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The ARIEL space mission

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ABSTRACT

The Atmospheric Remote-Sensing Infrared Exoplanet Large-survey, *ARIEL*, has been selected to be the next M4 space mission in the ESA Cosmic Vision programme. From launch in 2028, and during the following 4 years of operation, *ARIEL* will perform precise spectroscopy of the atmospheres of about 1000 known transiting exoplanets using its metre-class telescope, a three-band photometer and three spectrometers that will cover the $0.5\,\mu m$ to $7.8\,\mu m$ region of the electromagnetic spectrum. The payload is designed to perform primary and secondary transit spectroscopy, and to measure spectrally resolved phase curves with a stability of < 100 ppm (goal 10 ppm). Observing from an L2 orbit, *ARIEL* will provide the first statistically significant spectroscopic survey of hot and warm planets. These are an ideal laboratory in which to study the chemistry, the formation and the evolution processes of exoplanets, to constrain the thermodynamics, composition and structure of their atmospheres, and to investigate the properties of the clouds.

Keywords: Astronomy, Instrumentation, Exoplanets, Spectroscopy, Space, Transit, Telescope, Atmosphere

1. INTRODUCTION

Planets are ubiquitous in our Galaxy. More than 3 700 exoplanets have been detected in the past 20 years from space and from the ground. Thanks to space missions such as TESS, Cheops and PLATO, and to similar ongoing effort using ground instrumentation, this number is destined to see a dramatic increase over the next decade.

The exoplanets detected have a huge range of masses, sizes and orbits: from rocky Earth-like planets to large gas giants grazing the surface of their host star. This diversity is not seen in our Solar System and 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 planets birth and evolution.

ARIEL[*] (see e.g. Refs.[1–3]) has been selected by ESA as he next medium-class science mission (M4) in the Cosmic Vision programme, and is due 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 about 1 000 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. *ARIEL* will achieve this through transit spectroscopy and multi-band photometry over the $0.5\,\mu m$ to $7.8\,\mu m$ region 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*[†] which summarizes the outcome of the Phase/A study.

2. *ARIEL* SCIENCE GOALS

What are exoplanets made of? How do planets and planetary systems form? How do planets and their atmospheres evolve over time? *ARIEL* was conceived to answer these questions.

The observed diversity of exoplanets can only be investigated by 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 by focusing on warm and hot planets to take advantage of their well-mixed atmospheres which should show minimal condensation and sequestration of high-Z materials. *ARIEL* observations will reveal the planetary bulk and elemental composition (especially C, O, N, S, Si).

Observations of these warm/hot exoplanets will allow the understanding of the early stages of planetary and atmospheric formation during the nebular phase and the following few million years. *ARIEL* will thus provide

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[*]http://ariel-spacemission.eu/

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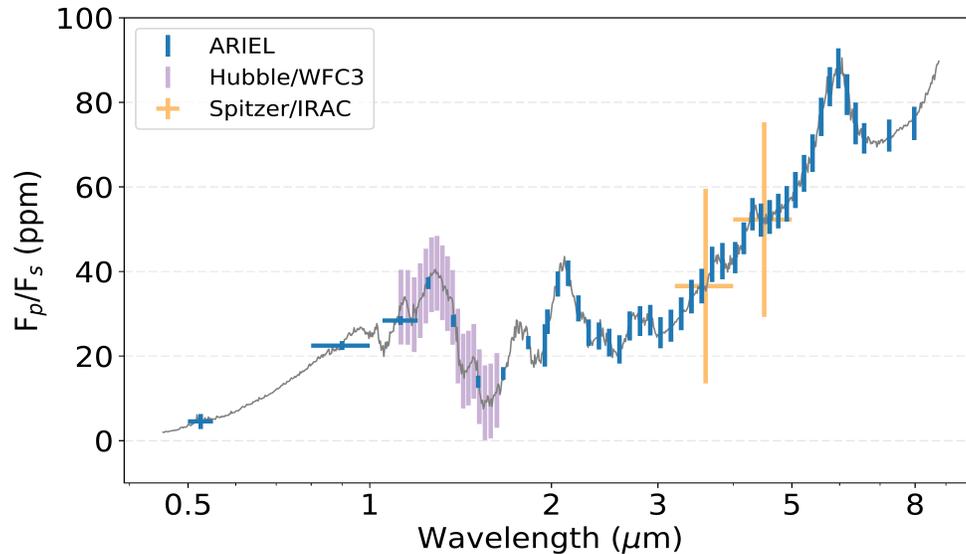
Figure 1. Expected output (with error bars) from the *ARIEL* processed data product compared with the input model assumption for a hot super-Earth similar to 55 Cnc e around a G-type star with Kmag of 4. *ARIEL* performances using 8 eclipses (32 hours of observation) are compared to currently available data for 55 Cnc e from Spitzer-IRAC (8 eclipses[7]) and performances of Hubble-WFC3 extrapolated from transit observations of 55 Cnc e.[8]

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.

ARIEL is designed as a dedicated survey mission for transit and eclipse spectroscopy. Transit, eclipse and phase-curve spectroscopy, whereby the signals form the star and planet are differentiated using knowledge of the planetary ephemeris, will 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. H_2O, CO_2, CH_4, NH_3, HCN, H_2S, as well as exotic metallic compounds such as TiO, VO, and condensed species.[4]

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 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 circmustellar 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 .[5] 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 allow us to discriminate between a primordial atmosphere, expected to be primarily made of H/He, and a more evolved atmosphere made of heavier elements as illustrated 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[6]), *ARIEL*'s simultaneous spectroscopy from the visible to the mid-IR will allow the simultaneous characterization of the atmosphere chemistry and of the clouds and hazes.

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, plausibly beyond
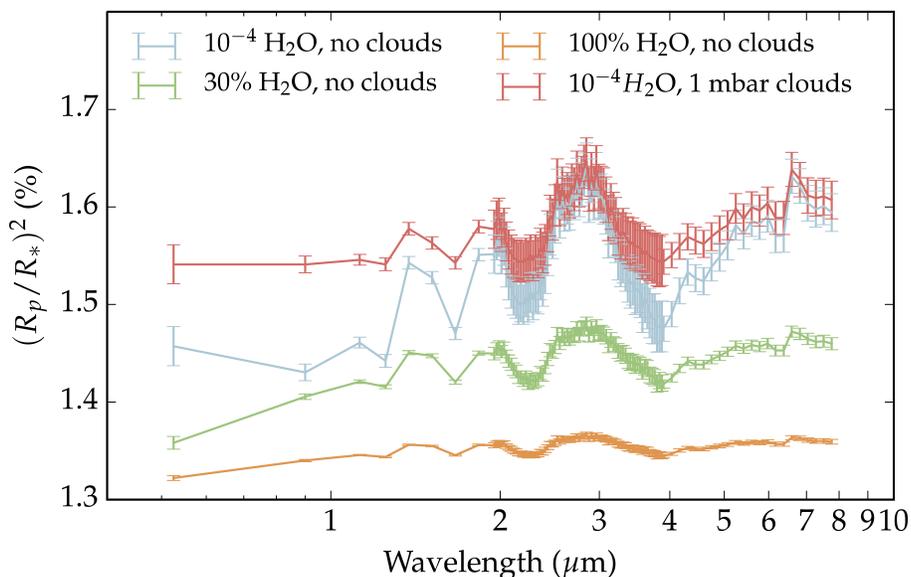
Figure 2. Simulated *ARIEL* transit spectra for a hot super-Earth whose atmosphere shows different fractions of H/He and H_2O. The heavier the main atmospheric component (i.e. water dominated in this case) is, the more compact the atmosphere is, and the smaller the signal detected is. While clouds can mimic this effect to a degree, they mostly influence the short wavelengths (especially VIS-NIR). The figure was produced using a TauREx model.[10]

the water ice condensation line - and migrated to their present location. These warm/hot planets are *ARIEL*'s primary targets. Their well mixed atmospheres will reveal the bulk composition of their envelops, 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.[9] Therefore 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.

3. SCIENCE REQUIREMENTS

The *ARIEL* science translates into top-level requirements on stability, wavelength coverage and spectral resolving power. A stability of $< 100\,ppm$ is required for the accurate detection of chemical abundances from the measured spectra. This has to be achieved over the temporal bandwidth of the transit, typically less than 10 hours. 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. The *ARIEL* payload is designed to achieve a stability of 10-50 ppm.

The onboard instrumentation is designed to provide instantaneus, uninterrupted spectra over the 0.5 μm–7.8 μm band. This is achieved through a three narrow-band photometers in the visible/nearIR and three spectrometers of moderate spectral resolving power in the nearIR and in the midIR, discussed in Section 6.

4. OBSERVATIONAL STRATEGY

The *ARIEL* science case calls for atmospheric spectra or photometric light-curves of a large and diverse sample of known exoplanets, covering a wide range of masses densities, equilibrium temperatures, orbital properties and host-stars. For a sub-sample, it will also acquire a very deep knowledge (e.g. weather, variability, dynamics, etc.). To maximise the science return of *ARIEL* a three-tiered approach has been considered, where three different samples are observed at optimised spectral resolutions, wavelength intervals and signal-to-noise ratios. A summary of the survey tiers is given in Table 1.

Tier name	Observational strategy	Science case
Reconnaissance survey (~30%)	Low Spectral Resolution observations of ~1000 planets in the VIS & IR, with SNR ~ 7	• *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	• *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	• *Very detailed knowledge of the planetary chemistry and dynamics* • *Weather, spatial & temporal variability*

Table 1. Summary of the survey tiers and the detailed science objectives they will address.

5. *ARIEL* TARGETS

ARIEL will study a large population of planets already discovered by other facilities. In particular, it will focus on hundreds of warm/hot gaseous objects (Jupiters, Saturns, Neptunes) and of super-Earths/sub-Neptunes around bright stars of all types. There are > 200 currently known planets complying with these requirements.

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 current *ARIEL* design enables the observation of about 1 000 planets during the mission lifetime. It is clear that this nominal list of planets will change over the years depending on the new exoplanet discoveries. Figure 3 shows a possible mission scenario where the *ARIEL* planets are grouped according to their size.
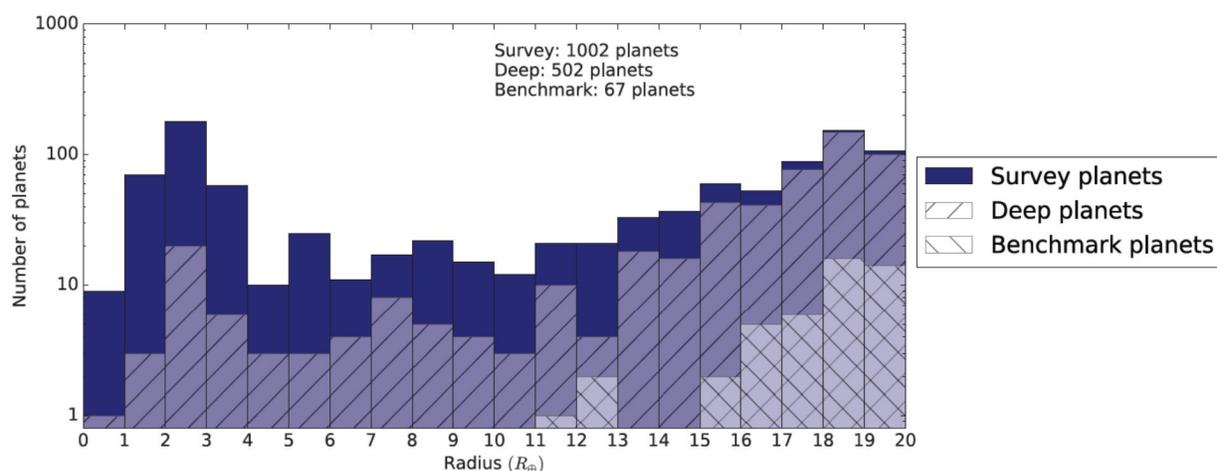
Figure 3. Overview of the *ARIEL* Mission Refernce Sample (MRS). The graph shows how the *ARIEL* 3 Tiers, i.e. Reconnaissance Survey, Deep Survey and Benchmark planets, are nested.[11]
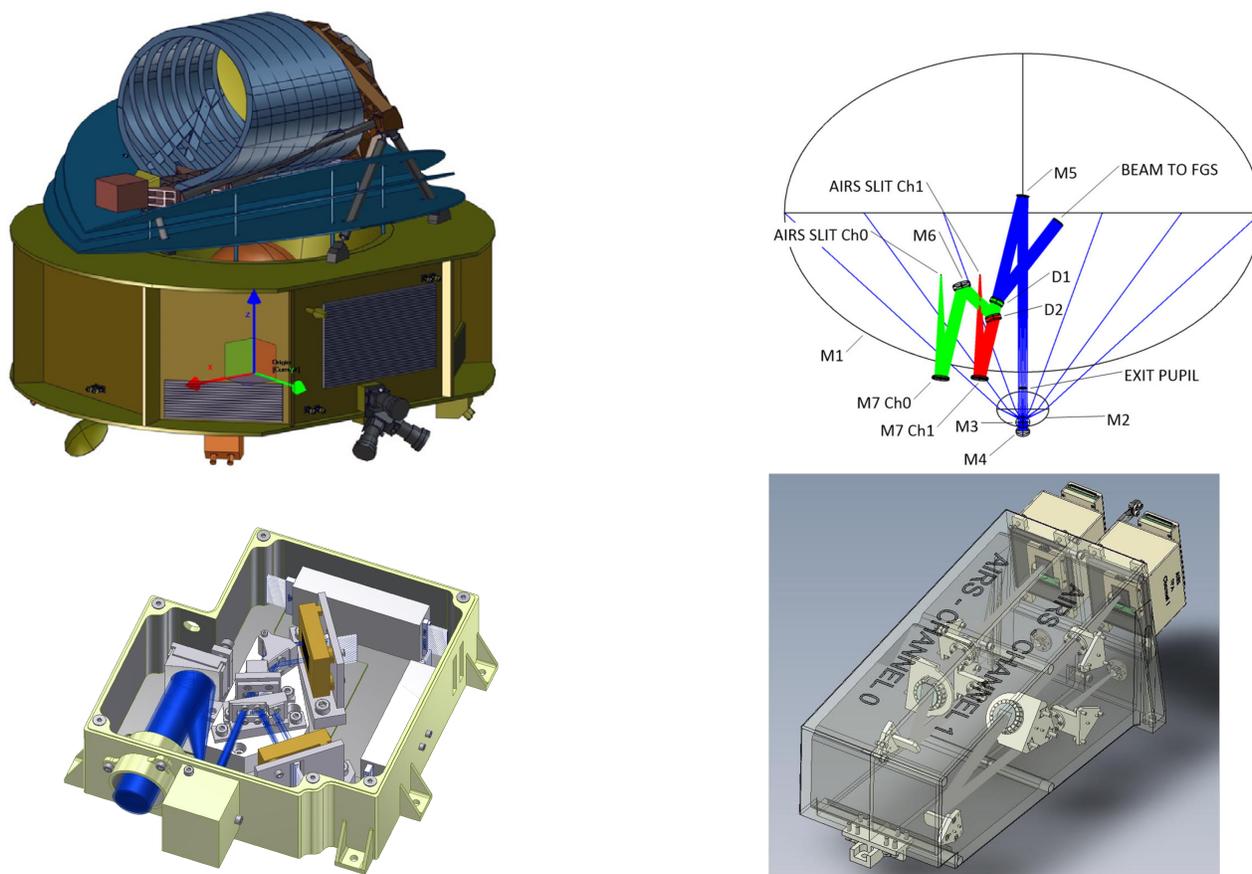
Figure 4. Clockwise from top-left: *ARIEL* Payload and Service Modules, common optics layout, photometers and NIRSpec, implementation of AIRS optical design into the allocated volume.

6. MISSION DESIGN

The *ARIEL* spacecraft shown in Figure 4 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 ($1.1\,\mathrm{m}\times0.7\,\mathrm{m}$). No imaging capabilities are required and the telescope is diffraction limited at $3\,\mu\mathrm{m}$. All mirrors, optical bench and telescope are manufactured in aluminium. A refocussing mechanism actuates the secondary mirror and allows correction for any misalignment generated during telescope assembly or launch and cool down.

The telescope feeds a collimated beam into two separate instrument modules. The first module hosts a near-IR Spectrometer (NIRSpec) covering the $1.2\,\mu\mathrm{m}$–$1.95\,\mu\mathrm{m}$ band with moderate spectral resolving power (> 10), and it is optimized for cloud characterisation. This module also contains a Visible Photometer (VISPhot, $0.50\,\mu\mathrm{m}$–$0.55\,\mu\mathrm{m}$) and two additional photometers: FGS-1 (Fine Guidance System 1, $0.8\,\mu\mathrm{m}$–$1.0\,\mu\mathrm{m}$) and FGS-2 ($1.0\,\mu\mathrm{m}$–$1.2\,\mu\mathrm{m}$). These two FGS photometers are used as a redundant system for providing guidance and closed-loop feedback to the high stability pointing of the spacecraft, as well as simultaneous information on the photometric stability of the target stars. The second channel hosts the *ARIEL* InfraRed Spectrometer (AIRS) sensitive over the $1.95\,\mu\mathrm{m}$—$7.8\,\mu\mathrm{m}$ band, with spectral resolving power between 30 and 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 (PSF). These slits are used as stray-light barriers.

The splitting of the channels by wavelengths is done by dichroic mirrors. An on-board calibration unit is placed in the common optics, behind M5. When the calibrator is operated, it provides a uniform illumination sources on all focal planes. This is used during commissioning and calibration to monitor variations in quantum efficiency (QE), as an alternative to diffuse astronomical sources, and to transfer over time the calibration

obtained on the ground. During science operation, the focal plane flat field calibration can be monitored in a similar way if necessary.

The whole payload module is passively cooled to about 55 K by isolation 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 < 42 K via an active Neon Joule-Thomson cooler.

To achieve the required photometric stability, the line-of-sight of the telescope has to be maintained stable during an observation, with a pointing stability better than 200 mas (99.7% confidence level, C.L.) at time scales shorter than 90 s. On longer time scales, up to 10 hours, the pointing stability is better than 100 mas (99.7% C.L.)

6.1 *ARIEL* IR Spectrometer

The AIRS two channel spectrometer uses two prisms as dispersive elements. The first channel (CH0) has sensitivity between 1.95 μm and 3.9 μm, while the second channel (CH1) has sensitivity between 3.9 μm and 7.9 μm. The main advantage of this design is to limit the dilution of flux by circularizing the PSF of the elliptical telescope making best use of prism anamorphosis. The selected material for the prisms is CaF_2, which has heritage from previous IR space missions. The optimised optical model introduces doublets systems for the Camera (CaF_2/Sapphire) and the Collimator (CaF_2/ZnSe) in order to control the chromatic aberrations. With this correction the system is diffraction limited over the useful wavelength ranges.

The AIRS detection chain is defined as the functional sub-assembly of the AIRS that is necessary to detect the AIRS spectral images and to pre-process scientific data to fit with the telemetry allocation. The AIRS detection chain electrical system encompasses the detector array assemblies, the Cold Front End Electronics (CFEE) and the Detector Control Unit (DCU) which is the warm front end electronics.

The baseline detector for CH1 is Teledyne Imaging Sensors (TIS) H1RG with 10.5 μm cut-off developed in the frame of the *NEOCam* program.[12] Currently tested devices for CH1 have a cut-off wavelength between 9.3 μm and 10.6 μm. When operated at a temperature of 42 K the device has an operability of 94%, with a dark current of 16 e/s for 90% of detector pixels. The Quantum Efficiency without anti-reflection (AR) coating is measured in excess of 60%. The baseline CH0 detector is a standard H1RG product with cut-off at 5.3 μm.

6.2 FGS, VISPhot and NIRSpec

The optical module interfaces to the collimated beam fed by the telescope and common optics. It then includes an off-axis Gregorian mirror telescope before inputting to the dichroics system to divide the field 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 for the FGS are H1RG from Teledyne. These detectors have demonstrated performance that meets and exceeds the required capabilities in terms of wavelength coverage, quantum efficiency, read noise, dark current and linear well capacity, while also meeting the necessary engineering constraints in terms of operating temperature, power consumption and packaging. They have high heritage and good performance in this wavelength range.[13]

7. *ARIEL* PERFORMANCE 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).

Transit spectroscopy and multi-band photometry has been so far conducted using general-purpose, space-based instruments. Some success has been obtained using ground-based instrumentation as well. These measurements however suffer from a high level of systematic error due to a number of issues such as pointing jitter, thermal and optomechanical stability, wavelength and photometric calibration, and detector stability.

The *ARIEL* instrument is designed to perform time series spectroscopy and photometry from the visible to the mid-IR with a stability of better than 50 ppm during one transit observation. Key aspects which allow *ARIEL* to obtain its stable performance are:

Type of uncertainty	Source	Mitigation Strategy
Detector noise	Dark current noise	Choice of low-noise detectors
	Readout noise	
	Gain stability	Calibration, post- processing data analysis, choice of stable detectors.
	Persistence	Post-processing decorrelation. Continuously staring at a target for the whole duration of the observation.
Thermal noise	Emission from telescope, common optics and all optical elements	Negligible due to surface emissivity properties and in-flight temperatures of the payload.
	Temperature fluctuations in time	Negligible impact by design
Astrophysical noise	Photon noise arising from the target	Fundamental noise limit, choice of aperture size (M1 diameter).
	Photon noise arising from local zodiacal light	Negligible over ARIEL band
	Stellar variability with time	Multi-wavelength stellar monitoring, post-processing decorrelation
Pointing jitter	RPE and PDE effects on the position, Spectral Energy Sistribution, and detector intra/inter pixel response	Small RPE and PDE, Nyquist sampling, post-processing decorrelation
	Slit losses	Spectrometer input slit sufficiently large

Table 2. Summary of noise sources and systematic errors.
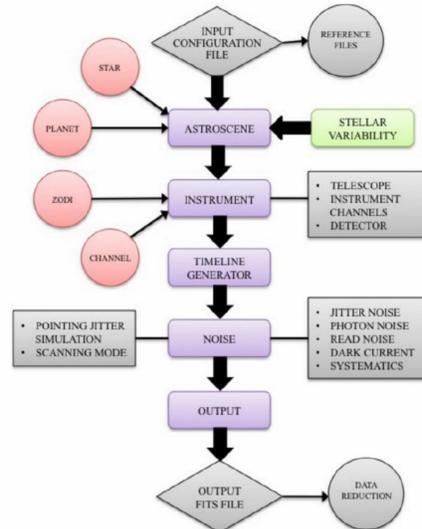
Figure 5. ExoSim Model Architecture

1. Simultaneous observations of the same transit event by all photometric and spectroscopic channels;

2. Continuous observation of the transit event such that the measurement is conducted in a thermally and photometrically stable condition.

3. A payload design which makes ARIEL resilient to major sources of systematics or makes their removal possible in post processing.

This is summarised in Table 2, which lists the most important sources of noise and systematics identified, along with the approach used to mitigate their impact on the detection, and on the overall photometric stability.

ARIEL's performance is simulated using the end-to-end transit spectroscopy simulator ExoSim[14] (Figure 5), which accounts for all major sources of photometric uncertainty. Among these are: photodetector non uniform response; intra-pixel 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.

8. DATA POLICY

It is recognized that *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. The intention is to provide publicly available high quality data products in a timely manner and to have a continuous dialogue with the wider community, optimising the mission planning and target list, both before launch and during the mission, and hence ultimately maximising the science that can be achieved by *ARIEL*.

9. CONCLUSIONS

ARIEL is the first space mission selected which is 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 about 1 000 exoplanets chosen to uniformly sample a large parameter space in planet temperatures, sizes and masses, stellar types and metallicities. 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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