

The *ARIEL* Space Mission

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Abstract—*ARIEL*, the Atmospheric Remote-Sensing Infrared Exoplanet Large-survey, has been selected to be the next ESA M4 space mission. From launch in 2028 and during its 4 years of operation, *ARIEL* will perform a spectroscopic survey of the atmospheres of about 1 000 transiting planets orbiting stars other than our Sun. *ARIEL* will provide the scientific community the first spectroscopic survey of a statistically significant sample of exoplanet atmospheres, covering the portion of the electromagnetic spectrum spanning from the visible to the mid-IR. *ARIEL* will allow us to answer questions about the true nature of these far away worlds, their atmospheric and physical conditions, and their formation and evolutionary histories.

Index Terms—Exoplanets, Spectroscopy, Atmospheric science, IR astronomy, Space missions

I. INTRODUCTION

Planets are ubiquitous in our Galaxy. More than 3 800 exoplanets have been detected in the past 20 years from space and from the ground. Thanks to space missions such as TESS [1], CHEOPS [2] and PLATO [3], and to similar ongoing effort using ground instrumentation, this number is destined to see a dramatic increase over the time scale of these projects.

The exoplanets detected have a large range of masses, sizes and orbits: from Earth-like planets to large gas giants grazing the surface of their host star. A diversity unseen in our Solar System while the essential nature of these exoplanets remains largely mysterious. It is unclear whether a pattern linking the presence, size, or orbital parameters of a planet to the nature of its parent star exists. We have little idea whether the planet chemistry is linked to its formation environment, or whether the physics and chemistry of the planets birth and evolution is driven by the type of the host star.

*ARIEL*¹ (see e.g. [4], [5]) has been selected by ESA as the next medium-class science mission (M4) in the Cosmic Vision programme, expected to be launched in 2028.

ARIEL will address the fundamental questions on what exoplanets are made of and how planetary systems form and evolve by investigating the atmospheres of $\sim 1\,000$ of diverse planets orbiting different star types. An unbiased survey is needed for a statistical understanding of gas giants, Neptunes, super-Earths and Earth-size planets, and *ARIEL* will achieve this through transit spectroscopy and multi-band photometry over the $0.5\,\mu\text{m}$ to $7.8\,\mu\text{m}$ band of the electromagnetic spectrum, with a 1 m class telescope in space at L2.

A detailed description of the *ARIEL* science and mission design can be found in the *Yellow Book*² which summarizes the outcome of the Phase/A study.

II. THE SCIENCE OF ARIEL

The observed diversity of exoplanets can only be investigated surveying a large parameter space in planetary radii and masses, thermodynamical conditions, chemical properties, and host star types. *ARIEL* will allow such a statistical understanding focusing on hot and warm planets, taking advantage of their well-mixed atmospheres which should show minimal condensation and sequestration of high Z materials, thus revealing their bulk and elemental composition (in particular C, O, N, S, Si).

Observations of these hot and warm exoplanets will allow us to understand of the early stages of planetary and atmospheric formation in the nebular phase and of the few million years after that. *ARIEL* will thus provide a truly representative picture of the exoplanet chemical nature and relate this directly to the type and chemical environment of the host star.

ARIEL is designed as a dedicated survey mission for transit and eclipse spectroscopy. Transit, eclipse and phase-curve spectroscopy, whereby the signals from the star and planet are differentiated using knowledge of the planetary ephemeris, allow us to measure atmospheric signals from the planet at levels of 10-100 ppm relative to the star. Eclipse mapping can also be applied to bright targets to give a deeper insight into the nature of the atmosphere. *ARIEL*'s wavelength range, Figure 1, covers all the expected major atmospheric gases from e.g. H₂O, CO₂, CH₄, NH₃, HCN, H₂S, as well as exotic metallic compounds such as TiO, VO, and condensed species.

It is known from Solar System studies that to explore the formation and evolution of planetary bodies requires the characterization of their composition. A breakthrough in our understanding of the planet formation and evolution mechanisms, capable of explaining the observed diversity of exoplanetary systems and placing our Solar System into a Galactic context, requires the direct observation of the chemical composition of a statistically large sample of planets. This should include gas rich planets ($> 15M_{\oplus}$), rocky planets ($< 5M_{\oplus}$), which are expected to be gas-poor and mainly

¹<http://ariel-spacemission.eu/>

²<http://sci.esa.int/cosmic-vision/59109-ariel-assessment-study-report-yellow-book/>

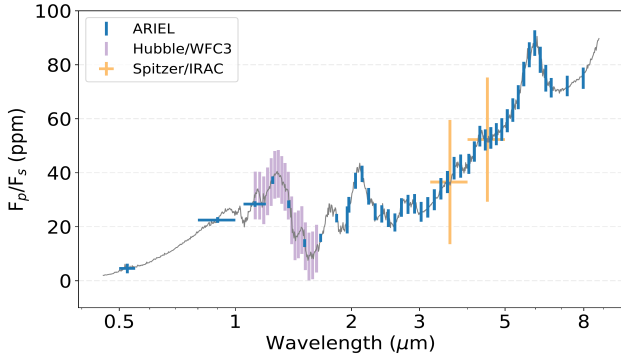


Fig. 1: Expected output (with error bars) from the *ARIEL* processed data product compared with the input model assumption for a hot super-Earth similar to 55 Cnc e around a G-type star with K_{mag} of 4. *ARIEL* performances using 8 eclipses (32 hours of observation) are compared to currently available data for 55 Cnc e from Spitzer-IRAC (8 eclipses [8]) and performances of Hubble-WFC3 extrapolated from transit observations of 55 Cnc e [9].

composed of rocks and ices, as well as transitional planets. These are bodies with mass $\sim 5 - 15M_{\oplus}$ that, depending on their formation histories (i.e. before or after the dispersal of the circumstellar disc), can either be massive super-Earths or sub-Neptunians gaseous planets. While it is possible to estimate the bulk density of exoplanets of known radius and mass, this is not sufficient to unambiguously determine a composition. An example is the case of GJ 1214b, a super-Earth with mass $6.55 M_{\oplus}$. A pure water world, or a 90% rocky core with a 10% envelope of mixed water and H/He are compatible with present data on the radius and mass of this planet [6]. For this type of transitional planets, spectroscopic measurements are needed to detect the chemical composition of the envelope, breaking the degeneracy. *ARIEL* spectroscopy from the visible to the mid-IR will enable to discriminate from a primordial atmosphere, expected to be made primarily of H/He, and a more evolved atmosphere made of heavier elements as shown in Figure 2. While high altitude clouds or hazes can somehow be degenerate with high molecular weight atmospheres at short wavelengths (a problem for studies using current facilities [7]), *ARIEL*'s simultaneous spectroscopy from the visible to the mid-IR will allow the characterization of the atmosphere chemistry and of the clouds and hazes, at the same time.

The current sample of known extrasolar planets highlights how planetary migration is widespread. This is a strong indication that these planets, and in particular gas-rich planets, formed somewhere else, likely beyond the water ice condensation line - and migrated to their present condition. These warm/hot planets are *ARIEL*'s primary targets. Their well mixed atmospheres will reveal the bulk composition of their envelopes, hence breaking the degeneracy in the planet composition. Moreover, envelopes also contain a record of the planet origin and migration history, which can be used to constrain models of planetary formation and evolution [10]. Therefore

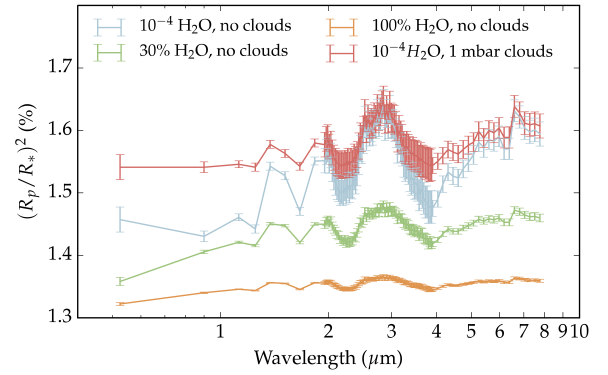


Fig. 2: Simulated *ARIEL* transit spectra for a hot super-Earth whose atmosphere shows different fractions of H/He and H_2O . The heavier is the main atmospheric component (i.e. water dominated in this case), the more compact is the atmosphere, the smaller is the signal detected. While clouds can mimic this effect to a degree, they mostly influence the short wavelengths (especially VIS-NIR). The figure was produced using TauREx model [11].

with *ARIEL* it will be possible to study the composition of exoplanets, the formation of planets and planetary systems, and the evolution of planetary atmospheres over time.

III. *ARIEL* OBSERVATIONAL STRATEGY

The *ARIEL* science case calls for atmospheric spectra of a large and diverse sample of known exoplanets, spanning a wide range of masses densities, equilibrium temperatures, orbital properties and host-stars. For a sub-sample, a very deep knowledge is also needed (e.g. weather, variability, dynamics, etc.). A three-tiered approach has been considered, where three different samples are observed with optimised spectral resolutions, wavelength intervals and signal-to-noise ratios. The table below gives a summary of the science addressed in each tier.

Tier name	Observational strategy	Science case
Reconnaissance survey (~30%)	Low Spectral Resolution observations of ~1000 planets in the VIS & IR, with SNR ~ 7	<ul style="list-style-type: none"> What fraction of planets are covered by clouds? What fraction of small planets have still retained H/He? Classification through colour-colour diagrams? Constraining/removing degeneracies in the interpretation of mass-radius diagrams Albedo, bulk temperature & energy balance for a subsample.
Deep survey (~60%)	Higher Spectral Resolution observations of a sub-sample in the VIS-IR	<ul style="list-style-type: none"> Main atmospheric component for small planets Chemical abundances of trace gases Atmospheric thermal structure (vertical/horizontal) 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

IV. *ARIEL* TARGETS

ARIEL will study a large population of planets discovered from space and from the ground. It will focus on several hundreds of hot/warm gaseous targets (Neptunes, Saturns, Jupiters) and of super-Earths/sub-Neptunes around bright stars of all spectral types. There are more than 200 currently known planets complying with these requirements.

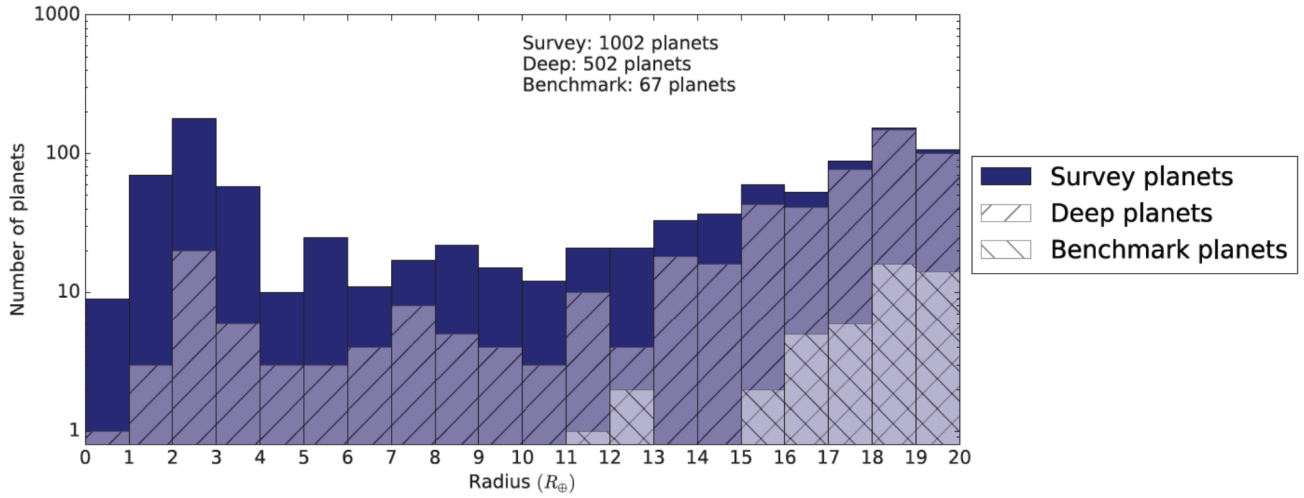


Fig. 3: Overview of the *ARIEL* MRS. The graph shows how the *ARIEL* 3 Tiers, i.e. Reconnaissance Survey, Deep Survey and Benchmark planets are nested [12].

An optimal sample of exoplanets including both the already known exoplanets and the “expected” ones yet to be discovered, but likely to be known by mid-2020’s, and observable by *ARIEL*, was estimated: the Mission Reference Sample (MRS). The *ARIEL* design allows the observation of $\sim 1\,000$ planets during the mission lifetime. Clearly, this nominal list of planets will change over the years taking into account the new exoplanet discoveries. In Figure 3 a possible mission scenario is shown, where the *ARIEL* planets are grouped according to their size.

V. *ARIEL* PERFORMANCE REQUIREMENTS

ARIEL’s top-level requirement is that the experimental uncertainties shall not add significantly to the photometric noise from the astrophysical scene (star, planet, zodiacal light). The frequency band over which the requirement applies is between 90 seconds to 10 hours. This implies having the capability to remove any residual systematics down to a negligible residue, and to co-add the elementary observations from many repeat visits to a given target. To achieve the required performance, *ARIEL* is conceived to design-out at instrument level all major systematic effects which limit the capabilities of existing space instrumentation. Particular attention is required to the design of the spacecraft, payload and instrument, to the calibration stability, to characterize all possible systematic variations in performance, and to the data processing pipeline.

ARIEL’s performance is simulated using the end-to-end transit spectroscopy simulator ExoSim [13] (Figure 4), which accounts for all major sources of photometric uncertainty. Among these are: photodetector non uniform response; intrapixel variations; pointing stability; stellar noise from active stars; photon shot noise; detector read noise. It is found that *ARIEL* is photon noise limited by the signal from the host star for all targets *ARIEL* will observe, which span a range in k-band magnitudes from ~ 9 to ~ 3 .

VI. MISSION DESIGN

The *ARIEL* spacecraft shown in Figure 5 is composed of a science payload and a service module. The payload for *ARIEL* consists of an off-axis Cassegrain telescope with an elliptical primary mirror ($1.1\text{ m} \times 0.7\text{ m}$). No imaging capabilities are required and the telescope is diffraction limited at $3\ \mu\text{m}$. All mirrors, optical bench and telescope are manufactured in Aluminium. A refocussing mechanism actuates M2 to correct possible misalignments generated during telescope assembly, launch and cool down.

The fore-optics feed a collimated beam into two separate instrument modules. The first module hosts a near-IR Spectrometer (NIRSpec) covering the $1.2\ \mu\text{m}$ - $1.95\ \mu\text{m}$ band

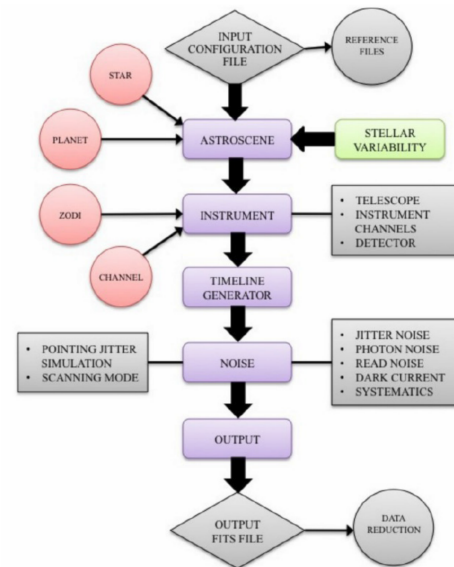


Fig. 4: ExoSim Model Architecture

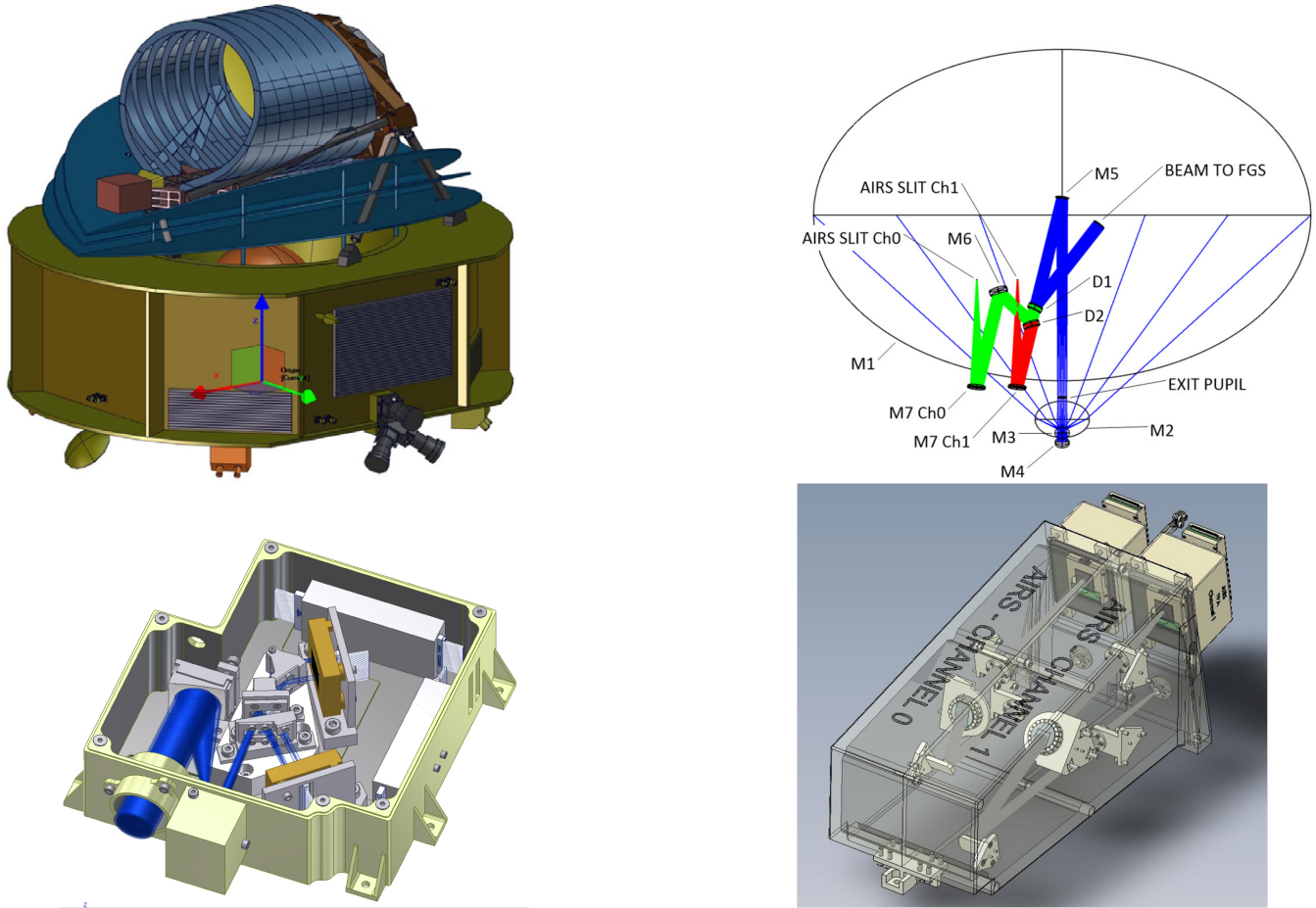


Fig. 5: Clockwise from top-left: *ARIEL* Payload and Service Modules, common optics layout, photometers and NIRSpec, implementation of AIRS optical design into the allocated volume.

with moderate spectral resolving power (> 10), and it is optimized for cloud characterisation. This module also contains a Visible Photometer (VISPhot, $0.50\ \mu\text{m}$ - $0.55\ \mu\text{m}$) and two additional photometers: FGS-1 (Fine Guidance System 1, $0.8\ \mu\text{m}$ - $1.0\ \mu\text{m}$) and FGS-2 ($1.0\ \mu\text{m}$ - $1.2\ \mu\text{m}$). These two FGS photometers provide information on the photometric stability of the target star. They are also used as a redundant system to provide the pointing information in a closed-loop feedback to the attitude and orbital control system, needed for the high pointing stability of the spacecraft. The second channel hosts the *ARIEL* InfraRed Spectrometer (AIRS) sensitive over the $1.95\ \mu\text{m}$ — $7.8\ \mu\text{m}$ band, with spectral resolving power between 30-100. All spectrometers are used in a slit-less mode, although slits are present at the AIRS inputs, are located at an image plane, and are wider than the telescope Point Spread Function. These slits are used as stray-light barriers.

Dichroic mirrors split the light into channels by wavelength. An on-board calibration unit is placed behind M5, in the common optics. It provides a uniform illumination source feeding all focal planes. This is used to monitor variations in detector quantum efficiency during commissioning and calibration, as

an alternative to observations of diffuse astronomical sources, and to transfer over time the ground calibration. The focal plane flat field calibration can be monitored in a similar way if necessary during science operations as well.

The payload module is passively cooled to about 55 K. This is obtained isolating the payload from the spacecraft bus via a series of V-Groove radiators. The detectors of the AIRS are the only items that require active cooling to less than 42 K via an active Neon JT cryocooler.

To achieve the required photometric stability, the line-of-sight of the telescope has to be maintained stable during an observation, with $\text{RPE} \leq 200\ \text{mas}$ up to 90 s, and a $\text{PDE} \leq 100\ \text{mas}$ up to 10 hrs for integrations of 90 s.

A. *ARIEL* IR Spectrometer

AIRS is a two channel spectrometer (CH0 and CH1) and uses two prisms as dispersive elements. This design allows circularising the PSF of the elliptical telescope making use of the prism anamorphosis, therefore reducing the dilution of the flux. The prism material is CaF_2 .

The optical model uses doublets for the Camera ($\text{CaF}_2/\text{Sapphire}$) and the Collimator (CaF_2/ZnSe) to control

chromatic aberrations. The system achieves diffraction limited performances over the useful wavelength ranges.

The AIRS detection chain electrical system is made of the detector array assemblies, the Cold Front End Electronics and the Detector Control Unit which is the warm front end electronics.

The baseline detectors for ARIS are Teledyne Imaging Sensors (TIS) HIRG, which for CH0 is a standard product with cut-off at $5.3\ \mu\text{m}$. For CH1, the baseline is a detector with $10.5\ \mu\text{m}$ cut-off developed for the *NEOCam* programme [14]. The CH1 device has an operability of 94%, with a dark current of 16 e/s for 90% of detector pixels when operated at a temperature of 42K. The Quantum Efficiency without AR coating is measured in excess of 60%.

B. FGS, VISPhot and NIRSspec

The optical module includes an off-axis Gregorian telescope interfacing to the collimated beam fed by the common optics, and a system of dichroic mirrors to divide the signal into the four separate channels.

Detailed modeling of the WFE of the telescope, significant at these wavelengths, shows that the PSF remains coherent, spectral-photometric performance is not degraded, and will allow centroiding of the position of the star for guiding.

The baseline detectors are HIRG from Teledyne, with demonstrated performance that meets and exceeds the *ARIEL* requirements in terms of wavelength coverage, quantum efficiency, read noise, and dark current. They have high heritage and good performance in this wavelength range [15] and meet the necessary engineering constraints in terms of operating temperature and power consumption.

VII. DATA POLICY

The *ARIEL* data and science will be of interest to a large community of “external” exoplanetary scientists, and there is a strong wish to embrace them. For that, publicly available high quality data products will be provided in a timely manner. It is also planned to have a continuous dialogue with the wider community, optimising the mission planning and target list and hence ultimately maximising the science that can be achieved by *ARIEL*.

VIII. CONCLUSIONS

ARIEL is the first space mission dedicated to the characterization of exoplanets through transit spectroscopy. After a phase/A study, *ARIEL* has been selected by ESA for the M4 launch slot in the Cosmic Vision programme. The integrated payload design is optimised to obtain photon noise limited performance with high photometric stability over the timescale of the transit for warm and hot planets. Together with its agility, *ARIEL* will deliver the first survey of a sample of ~ 1000 exoplanets chosen to uniformly sample a large parameter space in planet temperatures, sizes and masses, stellar types and metallicities. Therefore the *ARIEL* sample will be of statistical significance to begin to unravel the history of formation and evolution of planets orbiting stars in the Solar System neighbourhood.

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