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An Updated Study of Potential Targets for Ariel

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Abstract

Ariel has been selected as ESA's M4 mission for launch in 2028 and is designed for the characterization of a large and diverse population of exoplanetary atmospheres to provide insights into planetary formation and evolution within our Galaxy. Here we present a study of Ariel's capability to observe currently known exoplanets and predicted *Transiting Exoplanet Survey Satellite* (*TESS*) discoveries. We use the Ariel radiometric model (ArielRad) to simulate the instrument performance and find that ∼2000 of these planets have atmospheric signals which could be characterized by Ariel. This list of potential planets contains a diverse range of planetary and stellar parameters. From these we select an example mission reference sample (MRS), comprised of 1000 diverse planets to be completed within the primary mission life, which is consistent with previous studies. We also explore the mission capability to perform an in-depth survey into the atmospheres of smaller planets, which may be enriched or secondary. Earth-sized planets and super-Earths with atmospheres heavier than H/He will be more challenging to observe spectroscopically. However, by studying the time required to observe ∼110 Earth-sized/super-Earths, we find that Ariel could have substantial capability for providing in-depth observations of smaller planets. Trade-offs between the number and type of planets observed will form a key part of the selection process and this list of planets will continually evolve with new exoplanet discoveries replacing predicted detections. The Ariel target list will be constantly updated and the MRS re-selected to ensure maximum diversity in the population of planets studied during the primary mission life.

Key words: planets and satellites: atmospheres – techniques: spectroscopic

1. Introduction

Nearly 4000 exoplanets have been discovered (around 3000 of which transit their stars) as well as 2900 *Kepler* and *K2* candidates yet to be confirmed as planets. On top of this, in the next few years *Gaia* is anticipated to discover up to ten thousand Jupiter-sized planets (Sozzetti 2010; Perryman et al. 2014) while the *Transiting Exoplanet Survey* (*TESS*; Ricker et al. 2014) is expected to detect thousands of transiting planets of Earth size or larger (Sullivan et al. 2015; Barclay et al. 2018; Huang et al. 2018). Additionally, space surveys *Characterising Exoplanet Satellite* (CHEOPS; Broeg et al. 2013) and Planetary Transits and Oscillations (PLATO; Rauer et al. 2016), along with ground-based surveys like the Next-generation Transit Survey (NGTS; Wheatley et al. 2018), Wide Angle Search for Planets (WASP; Pollacco et al. 2006), Hungarian-made Automated Telescope Network (Bakos et al. 2004), Hungarian-made Automated Telescope Network-South (Bakos et al. 2013), MEarth (Nutzman et al. 2009), Transiting Planets and Planetesimals Small Telescope (TRAPPIST; Jehin et al. 2013) and KPS (Kourovka Planet Search; Burdanov et al. 2016), will lead to many more transiting exoplanet detections as well as further characterization of planetary parameters.

Although many planets have been detected and it is thought that planets are common in our Galaxy (e.g., Cassan et al. 2012; Wright et al. 2012; Batalha et al. 2013; Howard 2013; Dressing & Charbonneau 2013), our current knowledge of their atmospheric, thermal, and compositional characteristics is still

very limited. Space telescopes such as *Hubble* and *Spitzer*, as well as some ground-based observatories, have provided constraints on these properties for a limited number of targets and, in some cases, have identified the key molecules present in their atmospheres while also detecting the presence of clouds and probing the thermal structure (e.g., Brogi et al. 2012; Majeau et al. 2012; Stevenson et al. 2014; Sing et al. 2016; Fu et al. 2017; Tsiaras et al. 2018; Zhang et al. 2018; Pinhas et al. 2019). However, currently available space-based data sets have been achieved with instruments that are not specifically designed for exoplanet science. Therefore, the data obtained is inhibited due to a narrow wavelength coverage and, where observations are taken over a wider spectral range, these observations are usually not simultaneous, potentially injecting an extra source of systematic noise. Additionally, being general observatories, the time allocated to exoplanet science does not fully meet the need of the community. Hence, the breadth and quality of currently available data is limited by the absence of a dedicated space-based exoplanet spectroscopy mission and thus progress in this area has been slower than desired. A dedicated mission would also provide a heterogeneous data set, with a consistent pipeline and an well-defined target selection strategy, maximizing the scientific yield.

Ariel has been selected as the next ESA medium-class science mission and is due for launch in 2028. During its 4 yr mission, Ariel aims to observe ∼1000 exoplanets ranging from Jupiters and Neptunes down to super-Earth size in the visible and the infrared with its meter-class telescope. The analysis of Ariel spectra and photometric data will deliver a homogeneous catalog of planetary spectra which will allow for the extraction of the chemical fingerprints of gases and condensates in the planets atmospheres, including the elemental composition for

Table 1
Wavelength Ranges and Spectral Resolutions of Ariel's Instrumentation

Instrument Name	Wavelength Range (μm)	Resolution
VISPhot	0.5–0.6	
FGS 1	0.6–0.81	Photometric bands
FGS 2	0.81–1.1	
NIRSpec	1.1–1.95	20
AIRS Ch0	1.95–3.9	100
AIRS Ch1	3.9–7.8	30

the most favorable targets. It will also enable the study of thermal and scattering properties of the atmosphere as the planet orbits around the star. A basic summary of Ariel's instrumentation is given in Table 1. For more detail on the Ariel design see Tinetti et al. (2018).

Ariel will enable the simultaneous study of exoplanets at multiple wavelengths through transit, eclipse, and phase-curve observations (see, e.g., Tinetti et al. 2013 for an overview of the information content of these techniques). During transit, stellar light can be observed passing through the terminator region of the planet (transmission spectroscopy). Similarly, when the star eclipses the planet (i.e., the planet passes behind its host star in our line of sight) the flux difference resulting from the planet's day-side emission or reflection (emission or reflection spectroscopy) can be measured. Phase curves are observed by monitoring the star–planet system over a large portion of the planets orbit. Here, we focus on transit and eclipse observations as these will be the main science observations. Additional science time to be dedicated to phase curves is currently under study.

During Phase A, a study of Ariel's capabilities to observe known and predicted planets was conducted and a mission reference sample (MRS; i.e., a list of exoplanets to be observed during the primary mission life) of ∼1000 potential targets was created (Zingales et al. 2018). Here an updated review of the performance of Ariel's instrumentation to observe currently known planets and potential future detections by *TESS* is undertaken. According to a recent study by Barclay et al. (2018), *TESS* is anticipated to detect over 4500 planets around bright stars and nearly 10,000 giant planets around fainter stars. The predicted *TESS* discoveries are incorporated into our analysis to test Ariel's capabilities. The list of known and predicted exoplanets are analyzed using the Ariel radiometric model (ArielRad; L. Mugnai et al. 2019, in preparation), a new Ariel simulator which is more suitable to capture the details and updates of Ariel's design as considered in Phase B (see Section 3.2). ArielRad includes greater margins on the instrument noise and an additional noise floor of 20 ppm than the previously used ESA radiometric model (Puig et al. 2015). This exercise will be regularly repeated to incorporate new discoveries and validate that the mission's science goals can be achieved as the instrumentation evolves in Phase B.

Finally we focus part of our simulations and discussion on smaller planets to refine some of the science objectives considered in Phase A for the mission and address new science questions emerging from the recent discoveries, e.g., the Fulton gap (Fulton & Petigura 2018).

2. Creation of a Catalog of Exoplanets

2.1. Known Exoplanets

Exoplanetary data was downloaded from NASA's Exoplanet Archive in order to account for all confirmed planets before being filtered such that only transiting planets were considered. The database was last accessed on 2019 February 26. However, the major exoplanet catalogs are sometimes incomplete and thus an effort has been made here to combine them (for a review of the current state of exoplanet catalogs, see Christiansen 2018).

Hence, the data was verified, and in some cases gaps filled, utilizing the Open Exoplanet Catalog (Rein 2012), exoplanet. eu (Schneider et al. 2011), and TEPCat (Southworth 2011). Planets not included in the NASA Exoplanet Archive were not added to the analysis to ensure that only confirmed planets were utilized. As of 2019 March, 3022 planets within the NASA Exoplanet Archive were sufficiently characterized for inclusion in this analysis.

Unknown parameters were inferred based on the following assumptions.

1. If the inclination is known, the impact parameter is calculated from

$$b = \frac{a\cos(i)}{R_*}. \tag{1}$$

2. Else, it was assumed that $b = 0.5$ (i.e., the midpoint of the equator and limb of the star).
3. The planetary effective temperature (T_p) is estimated from

$$T_p = T_*\left(\frac{\sqrt{1-A}\,R_*}{2a\epsilon}\right)^{1/2}, \tag{2}$$

where a greenhouse effect of $\epsilon = 0.8$ and a planetary albedo of $A = 0.3$ ($T_P < 700\,\mathrm{K}$) or $A = 0.1$ ($T_P > 700\,\mathrm{K}$) are assumed (Seager & Mallén-Ornelas 2003; Tessenyi et al. 2012).
4. Planetary mass (M_p) was estimated utilizing Forecaster (Chen & Kipping 2017).
5. Atmospheric molecular mass was assumed to be 2.3.

2.2. Future Planet Discoveries

TESS and other surveys are predicted to discover thousands of planets around bright stars. In the first two years of operation, *TESS* is anticipated to detect over 4500 planets around bright stars and more than 10,000 giant planets around fainter stars (Barclay et al. 2018). Here, these predicted *TESS* discoveries around brighter stars are incorporated into the analysis to highlight Ariel's capabilities to study anticipated future discoveries. The MAST archive[4] has been utilized to obtain stellar parameters for these planets by cross-referencing the *Gaia* catalog. The first planets from *TESS* have begun to be discovered (e.g., Huang et al. 2018) but these have not been included in this work to avoid overlap with the predicted yield. The known and predicted exoplanets were compiled into a single data set (∼7000 planets), which has been used to analyze Ariel's capabilities and provide an indicative look at the number and type of planets Ariel could observe.

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[4] https://archive.stsci.edu

Potential discoveries by other surveys (Planetary Transits and Oscillations of stars, PLATO; Search for habitable Planets Eclipsing Ultra-cool Stars, SPECULOOS; etc.) have not been included in this analysis as thus far predictions for these surveys just resulted in an estimate of the number of expected detections, but no specific target coordinates and characteristics have been released. When such information becomes available, predicted/real detections from these surveys will be incorporated into this analysis. In any case, these surveys are expected to find thousands of planets which could be suitable for study with Ariel, enhancing the population of planets from which the final target list (MRS) is selected. Hence, although these predicted yields have not been included, planets found by these surveys will be added to the sample as they are detected.

3. Creating a List of Potential Targets

3.1. ESA Radiometric Model

During Phase A, the ESA radiometric model (Puig et al. 2015) was utilized to assess the duration and type of observations needed to meet the mission requirements. Although the Near Infrared Spectrograph (NIRSpec) instrument will also be used for spectroscopy, the mission requirements are baselined on the Atmospheric Infrared Sounder (AIRS) channels, as these bands are typically the most demanding. The ESA radiometric model calculates the signal and noise contributions for exoplanet spectroscopic observations (Puig et al. 2015; Sarkar et al. 2017). This model simulates observational and instrumentation effects, utilizing target characteristics to assess whether emission or transmission spectroscopy is preferable and to estimate the required number of observations to achieve a desired resolving power and signal-to-noise ratio (S/N). The ESA radiometric model requires the host star temperature to be in the range of 3070–7200 K. The MRS during Phase A was obtained using this model (Zingales et al. 2018).

3.2. Ariel Radiometric Model

The ESA radiometric model assumes that the systematic noise does not vary from target to target. ArielRad (L. Mugnai et al. 2019, in preparation) has been developed to provide a comprehensive model of the instrument performance. While the ESA radiometric model assumes a constant instrument noise, ArielRad provides systematic noise on a case-by-case basis. The Ariel team has validated ArielRad against the ESA radiometric model and ExoSim (Sarkar et al. 2017) by running the simulators with the same instrument noise characteristics. ArielRad includes greater margins on the instrument noise and a noise floor of 20 ppm.

We use the ArielRad simulator to provide realistic noise models for all planets within the catalog described in Section 2. These noise models are used to create a new list of potential targets, based on the expected performance from ArielRad. The fine guidance sensor (FGS) signal requirements for accurate pointing are now accounted for as these are not included in the ESA radiometric model but are key for target selection. In the ESA radiometric model, simulations were restricted to planets orbiting stars with temperatures in the range of 3070–7200 K due to the stellar spectral energy distributions (SEDs) used. For ArielRad, this range is expanded to include early-type stars and M dwarfs such as Trappist-1 by using a

Table 2
Resolution of the Final Data Set across Each Instrument in Each Tier

Instrument Name	Tier 1	Tier 2	Tier 3
NIRSpec	$R \sim 1$	$R \sim 10$	$R \sim 20$
AIRS Ch0	$R \sim 3$	$R \sim 50$	$R \sim 100$
AIRS Ch1	$R \sim 1$	$R \sim 10$	$R \sim 30$

broader range of SEDs from the Phoenix atmospheric models, increasing the diversity of input catalog.

3.3. The Three Tier Approach

Planning of observations with Ariel is based around a tiered approach and Table 2 describes the requirements on each tier. As envisaged in Phase A, a survey tier aims to observe 1000 planets with low-resolution spectroscopy to produce a statistically viable data set of a diverse range of exoplanetary atmospheres. Tier 1 observations will help refine orbital and planetary parameters and constrain (or remove) degeneracies in the interpretation of mass–radius diagrams. Additionally, it will offer the opportunity to generate color–color and color–magnitude diagrams and investigate what fraction of planets have a transparent atmosphere, are partially clouded, or are completely overcast.

From this initial survey of planets, around half will be selected for spectroscopic follow-up: Tier 2 spectroscopic measurements are crucial for uncovering atmospheric structure and composition. Additionally, Tier 2 observations are critical to search for potential correlations between atmospheric chemistry and basic parameters such as planetary size, density, temperature, stellar type, and metallicity. Tier 3 will consist of repeated observations of a select group of benchmark planets ($\sim$50–100) around bright stars which can be observed at high resolution within a small number of transits or eclipses to provide a very detailed knowledge of the planetary chemistry and dynamics (see Tinetti et al. 2018 for an in-depth description of the tiering system and the mission science questions and requirements). Figure 1 shows simulated observations in each tier for a planet with parameters similar to Wasp-39 b. The addition of a Tier 4—including phase curves and an ad hoc observational strategy for targets of interest that do not fit into the tier system—has been recently discussed by the Ariel team.

3.4. A List of Potential Targets for Ariel

From the noise models created by ArielRad, the catalog of known and predicted planets was cut down to those for which an S/N $\geqslant$ 7 could be achieved on the atmosphere within a reasonable number of transits or eclipses. For Tier 1, there are over 2000 potential planets for which the science requirements can be reached with five observations or less, far more than the 1000 that will make up the MRS. Being oversaturated in the number of possible targets is useful as it allows for redundancy in the scheduling of observations and it means there is a large catalog of planets to draw from to allow for a diverse sample to be observed. The distribution of various stellar and planetary parameters for these potential Tier 1 targets is shown in Figures 2 and 3. These show that: (i) to achieve a sample of $\sim$1000 planets; Ariel does not need to observe faint stars (except for special targets of interest); (ii) there is a large diversity in planet temperature and radius (iii); the stellar type of planet hosting stars is varied, although FG stars are more
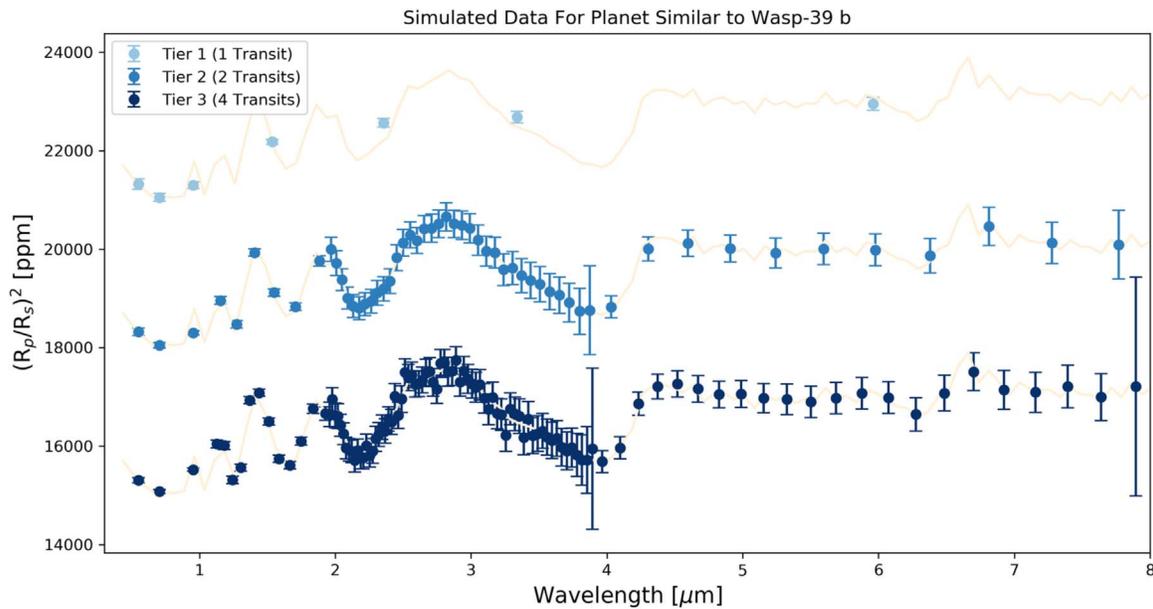
Figure 1. Simulated data for a planet similar to Wasp-39 b in each tier. The atmosphere has been modeled in chemical equilibrium with solar metallicity and C/O = 0.5. The error bars are calculated using ArielRad and the spectra are offset for clarity. The larger errors at the red end of AIRS channels 0 and 1 are due to a reduced sensitivity caused by optical filter cutoff, and detector sensitivity, respectively. This will however be mitigated by the cross-channel spectral overlap of the baseline design which is expected to reduce the error bars at the transition between channels 0 and 1.
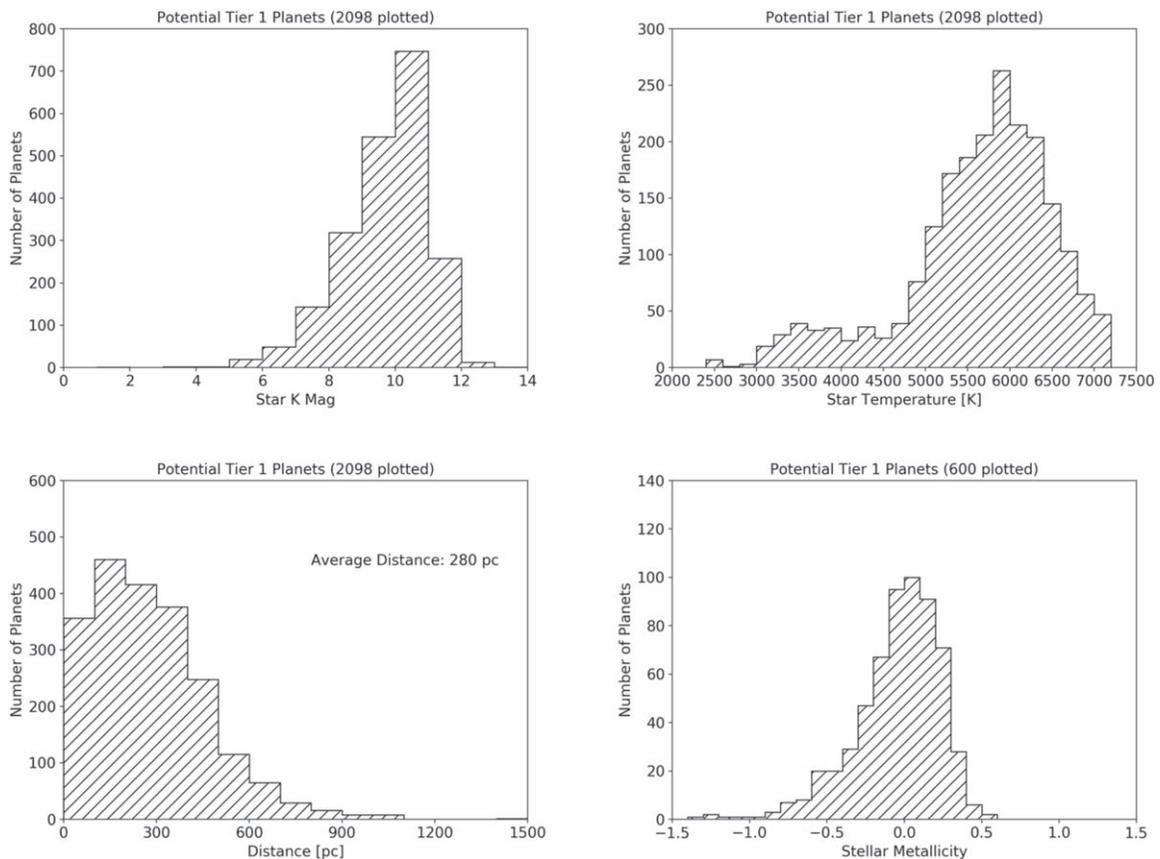
Figure 2. Histograms of the properties of the stellar hosts within the potential Ariel Tier 1 catalog. Metallicities were not available for all host stars.

dominant (iv); the majority of potential targets are located within a few hundred parsecs,; (v) most potential targets are close to their stars and have orbits of under 20 days; and (vi) although the metallicities of many of the host stars is unknown, there is a wide range of values included in the sample.

Additionally, ~1000 planets are found to be potentially observable in Tier 2 and Figure 4 details the distribution of the number of observations required for these planets as well as those in Tier 1. We find that the number of observable Jupiters ($R_p > 7 R_\oplus$) is approaching saturation at five observations while
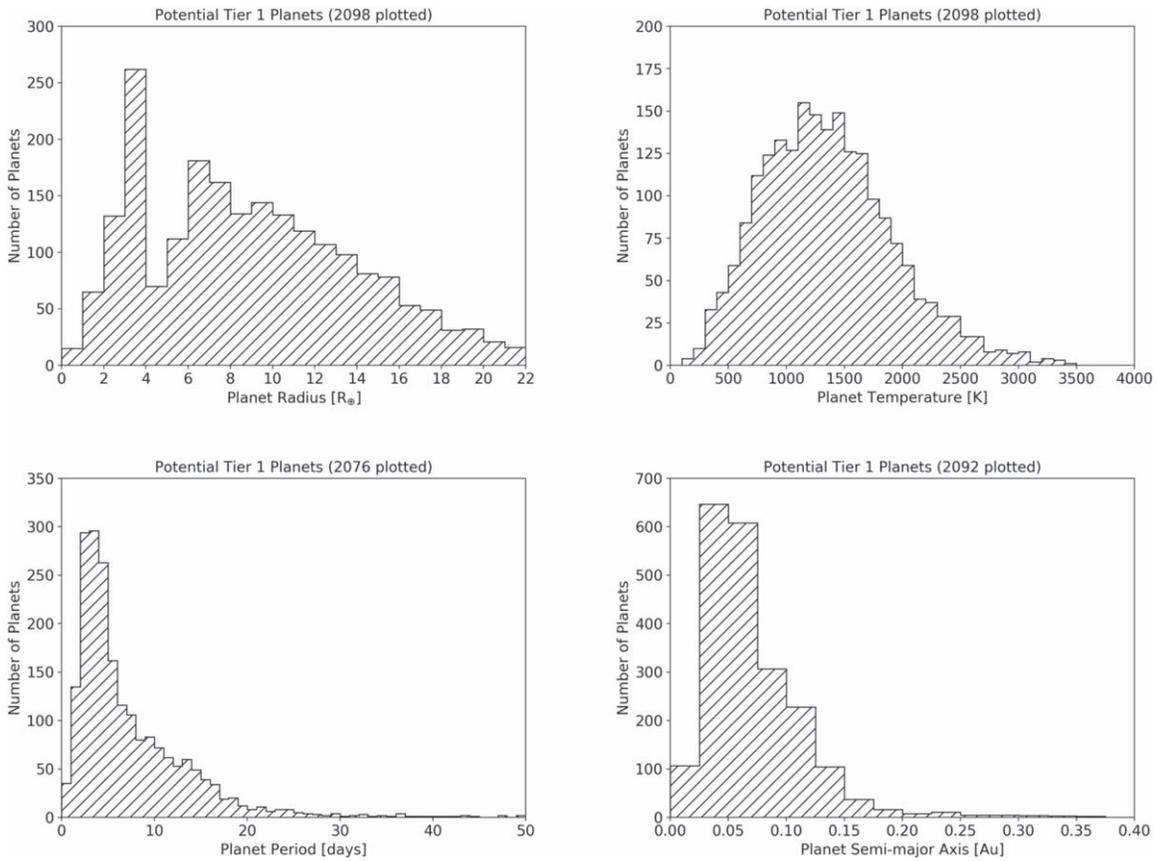
Figure 3. Histograms of the planetary properties within the potential Ariel Tier 1 catalog. In some cases, not all planets are plotted for aesthetic reasons.
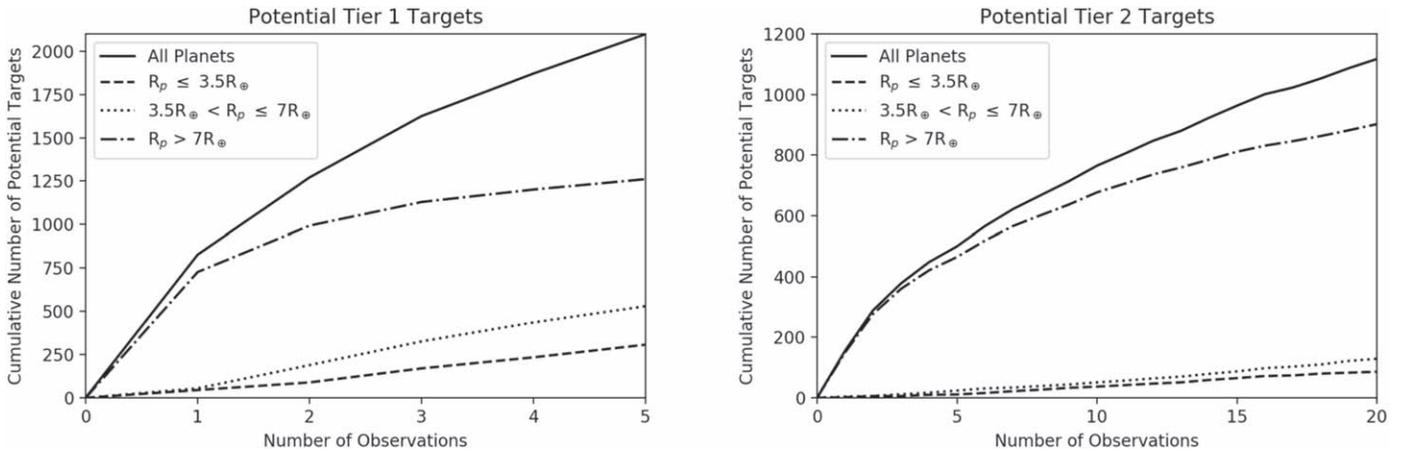
Figure 4. Cumulative number of planets that can be observed in Tiers 1 (left) and 2 (right) with a given number of transits or eclipses.

the number of suitable smaller planets is rising with increased observations. Ariel will have constant visibility of the ecliptic poles with a partial visibility of the whole sky at lower latitudes. The sky location of possible planets for study in each tier with Ariel is shown in Figure 5 and they are found to be well distributed across the sky but with a noticeable gap close to the ecliptic due to a lack of *TESS* coverage in its primary mission. A table of the currently known exoplanets that are suitable for study with Ariel is included in the appendix.

3.5. Creation of an Example MRS

Ariel has a nominal life of 4 yr (extendable to 6) including a six-month commissioning and calibration phase. Additionally,

scheduling constraints, such as telescope housekeeping, slewing between targets, and data down-link, reduce the available science time. Ariel will therefore have ∼3 yr of usable science time during its nominal life. Having established that there will be a large number of planetary atmospheres that are suitable for characterization with Ariel, we explore the number that could be observed over the mission lifetime.

The approach adopted during Phase A consisted of choosing a very diverse, and as complete as possible, combination of star–planet parameters while minimizing the number of repeated observations by selecting the planets around the brightest stars. Here, we chose three main parameters to classify the potential targets by: stellar effective temperature,

Figure 5. Sky locations of potential targets for study with Ariel. Having targets scattered across the entire sky is beneficial for the scheduling of observations.

planetary radius, and planetary equilibrium temperature. Each parameter is split into a number of classes and Table 3 summarizes these distinctions. We bin the planets by these three parameters, and where possible, ensure that at least two planets within each 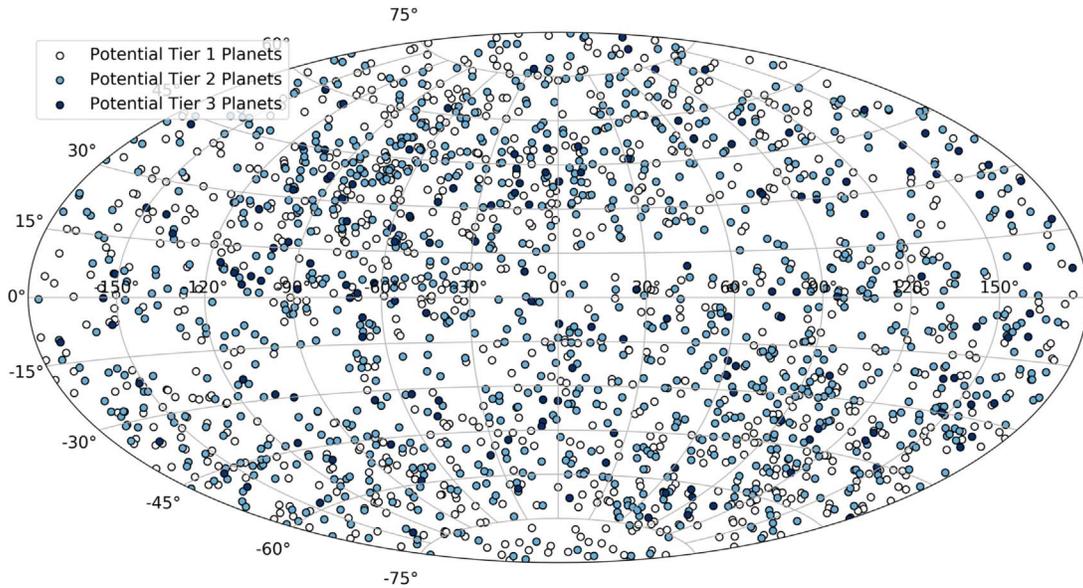bin are contained within the MRS. Future selections will also classify planets by their density and the metallicity of the host star. These five basic characteristics are thought to have a large impact on the chemistry and thus choosing planets with a broad range in these parameters should yield a multifarious exoplanet population for study.

Adopting this strategy we obtain a distribution of planets by radius and temperature as displayed in Figure 6. Table 6 contains a list of the known planets that are included in this example MRS. Planets selected for Tier 3 are also included in Tier 2 and, in turn, Tier 1 planets incorporate all those studied in Tier 2. Although not considered in depth here, 10% of mission time is reserved for Tier 4 and we highlight potential targets for phase curves in Figure 7. For larger planets, these are those which can easily be observed at Tier 2 resolutions in both transit and eclipse, while for smaller planets it is those that can be studied at Tier 1 resolutions in both methods. Phase-curve targets are also required to be on relatively short orbits and thus are generally found to be hot (or very hot).

Different observing strategies have been discussed within the Ariel team including acquiring data in both transit and eclipse for some Tier 2 planets. Such observations would increase our ability to characterize the atmospheres of these targets but would reduce the total number of planets studied. Table 4 highlights the science time (i.e., time on target) required to achieve different observations. These discussions are ongoing and further studies will be undertaken but it can be seen that acquiring data in the secondary method (i.e., the method which gives a lower S/N) for some of the best planets will not require significant mission time. However, the total number of Tier 2 planets may have to be sacrificed to achieve this.

Hence, ArielRad simulations combined with the *TESS* yield suggested by Barclay et al. (2018) predict that Ariel will be able to observe 1000 planets within the primary mission (e.g., Figure 6). The number of planets within this updated version of MRS is similar to that of the Phase A study although we find an

Table 3
Bounds Used to Classify Potential Planets to Ensure a Varied Population of Planets within the Mission Reference Sample

Parameter	Class	Bounds
Stellar Effective Temperature	M	$T_s < 3955$ K
	K	3955 K $< T_s < 5330$ K
	G	5330 K $< T_s < 6070$ K
	F	6070 K $< T_s < 7200$ K
Planetary Radius	Earth/super-Earth	$R_p < 1.8\ R_\oplus$
	Sub-Neptune	$1.8\ R_\oplus < R_p < 3.5\ R_\oplus$
	Neptune	$3.5\ R_\oplus < R_p < 6\ R_\oplus$
	Jupiter	$6\ R_\oplus < R_p < 16\ R_\oplus$
	Massive Jupiter	$R_p > 16\ R_\oplus$
Planetary Equilibrium Temperature	Temperate/warm	$T_p < 500$ K
	Very warm	500 K $< T_p < 1000$ K
	Hot	1000 K $< T_p < 1500$ K
	Very hot	1500 K $< T_p < 2500$ K
	Ultra hot	$T_p > 2500$ K

increase in the number of Tier 2 planets compared to the results of Zingales et al. (2018) on top of the 10% mission lifetime dedicated to Tier 4 planets. Therefore, from the input catalog of currently known and predicted planets, ArielRad simulations suggest that Ariel should be more than capable of achieving the science requirement of characterizing the atmospheres of hundreds of diverse extra-solar planets.

4. Characterization of Small Planets

Section 3.2 shows that from the catalog of known planets and predicted *TESS* detections ArielRad produces an MRS consistent with that created in Phase A with the ESA radiometric model and predicted targets by Zingales et al. (2018). Choosing the MRS in this way naturally leads to a proportionally larger number of gaseous planets being selected for observation. However, warm and hot super-Earths (and Earth-sized planets) are well within Ariel's capabilities,
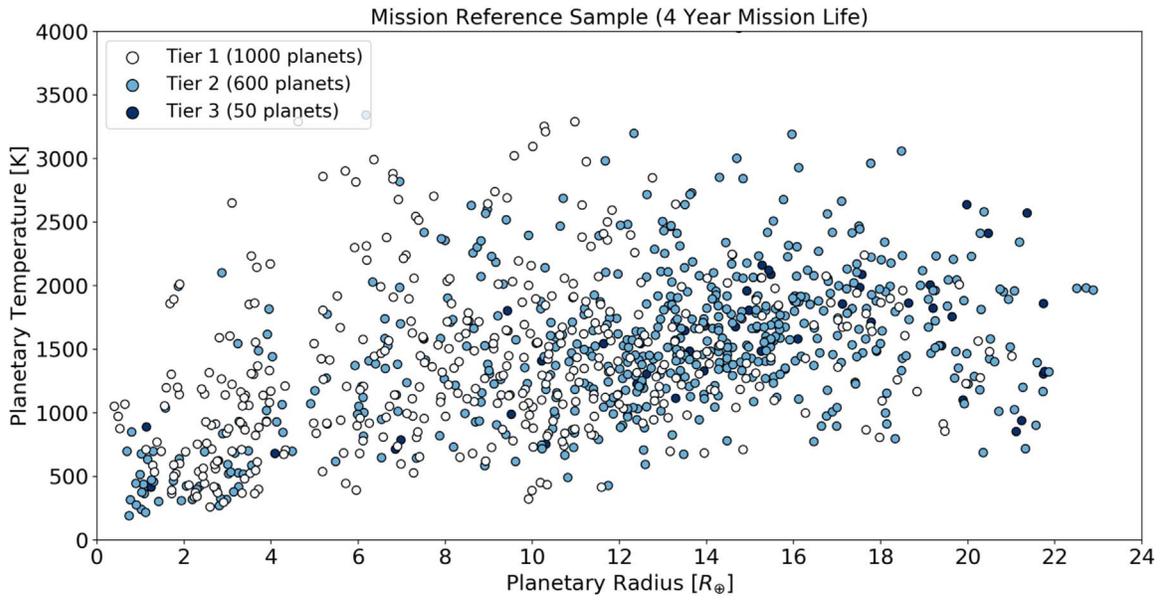
Figure 6. Planetary radius and temperature distribution of a potential Ariel mission reference sample from ArielRad.
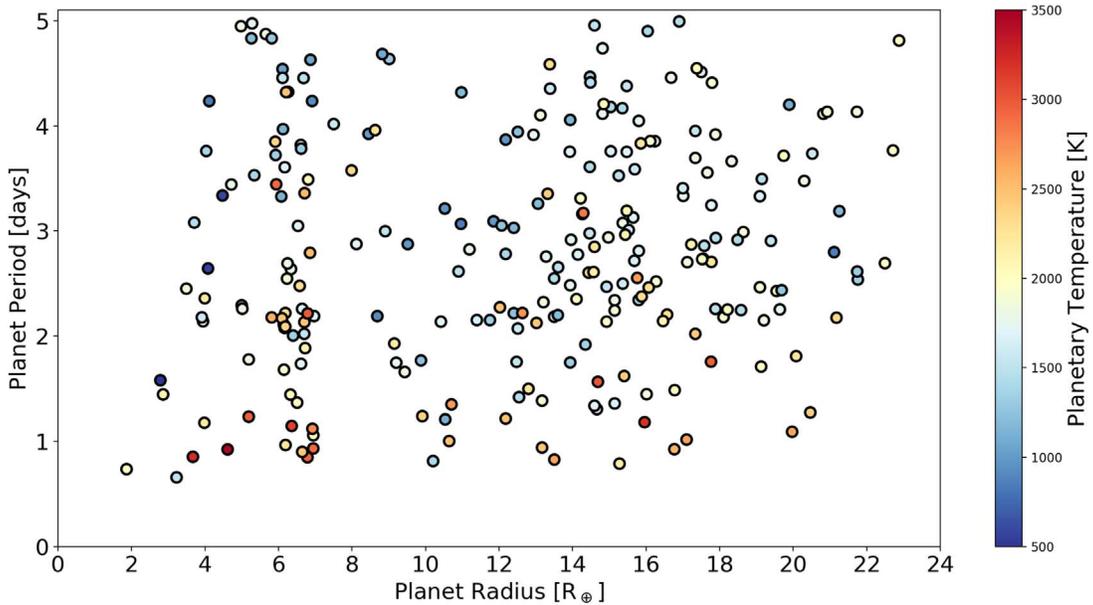
Figure 7. Potential phase-curve targets for Ariel. The color of points highlights the planetary equilibrium temperature. Spectroscopic phase curves should be possible for Jupiter-sized planets while smaller planets are suitable for multiband photometric observations.

especially given that they are expected to be more numerous around bright stars.

Smaller planets, particularly those which could be rocky, are an intriguing population of bodies, especially since the discovery of the Fulton gap at $\sim 1.8\,R_{\oplus}$ by the California-*Kepler* Survey (CKS; Fulton & Petigura 2018). This distribution seemingly indicates two populations of small planets: those which have retained a volatile dominated atmosphere and those which are expected to have lost this more primordial envelope (e.g., Owen & Wu 2017) or never had one. Characterizing the atmospheres of planets with radii smaller than $3.5\,R_{\oplus}$, and in particular, those within the transition region from rocky to gaseous, is fundamental in uncovering the nature of this population and would be very informative for planetary

formation and evolution theories. More specifically, understanding whether the atmosphere is still primordial (i.e., H/He-rich, possibly thick) or more evolved (i.e., richer in heavier elements, thin or completely absent) may constrain formation (formed in situ or remnants of more massive bodies which have migrated to closer orbits) and evolution scenarios (e.g., hydrogen escaped, a secondary atmosphere which might hint at the interior composition).

Here we explore a different option for the Ariel MRS, with more emphasis on the interpretation of the nature of smaller planets, by specifically devoting the mission lifetime to studying this dichotomy of small worlds.

In the MRS studied in Section 3.2, ~ 110 planets with a radius less than 3.5 Earth radii were selected for study over

Table 4
Mission Time Required to Achieve Different Observation Goals

Number of Planets	Observation Requirement	Required Science Time (hr)
1000	Achieve Tier 1 resolutions	~10,600
400	Increase resolution from Tier 1 to Tier 2	~3100
500		~6000
600		~10,500
200	Achieve Tier 1 resolutions in the second method	~1400
300		~2500
400		~4200
50	Tier 3 (five repeated observations per planet)	~1700
…	Tier 4 (additional science time)	~2300

Note. The total science time over the 4 yr primary life is ~24,800 hr. Note that for some bright targets (e.g., HD 209458 b), Tier 2 or 3 resolutions would be reached in a single observation.

Table 5
Mission Time Required to Achieve Tier 1 Resolutions (at S/N > 7) for the 113 Small Planets in the Example MRS Assuming Different Mean Molecular Weights

Atmospheric Mean Molecular Weight	Number of Planets	Required Science Time (hr)
2.3	All	~1000 (t_0)
5	50	$t_0 + $~360
	All	$t_0 + $~3000
8	50	$t_0 + $~1100
	All	$t_0 + $~9200
10	50	$t_0 + $~1900
15	50	$t_0 + $~4400
18	25	$t_0 + $~1700
	50	$t_0 + $~6400
28	25	$t_0 + $~4300
	50	$t_0 + $~15,600

Note. The total science time over the 4 yr primary life is ~24,800 hr. t_0 is the time spent observing small planets in Tier 1 of the standard MRS.

around 600 observations (~2100 hr of science time) in all three tiers. These planets are located on both sides of the Fulton gap. A key goal of Tier 1 is to discover the fraction of small planets with hydrogen/helium envelopes. For this reason, the number of required observations to detect an atmosphere is estimated assuming a low mean molecular weight so that if a planetary atmosphere has a primordial composition, this atmosphere should be detected with high confidence. Additionally, the atmospheric trace gases should be accurately constrained if the planet is observed in Tier 2 or 3. If no detection is made, the planet either has (i) an atmosphere with a higher molecular weight, (ii) opaque clouds across all wavelengths, or (iii) no atmosphere at all.

In all likelihood, some fraction of these planets will have far heavier atmospheres (higher mean molecular weight) and thus will be harder to characterize, requiring more observations to obtain the observational requirements in each tier. In particular, additionally to the H/He atmospheric content, the fraction of H_2O present in an atmosphere is also very important to constrain formation/evolution scenarios and the delivery of volatiles to the inner part of the planetary system. Water worlds, i.e., planets with a significant amount of H_2O on their surface or in the subsurface (e.g., Léger et al. 2004), or magma ocean planets with a steam atmosphere (e.g., Hamano et al. 2015), are expected to have atmospheres with a large fraction of H_2O.

However, the characteristics of a planet's atmosphere (if present) cannot be known before observations are undertaken, unless these targets are observed previously with other facilities from space or the ground. To quantify the fraction of lifetime needed to characterize the atmospheric composition of small planets with an atmosphere heavier than H/He, we select the small planets ($R_p < 3.5 R_\oplus$) from the example MRS for further study. The science time required to achieve Tier 1 resolutions (with S/N > 7) for different atmospheric compositions is determined and compared to the Tier 1 time assumed in Section 3 (Table 5).

As expected, the required number of observations (and thus science time) rises with the increasing atmospheric weight.

While the atmospheres of smaller planets will be easily probed if H/He dominated, heavier atmospheres would require significant mission time to observe. Distinguishing between primary and secondary atmospheres should be possible for all small planets studied here within a reasonable science time. However, the assumed noise floor of 20 ppm limits the characterization at very high mean molecular weights where the signals become increasingly small. Smaller, cooler planets may also have a nitrogen-based atmosphere and we find that, for the Earth-sized planets below 500 K in this chosen sample, 25–130 transits would be required to achieve Tier 1 resolutions if the atmospheres had a molecular weight of 28. Figure 8 shows simulated data for one such planet, LHS 1140c (Ment et al. 2019), for various atmospheric weights. The dampening in the spectra due to a heavier atmosphere can clearly be seen. Generally, the best targets could be easily characterized regardless of their atmospheric composition, while for others achieving the required signal uncertainty will be difficult if the atmosphere is dense. We note that the impact of clouds is expected to be well captured in the simulations for higher mean molecular weight, where signals are up to 14 times smaller than the ones for atmospheres which are cloud-free and H/He-rich. Additional observations of the planet at different phases may provide further constraints on the cloud types and distribution (e.g., Charnay et al. 2015). Observations of smaller planets could be undertaken in a tiering system where the data is analyzed after several visits, with decisions made on continuing the observations based on the results seen. Science goals for such an observing strategy could include the determination of whether an atmosphere is primary, secondary, or not present.

From this preliminary study, we appreciate that providing significant time to observe smaller planets would be valuable for their more in-depth chemical/cloud characterization after an initial survey. Here we have presented a possible option including the in-depth analysis of ~110 small planets, but of course different combinations of strategies could and will be considered in this and future mission Phases to optimize the breadth and depth of the Ariel sample during its mission
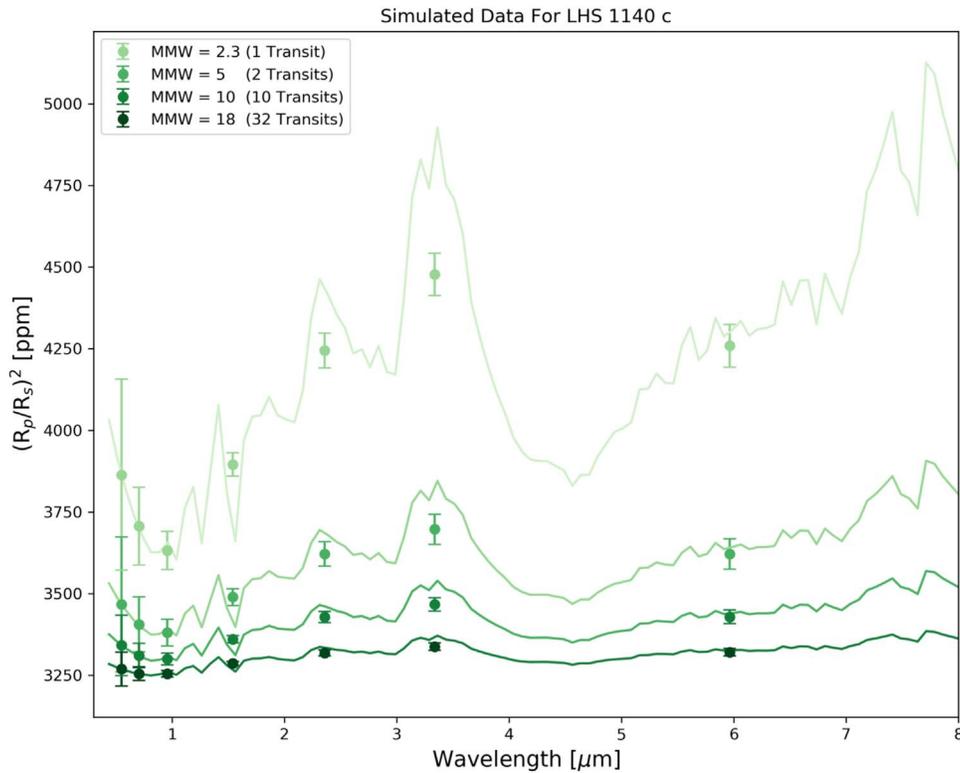
Figure 8. Simulated Tier 1 data of LHS 1140c for different atmospheric weights. The atmosphere is modeled with 10^{-5} of H_2O and CH_4 and the mean molecular weight is varied by modifying the nitrogen ratio. The number of transits quoted is the requirement for an S/N > 7 to be achieved on the atmosphere at Tier 1 resolutions.

lifetime and prioritise its science objectives. If much of the primary mission is dedicated to an in-depth survey of smaller planets, the total number of planets observed by Ariel would be reduced. Hence, some of the more speculative questions could be left for a potential extended mission. This study shows that Ariel has the potential to characterize the atmospheres of planets of all sizes. Data from such a multifarious population would be invaluable for our knowledge of planetary formation and evolution.

5. Discussion

5.1. Dependence of Predicted Yields on the Accuracy of Planetary Occurrence Statistics

Here, expected *TESS* detections have been used to estimate the number, and type, of exoplanets that could be potential targets for ARIEL. Predicted yields for future missions are, of course, speculative in nature and highly dependent on the assumptions of the study. In Barclay et al. (2018) the planetary occurrence statistics for AFGK stars were taken from Fressin et al. (2013) and from Dressing & Charbonneau (2013) for M dwarfs. More recent studies may suggest higher occurrence rates for some classes of small planets (e.g., Mulders 2018; Fulton & Petigura 2018) and the differences between these could affect the yield of *TESS*. The NASA Exoplanet catalog currently contains nine confirmed *TESS* planets and many more are yet to be added. Comparing these first detections to the expected yield does not result in any large discrepancies and all these current *TESS* planets are found to be excellent targets for study with Ariel (see Table 7). However, with only a handful of confirmed detections it is too early to speculate on the accuracy of the predicted yield. Further constraints on the occurrence of

planets on short periods is likely to be a key outcome of the *TESS* mission, particularly for M dwarfs. In any case, the primary mission of *TESS* is due to finish in 2020 and thus the yield from this mission will be known long before Ariel launches.

5.2. Scheduling of Observations

Here, the scheduling of observations has not been considered although studies in the Ariel consortium are being undertaken that will utilize the MRS (Garcia-Piquer et al. 2015; Morales et al. 2015). Such studies will provide a greater understanding of the impact of scheduling constraints (telescope house-keeping, slewing between targets, etc.) and a key issue may be observation overlaps (i.e., two planets transiting at the same time). Having additional, backup targets is likely to be useful for scheduling purposes and this study shows that there should be an oversaturation of suitable planets for characterization. The list of potential targets constructed here will be used as an input for such efforts.

5.3. Tiering System for Smaller Planets

The ambiguity in the atmospheric composition of smaller planets results causes complexities when planning via the originally proposed three tier observing structure. Additionally, the major constituents of an atmosphere could be recovered at resolutions below that of Tier 2. Therefore, a separate tiering system for smaller planets that is based around confirming the presence (or absence) of a clear atmosphere of a given mean molecular weight may be required. Once the catalog of potential planets is completely formed of known planets, additional considerations in the selection of smaller planets

Table 6
Currently Known Exoplanets Which Are Considered Here to Be Potential Targets for Ariel

Planet Name	Star Properties		Planet Properties		Maximum Tier	Preferred Method
	Eff. Temp (K)	K Magnitude	Radius ($R_\oplus$)	Equil. Temp (K)		
55Cnce	5196	4.01	1.87	1997	2	Transit
CoRoT-10b	5075	11.78	10.64	685	1	Transit
CoRoT-11b	6440	11.25	15.69	1771	2	Eclipse
CoRoT-19b	6090	11.84	14.16	1697	2	Eclipse
CoRoT-2b	5625	10.31	16.09	1582	3	Eclipse
CoRoT-23b	5900	12.36	11.52	1679	2	Eclipse
CoRoT-28b	5150	11.03	10.48	1395	1	Eclipse
CoRoT-3b	6740	11.62	11.08	1737	1	Eclipse
EPIC211945201b	6069	8.84	5.64	913	1	Transit
EPIC246851721b	6202	9.89	11.53	1434	2	Transit
GJ1132b	3270	8.32	1.16	636	2	Transit
GJ1214b	3026	8.78	2.79	627	3	Transit
GJ3470b	3600	7.99	4.48	698	2	Transit
GJ436b	3475	6.07	4.08	681	3	Transit
GJ9827b	4269	7.19	1.59	1198	1	Transit
GJ9827d	4269	7.19	2.03	695	1	Transit
HAT-P-1b	5980	8.86	14.47	1353	3	Eclipse
HAT-P-11b	4780	7.01	4.27	848	2	Transit
HAT-P-12b	4650	10.11	10.52	979	2	Transit
HAT-P-13b	5653	8.98	13.96	1685	2	Eclipse
HAT-P-14b	6600	8.85	15.58	1601	2	Eclipse
HAT-P-15b	5568	9.64	11.63	917	2	Eclipse
HAT-P-16b	6158	9.55	14.14	1664	3	Eclipse
HAT-P-17b	5246	8.54	11.52	793	2	Transit
HAT-P-18b	4803	10.23	10.92	867	2	Transit
HAT-P-19b	4990	10.55	12.42	1032	2	Transit
HAT-P-20b	4595	8.6	9.51	990	3	Transit
HAT-P-21b	5588	10.11	12.18	1303	2	Transit
HAT-P-22b	5302	7.84	12.62	1307	3	Eclipse
HAT-P-23b	5905	10.79	11.96	2094	2	Eclipse
HAT-P-24b	6373	10.54	14.27	1672	2	Eclipse
HAT-P-25b	5519	10.82	12.45	1209	2	Eclipse
HAT-P-26b	5079	9.58	6.91	1013	2	Transit
HAT-P-27b	5300	10.11	11.19	1236	2	Eclipse
HAT-P-28b	5680	11.1	13.3	1412	2	Eclipse
HAT-P-29b	6087	10.3	12.84	1285	2	Eclipse
HAT-P-3b	5185	9.45	10.31	1184	2	Eclipse
HAT-P-30b	6304	9.15	15.8	1675	3	Eclipse
HAT-P-31b	6065	10.08	11.96	1408	2	Transit
HAT-P-32b	6207	9.99	19.2	1823	3	Eclipse
HAT-P-33b	6446	10	20.3	1816	3	Eclipse
HAT-P-34b	6442	9.25	14.81	1333	2	Eclipse
HAT-P-36b	5560	10.6	12.62	1858	2	Eclipse
HAT-P-37b	5500	11.67	12.93	1306	2	Eclipse
HAT-P-38b	5330	10.5	9.05	1101	1	Transit
HAT-P-39b	6430	11.16	17.24	1789	2	Eclipse
HAT-P-4b	5860	9.77	13.98	1472	2	Eclipse
HAT-P-40b	6080	10.01	16.68	1805	2	Eclipse
HAT-P-41b	6390	9.73	22.5	1981	3	Eclipse
HAT-P-42b	5743	10.63	14.05	1460	2	Eclipse
HAT-P-43b	5645	11.76	14.06	1386	2	Eclipse
HAT-P-44b	5295	11.28	13.63	1130	2	Transit
HAT-P-45b	6330	10.2	15.65	1686	2	Eclipse
HAT-P-46b	6120	9.92	14.09	1488	2	Eclipse
HAT-P-49b	6820	9.35	17.45	2171	3	Eclipse
HAT-P-5b	5960	10.48	13.28	1569	2	Eclipse
HAT-P-50b	6280	10.5	14.13	1897	2	Eclipse
HAT-P-51b	5449	11.61	14.19	1216	2	Transit
HAT-P-52b	5131	11.62	11.07	1241	2	Eclipse
HAT-P-53b	5956	12.1	14.46	1818	2	Eclipse
HAT-P-54b	4390	10.33	10.36	839	2	Eclipse
HAT-P-55b	5808	11.63	12.97	1342	2	Eclipse

Table 6
(Continued)

Planet Name	Star Properties		Planet Properties		Maximum Tier	Preferred Method
	Eff. Temp (K)	K Magnitude	Radius ($R_\oplus$)	Equil. Temp (K)		
HAT-P-56b	6566	9.83	16.57	1880	2	Eclipse
HAT-P-57b	6330	9.43	19.09	1895	3	Eclipse
HAT-P-6b	6570	9.31	16.24	1706	3	Eclipse
HAT-P-65b	5835	11.53	20.74	1974	2	Eclipse
HAT-P-66b	6002	11.68	17.45	1944	2	Eclipse
HAT-P-67b	6406	8.9	22.88	1967	3	Transit
HAT-P-7b	6389	9.33	16.57	2272	3	Eclipse
HAT-P-8b	6200	8.95	15.36	1809	3	Eclipse
HAT-P-9b	6350	11.02	15.36	1565	2	Eclipse
HATS-1b	5870	10.58	14.29	1399	2	Eclipse
HATS-10b	5880	11.51	10.63	1435	1	Eclipse
HATS-11b	6563	12.24	17.66	1783	2	Eclipse
HATS-12b	6357	11.39	7.59	1614	1	Transit
HATS-13b	5523	11.98	13.3	1276	2	Eclipse
HATS-17b	5846	10.7	8.53	832	1	Transit
HATS-2b	5227	11.39	12.82	1614	2	Eclipse
HATS-22b	4803	10.94	10.46	877	2	Transit
HATS-24b	6346	11.38	16.32	2121	2	Eclipse
HATS-25b	5715	11.42	13.83	1307	2	Eclipse
HATS-26b	6071	11.44	19.2	1964	2	Eclipse
HATS-27b	6438	11.55	16.46	1693	2	Eclipse
HATS-29b	5670	10.88	13.73	1236	2	Eclipse
HATS-3b	6351	10.69	15.15	1682	2	Eclipse
HATS-30b	5943	10.79	12.89	1446	2	Eclipse
HATS-31b	6050	11.57	18	1867	2	Eclipse
HATS-33b	5659	10.29	13.5	1460	2	Eclipse
HATS-35b	6300	11.12	16.06	2076	2	Eclipse
HATS-39b	6572	11.52	17.23	1683	2	Eclipse
HATS-4b	5403	11.61	11.19	1350	2	Eclipse
HATS-40b	6460	12.15	17.34	2142	2	Eclipse
HATS-41b	6424	11.5	14.59	1716	1	Eclipse
HATS-43b	5099	11.56	12.95	1017	2	Transit
HATS-45b	6450	12.14	14.11	1551	1	Eclipse
HATS-46b	5495	11.96	9.91	1078	2	Transit
HATS-5b	5304	10.7	10.01	1047	2	Transit
HATS-51b	5758	10.87	15.47	1581	2	Eclipse
HATS-52b	6010	12.11	15.17	1922	2	Eclipse
HATS-6b	3724	11.22	10.95	729	2	Transit
HATS-60b	5688	10.99	12.65	1561	2	Eclipse
HATS-61b	5542	11.48	13.11	1252	1	Eclipse
HATS-64b	6554	11.7	18.42	1833	2	Eclipse
HATS-65b	6277	11.1	16.47	1670	2	Eclipse
HATS-67b	6594	12.33	18.49	2240	2	Eclipse
HATS-68b	6147	10.95	13.52	1781	2	Eclipse
HATS-7b	4985	10.98	6.18	1104	1	Transit
HATS-9b	5599	11.48	13.56	1953	2	Eclipse
HD106315c	6277	7.85	4.22	898	2	Transit
HD149026b	6179	6.82	8.12	1715	2	Eclipse
HD17156b	6040	6.76	12.07	904	2	Transit
HD189733b	5052	5.54	12.4	1230	3	Transit
HD209458b	6091	6.31	15.25	1487	3	Transit
HD219134b	4699	3.26	1.57	1040	2	Transit
HD3167b	5528	7.07	1.67	1861	1	Transit
HD3167c	5528	7.07	2.8	630	2	Transit
HD80606b	5561	7.32	11.74	432	2	Transit
HD89345b	5576	7.72	7.24	1114	2	Transit
HD97658b	5175	5.73	2.3	756	2	Transit
HIP41378e	6199	7.72	5.4	530	2	Transit
HIP41378f	6199	7.72	9.99	392	2	Transit
K2-100b	6168	9.18	3.51	1954	1	Transit
K2-107b	6061	11.21	15.65	1845	2	Eclipse
K2-113b	5660	11.95	11.88	1227	1	Transit

11

Table 6
(Continued)

Planet Name	Star Properties		Planet Properties		Maximum Tier	Preferred Method
	Eff. Temp (K)	K Magnitude	Radius ($R_\oplus$)	Equil. Temp (K)		
K2-115b	5657	11.72	11.81	692	1	Transit
K2-121b	4551	10.62	7.34	807	2	Transit
K2-129b	3459	8.85	1.02	457	1	Transit
K2-132b	4840	9.54	14.27	1578	1	Eclipse
K2-136 c	4499	8.37	2.85	558	1	Transit
K2-139b	5370	9.66	8.92	624	2	Transit
K2-140b	5705	11	11.99	1068	2	Transit
K2-141 c	4599	8.4	6.85	715	3	Transit
K2-155 c	4258	9.5	2.55	544	1	Transit
K2-18b	3457	8.9	2.33	307	1	Transit
K2-19b	5430	11.16	7.58	901	1	Transit
K2-198b	5262	9.23	4.03	698	1	Transit
K2-199 c	4648	9.62	2.72	731	1	Transit
K2-232b	6154	8.43	10.97	1015	2	Transit
K2-233d	4950	8.38	2.59	572	1	Transit
K2-237b	6257	10.22	18.11	1952	3	Eclipse
K2-238b	5630	12.03	14.27	1649	2	Eclipse
K2-24b	5625	9.18	5.29	767	1	Transit
K2-24 c	5625	9.18	7.34	645	2	Transit
K2-25b	3180	10.44	3.36	521	2	Transit
K2-260b	6367	11.09	17.03	2001	2	Eclipse
K2-261b	5537	8.89	9.33	1089	2	Transit
K2-266b	4285	8.9	3.23	1545	2	Transit
K2-266d	4285	8.9	2.86	584	1	Transit
K2-280b	5742	10.76	7.51	830	1	Transit
K2-287b	5695	9.19	9.29	836	2	Transit
K2-289b	5529	10.64	8.91	841	1	Transit
K2-29b	5358	10.06	13.06	1193	2	Eclipse
K2-3b	3896	8.56	2.13	552	1	Transit
K2-30b	5425	11.09	11.4	1114	2	Eclipse
K2-31b	5280	8.87	11.63	1547	3	Eclipse
K2-32b	5275	9.82	5.03	840	2	Transit
K2-33b	3540	10.03	4.94	801	1	Transit
K2-34b	6071	10.19	13.66	1740	2	Eclipse
K2-52b	7147	11.85	17.62	2242	2	Eclipse
K2-55b	4456	10.47	3.74	933	1	Transit
K2-99b	6217	9.72	11.48	1244	1	Transit
KELT-1b	6518	9.44	12.18	2482	3	Eclipse
KELT-10b	5948	9.34	15.35	1408	3	Eclipse
KELT-11b	5375	6.12	14.81	1741	3	Transit
KELT-12b	6279	9.36	19.53	1840	3	Eclipse
KELT-14b	5720	9.42	19.13	2005	3	Eclipse
KELT-15b	6003	9.85	19.09	1676	3	Eclipse
KELT-16b	6236	10.64	15.53	2509	3	Eclipse
KELT-18b	6670	9.21	17.23	2132	3	Eclipse
KELT-2Ab	6327	7.35	14.81	1799	3	Eclipse
KELT-3b	6304	8.66	17.12	1859	3	Eclipse
KELT-4Ab	6206	8.69	18.64	1863	3	Eclipse
KELT-6b	6102	9.08	14.27	1343	2	Eclipse
KELT-7b	6768	7.54	17.56	2088	3	Eclipse
KELT-8b	5754	9.18	17.78	1714	3	Eclipse
KOI-12b	6820	10.23	16.9	1101	2	Eclipse
KOI-94d	6182	10.93	11.03	915	1	Transit
KPS-1b	5165	10.93	11.3	1482	2	Eclipse
Kepler-12b	5947	12.07	19.25	1512	2	Transit
Kepler-138b	3841	9.51	0.52	490	1	Transit
Kepler-138d	3841	9.51	1.19	374	1	Transit
Kepler-1514b	6251	10.69	11.58	417	1	Transit
Kepler-16b	4450	9	8.27	234	2	Transit
Kepler-18d	5345	11.76	6.84	811	1	Transit
Kepler-396 c	5384	10.28	5.19	505	1	Transit
Kepler-422b	5972	12.04	12.62	1150	1	Transit

Table 6
(Continued)

Planet Name	Star Properties		Planet Properties		Maximum Tier	Preferred Method
	Eff. Temp (K)	K Magnitude	Radius ($R_{\oplus}$)	Equil. Temp (K)		
Kepler-444b	5046	6.7	0.4	1052	1	Transit
Kepler-444 c	5046	6.7	0.48	973	2	Transit
Kepler-444d	5046	6.7	0.52	878	1	Transit
Kepler-444e	5046	6.7	0.54	815	1	Transit
Kepler-447b	5493	10.81	18.11	1001	2	Eclipse
Kepler-5b	6297	11.77	15.65	1847	2	Eclipse
Kepler-6b	5647	11.63	14.31	1537	2	Eclipse
Kepler-7b	5933	11.54	17.8	1643	2	Eclipse
Kepler-76b	6409	12.09	14.92	2178	2	Eclipse
Kepler-854b	6179	12.05	16.37	1854	2	Eclipse
Kepler-91b	4550	10.14	15	2089	1	Eclipse
LHS1140b	3216	8.82	1.69	253	1	Transit
LHS1140c	3216	8.82	1.25	473	2	Transit
NGTS-2b	6478	9.8	17.5	1659	2	Eclipse
PH2b	5629	11.12	9.91	325	1	Transit
Qatar-1b	5013	10.41	12.54	1447	2	Eclipse
Qatar-2b	4645	10.62	13.76	1380	3	Eclipse
Qatar-3b	6007	11.22	12.03	1716	1	Eclipse
Qatar-4b	5215	11.52	12.45	1416	2	Eclipse
Qatar-5b	5747	10.96	12.15	1450	2	Eclipse
TRAPPIST-1b	2559	10.3	1.06	442	2	Transit
TRAPPIST-1 c	2559	10.3	1.03	377	2	Transit
TRAPPIST-1d	2559	10.3	0.76	318	2	Transit
TRAPPIST-1e	2559	10.3	0.9	277	2	Transit
TRAPPIST-1f	2559	10.3	1.02	242	2	Transit
TRAPPIST-1g	2559	10.3	1.11	219	2	Transit
TRAPPIST-1h	2559	10.3	0.74	191	2	Transit
TrES-1b	5230	9.82	12.4	1167	2	Eclipse
TrES-2b	5850	9.85	14.92	1533	2	Eclipse
TrES-3b	5650	10.61	14.66	1680	3	Eclipse
TrES-4b	6200	10.33	17.67	1821	2	Eclipse
TrES-5b	5171	11.59	13.1	1517	2	Eclipse
WASP-1b	6304	10.28	16.27	1910	2	Eclipse
WASP-10b	4675	9.98	11.85	993	3	Transit
WASP-100b	6900	9.67	14.59	2245	3	Eclipse
WASP-101b	6380	9.07	15.69	1588	3	Eclipse
WASP-103b	6110	10.77	16.77	2565	3	Eclipse
WASP-104b	5475	9.88	12.48	1547	3	Eclipse
WASP-106b	6055	10.16	11.19	1176	2	Eclipse
WASP-107b	4430	8.64	10.31	754	3	Transit
WASP-11b	4800	9.42	12.18	971	2	Eclipse
WASP-113b	5890	10.31	15.46	1519	2	Eclipse
WASP-114b	5940	13.17	14.69	2074	2	Eclipse
WASP-117b	6040	8.78	11.63	1045	2	Transit
WASP-118b	6410	9.79	15.8	1765	2	Eclipse
WASP-119b	5650	10.54	15.36	1602	2	Eclipse
WASP-12b	6300	10.19	19.97	2638	3	Eclipse
WASP-120b	6450	9.88	16.16	1918	2	Eclipse
WASP-121b	6459	9.37	20.47	2413	3	Eclipse
WASP-123b	5740	10.71	14.46	1550	3	Eclipse
WASP-124b	6050	11.31	13.61	1420	2	Eclipse
WASP-126b	5800	9.6	10.53	1520	2	Eclipse
WASP-127b	5620	8.64	15.03	1431	3	Transit
WASP-129b	5900	10.41	10.21	1101	2	Eclipse
WASP-13b	5950	9.12	13.39	1588	3	Transit
WASP-130b	5625	9.46	9.77	854	1	Eclipse
WASP-131b	6030	8.57	13.39	1491	2	Transit
WASP-132b	4775	9.67	9.55	781	2	Transit
WASP-133b	5700	11.18	13.28	1815	2	Eclipse
WASP-135b	5675	11.04	14.27	1757	2	Eclipse
WASP-136b	6260	8.8	15.14	1786	3	Eclipse
WASP-138b	6272	10.49	11.96	1622	2	Eclipse

Table 6
(Continued)

Planet Name	Star Properties		Planet Properties		Maximum Tier	Preferred Method
	Eff. Temp (K)	K Magnitude	Radius ($R_\oplus$)	Equil. Temp (K)		
WASP-139b	5310	10.47	8.78	938	2	Transit
WASP-14b	6475	8.62	15.14	1903	3	Eclipse
WASP-140b	5260	9.16	15.8	1346	3	Eclipse
WASP-141b	5900	11.19	13.28	1573	2	Eclipse
WASP-142b	6010	11.44	16.79	2035	2	Eclipse
WASP-144b	5200	10.9	9.33	1298	1	Eclipse
WASP-145Ab	4900	9.19	9.88	1233	2	Eclipse
WASP-147b	5702	10.86	12.24	1435	2	Transit
WASP-15b	6300	9.69	15.47	1691	2	Eclipse
WASP-151b	5871	11.19	12.4	1318	2	Transit
WASP-153b	5914	11.05	17.01	1748	2	Eclipse
WASP-156b	4910	9.34	5.6	992	1	Transit
WASP-157b	5772	10.76	10.95	1336	2	Transit
WASP-158b	6350	10.88	11.74	1623	2	Eclipse
WASP-159b	6120	11.02	15.14	1889	2	Eclipse
WASP-16b	5700	9.59	13.39	1334	2	Eclipse
WASP-160Bb	5298	11.06	11.96	1145	2	Transit
WASP-162b	5300	10.47	10.97	933	2	Transit
WASP-164b	5806	10.96	12.38	1643	2	Eclipse
WASP-165b	5599	11.02	13.83	1662	2	Eclipse
WASP-167b	7000	9.76	17.34	2416	3	Eclipse
WASP-168b	6000	10.44	16.46	1374	2	Transit
WASP-17b	6550	10.22	20.52	1583	2	Eclipse
WASP-172b	6900	10.13	17.23	1784	2	Eclipse
WASP-173Ab	5800	10	13.17	1916	3	Eclipse
WASP-174b	6400	10.58	14.27	1528	2	Eclipse
WASP-18b	6431	8.13	13.17	2466	3	Transit
WASP-19b	5568	10.48	15.27	2161	3	Eclipse
WASP-2b	5200	9.63	11.75	1326	2	Eclipse
WASP-20b	5940	9.39	16.04	1410	3	Transit
WASP-21b	5800	9.98	11.74	1366	2	Eclipse
WASP-22b	6000	10.32	13.5	1452	2	Eclipse
WASP-23b	5150	10.45	10.56	1158	2	Eclipse
WASP-24b	6075	10.15	15.14	1810	2	Eclipse
WASP-25b	5750	10.17	11.74	1246	2	Eclipse
WASP-26b	6034	9.69	13.28	1718	2	Eclipse
WASP-28b	6150	10.73	13.31	1499	2	Eclipse
WASP-29b	4800	8.78	8.45	996	2	Transit
WASP-3b	6140	9.36	15.58	1717	3	Eclipse
WASP-31b	6302	10.65	17	1610	2	Eclipse
WASP-32b	6140	10.16	10.53	1596	2	Eclipse
WASP-34b	5700	8.79	10.97	1185	2	Eclipse
WASP-35b	5990	9.52	14.27	1483	3	Eclipse
WASP-36b	5959	11.29	14.56	1778	2	Eclipse
WASP-37b	5800	11.09	12.73	1353	2	Eclipse
WASP-38b	6180	8	13.5	1285	3	Transit
WASP-39b	5400	10.2	13.94	1146	2	Transit
WASP-4b	5500	10.75	14.59	1708	3	Eclipse
WASP-41b	5545	9.68	12.07	1271	2	Eclipse
WASP-42b	5315	10.03	12.31	1044	2	Eclipse
WASP-43b	4400	9.27	10.21	1409	3	Eclipse
WASP-44b	5410	11.34	12.51	1381	2	Eclipse
WASP-45b	5140	10.29	12.51	1224	2	Eclipse
WASP-46b	5600	11.4	12.88	1676	2	Eclipse
WASP-47b	5552	10.19	12.37	1291	2	Eclipse
WASP-48b	5920	10.37	16.46	2078	2	Eclipse
WASP-49b	5600	9.75	12.18	1401	2	Eclipse
WASP-5b	5700	10.6	11.93	1745	2	Eclipse
WASP-50b	5400	9.97	13.39	1422	2	Eclipse
WASP-52b	5000	10.09	13.94	1330	3	Eclipse
WASP-53b	4953	10.39	11.79	1079	2	Eclipse
WASP-54b	6100	9.04	17.34	1822	3	Eclipse

Table 6
(Continued)

Planet Name	Star Properties		Planet Properties		Maximum Tier	Preferred Method
	Eff. Temp (K)	K Magnitude	Radius ($R_\oplus$)	Equil. Temp (K)		
WASP-55b	5900	10.4	14.59	1296	2	Eclipse
WASP-56b	5600	10.53	10.31	1230	2	Eclipse
WASP-57b	5600	11.24	11.52	1371	2	Eclipse
WASP-58b	5800	10.28	15.69	1306	2	Eclipse
WASP-6b	5450	10.32	11.3	1210	2	Eclipse
WASP-60b	5900	10.58	9.66	1343	1	Eclipse
WASP-61b	6250	11.01	15.47	1583	2	Eclipse
WASP-62b	6230	8.94	14.48	1459	3	Eclipse
WASP-63b	5550	9.39	15.47	1565	2	Eclipse
WASP-64b	5400	10.96	13.95	1685	2	Eclipse
WASP-65b	5600	10.35	12.2	1518	2	Eclipse
WASP-66b	6600	10.45	15.36	1841	2	Eclipse
WASP-67b	5200	10.13	12.62	1049	2	Eclipse
WASP-68b	5910	8.95	14.48	1516	2	Eclipse
WASP-69b	4700	7.46	12.18	982	3	Transit
WASP-7b	6400	8.4	14.59	1518	3	Eclipse
WASP-70Ab	5763	9.58	12.77	1424	2	Eclipse
WASP-71b	6050	9.32	12.95	2111	2	Eclipse
WASP-72b	6250	9.62	14.16	2104	2	Eclipse
WASP-73b	6030	9.03	15.58	1820	2	Eclipse
WASP-74b	5990	8.22	14.92	1959	3	Eclipse
WASP-75b	6100	10.06	13.94	1743	2	Eclipse
WASP-76b	6250	8.24	20.08	2232	3	Transit
WASP-77Ab	5365	8.4	15.14	1667	3	Eclipse
WASP-78b	6100	11.01	21.18	2345	3	Eclipse
WASP-79b	6600	9.06	18.33	1798	3	Eclipse
WASP-8b	5600	8.09	12.4	948	3	Transit
WASP-80b	4143	8.35	10.96	845	2	Eclipse
WASP-81b	5870	10.89	15.68	1656	2	Eclipse
WASP-82b	6480	8.76	17.78	2225	3	Eclipse
WASP-83b	5510	10.39	11.41	1146	2	Transit
WASP-84b	5314	8.86	10.34	817	2	Eclipse
WASP-85Ab	6112	8.73	13.61	1487	3	Eclipse
WASP-88b	6430	10.32	16.02	1802	2	Eclipse
WASP-89b	5130	11	11.41	1149	2	Transit
WASP-90b	6430	10.25	17.89	1881	2	Eclipse
WASP-92b	6280	11.52	16.03	1921	2	Eclipse
WASP-93b	6700	9.94	17.52	1986	3	Eclipse
WASP-94Ab	6170	8.87	17.34	1536	3	Eclipse
WASP-95b	5830	8.56	13.5	1649	3	Eclipse
WASP-96b	5540	10.91	13.17	1314	2	Eclipse
WASP-97b	5640	9.03	12.51	1576	3	Eclipse
WASP-98b	5473	11.28	12.55	1197	2	Eclipse
WASP-99b	6150	8.09	11.19	1501	2	Transit
Wolf503b	4716	7.62	1.99	808	1	Transit
XO-1b	5750	9.53	12.51	1229	2	Eclipse
XO-2Nb	5762	9.31	10.9	1474	2	Eclipse
XO-3b	6429	8.79	15.47	2091	3	Eclipse
XO-4b	6397	9.41	13.72	1666	2	Eclipse
XO-5b	5430	10.34	12.51	1254	2	Eclipse
XO-6b	6720	9.25	22.71	1983	3	Eclipse

Note. This list will continue to evolve as surveys discover more planets.

such as photoevaporation and isolation flux (e.g., Owen & Wu 2017; Swain et al. 2018) will need to be taken into account to ensure a diverse population of planets are studied.

5.4. Next Steps and Final Selection of the MRS

The MRS presented here is merely one example of a population of planets that Ariel could observe. The selection of the final list of targets will require far more discussion and input from scientists from across the exoplanet community, particularly as the predicted planets from this list are replaced with actual detections. In the coming years, observations with current ground- and space-based facilities (e.g., Very Large Telescope, *Hubble Space Telescope*, *Spitzer*) and future observatories (e.g., European Extremely Large Telescope,

Table 7
Planets in the NASA Exoplanet Archive That Have Been Detected by *TESS*, All of Which Are Found to Be Suitable for Study with Ariel

Planet Name	Star Properties		Planet Properties		Maximum Tier	Preferred Method
	Eff. Temp (K)	*K* Magnitude	Radius ($R_\oplus$)	Equil. Temp (K)		
GJ 143 b	4975	5.375	6.05	508	3	Transit
HD 1397 b	5521	5.988	11.26	1258	2	Eclipse
HD 202772 A b	6272	7.149	16.95	2181	3	Eclipse
HD 219666 b	5527	8.158	4.61	1101	2	Transit
HD 23472 b	4900	7.207	4.39	633	2	Transit
HD 23472c	4900	7.207	4.27	533	2	Transit
LHS 3844 b	3036	9.145	1.27	827	2	Transit
TOI 172 b	5645	9.722	10.59	1229	2	Transit
pi Men c	6037	4.241	2.00	1193	2	Transit

Brandl et al. 2018; *James Webb Space Telescope*, Greene et al. 2016; Twinkle, Edwards et al. 2018) will further characterize the atmospheres of the known exoplanet population. These studies will increase our knowledge of these distant worlds and may begin to highlight trends in atmospheric chemistry. Such insights will inevitably be used to optimize the Ariel MRS, maximizing the synergies between different facilities, and to this end a website has been created to host the list of potentially observable planets.[5] This open access site will contain all available data sets on these planets, highlighting planetary systems for which further characterization would be beneficial (e.g., refinement of ephemerides or stellar parameters) and providing the chance for the entire community to contribute to the Ariel target selection. Therefore, Ariel will embrace the exoplanet community by offering open involvement in the observation planning process as well as providing regular timely public releases of high-quality data products at various processing levels throughout the mission. Additionally, targets within the list are being used as the basis for simulated data in several data challenges organized to engage the exoplanet community in Ariel.[6] These efforts, particularly the continuous dialog with the wider community, will ensure that the Ariel observation strategy facilitates the maximum possible science yield for the entire exoplanet field.

6. Conclusions

An updated analysis of the currently known planets and predicted *TESS* discoveries, as well as Ariel predicted performances, supports and improves the conclusions of the previous MRS study from Phase A: Ariel will be capable of characterizing 1000 exoplanet atmospheres during the primary mission life. The total number of potential planets to choose this MRS from is found to be over 2000, meaning that there is a surplus of targets. Within this list of planets there is a large range of planetary and stellar parameters, ensuring that the MRS is diverse, a key requirement for meeting Ariel's mission objectives. The example MRS selected here allows for 1000 planets to be studied, with high-quality spectroscopic data being obtained for 600 of these during the 4 yr primary mission life. The selection also reserves mission time for other observation strategies (Tier 4). These could include phase curves, non-transiting planets, or targets of interest that are not captured by the current tier system.

Additionally we have explored the mission capability to perform an in-depth analysis of small planets' atmospheres, which are expected to be more diverse compared to the gaseous ones. Given the increased observational difficulty to probe atmospheres heavier than H/He, significant mission time may have to be allocated to this task. Trade-offs between studying more planets, observing fewer targets but in greater detail, and/or choosing interesting planets that require more observational time, will form a key part in the selection of the final MRS. Generating an optimal catalog of potential candidates is key in these efforts and this list of targets will be constantly updated with new planet discoveries.

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[5] https://arielmission.space/target-list/
[6] https://ariel-datachallenge.azurewebsites.net

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