Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL)

Assessment Phase Payload Study

The parameter space of planetary systems explored by ARIEL

ARIEL-INAF-SCI-TN-0002

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1. Scope of the document

The goal of this technical note is to show that it is possible to optimize the parameter space covered by the ARIEL targets. In particular we will present a possible selection of the Tier 1 survey sample, that maximizes the coverage of the physical parameters of the systems.
This work is based on simulations produced to generate the Mission Reference Sample by Zingales.

1. Introduction

ARIEL will observe the atmospheres of a plethora of planetary systems discovered by ground based facilities (e.g., HARPS, HAT, WASP/SuperWASP, ELODIE, MEarth, TRAPPIST, CARMENES etc.) and by space-borne satellites (e.g., Kepler/K2, PLATO, TESS, GAIA). The planetary yields foreseen from these facilities include several tens of thousands objects, with a significant fraction of them accessible to ARIEL. A fundamental characteristic of the ARIEL mission is the diversity of systems that will be studied, ranging from Earths to Jupiter-like planets and hosted by stars from early M to G and F stars (see ARIEL proposal).
In this technical note we want to show how the ARIEL mission allows us to optimize the scientific outcome. In particular, we will explore how we can select the target sample maximizing the variety of the physical properties and configurations of planetary systems. Among all the possible choices, we will show one specific selection that maximizes the coverage of the parameters space explored with the Tier 1.
This work builds up on the simulations made by T. Zingales (ARIEL-TN-0001-UCL) of planets accessible to ARIEL. We will limit our analysis to those systems accessible with a budget of up to six visits for each planet (either transit or occultation).

2. Method

Among all the possible choices of the star-planet system parameters, we chose four physical quantities that define a 4D space on which to distribute the ARIEL targets. The quantities are: stellar effective temperature (T_{eff}), metallicity ([Fe/H]), planetary radius (R_{pl}) and planetary theoretical equilibrium temperature (T_{pl}). We adopt three bins for T_{eff} , [Fe/H] and R_{pl}, while for the T_{pl} we use five bins, as detailed in Table 1. The three T_{eff} bins correspond approximately to the ranges of spectral types M-Late / K stars, Early K-G stars and F-G stars, respectively, as indicated by the labels in the following plots. Analogously, we separated the sample in low metallicity, solar metallicity and high metallicity, according individual [Fe/H] values. The R_{pl} binning roughly identifies Earths and Super-Earths, Neptunes and Jupiters, respectively. Finally, the five bins of T_{pl} separate the systems in cold, temperate, warm, hot and very hot planets. The binning into 3 intervals of $T_{eff,}$ [Fe/H] and R_{pl} is a reasonable trade-off between a detailed representation of the sample and a simple visualization of the richness and diversity of the physical configurations of the sample. This binning offers a tool to control and display the variety and the statistics of the ARIEL sample.
Individual metallicity values are not available for the simulated targets so our approach was to simulate values of [Fe/H] starting from the values observed in the solar neighbourhood and reported by Casagrande et al. (2011, A&A, 530A, 138C). From this work we inferred that the metallicities of stars in the solar neighbourhood are consistent with a normal distribution with mean -0.1 and standard deviation sd=0.2. Using such model distribution we simulated the values of [Fe/H] for the ARIEL targets simulated by T. Zingales.

The 4D space of T_{eff} , metallicity ([Fe/H]), planetary radius (R_{pl}) and planetary theoretical equilibrium temperature (T_{pl}) is composed by a total of 3x3x3x5=135 cells. We decide that 10 systems are sufficient to reliably determine the properties of the atmospheres of planets in each cell.

3. Results

The starting sample is constituted by the simulations of planetary systems in various configurations (see Zingales et al., ARIEL-TN-0001-UCLTN) based on the throughput of the instrument and a model of planet distribution in the solar neighbourhood as derived from Kepler results (Fressin et al. 2013, ApJ, 766, 81). Our "population", contains the 9545 systems of Zingales et al. observable with up to 6 visits, including 211 known exoplanets. From these 9545 systems it is possible to select the targets suitable for the ARIEL Tier 1 sample.

The first example of target selection for Tier 1 is reported by Zingales et al. who selected about 1002 "easy" planets drawn from the initial population plus a handful of very few small planets (Earths/Super Earths) "manually" added to diversify the parameter space. Here "easy" identifies planets with favourable signal to noise and thus easy to observe with 1 or 2 visits. This sample maximizes the number of observed planets, which results thus in 1002 targets, requiring altogether 1538 satellite visits. These 1002 planets are distributed in the 4D space as shown in Fig. 1.

We will make use of several figures as Fig. 1 so a detailed description is in order here. The 3x3 panel grid distributes the sample along the 3 spectral types and the metallicity ranges reported in Table 1. The headings of the panels indicate the spectral type and metallicity. Top row refers to M-Late K host stars, central row to early K-G host stars, while bottom row refers to F-G host stars. Left column refers to low [Fe/H] stars, central column to solar [Fe/H] systems, and right column indicates high [Fe/H] stars.

Each panel is a matrix with planetary radii along x-axis and (calculated) equilibrium temperatures along y-axis, as specified in Table 1 and discussed above. The numbers in each box identify the numbers of systems with the corresponding R_{pl}, T_{pl}, Sp. Type, and [Fe/H] values, with the colour scale indicating more populated cells (darker orange/brown). Gray cells without any number indicate no objects falling in those cells.

As a general comment, we notice that some cells, as those corresponding to planets with very high temperatures orbiting around low mass M stars, are empty because these systems are not physically plausible or, for other configurations, impossible to observe with a maximum of six visits. The 1002 "easy" systems in Fig. 1 tend to populate the cells corresponding to F-G-early and K stars orbited by Neptunes/Jupiters size planets (with a number of planets per cell N>20), as these systems are the easiest to be observed with high signal to noise and, on average, with one or two visits. At the same time, planets around M or late K stars are much less represented in this distribution, especially planets of size of Earths/Super Earths and Neptunes. One may wonder if these were not present in the original "population" and thus impossible to be observed with a number of visits less than six. The distribution of the population in the 4D space is shown in Fig. 2. Here, we can see that actually there are systems composed by M or late K stars orbited by Earths/Super Earth or Neptunes observable with less than 6 visits. The choice of the 1002 "easy" planets has maximized the number of observed planets, oversampling some parts of the parameter space at the cost of significantly reducing the time spent to observe systems with different properties.

Table 1: Bins of T_{eff}, [Fe/H], R_{pl}, T_{pl} defining the 4D parameter space

Stellar temp. T_{eff} Labels	3000 K< T_{eff} < 4100 K M-Late K	4100 K < T_{eff}< 5800 K Early K-G	T_{eff} > 5800 K F-G
Metallicity [Fe/H] Labels	[Fe/H] < -0.15 Low [Fe/H]	-0.15 < [Fe/H} < 0.15 Solar	[Fe/H] > 0.15 High [Fe/H]
Planet Radius R_{pl} Labels	R_{pl} < 3 R_{earth} Earths/ Super Earths	3 R_{earth} < R_{pl} < 8 R_{earth} Neptunes	R_{pl} > 8 R_{earth} Jupiters
Planet Temp T_{pl}	Five contiguous bins: [250, 500, 800, 1200, 1600, 2600] K		

We will show that it is possible to make an alternative choice of the targets in order to explore a larger physical parameters space. Assuming a total number of visits as in the "easy" configuration (approximately 1500 visits), we fixed the maximum number of systems (10 planets in our choice) in each 4D space cell. This choice implies that any additional targets falling in an "already full" cell will be discarded. In this way we can include planets falling in the empty or poorly populated parts of the parameter space. The goal is to verify that we can cover with enough statistics most of the 4D parameter space. The distribution of systems selected with such criteria is shown in Fig. 3. Compared to Fig. 1, we see that we have efficiently covered most of the 4D space in planetary sizes, planetary temperatures, host temperatures and metallicities, apart from those combination of parameters corresponding to unphysical or rare systems (e.g., very hot planets around very cool stars). Our selection is composed by 908 unique planets requiring a total of 1504 visits. Among already known systems, 92 of the initial 211 systems are in this new list. This selection is not unique, and depends on our choices, but our exercise shows that we have great freedom on the final choice on how to spend ARIEL observing time, as it can be easily tuned on specific needs.

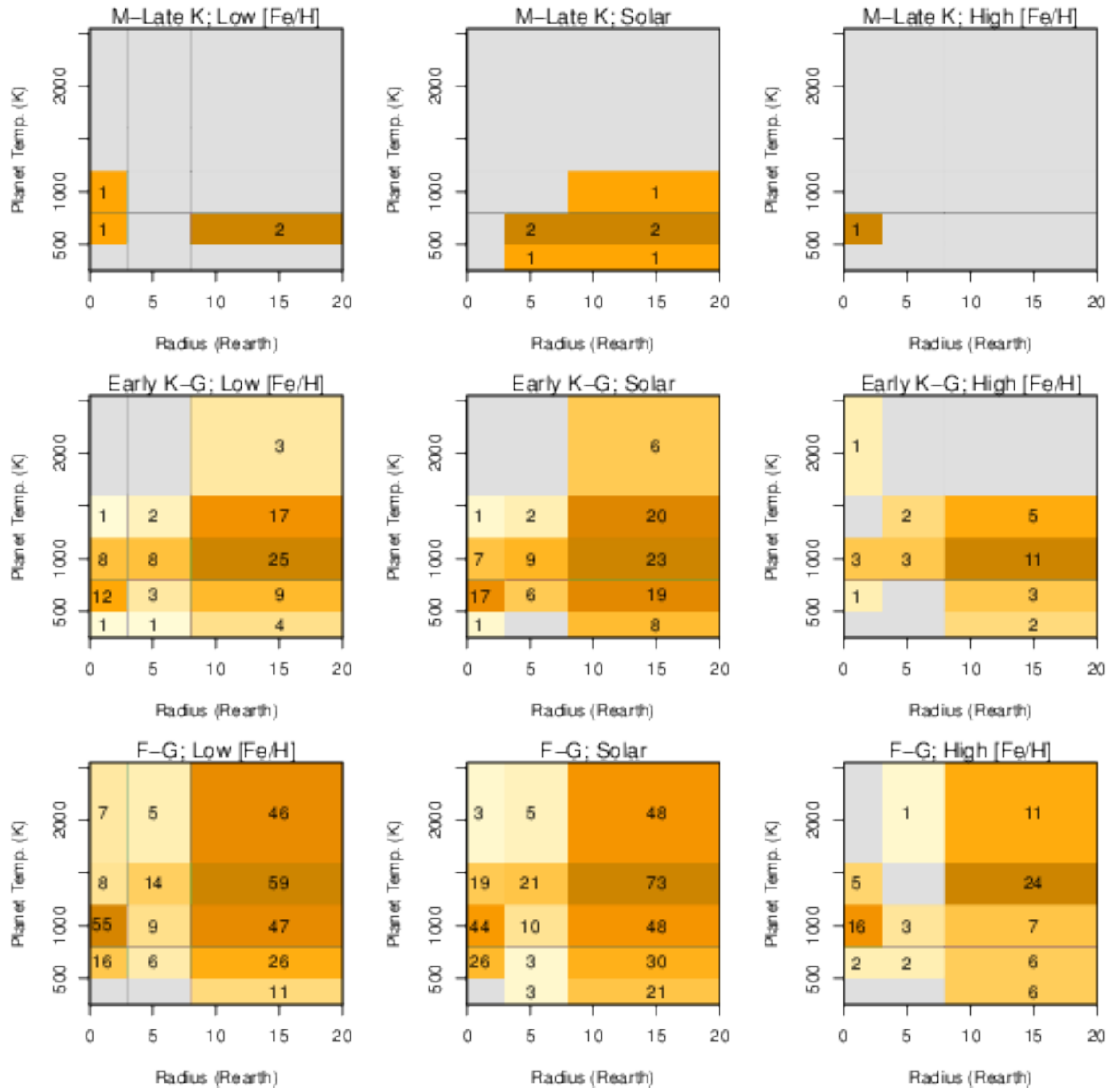

Figure 1: Distribution of the planets of the "easy" sample of Zingales et al. in the 4D space of T_{eff}, [Fe/H], R_{pl}, T_{pl}. Above each panels we indicate the spectral type and metallicity. The numbers in each cell are the numbers of planets with the corresponding properties.

Fig. 4 shows the average number of visits required to cover each cell of the 4D space. The number of visits needed for Jupiters and Neptunes is, typically, one or two, while Earths/Super Earths require from 3 to 5 visits each. Planets around M stars require on average more visits than the analogues around early K, G, and F stars. Summarizing, out of the 908 planets of our selection there are 594 planets requiring only 1 visit (65.4%), 151 planets requiring 2 visits (16.6%), 83 planets requiring 3 visits (9.1%), 41 planets requiring 4 visits (4.5%), and 39 planets requiring 5 visits (4.4%).

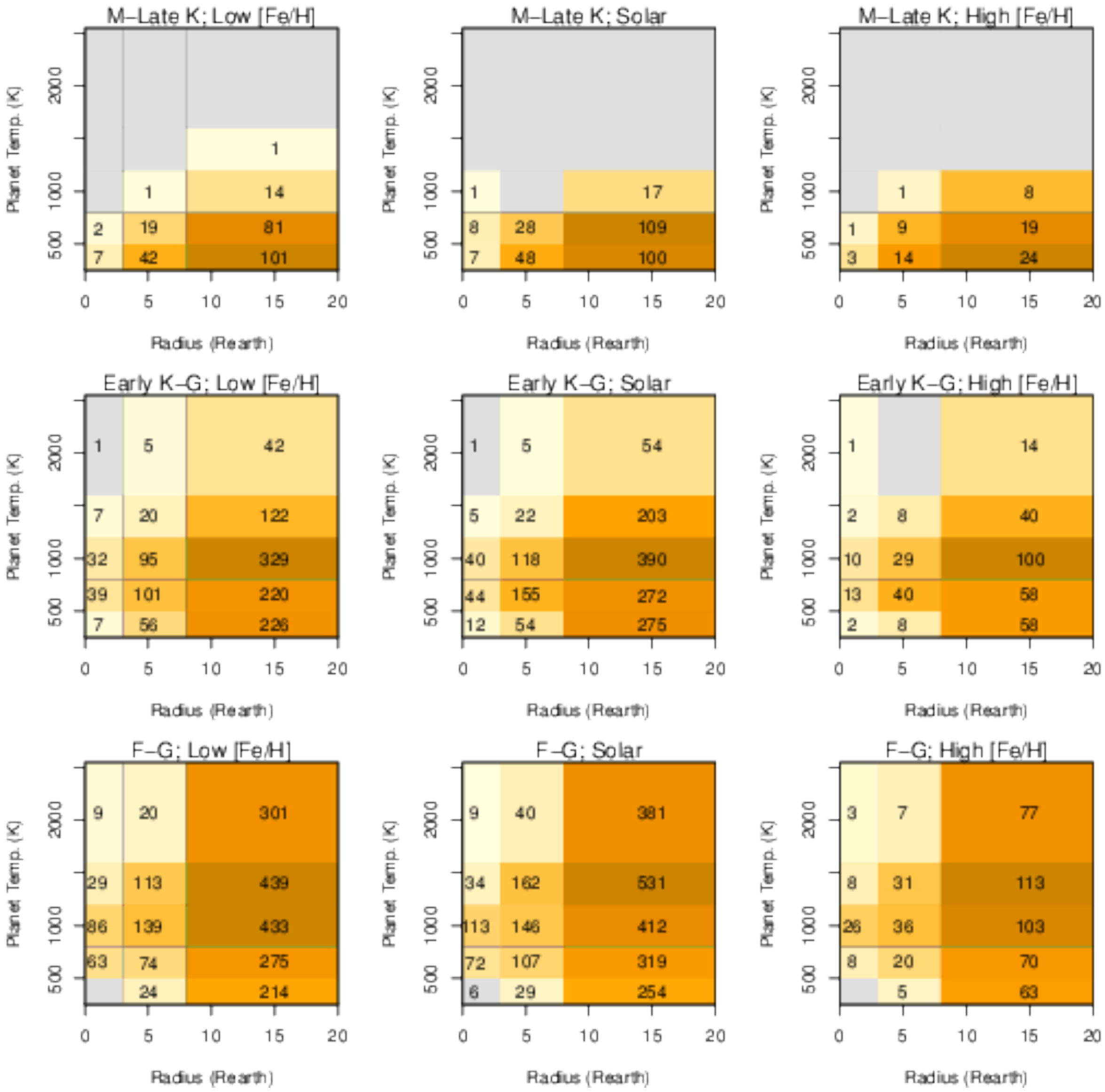

Figure 2: Same as Fig. 1 for the initial population of 9545 known and simulated planetary systems.

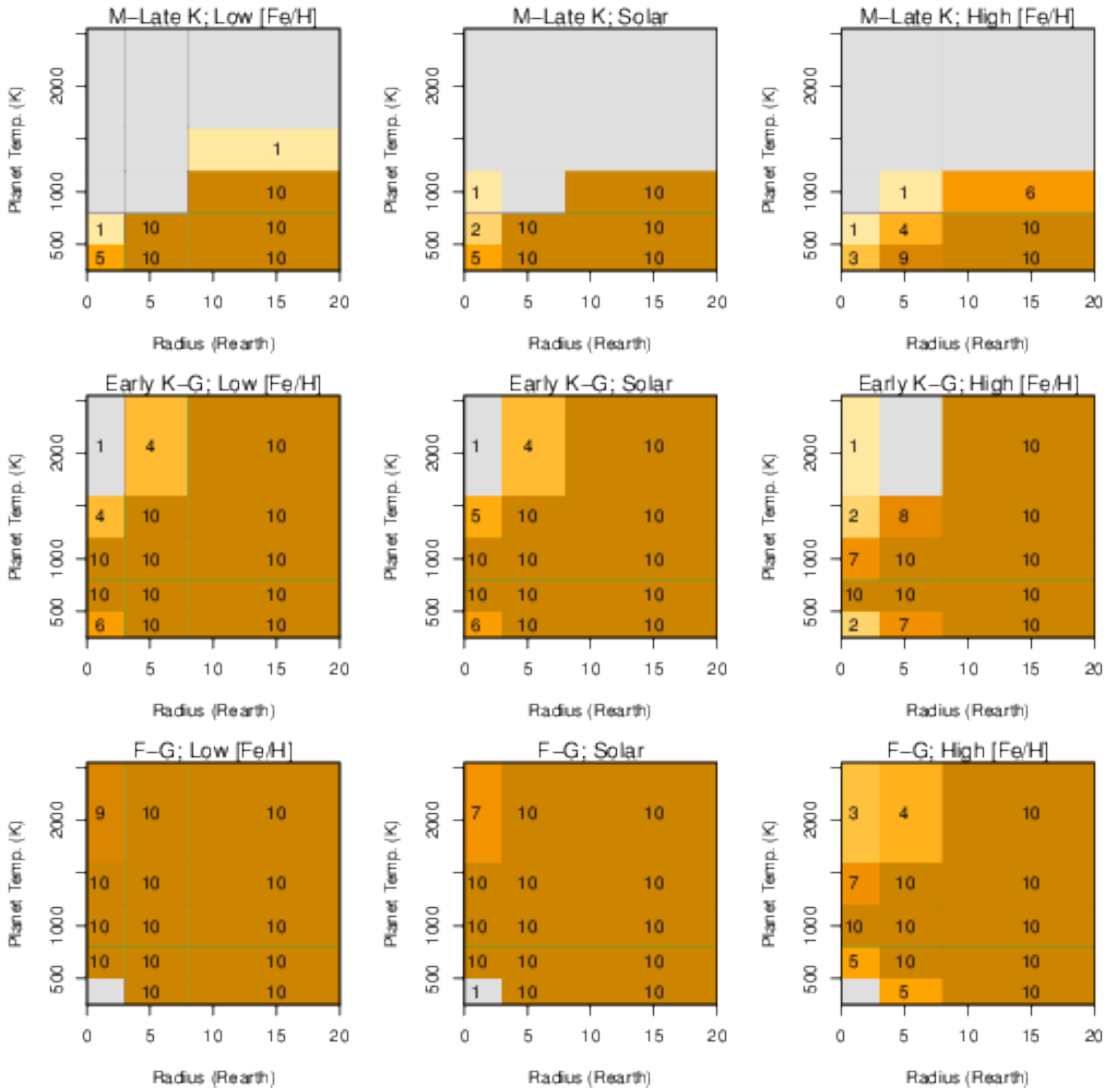

Figure 3: Same as Fig. 1 for the selected sample of 908 known and simulated planetary systems. They have been selected by filling each cell with up to 10 objects and for a budget of total satellite visits of about 1500.

As a final comment, we have verified that, by increasing the number of systems per 4D cell while keeping fixed the total number of visits to ~1500, we obtain that the number of observed planets increases (for example assuming N=15 as maximum systems per cell, we can observe up to 1000 systems), but at the same time the 4D cells of systems with cold/warm Earths/Super Earths tend to be left empty and thus unexplored.

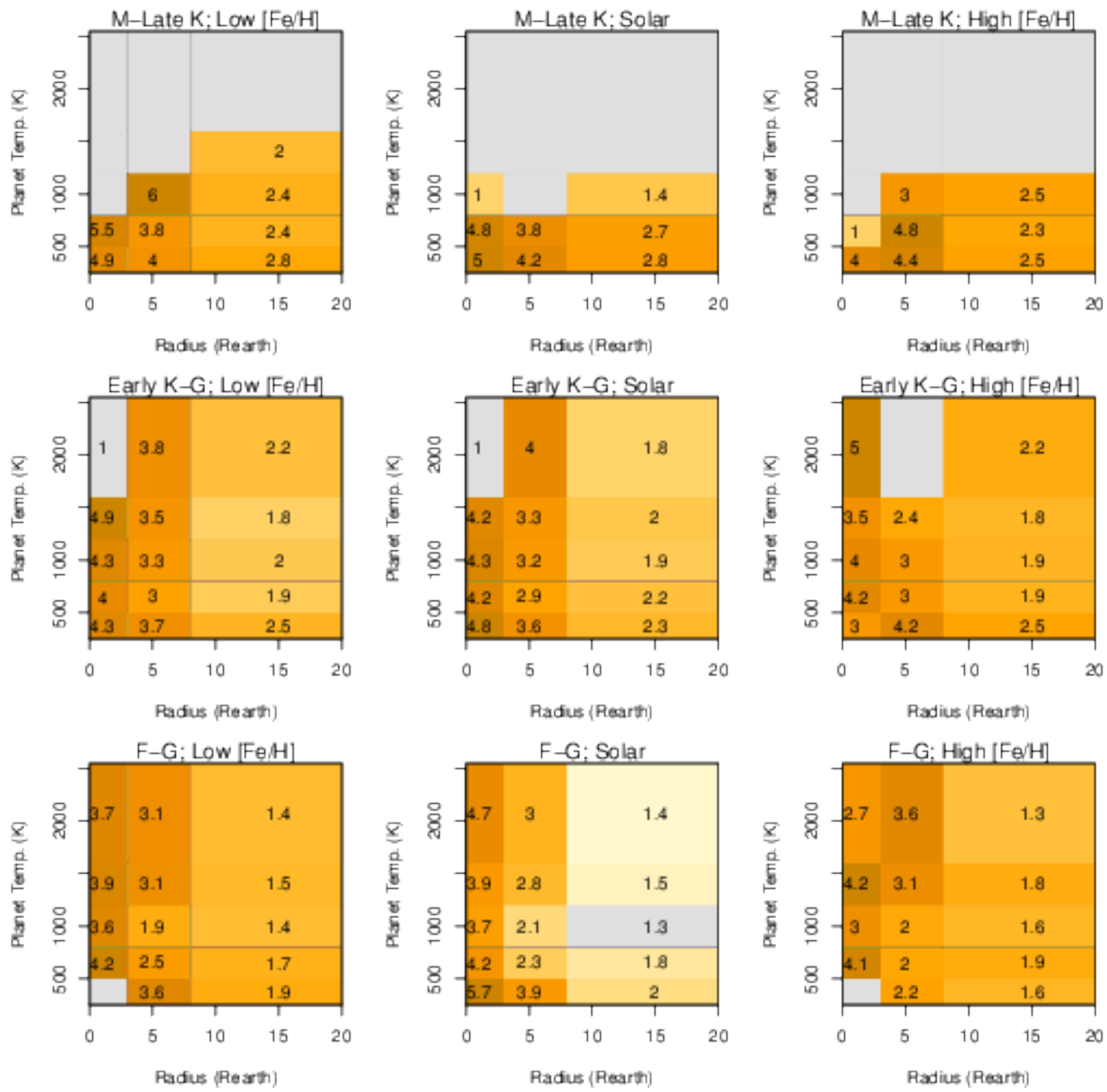

Figure 4: Average number of visits required for the sample selected in Fig. 3. The binning is as in Figs. 1 to 3.

4. Conclusions

ARIEL will study a large sample of exoplanetary systems with various configurations and physical properties. In this technical note we have shown that it is possible to optimize the parameter space covered by the ARIEL targets. In particular we have presented a possible choice of the Tier 1 survey sample, that maximizes the coverage of the physical parameters of the systems. The selection includes 908 planets for a total of 1504 visits devoted to the Tier 1.

This exercise shows the degree of flexibility offered by ARIEL in the choice of target sample, allowing us to explore a large variety of the star-planet configurations and physical properties.