Atmospheric Remote-sensing Infrared Exoplanet Large-survey

(ARIEL)

Assessment Phase Payload Study

Contaminant analysis for ARIEL

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1. Scope of the document

In this report, we show how the existing and forthcoming stellar catalogs can be exploited to retrieve the needed information to estimate the contamination from point sources falling within the slit and to optimize the observing strategy of ARIEL.

2. Abbreviations

- FOV: Field Of View
- FWHM: Full Width at Half Maximum
- MIR: Mid-InfraRed
- NIR: Near-InfraRed
- PSF: Point Spread Function

3. Applicable Documents

AD #	APPLICABLE DOCUMENT TITLE	DOCUMENT ID	ISSUE / DATE
1	ARIEL ESA M4 proposal		
2			
3			
4			
5			
6			
7			

4. Reference Documents

RD #	REFERENCE DOCUMENT TITLE	DOCUMENT ID	ISSUE / DATE
1	Rauer et al. (2014)	ExA, 38, 249	2014
2	Nascimbeni, Piotto et al. (2016)	MNRAS, 463, 4210	2016
3	Lasker et al. (2008)	AJ, 136, 735	2008
4	Montet et al. (2016)	ApJ, 809, 25	2016
5	Gaia Collaboration et al. (2016)	A&A, 595, 2	2016
6	De Bruijne et al. (2015)	A&A, 576, 74	2015
7	Keller et al. (2007)	PASA, 24, 1	2007
8	Chambers et al. (2016)	Arxiv:1612.05560	2016
9	Tyson et al. (2002)	SPIE, 4836, 154	2002
10	Baranec et al. (2012)	SPIE, 8448, 04	2012

5. INTRODUCTION

The ARIEL NIR spectrograph will employ a 6.4" × 26.4" slit and is aimed at detecting features at the $10^{-4}/10^{-5}$ level [AD#1]. A detailed preliminary analysis is required for each target to avoid that contaminating sources within the slit could impact the scientific output of the mission.

For every high-precision photometric or spectroscopic instrument where, by design, the optical aperture or entrance slit is large as seen projected on the sky and/or when the background stellar field is a crowded one, contamination by light sources even much fainter than the target can decrease the achievable performances and, of course, reduce the scientific value of the observation. This is a very common problem among space missions focused on exoplanetary science, due to the need of maximizing the available field of view (e.g. for transit-search missions such as CoRoT, Kepler, TESS, PLATO) or, in the case of ARIEL, to the need of minimizing slit losses.

There are two main “families” of noise sources due to flux contamination:

1) Increased *random noise* (a. k. a. “white noise”) impacting *precision*. The Poissonian noise associated to photon counts increases due to the additional flux from resolved sources, or from the background, which is blended to the target flux. The only solution in this case is to minimize the amount of contaminating flux by optimizing the observing strategy beforehand, since there is no a-posteriori correction able to remove random noise once the spectrum is read out.

2) Increased *systematic noise* (a. k. a. “red noise”) impacting *accuracy*. Contaminating sources can be variable (for instance, active stars or eclipsing binaries) and introduce a time-dependent signal which is not negligible with respect to the planetary spectrum. Even perfectly stable sources, combined with the unavoidable jitter or drift due to the spacecraft motion, can introduce systematics because the fraction of contaminating flux entering the slit is, again, a function of time. Moreover, even in the ideal case where the total amount of contaminating flux is perfectly constant, its net effect is to dilute the features of the target spectrum according to the flux ratio at a given wavelength. If the latter effect is not properly quantified and taken into account, one would measure a transit/occultation depth smaller than the real one, and for the same reason the molecular features in the planetary spectrum would be underestimated by an unknown factor.

In this report, we show how the existing and forthcoming stellar catalogs can be exploited to retrieve the needed information and to optimize the observing strategy of ARIEL. Our experience is partly built on our previous and ongoing work within the ESA PLATO mission [RD#1], in particular on the preparation of the *PLATO Input Catalog* (PIC) which will include a detailed characterization of the contaminants around each scientific target of interest [RD#2].

6. THE CASE OF ARIEL

Given the slit size of its spectrograph, ARIEL will be particularly exposed to contaminants. Of course, things get worse at fainter target magnitudes, low Galactic latitudes, or other particularly crowded environments such as star clusters. Fig. 1 shows how a typical target on a crowded field (WASP-12, a V=11.6, J=10.4 star hosting a Hot Jupiter planet) will look like as seen by ARIEL. At least one contaminant source, ~4 mag fainter than the target, falls within the ARIEL slit, while other potential contaminants could do so at different roll angles of the spacecraft.

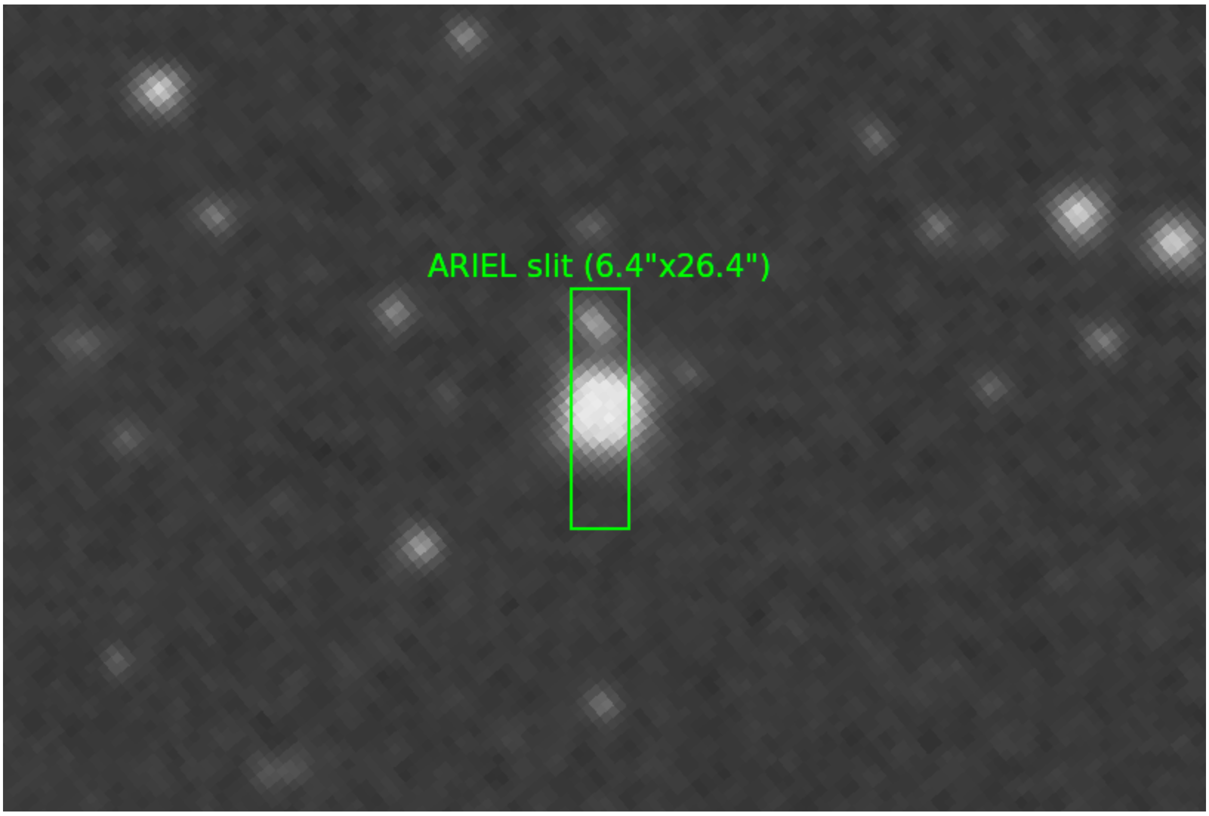

Figure 1. The stellar field surrounding WASP-12 (in the center) compared with the ARIEL slit size (green rectangle). At least two detected contaminants can fall within the slit at different rotation angles. Image taken from DSS-2 infrared.

A simple way to estimate the order of magnitude of the problem is to calculate, at some reference wavelength, the flux ratio F_s/F_c between the target star and the combined light of all contaminants, including the background. The corresponding difference in magnitude is then :

$$\Delta m = -2.5 \times \log(F_c/F_s).$$

This means that if we want to avoid systematics at the 10^{-4} level, without any previous knowledge on the variability of the contaminants and on the performance of the spacecraft tracking system, we must design the observation such as to exclude any contaminant brighter than the target plus 10 mag.

ARIEL will be focused on characterizing planets hosted by late-type stars brighter than K=9.5 [AD#1]. In the worst case of a target at the fainter limit, this would imply the need of mapping and characterize any contaminant down to K~19.5, that is, at visible wavelengths, down to V~21 for a G2V star, and down to V~23.3 for an M0V. The minimal requirement is to identify such sources and measuring their flux in at least two different photometric bands; the color information is crucial to translate the optical/NIR flux given by most high-resolution catalogs into the longer wavelengths exploited by ARIEL, i. e. the 2-8 μm range (see also Sec. 7 and Fig. 5). A more detailed and advisable characterization would include information about the proper motion, variability, and the spectral energy distribution (SED) of the contaminants.

Once that the stellar field within ~20" from a given target[1] has been properly mapped, and knowing the effective ARIEL bandpass and point-spread function (PSF), it will be possible to model spatial distribution of the sources entering the ARIEL slit as a function of wavelength. Fig. 2 illustrates a very over-simplified example of this modeling, where the stellar field is simulated from a synthetic catalog, and the instrumental PSF is assumed to be Gaussian with the FWHM specified in [AD#1]. The total flux integrated over the slit divided by the target flux gives the dilution factor to be applied to correct the light curves, as explained in Sec. 5, point 1). This estimate can also be exploited to choose the most favorable rotation angle at which to carry out the observation, if the target schedulability and the spacecraft pointing constraints allow us to do so. Furthermore, using the information about the spacecraft jitter during the scientific acquisition (i.e., from telemetry) it is possible to model the temporal derivative of the flux loss and to correct the resulting systematic errors from the transit/occultation light curve, as it is routinely performed to correct low-resolution differential spectrophotometry from ground-based instruments.

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[1] The actual avoidance radius is, of course, a function of the actual size of the PSF, and is also dependent on the Δm between the target and the contaminant(s); its value will be determined case-by-case through detailed simulations.

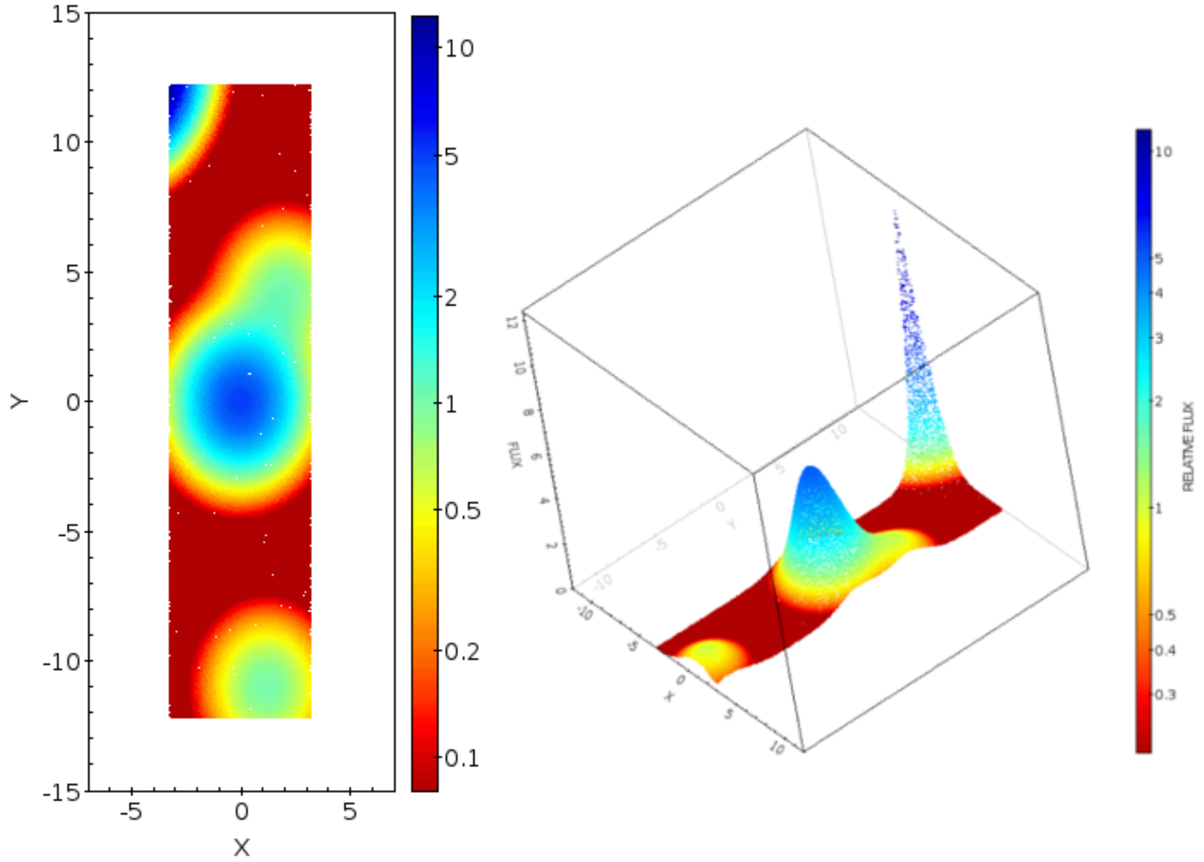

Figure 2. Modeling the contaminants around an ARIEL target through synthetic catalogs and Gaussian PSFs.

7. EXISTING CATALOGS

A preliminary contaminant analysis, to be considered as preparatory to the exploitation of forthcoming and more reliable catalogs (see Sec. 8) can be performed by using already-available, all-sky catalogs. Those can be roughly classified in two large families:

1) *catalogs based on photographic plates*, such as DSS, USNO, GSC and derivatives. They fill up the whole sky down to about $V<21$ through at least three different photometric bands (photographic *B*, *R*, *I*). Despite the low spatial resolution of these data, the huge temporal baseline between DSS1 and DSS2 (~35 yr), reaching >50 yr with respect to present time, is very useful to map contaminants at extremely small angular separation, provided that the target has a proper motion large enough (Fig. 3). This technique is especially effective for nearby GKM dwarfs. On the other hand, the astrometric and photometric accuracy of photographic catalogs is quite poor: GSC claims 300 mas and 0.3 mag, respectively [RD#3]. Photographic plates also show many artefacts, especially around bright sources.

2) *digital catalogs* such as UCAC4, 2MASS, SDSS (just one third of the sky), WISE and others. Their astrometric and photometric accuracy is, of course, much better: on the order of 15-70 mas and ~0.05 mag for bright objects. Their spectral coverage is also much more suited for our purposes, as they range from the optical (UCAC4 *Bvgri*, SDSS *ugriz*) down to NIR (2MASS JHK_s) and MIR (WISE W1, W2, W3, W4). Unfortunately, except for SDSS, which is not all-sky) they are too shallow: $r<17$ (UCAC4, with only a single band) and $K_s<14$ (2MASS). This means that they could be useful only to map contaminants of very bright ARIEL targets.

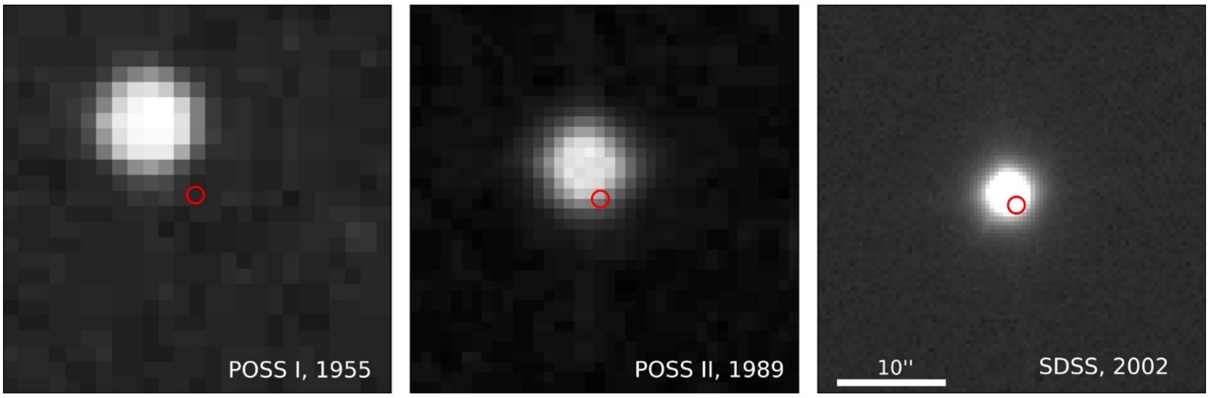

Figure 3. How catalogs based on old photographic plates can be exploited to map contaminants at very small angles from high-proper-motion ARIEL targets. Example from [RD#4].

8. FORTHCOMING CATALOGS

For many reasons, the final Gaia catalog [RD#5] will be the main source for the contaminant analysis for ARIEL:

1) extremely high spatial resolution: stellar blends will be resolved by the star mapper down at least 0.3" (Fig. 4) [RD#6]
2) complete down to V~21, in a single, wide optical band (the G band, ~330-1050 nm);
3) spectro-photometry down to V~15 (to be confirmed);
4) information on photometric variability: time series spanning ~5 yr and 40-200 sampled epochs, depending on the ecliptic coordinates.

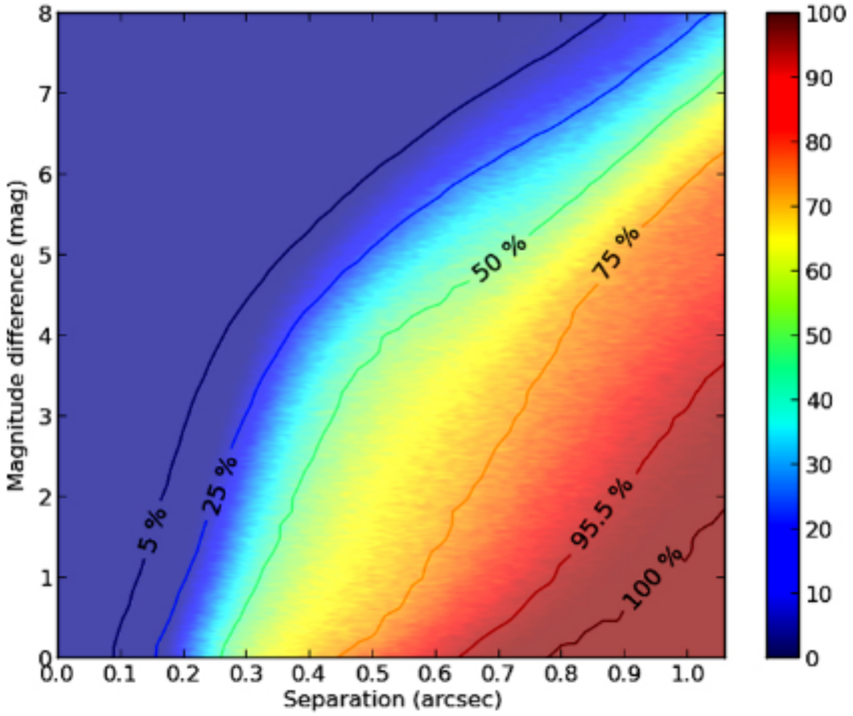

Figure 4. Gaia performances on deblending close contaminants, from [RD#6]. "Probability (in %) of a double star with a primary component with G=13 mag being resolved into two local maxima as a function of separation, in units of arcsec, and magnitude difference DG (averaged over all orientation angles".

Unfortunately, while Gaia will be essential to our purposes, it will be mandatory to complement it with other sources for at least three reasons:

1) lack of *color information* especially on the faint end, and even on the bright end the spectro-photometric data will have a lower spatial resolution, comparable with present-day ground-based instruments. In particular, the lack of infrared magnitudes make the estimate of the flux through the ARIEL passband much more difficult (see later);

2) the real (in-orbit) performance of Gaia and the completeness of its star counts, especially for faint targets in very rich field and close to bright objects, must been fully assessed. In particular, some unexpected problems such as the stray light issue [RD#6] could limit the initial expectations;

3) for very late-type ARIEL targets the V~21 limiting magnitude can be not enough to map all contaminants, because an M5V star is expected to have V-K~6.

Some of the above problems can be mitigated by exploiting other catalogs which are already available. For instance, we devised a calibration technique able to estimate the NIR/MIR fluxes by matching optical fluxes, for instance the Gaia "white" *G* magnitude or the

Sloan *g′* and the Sloan *z′* magnitude from the SDSS DR9 catalog (Fig. 5). The effective ARIEL passband is not known in detail yet, but we can make the rough assumption that the WISE *W2* channel, centered at about 5 µm, is representative of the whole 2-8 µm flux gathered by the ARIEL spectrograph. Using WISE *W2* magnitudes as a proxy, we were able to extrapolate the 5 m flux just by fitting a straight line to the Sloan *g′-z′* colors, getting a reasonable fit of the measured fluxes (residual rms < 0.1 mag) over a very wide range of optical colors (0.4<*g-z*<2.5). In other words, deep, all-sky, high-resolution NIR/MIR catalogs are not strictly necessary.

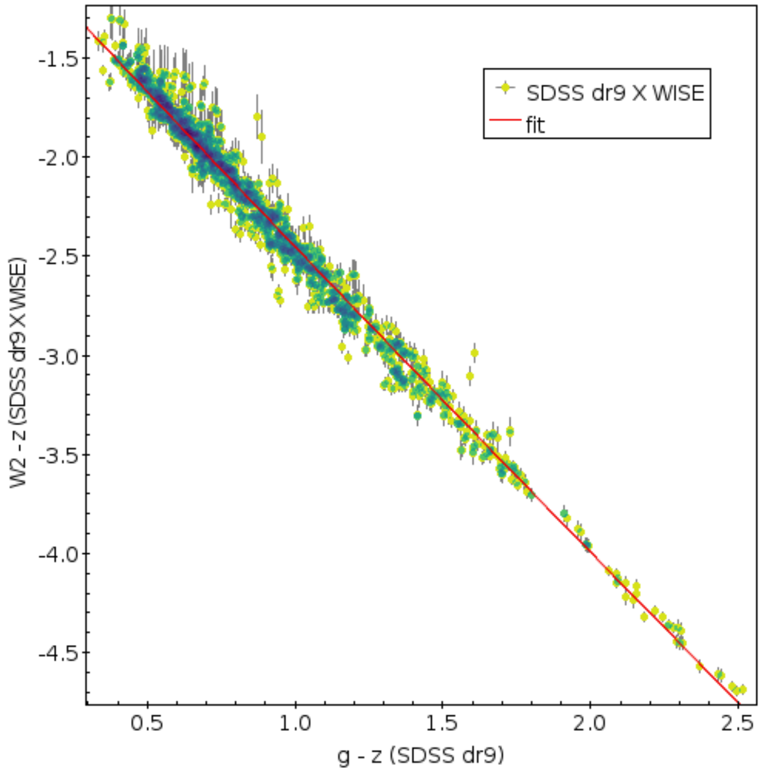

Figure 5. Extrapolating a MIR magnitude (in this case, in the WISE W2 band at ~4 mm) from optical colors (in this case g-z from SDSS DR9.

Next years will see the release of new wide-field, ground-based catalogs much deeper or more extended than the previous ones:

1) *SkyMapper* [RD#7], covering the full southern hemisphere through six optical bands (*uvgriz*) with a limiting magnitude of *r*~21.7. The angular resolution, however, will be limited at ~2.5" by design, making this catalog useless to map contaminants very close to the target;

2) *Pan-STARRS* 3π survey [RD#8], covering the full southern hemisphere through five optical bands (*grizy*) with a limiting magnitude of *r*~24 at the end of the program. The survey will be seeing limited from the Mauna Kea observatory (median ~0.7"). Delays in the program make

it difficult to estimate a possible release date for a reasonably complete intermediate catalog;

3) *LSST*, the Large Synoptic Survey Telescope [RD#9], led by a US + Chile + France consortium and presently under construction. The start of the scientific observation is expected around ~2022, with the first data release (DR1) public on 2024-2025. It will map the full southern hemisphere in multiple epochs through *ugrizy*, reaching *r*~24 in one single visit, with accurate photometry (~0.1 mag at the fainter end) and astrometry (15-70 mas). It will be seeing limited at about 0.65” median. Unrivaled for mapping the faint contaminants and to add color information to the GAIA monochromatic magnitudes. Timeliness could be an issue, should there be delays in the data release schedule.

9. CONCLUSIONS AND NEXT STEPS

Our preliminary review showed that there is no single catalog that enables us to carry out an effective mapping of the contaminants around the ARIEL targets, although the next intermediate data releases of Gaia (starting with DR2), combined with present and future ground-based surveys, will enable us at least to estimate the amount of contaminating flux as a function of wavelength, and to devise mitigation techniques to minimize the impact of contamination on the scientific measurements. The release of Gaia DR2 in early 2018 will make it easier to assess what are the actual performances of Gaia and how and to what extent the Gaia data must be complemented, not only by other catalogs, but also by a careful review of the existing literature. Being ARIEL a follow-up mission, it is expected that most of its target will be quite well characterized, in some cases with high-resolution imaging or coronography, or by spectroscopy.

As a final note, it is worth noting that dedicated preparatory observations are also feasible with a reasonable investment of observing time and resources. Let us assume that the main target list of ARIEL will be made of ~500 targets [AD#1]. A generic 2-m class telescope such as the Nordic Optical Telescope requires an observing block with two NIR exposures 400 s *J* + 1800 s *K* + 180 s overheads to reach *K*~20 at S/N ~ 5 under good seeing conditions, that is about ~0.6 hours per target. The whole sample can be characterized with 33 net observing nights, to be spread out over many years. Of course, one could in principle select a subset of highest-priority targets with a stronger science case and/or lacking acceptable contaminant analysis. Such subsample could also be monitored with more sophisticated instruments, such as adaptive optics (AO) systems and/or coronographs [RD10].