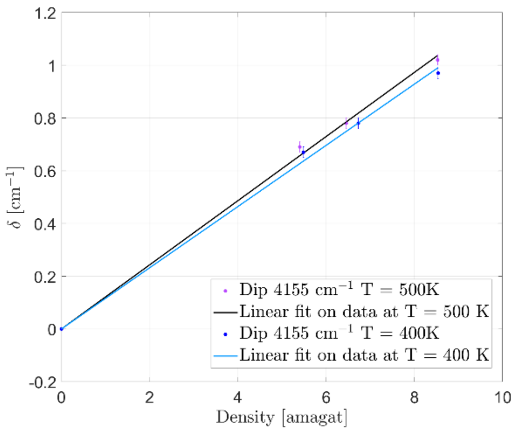

Figure 3: *FWHM of the dip at 4155 cm^{-1} in function of the density for 400 K (blue dots) and 500 K (violet dots). The solid lines represent the linear fits performed over the experimental data at 400 K (black line) and 500 K (light blue line).*

As one can observe, the data follow a linear trend, as expected by Van Kranendonk's theory [9].

Conclusions: Performing experimental measurements is important for two main reasons. Firstly, they can be used as input parameters in the radiative transfer models to study the chemistry and physical composition of an atmosphere.

Moreover, laboratory data can provide additional elements that can help in the retrieval of atmospheric parameters, which, in general, are difficult to access.

Apart from the H_2 CIA, which plays a major role in Jupiter's atmospheric opacity, molecules such as N_2, O_2, or CO_2 present intense CIA bands in different spectral regions. Their investigation, which will be part of future studies, can provide key parameters about the environmental conditions that can define a planet as habitable, in particular for the physical conditions allowing the presence of liquid water on the surface.

Finally, to be noted that the CIA can impact the metereology and climatology of a planet on a long time scale, along with its evolution.

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THE IMPACT OF EXTREME SPACE WEATHER EVENTS ON EARTH'S CLIMATE AND HABITABILITY

L. Biasiotti[1], P. Simonetti[1], D. Locci[2], C. Cecchi-Pestellini[2], G. Vladilo[1], L. Calderone[1], F. Dogo[1], S. Monai[1], S.L. Ivanovski[1]
[1]INAF-OATs (lorenzo.biasiotti@inaf.it), [2]INAF-OAPa.

Keywords: exoplanets, habitability, astrobiology, space weather, archean Earth.

Introduction: Space Weather (SWE) has a profound impact on Earth's atmospheric chemistry and climate. Compared to the present-day Sun, the young Sun was more magnetically active and experienced more frequent extreme space weather events (e.g., [1,2,3,4,5]), such as coronal mass ejections (CMEs) and solar energetic particles (SEPs), which steadily bombarded Earth's upper atmosphere. These particles enhanced atmospheric chemistry, potentially resulting in large amounts of kinetically produced greenhouse gases, such as CO, H_2, N_2O, and HCN [6,7,8,9,10,11]. In this work, we used a chain of three models – (i) a thermochemical and photochemical kinetic model [12,13], (ii) a radiative-convective model (EOS) [14], and (iii) an energy balance model (ESTM) [15,16] – to explore the impact of an extreme SWE event on Earth's atmosphere, in terms of variation of atmospheric species and the consequences on Earth's climate. Specifically, we tested whether the Sun-Earth interaction could address the Faint Young Sun Paradox (FYSP), as proposed by [3].

Method: To conduct this analysis, the first step involves using a one-dimensional thermochemical and photochemical kinetics model to simulate the interaction between atmospheric gases and ionizing stellar radiation. This model utilizes the energy spectrum of proton fluences for the Carrington event [3] and the XUV flux of the young Sun [3] to calculate ionization, excitation, and dissociation rates. By integrating stellar particle interactions, the model yields detailed vertical chemical profiles of atmospheric components. These vertical profiles are then used as inputs to our radiative-convective model, which calculates the outgoing longwave radiation (OLR) and the top-of-atmosphere (TOA) albedo for a set of atmospheric columns with different surface pressures and chemical compositions. The radiative lookup tables compiled by EOS are included in our energy balance model to derive the seasonal evolution of surface temperature in each latitudinal band. We also applied this modeling pipeline to the present-day Earth atmosphere to assess the potential impact of a prolonged period of intense solar activity.

Results: First, we found that for each atmosphere considered, due to the dissociation of N_2 by SEPs, $N(^2D)$ is produced, giving rise to a rich chemistry that results in the production of greenhouse gases such as N_2O and HCN (Figure 1). H_2 is also produced. Additionally, another greenhouse gas, CO, is thermochemically produced. Finally, we observed that in the case of secondary atmospheres, the chemical abundances of the species are dominated by SEP-driven chemistry, while high-energy radiation plays a marginal role. Second, for an Archean Earth-like atmosphere of 90% N_2, 10% CO_2, and trace amounts of either CH_4 or H_2, the two most abundant species produced are CO (71 ppm) and H_2 (0.03 ppm). In this condition, the surface temperature increase is no larger than 0.3 K, which makes this solution to the FYSP unviable. Notably, the contribution of nitrogen species (N_2O and HCN) to this temperature increase is negligible. Third, revisiting the atmospheric scenario proposed by [3], we found a modest temperature increase (~0.2 K). Even when the SEP flux is enhanced by a factor of 10 with respect to Carrington-like conditions, the chemical composition of the atmosphere remains unchanged. This indicates that even under stronger space weather conditions, the impact on the planetary thermal state is minimal. Lastly, under present-day conditions, the cumulative effects of a prolonged period of intense solar activity, in terms of frequent Carrington-like SEP events, would decrease the surface temperature by ~4 K (Figure 2).

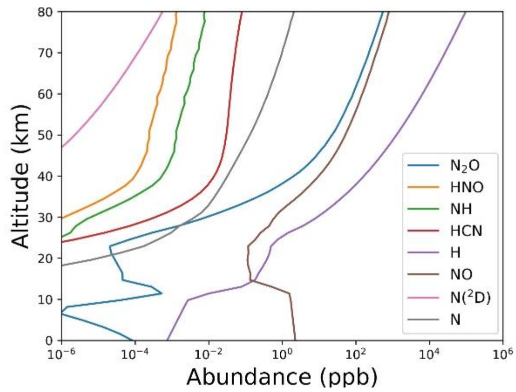

Figure 1. Chemical profiles of some key molecules for one of the scenarios studied in this work, corresponding to an initial Archean Earth-like atmosphere of 90% N_2, 10% CO_2 and trace amounts of CH_4. Credits: [17].

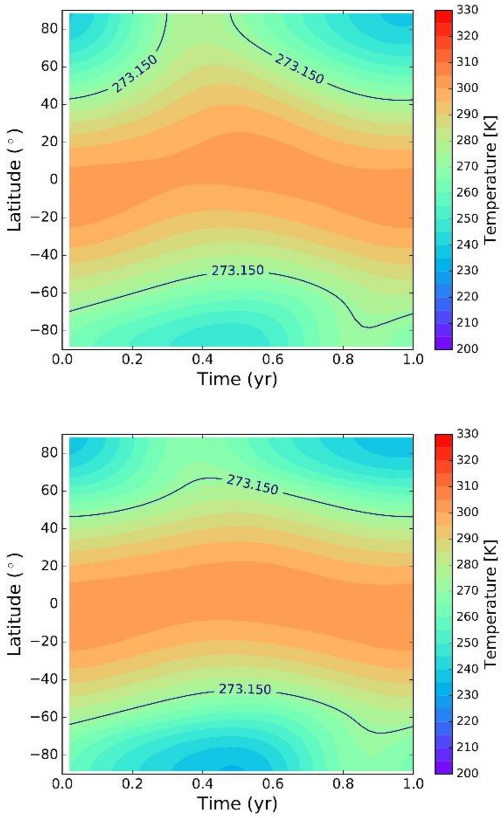

Figure 2. Seasonal and latitudinal variations of surface temperature. Top panel: unprocessed atmosphere. Bottom panel: processed atmosphere. Black contour lines highlight the regions of the parameter space for which pure liquid water can be liquid. Credits: [17].

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THE ACTIVITY-ROTATION-AGE RELATIONSHIP UNDER THE LENS OF ASTEROSEISMOLOGY

C. Pezzotti[1], J. Betrisey[2], G. Buldgen[1], M. Gilfanov[3,4], I. Bikmaev[5], R. Sunyaev[3,4], E. Isik[6], E. Gosset[1], N. J. Wright[7]

[1]STAR Institute, Université de Liège, Liège, Belgium (camilla.pezzotti@uliege.be), [2]Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden, [3]Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, 117997 Moscow, Russia, [4]Max Planck Institute for Astrophysics, Karl-Schwarzschild-Str 1, Garching b. München D-85741, Germany, [5]Kazan Federal University, 18 Kremlyovskaya Street, Kazan, Russia, [6]Max-Planck-Institut für Sonnensystemforschung Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany, Astrophysics Group ,[7]Keele University, Keele ST5 5BG, UK

Keywords: Stellar activity; stellar modelling; star-planet interactions; planetary mass loss; planetary habitability.

Introduction: Studying the relationship between magnetic activity, rotational period and age in low-mass stars ($M_\star \lesssim 1.5\ M_\odot$) is of high interest to the scientific community, as these quantities are critical observational proxies of the dynamo operating in stars. The rotational and magnetic properties of low-mass stars are tightly interconnected. As they evolve, their surface rotation and magnetism globally decrease, resulting in a less efficient dynamo and angular momentum removal. Although past studies have been crucially informative on the activity-rotation-age relationship for relatively young low-mass stars in clusters (e.g., [1]), the limited access to accurate ages for isolated, older (t > 1 Gyr) stars has prevented a comprehensive further investigation of this relation (e.g., [2]).

Thanks to the advent of space-based photometry missions, such as CoRoT ([3]), *Kepler* ([4]) and TESS ([5]), asteroseismology has established itself as a powerful tool to determine stellar ages with unprecedented precision and accuracy. Specifically, the *Kepler* mission has provided a sample of 66 solar-like stars (*Kepler* LEGACY sample, [6]) with exquisite asteroseismic data.

Starting from this sample of stars, we searched for related X-ray luminosity measurements, which represent robust activity indicators unambiguously associated with the magnetic heating of the plasma in the stellar coronae. Thanks to SRG/eROSITA ([7], [8]), the vast majority of the *Kepler* LEGACY sample stars has been observed for the first time, measuring X-ray fluxes for 13 stars.

In our work we aim at expanding the magnetic activity-rotation-age relation using these 13 solar-like stars with remarkably accurate parameters, rotational periods and firstly detected X-ray luminosities in the attempt to investigate the properties and evolution of stellar dynamos. Since this relationship has strong consequences also in star-planet interaction studies, we investigate the impact on planetary mass loss due to a potential change in the X-ray luminosity vs age (or rotational period) relationship for planetary habitability.

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DETECTING ATMOSPHERIC CO_2 TRENDS AS POPULATION-LEVEL SIGNATURES FOR LONG-TERM STABLE WATER OCEANS AND BIOTIC ACTIVITY ON TEMPERATE TERRESTRIAL EXOPLANETS

J. Hansen[1], D. Angerhausen[2], S.P. Quanz[3], D. Vance[4], B.S. Konrad[5], E.O. Garvin[6], E. Alei[7], J. Kammerer[8], and F.A. Dannert[9]

[1]ETH Zurich, Institute for Particle Physics & Astrophysics, Wolfgang-Pauli-Str. 27, 8093 Zurich, Switzerland; National Centre of Competence in Research PlanetS (www.nccr-planets.ch); Mailing address: Regensdorferstrasse 153, 8049 Zurich, Switzerland; Email: jahansen@phys.ethz.ch, [2]ETH Zurich, Institute for Particle Physics & Astrophysics, Wolfgang-Pauli-Str. 27, 8093 Zurich, Switzerland; National Centre of Competence in Research PlanetS (www.nccr-planets.ch); Blue Marble Space Institute of Science, Seattle, WA, USA; SETI Institute, 189 N. Bernado Ave, Mountain View, CA 94043, USA, [3]ETH Zurich, Institute for Particle Physics & Astrophysics, Wolfgang-Pauli-Str. 27, 8093 Zurich, Switzerland; National Centre of Competence in Research PlanetS (www.nccr-planets.ch); ETH Zurich, Department of Earth and Planetary Sciences, Sonneggstrasse 5, 8092 Zurich, Switzerland, [4]ETH Zurich, Institute of Geochemistry and Petrology, Department of Earth and Planetary Sciences, Clausiusstrasse 25, 8092 Zurich, Switzerland, [5]ETH Zurich, Institute for Particle Physics & Astrophysics, Wolfgang-Pauli-Str. 27, 8093 Zurich, Switzerland; National Centre of Competence in Research PlanetS (www.nccr-planets.ch), [6]ETH Zurich, Institute for Particle Physics & Astrophysics, Wolfgang-Pauli-Str. 27, 8093 Zurich, Switzerland; National Centre of Competence in Research PlanetS (www.nccr-planets.ch), [7]NASA Postdoctoral Program Fellow, NASA Goddard Space Flight Center, 8800 Goddard Rd, Greenbelt, 20771, MD, USA , [8]European Southern Observatory, Karl-Schwarzschild-Straße 2, 85748 Garching, Germany, [9]ETH Zurich, Institute for Particle Physics & Astrophysics, Wolfgang-Pauli-Str. 27, 8093 Zurich, Switzerland; National Centre of Competence in Research PlanetS (www.nccr-planets.ch)

Keywords: Habitable zone, Exoplanet atmospheres, Biosignatures, Exoplanet atmospheric variability, Infrared spectroscopy

Abstract: Identifying key observables is essential for enhancing our knowledge of exoplanet habitability and biospheres, as well as improving future mission capabilities. While currently challenging, future observatories such as the Large Interferometer for Exoplanets (LIFE) will enable atmospheric observations of a diverse sample of temperate terrestrial worlds. Using thermal emission spectra that represent conventional predictions of atmospheric CO_2-variability across the Habitable Zone (HZ), we assess the ability of the LIFE mission to detect CO_2 trends indicative of the carbonate-silicate (Cb-Si) weathering feedback, a well-known habitability marker and potential biological tracer. Therefore, we explore the feasibility of differentiating between CO_2 trends in biotic and abiotic planet populations. We create synthetic exoplanet populations based on geochemistry-climate predictions and perform retrievals on simulated thermal emission observations. The results demonstrate the robust detection of population-level CO_2 trends in both biotic and abiotic scenarios for population sizes as small as 30 Exo-Earth Candidates (EECs) and the lowest assessed spectrum quality in terms of signal-to-noise ratio, S/N = 10, and spectral resolution, R = 50. However, biased CO_2 partial pressure constraints hinder accurate differentiation between biotic and abiotic trends. If these biases were corrected, accurate differentiation could be achieved for populations with ≥100 EECs. We conclude that LIFE can effectively enable population-level characterization of temperate terrestrial atmospheres and detect Cb-Si cycle driven CO_2 trends as habitability indicators. Nevertheless, the identified biases underscore the importance of testing atmospheric characterization performance against the broad diversity expected for planetary populations.

ExoNAMD: a community tool to gauge multi-planetary systems

A. Bocchieri[1], J. Zak[2], and D. Turrini[3]
[1]Dipartimento di Fisica, La Sapienza Università di Roma, Piazzale Aldo Moro 5, Roma, 00185, Italy (e-mail: andrea.bocchieri@uniroma1.it), [2]Astronomical Institute of the Czech Academy of Sciences, Friˇcova 298, 25165 Ondˇrejov, Czech Republic, [3]INAF - Osservatorio Astrofisico di Torino, Via Osservatorio 20, I-10025, Pino Torinese, Italy.

Keywords: Multiplanetary systems, NAMD, stellar obliquity, Ariel, PLATO.

Abstract: Multi-planetary systems reveal diverse dynamical histories. Stellar obliquity is a key diagnostic of these histories, linking past dynamical interactions to migration pathways (e.g., quiescent disc vs. violent high-eccentricity). To measure the remaining dynamical violence of planetary systems, we introduce an obliquity-based NAMD (Normalized Angular Momentum Deficit), improving on the previous relative inclination-based NAMD [1] in capturing the systems' architectures. Our open-source ExoNAMD Python tool calculates these metrics, enabling cross-system dynamical state comparisons. The dynamical context provided by the NAMD can be used for (1) interpreting planetary atmospheres, as migration history shapes composition and thermal structure; (2) unbiased target selection for future observations and to guide model testing; (3) enabling comprehensive dynamical descriptions alongside stability indicators (AMD, MEGNO, SPOCK) in the forthcoming era of PLATO and Ariel.

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Biosignatures: Traces of Life Across the Solar System

S. Pagnoscin[1, 2]

[1]Department of Physics and Astronomy, University of Florence, Via G. Sansone 1, Sesto Fiorentino, Firenze (silvia.pagnoscin@unifi.it); [2]INAF - Astrophysical Observatory of Arcetri, Largo E. Fermi, 5, Firenze, Istituto di Geoscienze e Georisorse del CNR, Via Moruzzi 1, 56124 Pisa, Italy

Keywords: -

Introduction: As Homo sapiens, we are driven by curiosity. We have wandered across our planet, discovering life in billions of different forms (and many more still await to be discovered) as we strive to understand the origin of life on Earth. This intrinsic desire to explore and understand our origins led us beyond Earth, giving rise to a new scientific discipline: Astrobiology. Astrobiology is an interdisciplinary field that brings together astronomy, biology, physics, geology, and chemistry to study the origin, evolution, and distribution of life in the Universe.

The aim of Astrobiology is thus the search for traces of life in the Universe, better known as biosignatures. A biosignature is defined as an 'object, substance, and/or pattern whose origin specifically requires a biological agent' (Des Marais et al., 2008). On Earth, biosignatures are typically unambiguous: complex organic molecules, cellular structures, isotopic fractionation patterns, fossils, and ecological footprints are all clearly tied to biological activity. However, searching for life beyond Earth presents more challenges. It is necessary to identify signatures that can be detected remotely via orbiters or in situ via rovers and distinguish them from purely abiotic processes. The first attempt to detect biosignatures beyond Earth was made during NASA's Viking mission to Mars in the 1970s. Carl Sagan, among others, helped shape the early philosophy of life detection. Although Viking's results were inconclusive, they set the stage for decades of research and the evolving definition of what constitutes a biosignature.

Today, biosignatures are sought all around the Universe, focusing on the most promising niches hidden in the Solar System and beyond:

- Mars has long been a primary target in the search for life beyond Earth, ever since Schiaparelli's observations of intricate networks of surface channels. These ancient fluvial landscapes and potential subsurface reservoirs may preserve chemical or isotopic traces of past life, making it one of the most promising sites for biosignature detection. In situ analyses have confirmed the presence of organic molecules in Martian mudstones (Freissinet et al., 2015), and recent laboratory studies suggest that hydrated sulfates may aid in preserving such biosignatures (Alberini et al., 2024).
- The icy moons of Jupiter and Saturn, such as Europa and Enceladus, hide subsurface global salty oceans beneath their thick icy crust. These huge liquid water reservoirs may harbor conditions suitable for life. The detection of organic molecules in Enceladus' plumes and signs of a dynamic ice shell on Europa offer direct insights into these exo-oceans. Furthermore, geophysical modeling of the internal oceans supports transport and release of potential biosignatures to the surface or space, which can be detected. (Pagnoscin et al. 2024)
- Asteroids and dwarf planets, such as Ceres, represent primordial bodies that may preserve organic compounds and hydrated minerals that are clues to both the prebiotic chemistry of the early Solar System and possible life-bearing niches (De Sanctis et al. 2024).
- Exoplanets outside the Solar System have been discovered within the so-called astronomical habitable zone, where conditions may allow liquid water to exist, supporting potential extraterrestrial life. There, biosignatures might take the form of atmospheric gases in disequilibrium (like oxygen-methane pairs) or surface features such as the red-edge signature of vegetation (Schwieterman et al., 2018). In this perspective, it is important to consider that recent climate–biosphere modeling suggests that the presence and spatial dynamics of life (i.e., vegetation cover and competition) can also influence habitability (Bisesi et al., 2024). These changes can thus modify the environmental context in which biosignatures may arise and persist.

The concept of biosignatures in astrobiology is continuously evolving. One of the greatest challenges in detecting extraterrestrial life is still to distinguish biotic signals from abiotic ones in unfamiliar planetary environments. Special emphasis is currently placed on Mars and the Icy Moons of Jupiter, which are the focus of ongoing and future missions such as NASA's Perseverance, ESA-ASI's JUICE, and NASA's Europa Clipper aimed at unraveling the mystery of life beyond Earth.

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JWST observations of the cornerstone temperate sub-Neptune K2-18 b

Renyu Hu[1,2]
[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, renyu.hu@jpl.nasa.gov,
[2]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA.

Keywords: Exoplanet atmospheres, Extrasoalr ice giants, Habitable planets, Ocean planets, Transmission spectroscopy.

Introduction: Earth-temperature, sub-Neptune-sized exoplanets are now within reach for detailed atmospheric characterization with JWST, with K2-18 b being one of the first to receive repeated observations. The initial observations revealed abundant CH_4, suggested CO_2, and indicated the absence of NH_3 [1]. They suggested three potential atmospheric scenarios: (1) a massive H_2-dominated envelope influenced by a high internal heat flux and possibly an underlying magma ocean, (2) a massive gas envelope with near-equal abundances of H_2O and H_2, or (3) a water-dominated envelope with a liquid water layer at the surface. To resolve these possibilities, we have conducted repeated JWST observations to capture four new transmission spectra of K2-18 b using NIRSpec's G235H and G395H grisms [2]. These spectra deliver high-precision measurements between 2 and 5 μm and enable detailed probes of the planet's atmospheric metallicity, cold trap, and abundances of NH_3, HCN, and organosulfur species. This unprecedented dataset offers critical insights into K2-18 b's internal structure and informs an updated roadmap for characterizing temperate sub-Neptunes, advancing our understanding of their atmospheric properties and potential habitability.

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SPECTROSCOPIC MEASURES OF HYDRATED SULFATE AS A RELEVANT PLANETARY ANALOGUE FOR JUPITER'S ICY MOONS

F. Furnari[1,2], G. Piccioni [1], S. Rubino[1], S. Stefani[1], S. DeAngelis[1], F. Tosi[1], C. Carli[1], M. Ferrari[1] and E. LaFrancesca[1]

[1] *Istituto di Astrofisica e Planetologia Spaziali (IAPS), Istituto Nazionale di Astrofisica (INAF), Via del Fosso del Cavaliere 100, 00133 Rome, Italy,*

[2] *Dipartimento di Fisica, Sapienza Università di Roma, Rome, Italy*

francesca.furnari@inaf.it

Keywords: Spectroscopy, icy moons, hydrated sulfate, planetary analogs

Introduction: On the surface of Jupiter's icy moons like Europa and Ganymede we expect to find non-water ice materials, especially hydrated minerals which can mimic the 1.5 and 2.0 µm water ice absorption bands. In particular, the presence of hexahydrite ($MgSO_4 \cdot 6H_2O$), which is hydrated magnesium sulfate, is suggested on the surface of these icy bodies and could interact with the subsurface ocean [1]. The key question is to understand if these non-water ice materials are detectable and distinguishable from the ice, whether they are of exogenic or endogenic origins, and eventually, how they interact with the subsurface ocean. Characterizing such minerals under environmental conditions similar to those found on the icy moons' surfaces is therefore crucial, especially considering the link between the presence of hydrated sulfates on Solar System bodies and geological processes that occurred in the presence of liquid water, with potential implications for the establishment of a habitable environment. This work is also important to support the future observations of the MAJIS (Moons and Jupiter Imaging Spectrometer) instrument [2,3] onboard the ESA JUICE mission. Although similar work on hexahydrite was carried out previously [4,5,6], the MAJIS spectral sampling, which is 3.6 nm from 0.50 to 2.35 µm and 6.5 nm from 2.25 to 5.54 µm, motivates performing new laboratory measurements at higher spectral resolution.

Experimental procedure and results: For this objective, we prepared powders of hexahydrite at different grain sizes to study the variation of the spectral features in the infrared and visible spectral ranges depending on the environmental conditions. We acquire both the reflectance and the visible image of the sample with a microscope coupled with an FTIR spectrometer and equipped with a cryogenic cell [*Figure 1*] that contains the sample in a controlled environment with pressure down to 10^{-4} mbar, and temperature down to 40 K.
Different grain sizes of the sample were put inside the cryogenic cell and brought to a pressure of 10^{-4} mbar while acquiring spectra during the process. As a consequence of the lowering in pressure, the sample shows a spectral variation due to dehydration and amorphization [7], also confirmed by Raman spectra. The reflectance spectra, as well as the computed spectral parameters, show that there is more than one critical pressure at which the sample starts to change part of its lattice structure. Moreover, different grain sizes respond differently to the variation of pressure.
As shown in *Figures 2 and 3*, the sample undergoes a first spectral variation, apparently in a permanent way, around 400 mbar.
Once the sample is exposed back to air, although it doesn't return to its pristine state spectrally, the surface of the sample seems to return to a crystalline structure, forming a crust on its surface that swells.

Figure 1: *Experimental setup composed of a cryogenic cell that allows a controlled environment for the sample, and a microscope coupled with an FTIR spectrometer that enables the acquisition of the spectral radiance of the samples.*

Conclusions: The results shown here seem to constrain the correlation between the spectral features of this kind of material, planetary analogs for the icy satellites, and their physical properties. One of the interesting aspects so far is the change in the lattice structure of this sample, which seems incompatible in its crystalline and hydrated form (hexahydrite) at the extremely low pressure on the icy moons surface, in the range 10^{-8} -10^{-12} mbar. In the laboratory, the process of amorphization and dehydration with vacuum occurs in a timescale of tens of minutes at room temperature. Therefore, if it was present on these bodies, it could be continuously replenished or ephemeral, and this may sustain the subsurface liquid water as a possible source. On the surface of Europa and Ganymede, this type of heavily hydrated salt could eventually be preserved thanks to some mechanism that involves the rapid emplacement in simultaneous surface conditions of low temperatures and ultra-high vacuum. With this regard, a deeper laboratory investigation is required. These results are extremely important to avoid any ambiguity in the determination of the surface composition of the icy moons of Jupiter once the data MAJIS will acquire is available, and could also allow some constraints on what could be present underneath the surface.

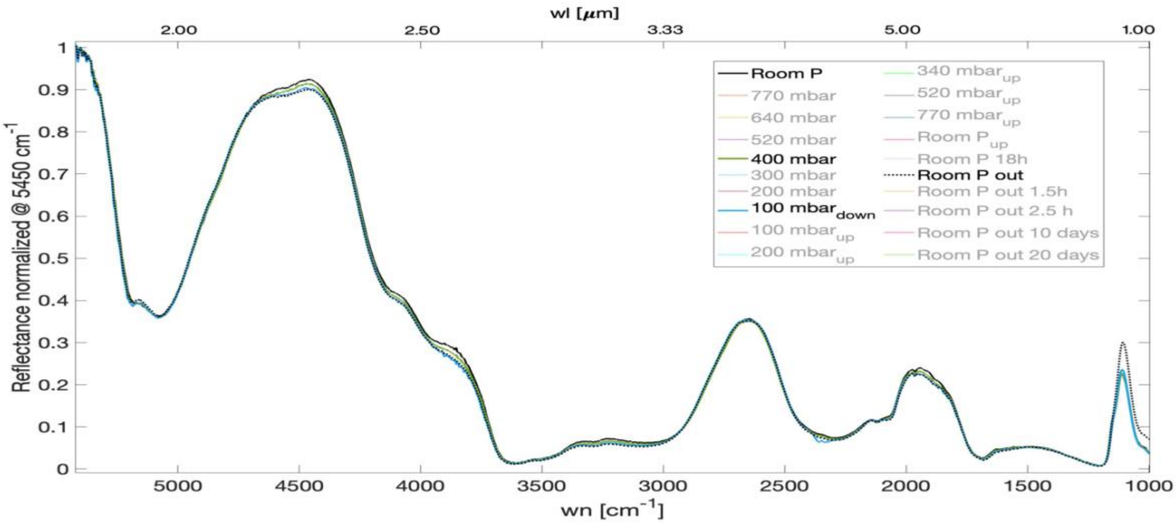

Figure 2: Infrared reflectance spectra of a hexahydrite powder with a grain size between 50 and 75 microns at different pressures and room temperature. At 400 mbar the spectrum starts showing variation with respect to its pristine state (room pressure).

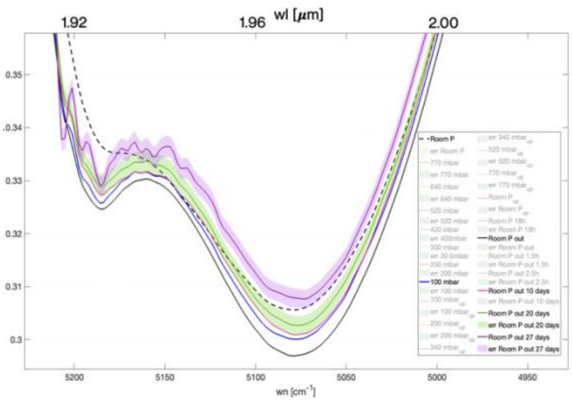

Figure 3: Close-up of the 2 microns water diagnostic absorption band in the continuum-removed reflectance spectra of a hexahydrite powder with a grain size between 50 and 75 microns at different pressures and room temperature. After being exposed for 27 days to room pressure, the sample keeps changing but never returns to its pristine state.

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Linking the prediction of biosignatures observability with climate models: the case of refraction and photosyntetic habitability for M stars planets

M. Maris[1,2,3], E. Bisesi[1,4], G. Murante[1,2], L. Silva[1,2],
J. Von Hardenberg[4,5], N. La Rocca[8,1], M. Battistuzi[9,8] and D.Billi[10]

[1]INAF – Astronomical Observatory of Trieste, Via G.B. Tiepolo 11, 34135, Trieste, Italy, michele.maris@inaf.it; [2]IFPU – Institute for the Fundamental Physics of the Universe, Trieste, Italy; [3]Fondazione ICSC - Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing; [4]DIATI, Politecnico di Torino, Torino, Italy; [5]CNR – Institute of Geosciences and Georesources, Pisa, Italy; [8]Dipartimento di Biologia, Università di Padova, Padova, Italy; [9]INAF – Osservatorio Astronomico di Arcetri, Firenze, Italy; [10]Dipartimento di Biologia, Università di Roma "Tor Vergata", Roma, Italy

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Introduction: In this talk, we aim to summarize key aspects of a study recently started within the framework of the ASTERIA collaboration, aimed at assessing the observability of potential photosynthetic biosignatures in habitable transiting exoplanets of M dwarf stars. The recent observation of exoplanets such as WASP-39b and K2-18b with the James Webb Space Telescope (JWST) [1, 2], the advancement of the Extremely Large Telescope (ELT) [3], and the approval of missions dedicated to studying exoplanetary atmospheres have paved the way for the search for gaseous biosignatures in the transmission spectra of habitable exoplanets. To define observational programs, enable instrumental development, and interpret data, it is necessary to predict the strength of any gaseous biosignature in the absorption spectra of transiting exoatmospheres, including those expected from photosynthetic activity. This, in turn, depends on the pressure of the deepest atmospheric layer that can be observed during a transit, as well as the vertical distribution and total abundance of the gaseous species forming the biosignature. It is well known that the deepest atmospheric layer observable during a transit is determined by the level of extinction and refraction that the light from the host star experiences while propagating through the exoplanet atmosphere [3-11]. For transiting exoplanets in the habitable zone of G stars, refraction prevents the observation of nearly the entire exotroposphere, whereas for habitable exoplanets around M stars, the main effect is to weight different atmospheric layers unevenly [3-11]. For a given chemical composition of an atmospheric layer, refraction scales as the p/T ratio and therefore depends on the planet climatic state. In our study, we start with a database of simulated exoclimates of M star exoplanets [12] (see also [13,14]) to analyze the impact of exorefraction on the observability of different atmospheric layers and to compare them with the expected vertical distribution of key gases. The abundance of biogenic gases responsible of photosynthetic biosignatures primarily depends on the productivity of a hypothetical biosphere hosted by the exoplanet, which is, in turn, linked to the exoplanet climate. Here, we follow the approach of [14], extending it to our 2D climatic maps of exoplanets as in [15] to predict the level of O_2 for different photosynthetic microorganisms, mainly cyanobacteria, taken as reference models. The analysis takes into account the varying amounts of photosynthetically active photons expected in different regions of the planetary surface, as well as the differences in temperatures. The expected end product of this analysis is to characterize the extent to which minimal conditions for the occurrence of significant photosynthesis could potentially exist on the surface of such planets—a condition referred in literature as Photosynthetic Habitability [15,16].

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Life in the Universe: From Bio to Techno

S. Berdyugina[1, 2]
[1]Istituto Ricerche Solari Aldo e Cele Daccò (IRSOL),
[2] Università della Svizzera italiana (USI), Via Patocchi 57, 6605 Locarno, Switzerland

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Introduction: Our search for life beyond Earth which started in the 1960s has been initially focused on technological signs of radio communicating civilizations. It has by now expanded to many other aspects of possible activities of alien intelligent life. Recent advances in developing both bio- and techno-signatures indicate that bio-signatures can also reveal the presence of technologically equipped life, and vice versa. In this talk, I will present an overview of techno-signatures, how they could be coupled with bio-signatures, what we so far learned about extraterrestrial intelligent life, and which current and future opportunities exist and emerge for detecting life and intelligence beyond Earth.

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