

## ORIGIN OF WATER AND LIFE: WHAT ASTROPHYSICAL AND INSTRUMENTAL CHALLENGES FOR TOMORROW?

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**Abstract.** Our goal is to present here a brief summary of the background, objectives, presented talks, discussions and conclusions of the splinter session organized on June 20<sup>th</sup> and 21<sup>st</sup>, 2023 during the Journ  es 2023 de la Soci  t   Fran  aise d'Astronomie & d'Astrophysique (SF2A). This session has been a nice opportunity to be informed about current theoretical, observing and instrumental developments, initiate the discussion on how to organize and structure the French community around these astrophysical themes, finally to initiate a coordinated response to the call of ideas of CNES 2023 to organize and structure our community with a proposed roadmap for 2024.

Keywords: exoplanets, habitability, exobiology, ground based instrumentation, space missions

### 1 Context

Understanding how giant and telluric planets form and evolve, their internal structure and that of their atmosphere, represents one of the major challenges of modern astronomy, and is directly linked to the ultimate search for life by 2050. However, several astrophysical (understanding the formation and physics of giant and telluric exoplanets), biological (identification of the best biomarkers) and technological (technical innovations for new-generation telescopes and instruments). We now know that rocky exoplanets are ubiquitous in the Milky Way, and very probably in the immediate vicinity of the Sun too. Detecting these closest planets, understanding the diversity the (atmospheric) diversity of other worlds, and the search for clues to habitability and biological activity, particularly that of water, are essential to understanding the origin of life. With this in mind, the coming decades will be rich in instrumental projects in space and on the ground, exploiting the various techniques for detecting and characterizing exoplanets in highly complementary ways. Within the next 10 years, major systematic surveys using velocimetry, transit, astrometry and imaging will provide a virtually complete census of exoplanetary systems in the near-solar environment. This will usher in an observational era dedicated primarily to characterizing the conditions conducive to the formation of habitable worlds, and to the physical and atmospheric characterization of known exoplanets, particularly temperate telluric planets suitable for the emergence of life. This phase, already initiated with Hubble and Spitzer, and with the first ground-based spectrographs, will intensify with the JWST, Roman and ARIEL space telescopes, and from 2028 with the new generation of extremely large telescopes that will offer unique spatial and spectral resolution, , as well as versatile multi-decade instrumentation for characterization of giant and rocky planets and the search for the first clues of habitability and life activity. However, it is very likely that a systematic atmospheric study of dozens of Earth analogues and a quantitative assessment of their habitability and the possible existence of biomarkers will require large-scale, highly optimized space missions.

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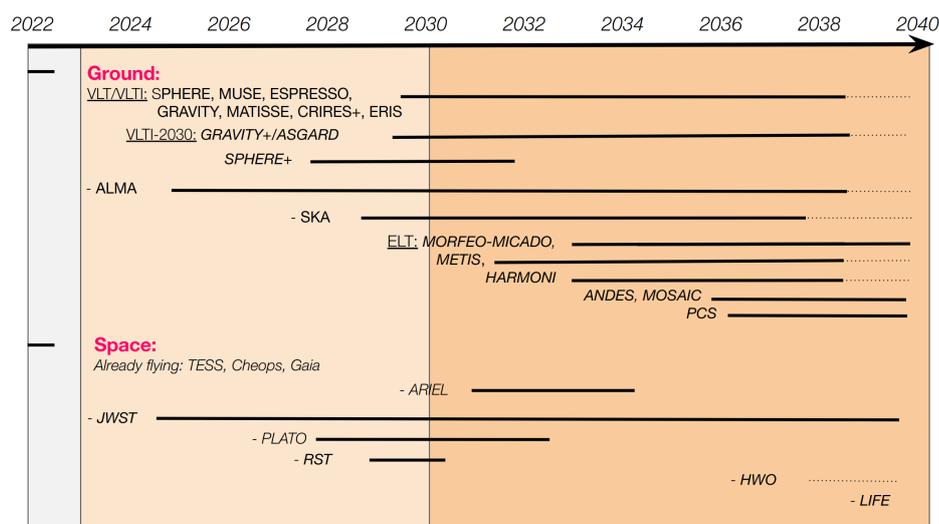
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**Fig. 1.** Timeline for key ground and space-based instruments and missions dedicated to studying exoplanets and planetary formation.

## 2 Objectives

Our workshop was divided into two sub-sessions with the aim of addressing the following three themes:

- theme 1 - delivering water to planets: from the interstellar medium to planetary formation and exoplanets (S12a). Life as we know it requires water, but there is considerable uncertainty as to the steps required for a planet in the habitable zone to be formed with an abundant water budget. To address the question of the origin of water on Earth and other rocky planets, we need to gather expertise from many fields of study: modeling of planet formation, meteorite measurements, observations of exoplanets and planet-forming disks, and studies of the chemistry of ice in the interstellar medium and during star formation. Recent theoretical and observational advances are conducive to the organization of a workshop on the cosmic pathways that carry water to planets. This first part will cover all the phases in the origin of water, from astrochemistry to the study of meteorites and exoplanets.
- theme 2 - the current state of scientific knowledge on the conditions of habitability, biological activity and indications of life for astrophysical observation (S12b). The second part of the workshop will deal more generally with the most recent results and prospects concerning the study of the population of telluric planets, the properties and influence of host stars in promoting the existence of habitability conditions conducive to the formation of life, the physical and atmospheric properties of telluric planets, and current knowledge on biological activity and the best life tracers for future dedicated observations,
- theme 3 - technological challenges (S12b). Finally, we will look at future projects on the ground (VLT/I and ELTs) and in space (Roman, PLATO, ARIEL, HWO, LIFE) dedicated to the research and characterization of telluric planets, and particularly the observation of the first signs of life in their atmosphere. This second session will enable us to revisit together an ambitious roadmap for the preparation of future space and ground missions, identifying the most important technological obstacles and the best strategy for the French community to play a key role in the detection and characterization of the first signs of life in the atmospheres of temperate extrasolar telluric planets.

## 3 Addressed topics

During the first day, the question of the origin of stars in the Galaxy and the impact on the composition of planets was presented (N. Cabral), together with the observations of water in solar-type protostars (A. Andreu). This was followed by focused talks and discussions on the potential sources of terrestrial water in the context of the Solar system formation (L. Piani), the loss of volatiles by geological and astrophysical effects (N. Cowan),

the modeling of the primitive Earth's atmosphere (B. Charnay), the case of the water-dominated atmospheres, their structure, signatures, and the implication for habitability (F. Selsis), and finally the importance of a proper consideration of condensation front in current simulation of planetary habitability (M. Turbet). From the observational perspective, the water content of detected exoplanets (L. Acuña) was presented, together with the SOPHIE results for the specific system HD88986 (N. Heidari) and the latest results of JWST about the thermal emission from the Earth-sized Exoplanet TRAPPIST-1 b (E. Ducrot). Finally, J. Moran highlighted the need for some additional dynamical ingredients to go from prebiotic chemistry to life.

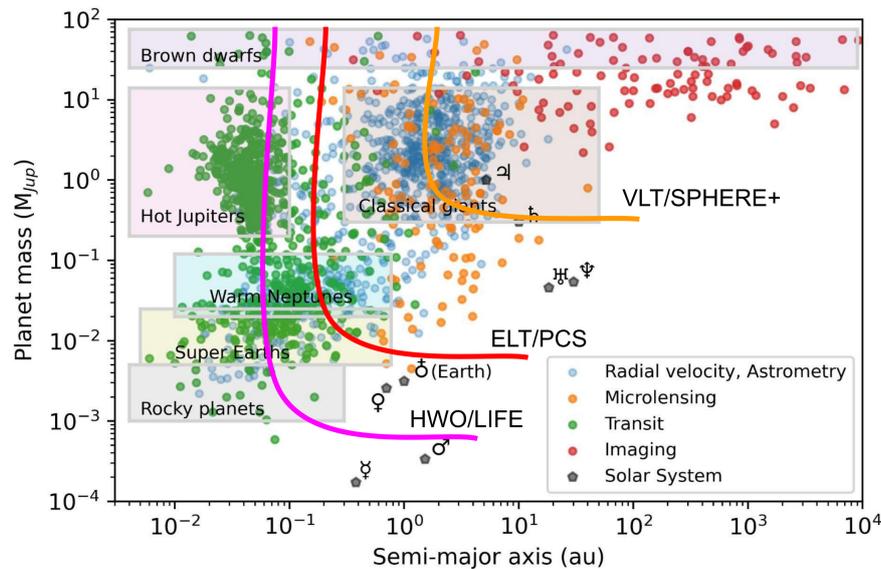
On the second day, the status of current atmospheric retrievals of terrestrial planets was discussed (E. Alei). This was followed by a summary of the current status of ground-based instruments: the VLT/RISTRETTO and ELT/ANDES spectrographs, aimed at characterizing the first atmospheres of very nearby rocky worlds at high spectral resolution and in reflected light (C. Lovis), and the VLT/SPHERE+ and ELT/PCS projects, designed to optimally combined spatial, spectral and temporal diversity to detect and characterize more systematically these rocky worlds in the case of PCS (M. Kasper). The prospect to identify the best rocky worlds for future characterization with extreme precision radial velocity surveys was also reported (N. Hara). In the perspective of space missions, the status of direct imaging below the diffraction limit with JWST via phase kernel interferometry was shown (T. Vandal), together with the status of the coronagraphic mode of the Roman Space Telescope (J. Mazoyer), the LUVOIR-POLLUX instrument (A. Ines Gomez), and the ambitious developments of the HWO and LIFE missions (L. Pueyo and S. Quanz, respectively).

#### 4 Discussion

Finally, the splinter session was concluded by a focused discussion about the preparation and the contribution of the French community to future long-term instruments and missions for exoplanet and exobiology (D. Mouillet). The scientific stakes and the size of the community mean that we need to start coordinating and structuring now, to ensure that we are strategically positioned ahead of the actual mission choices made by NASA or ESA for HWO and LIFE. The French community's involvement in this long-term strategic orientation is a major one, covering both i/ involvement in long-term scientific preparation, and ii/ the technological innovations and instrumental expertise required for future instruments, whose actions need to be pursued, stimulated and coordinated as of now. The PEPR-Origins program, due to start in 2023, fully illustrates the major commitment of our supervisory bodies and our community to studying these fundamental issues.

In the scientific field of exoplanetology, the French community, comprising several hundred researchers, has played a major role in exploiting the five main observational techniques used (radial velocity, transit,  $\mu$ -gravitational lensing, direct imaging and astrometry). Our community is at the forefront of the search for low-mass planets, sub-Neptunes and super-Earths, using radial velocity methods, a position further strengthened by the new SPIRou, NIRPS and ANDES instruments, but also in space with PLATO in transit. It has also played a pioneering role in the first discoveries in direct imaging and interferometry with ground-based instruments such as SPHERE and GRAVITY, and is ideally positioned at European level for future instruments on major observatories. It has also developed world-renowned theoretical expertise in the study of planetary formation, the structure of giant and rocky planets, and the modeling of their atmospheres, enabling it to play a key role in the operation of current and future JWST programs, and in preparations for the ARIEL mission.

On the instrumental side, the involvement and position of the French community is also major, with around a hundred researchers active in these fields, in a closely-knit community led in particular by ASHRA, and spread across a dozen or so laboratories. In the field of interferometry, France's leading role in the first VLTI instruments continues with the current developments Gravity+ and the ASGARD instrument suite, both of which include a strong focus on exoplanets, with optimization of the exoGravity or nulling mode. Similarly, high-contrast imaging has emerged in Europe from French laboratories, with a complete overhaul of system analysis, calibration and signal processing. The result is the best international high-contrast instrument currently available to the community (VLT/SPHERE). This expertise continues with the development of high-contrast modules for the future ELT (in the MICADO and HARMONI instruments), as well as very active R&D on components, demonstrations and innovative concepts. In space, the needs, constraints and final objectives are different, but the expertise involved benefits from a strong synergy with the ground. CNES has indeed supported innovative developments in components (such as coronagraphs, but a high level of expertise in photonics also has enormous potential for space applications), key technological masteries (such as advanced polishing of aspheric and/or active optics), and signal processing. We must also emphasize the importance of supporting laboratory testing capabilities (such as the THD test bench at LESIA), with the high level of stability and



**Fig. 2.** Indicative detection limits for future instruments (*VLT/SPHERE+*, *ELT/PCS*) and space missions (*HWO*, *LIFE*) dedicated to the search for and the characterization exoplanets.

calibration control required for space applications, as an essential step in the final testing of concepts and in the ramp-up to maturity. This combination has opened up opportunities for effective, high-impact contributions to the high-contrast modes of JWST (MIRI) and the Roman Space Telescope.

The take away messages of the discussion were that the discovery of rocky worlds and the characterization of their atmospheres is a major goal for the French community. We need to find collectively a programmatic way to reach that goal under discussion (missions, collaborations, instruments) including intermediate steps and synergies. The technology maturation can be worked-on now to be ready for decisions in 2030, to be organized coherently based on a wealth of expertise in France and in Europe. The timing is good with the CNRS/INSU and CNES prospectives starting in 2023.

## 5 Conclusions and perspectives

The "Origin of water and life" splinter session has been a nice opportunity and a first stone: i/ to be informed about current theoretical, observing and instrumental developments, including the two long-term HWO and LIFE projects, ii/ to initiate the discussion on how to organize and structure the French community around these astrophysical themes, finally iii/ to discuss on how to respond with a coordinated position to current requests, and future calls for proposals in a coordinated fashion (CNES, ESA, INSU...). The key action resulting from the splinter has been to submit a coordinated proposal to the call of ideas of CNES 2023 to organize structure our community with a proposed roadmap: 1/ The first phase (2023-2024) should enable us to establish a collective determination to position and organize ourselves in the indicated approach, in France, in a visible and coordinated way with our partners in Europe and the United States, with identified points of contact. We will also need to define a detailed action plan, identifying the specific developments to be carried out in France, in line with the expertise on hand, and the complementarity with other partners. A 2-3 days workshop (CNES-APR and INSU-AA proposals submitted in 2023) should conclude this first phase to propose a coordinated roadmap for our community. 2/ The following 4 years (2025-2028) will be the effective time for focused theoretical, modelling, and technological development. These conclusions will be essential for positioning the 2029 project for potential effective contributions, in line with NASA's milestone for the next decadal 2030. The potential application of this know-how to other areas of space instrumentation will also need to be analyzed, and could be anticipated in earlier years, possibly in conjunction with industrial partners.

The SF2A-S12 scientific organizing committee would like to warmly thank all the speakers and the SF2A organizing committee for assisting and supporting the organization of this splinter session which was a real trigger for opening a first series of discussions on this unifying theme for our community.