

The science of ARIEL (Atmospheric Remote-sensing Infrared Exoplanet Large-survey)

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ABSTRACT

The Atmospheric Remote-Sensing Infrared Exoplanet Large-survey (ARIEL) is one of the three candidate missions selected by the European Space Agency (ESA) for its next medium-class science mission due for launch in 2026. The goal of the ARIEL mission is to investigate the atmospheres of several hundred planets orbiting distant stars in order to address the fundamental questions on how planetary systems form and evolve.

During its four (with a potential extension to six) years mission ARIEL will observe 500+ exoplanets in the visible and the infrared with its meter-class telescope in L2. ARIEL targets will include gaseous and rocky planets down to the Earth-size around different types of stars. The main focus of the mission will be on hot and warm planets orbiting close to their star, as they represent a natural laboratory in which to study the chemistry and formation of exoplanets.

The ARIEL mission concept has been developed by a consortium of more than 50 institutes from 12 countries, which include UK, France, Italy, Germany, the Netherlands, Poland, Spain, Belgium, Austria, Denmark, Ireland and Portugal. The analysis of the ARIEL spectra and photometric data in the 0.5-7.8 micron range will allow to extract the chemical fingerprints of gases and condensates in the planets' atmospheres, including the elemental composition for the most favorable targets. It will also enable the study of thermal and scattering properties of the atmosphere as the planet orbit around the star.

ARIEL will have an open data policy, enabling rapid access by the general community to the high-quality exoplanet spectra that the core survey will deliver.

Keywords: Exoplanets, space missions, atmospheric science, IR spectroscopy

1. THE ARIEL SCIENCE

1.1 Background

Thousands of exoplanets have now been discovered with a huge range of masses, sizes and orbits: from rocky Earth-size planets to large gas giants grazing the surface of their host star (**Figure**). However, the essential nature of these exoplanets remains largely mysterious: there is no known, discernible pattern linking the presence, size, or orbital parameters of a planet to the nature of its parent star. We have little idea whether the chemistry of a planet is linked to its formation environment, or whether the type of host star drives the physics and chemistry of the planet's birth, and evolution. Progress with these science questions demands a large, unbiased spectroscopic survey of exoplanets. The ARIEL candidate mission has been conceived to conduct such a survey and to explore the nature of exoplanet atmospheres and interiors and, through this, the key factors affecting the formation and evolution of planetary systems.

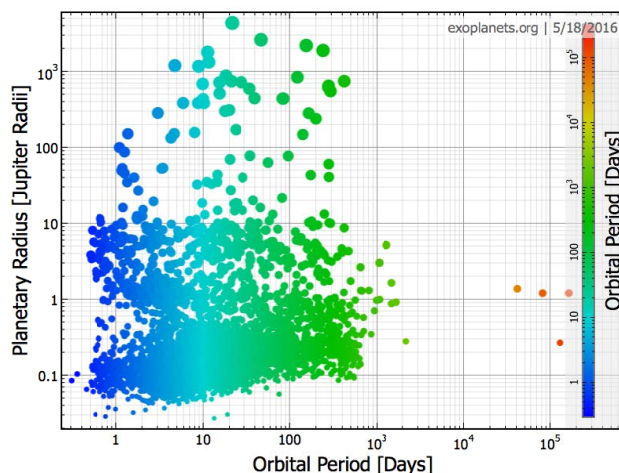


Figure 1-1: Currently known exoplanets, plotted as a function of distance to the star and planetary radii (courtesy of exoplanets.org). The graph suggests a continuous distribution of planetary sizes – from sub-Earths to super-Jupiters – and planetary temperatures than span two orders of magnitude.

1.2 ARIEL science goals

ARIEL will address the fundamental questions:

- What are exoplanets made of?
- How do planets form and evolve?

through the direct measurement of the atmospheric chemical composition and structure of a large population of objects. ARIEL will focus on warm and hot planets, for which the atmospheric composition is more representative of the bulk one.

ARIEL will observe a large number, i.e. over 500, of transiting gaseous and rocky planets around a range of host star types using combined-light spectroscopy in the $\sim 1.2\text{-}7.8\ \mu\text{m}$ spectral range and multiple band-photometry in the optical/Near IR. We target preferentially warm and hot planets to take advantage of their well-mixed atmospheres which should show minimal condensation and sequestration of high-Z materials and thus reveal their bulk and elemental composition (especially C, O, N, S, Si). Observations of these exoplanets will allow the understanding of the early stages of planetary and atmospheric formation during the nebular phase and the following few millions years. ARIEL will thus provide a truly representative picture of the chemical nature of the exoplanets and relate this directly to the type and chemical environment of the host star (Figure).

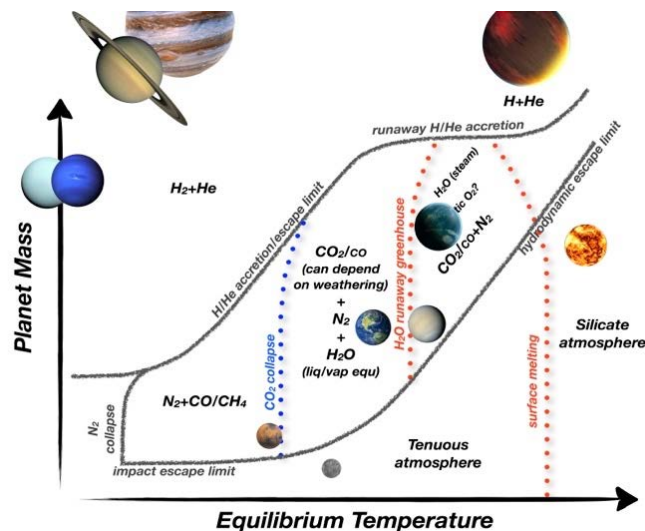


Figure 1-2: Schematic summary of the various classes of atmospheres as predicted by Forget & Leconte (2013). Only the expected dominant species are indicated, other (trace) gases will be present. Each line represents a transition from one regime to another, but these “transitions” need confirmation and tight calibrations from observations. The axes do not have numerical values as they are unknown. Solar System planets are indicated, together with a lava planet, an Ocean planet and a hot Jupiter. ARIEL will observe preferentially warm and hot planets heavier than the Earth: many atmospheric regime transitions are expected to occur in this domain.

1.3 Observational strategy

For this ambitious scientific programme, ARIEL is designed as a dedicated survey mission for transit, eclipse and phase-curves spectroscopy, capable of observing a large and well-defined planet sample within its four to six years mission lifetime. Transit and eclipse spectroscopy methods, whereby the signal from the star and planet are differentiated using knowledge of the planetary ephemerides, allow us to measure atmospheric signals from the planet at levels of $\sim 10\text{-}100$ ppm relative to the star (post-processing) and, the bright nature of the targets also allows more sophisticated techniques, such as phase curve analysis and eclipse mapping, to give a deeper insight into the nature of the atmosphere (Figure). Combined-light spectroscopy means that no angular resolution is required and detailed performance studies show that a 1-metre class telescope is sufficient to achieve the necessary observations on all the ARIEL targets within the mission

lifetime. The satellite is best placed into an L2 orbit to maximise the thermal stability and the field of regard (see Puig et al. and Eccleston et al., this conference).

To maximize the science return of ARIEL and take full advantage of the unique characteristics of this mission, a three-tiered approach has been considered, where three different samples are observed at optimised spectral resolutions. A summary of the survey tiers is given in **Table 1-1**.

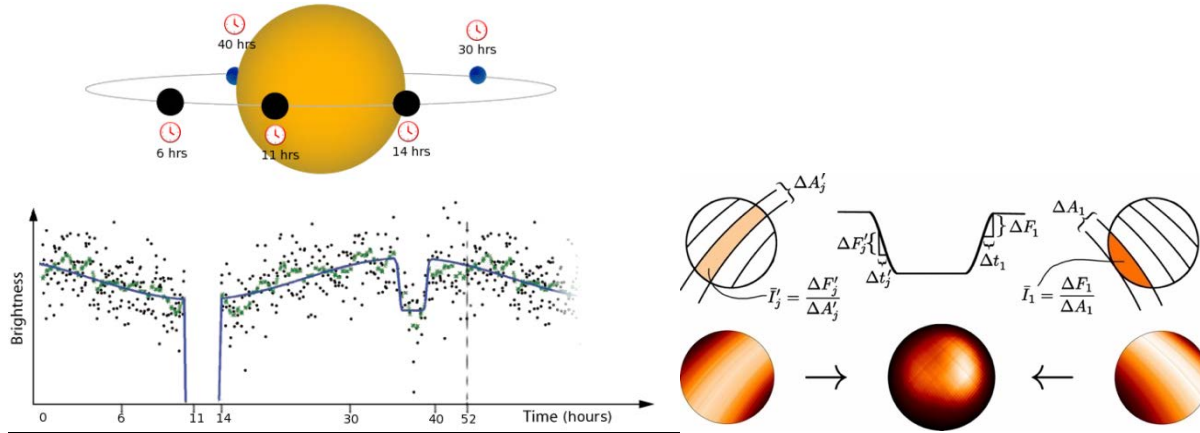


Figure 1-3: Methods adopted by ARIEL to probe the exoplanet composition and structure. Left: orbital lightcurve of the transiting exoplanet HAT-P-7b as observed by Kepler (Borucki et al., 2009). The transit and eclipse are visible. Right: slice mapping with ingress and egress maps as well as a combined map of HD189733b at 8 μm . These were achieved with Spitzer-IRAC (Majeau et al., 2012).

TIER NAME	OBSERVATIONAL STRATEGY	SCIENCE CASE
Reconnaissance survey (~30%)	Low Spectral Resolution observations of 500-1000 planets in the VIS-IR, with SNR ~ 7	<ul style="list-style-type: none"> • What fraction of planets are covered by clouds? • Have small planets still retained H₂? • Colour-colour diagrams • Constraining/removing degeneracies in the interpretation of mass-radius diagrams
Deep survey (~60%)	Higher Spectral Resolution observations of a sub-sample in the VIS-IR	<ul style="list-style-type: none"> • Main atmospheric component • Concentrations of trace gases • Atmospheric thermal structure • Cloud characterization • Elemental composition
Benchmark planets (~10%)	Very best planets, re-observed multiple time with all techniques	<ul style="list-style-type: none"> • Very detailed knowledge of the planetary chemistry and dynamics • Weather, spatial & temporal variability

Table 1-1: Description of the three-tiered approach considered for ARIEL. See sec. 2.4 for a more in depth evaluation of the science performances.

2. ARIEL SCIENCE REQUIREMENTS

2.1 Wavelength coverage & spectral resolving power

To fulfil the science requirements, ARIEL will be a specifically designed, stable payload and satellite platform with broad, instantaneous wavelength coverage to detect many molecular species, probe the thermal structure, identify/characterize clouds and monitor the stellar activity. The wavelength range considered covers all the expected major atmospheric gases from e.g. H₂O, CO₂, CH₄, NH₃, HCN, H₂S through to the more exotic metallic compounds, such as TiO, VO, TiH, CrH and condensed species (Figure and Table 2-1).

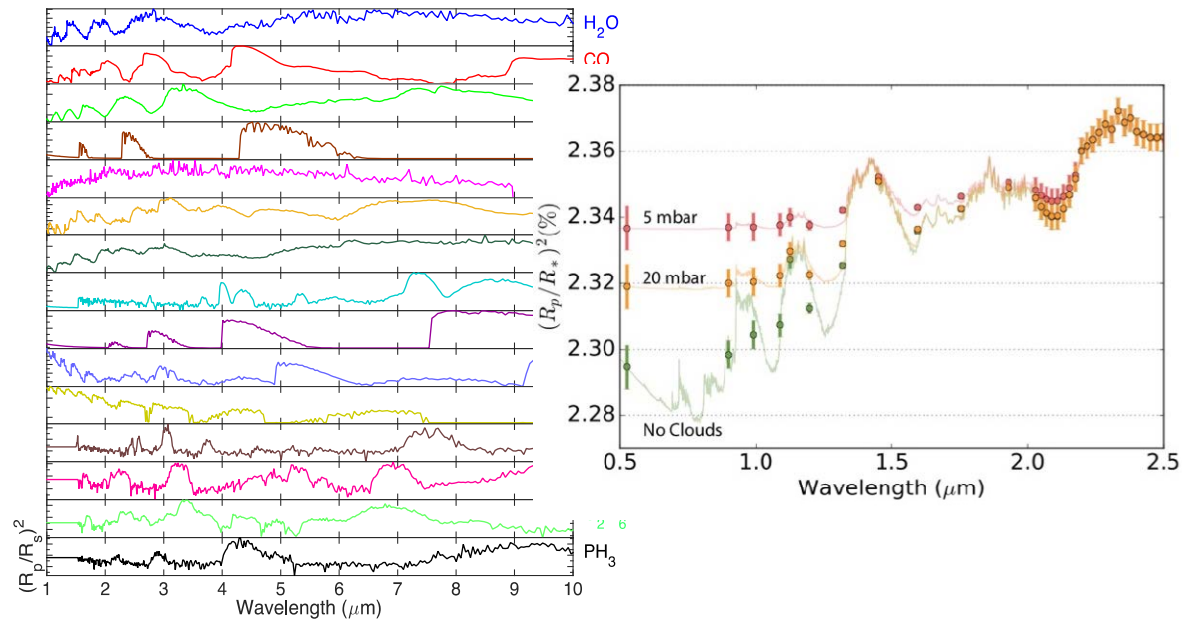


Figure 2-1: Left: Molecular signatures in the 1-10 μm range at the spectral resolving power considered for ARIEL ($R=100$). Right: cloud signature in the 0.5-2.5 μm range: ARIEL will measure simultaneously the relative contributions of the “blue” and “red” filters in the visible, the NIR filter and the spectral contribution in the 1.25-7.8 μm range. Through these measurements ARIEL will detect the presence of clouds/hazes, and constrain cloud parameters such as altitude, optical thickness and particle-size.

2.2 ARIEL performances requirements

ARIEL’s top-level requirement is that the photometric stability over the frequency band of interest shall not add significantly to the photometric noise from the astrophysical scene (star, planet and zodiacal light). The frequency band over which the requirement applies is between 2.8×10^{-5} to $\sim 3.7 \times 10^{-3}$ Hz, i.e. between ~ 2 minutes and 10 hours (see Pascale et al, 2014; Sarkar et al., this conference). This implies having the capability to remove any residual systematics and to co-add the elementary observations from many repeat visits to a given target.

Wavelength range	Resolving power	Scientific motivation
Blue filter 0.5 – 0.55 μm	Integrated band	<ul style="list-style-type: none"> • Correction stellar activity (optimised early stars) • Measurement of planetary albedo • Detection of Rayleigh scattering/clouds
Red filter 0.8 – 1.0 μm	Integrated band	<ul style="list-style-type: none"> • Correction stellar activity (optimised late stars) • Measurement of planetary albedo • Characterisation of clouds
NIR1 filter 1.05 – 1.2 μm	Integrated band	<ul style="list-style-type: none"> • Correction stellar activity (optimised late stars) • Characterisation of clouds
NIR2 spectrograph 1.25 – 1.95 μm	10	<ul style="list-style-type: none"> • Correction stellar activity (optimised late stars) • Characterisation of clouds • Detection of molecules (especially TiO, VO, metal hydrides) • Measurement of planet temperature (optimised hot) • Retrieval of molecular abundances • Retrieval of vertical and horizontal thermal structure • Detection temporal variability (weather/cloud distribution)
IR spectrograph – 1.95 – 7.8 μm	100	<ul style="list-style-type: none"> • Detection of atmospheric chemical components • Measurement of planet temperature (optimised warm-hot) • Retrieval of molecular abundances • Retrieval of vertical and horizontal thermal structure • Detection temporal variability (weather/cloud distribution)

Table 2-1: Summary of the ARIEL spectral coverage (left column) and resolving power (central column). The key scientific motivations are listed in the right column.

2.3 ARIEL core sample, observational strategy & sky visibility

ARIEL will study a large population of planets, already discovered by other facilities. In particular, ARIEL will focus on hundreds of gaseous objects (Jupiters, Saturns, Neptunes) and small planets (Earth-size planets, super-Earths and sub-Neptunes) around bright stars. There are ~ 200 currently known planets complying with these requirements (see Fig. 2-2). The current 200 known targets have been discovered mainly close to the ecliptic plane because provided by ground-based surveys. K2, Cheops and NGTS are expected to complete the search for planets around bright sources closer to the ecliptic plane. TESS and PLATO will extend the planet search closer to the ecliptic poles, which are where ARIEL has continuous coverage (see Fig. 2-3 and Eccleston et al, this conference).

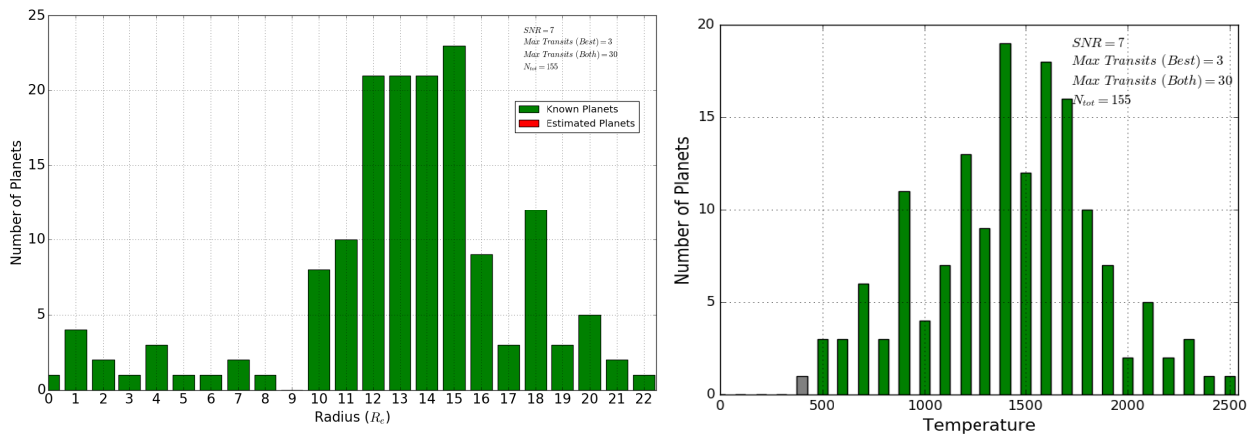


Figure 2-2: Select sample of currently known planets observable by ARIEL divided in size bins (left) and equilibrium temperature bins (right). These planets orbit around stars with different temperatures and metallicities.

To generate a core mission sample to be observed by ARIEL in 2026 during its lifetime, a list of targets with different stellar types (F, G, K, M, typically brighter than K=11) and planetary parameters (size: Jupiters, Neptunes, sub-Neptunes, super-Earths, Earth-size planets; temperature range: ~ 500K-2500K and bulk density) has been created. Said list was compiled using the statistics provided by the NASA Kepler mission combined with the number/types of stars in the Solar neighbourhood (Zingales et al., in prep.). The required number of transits/eclipses to achieve the spectral resolution (R) and Signal-to-Noise Ratio (SNR) needed to perform an accurate retrieval of the gas abundances and thermal properties has been calculated using the ESA Rad Model (Puig et al., 2014) and the end-to-end instrument simulator ExoSim (Sarkar et al., this conference, Pascale et al., 2014). These preliminary calculations have indicated that over 500 planets can be easily observed during the mission lifetime (four years with the possibility to extend it to six) with the required SNR/R (see Table 1-1). Figures 3-7, 3-8 and 3-9 show one of the many possible mission scenarios.

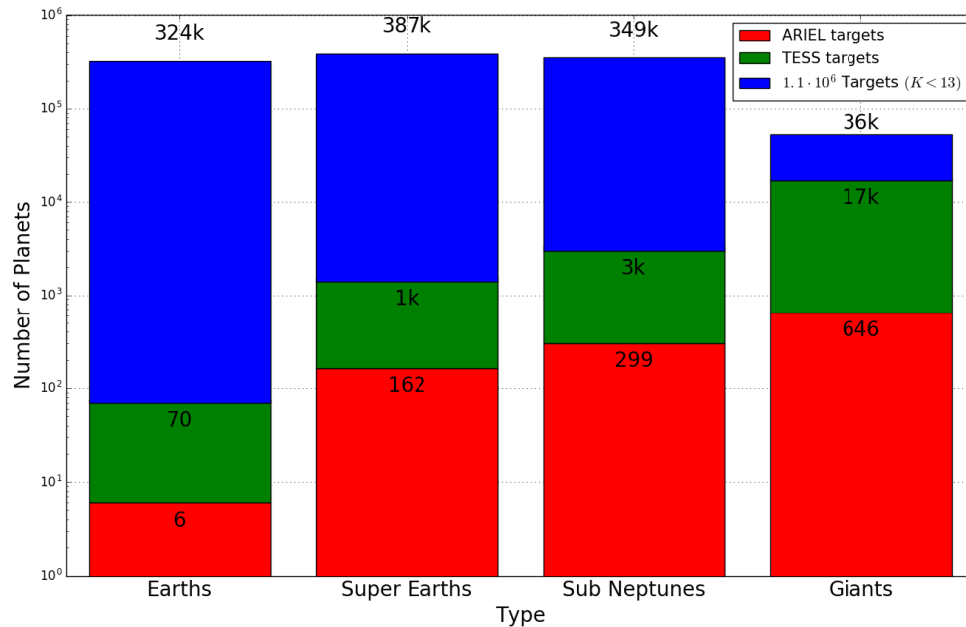


Figure 2-3: Estimated transiting planets according to Kepler’s statistics (Fressin et al., 2013) observable by ARIEL (blue). The fraction of said planets expected to be discovered by TESS is indicated in green (Sullivan et al, 2015). In red we show a select sample of planets observable by ARIEL during a nominal four years mission.

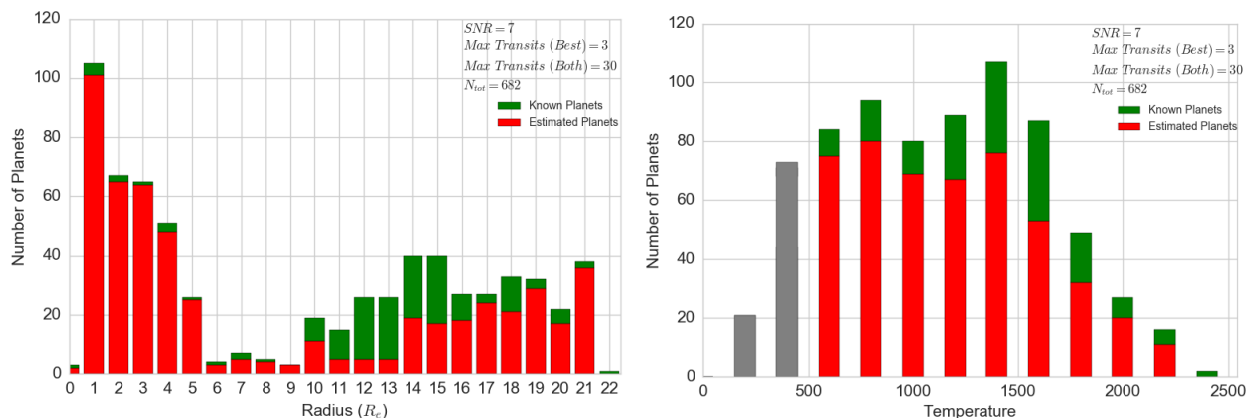


Figure 2-4: Number of planets observable by ARIEL in the Reconnaissance Survey modality (Tier 1) divided in size bins (left) and equilibrium temperature bins (right). In grey are highlighted cold planets that could be observed by ARIEL but are not currently prioritised in the mission sample. In this specific mission scenario ~ 35% of the mission lifetime can be used to complete the Tier 1 survey, and the rest to complete the other 2 Tiers (see Table 1-1).

2.4 Testing ARIEL performances requirements

To optimize the observational strategy in terms of SNR/R needed to achieve the science requirements and goals, we have used a suite of direct and inverse radiative transfer models developed by different teams part of the ARIEL collaboration and run in parallel. In particular, we used TauREx (Waldmann et al., 2015a, b) and NEMESIS (Irwin et al. 2008, Barstow et al, 2012) spectral retrievals to investigate the impact of SNR and spectral resolution on the retrievability of individual model parameters from transit and eclipse spectra as observed by ARIEL. Model parameters include the planetary temperature, molecular abundances and cloud parameters. We show in Figure 2-6 the results obtained by TauREx for a hot, cloudy Jupiter-size planet, whose simulated spectrum as observed by ARIEL (modality Tier 2, Deep survey) is shown in Figure 2-5. For the majority of the ARIEL targets, these performances can be reached between 1 and 20 transits.

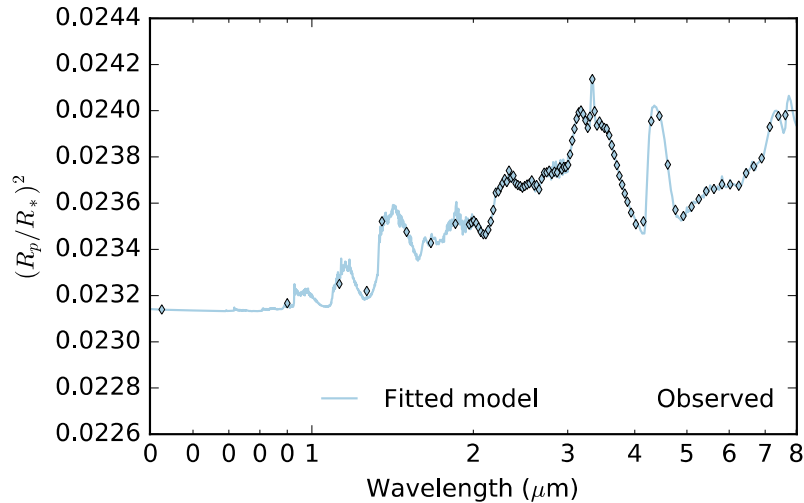


Figure 2-5: Simulated transit spectrum, as observed by ARIEL, of a hot, cloudy, giant planet. Several trace gases are included in the simulation, including water vapour, methane, carbon monoxide/dioxide, ammonia and HCN.

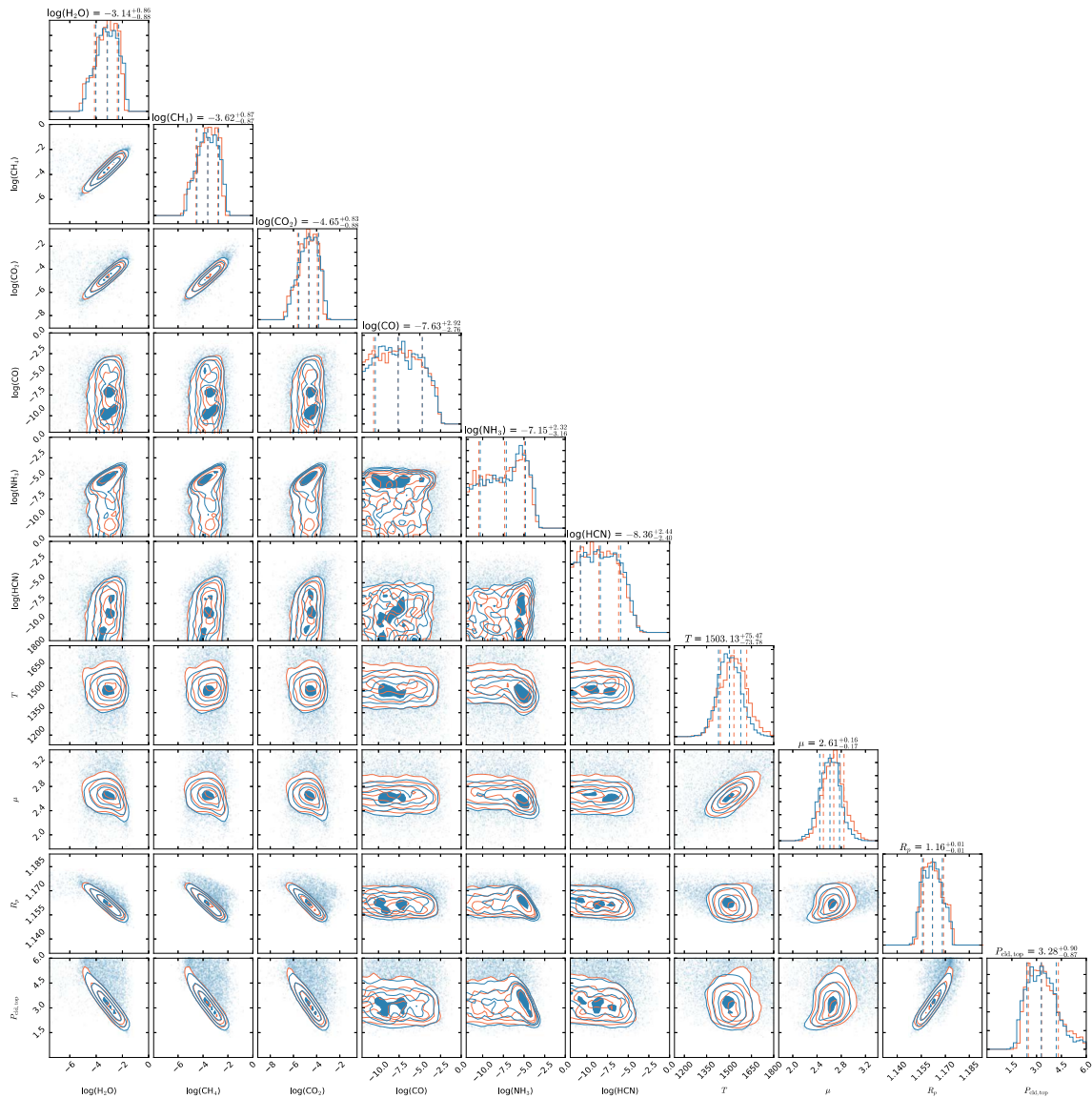


Figure 2-6: Posterior distributions of various atmospheric trace gases, temperature and top cloud pressure obtained with TauRex by retrieving the simulated spectrum shown in Fig. 2-5 (blue plots). Dashed lines in the histogram plots show the 1 sigma confidence intervals. Red plots indicate the results obtained with a degraded spectral resolution ($R=50$ instead of $R=100$) in the IR channel 1.95-4.5 micron. In this sensitivity study the posterior distributions are very similar, there is only a slightly greater uncertainty about the solution.

3. CONCLUSIONS

We have presented in this paper a brief overview of the science objectives and requirements for the ARIEL exoplanet spectroscopy mission. The combination of a stable platform, operating in a stable thermal environment and with a highly integrated payload and systems design, will ensure the very high level of photometric stability required to record exoplanet atmospheric signals, i.e. 10-100 ppm relative to the star (post-processing). The broad, instantaneous wavelength range covered by ARIEL will allow to detect many molecular species, probe the thermal structure, identify/characterize clouds and monitor the stellar activity. Finally, the agile, highly stable platform in L2, from which the complete sky is accessible within a year, will enable the observation of hundreds of planets during the mission lifetime.

ARIEL will enable a paradigm shift: by identifying the main constituents of hundreds of exoplanets in various mass/temperature regimes, we would be looking no longer at individual cases but at populations. Such a universal view is critical to understand the processes of planet formation and evolution and how they behave in various environments.

4. ACKNOWLEDGEMENTS

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