MOTE: Monitoring of Transiting Exoplanets

Abstract

In the last decade, exoplanetary science has moved from searching for new planets to characterize them. After the discovery of the first transiting planets, a large population of hot planets has revealed a wealth of properties that allow performing statistical analysis of the exoplanet population, informing formation and early evolution theories of exoplanets. Current space-based facilities are providing rich information on these populations, but because of their limited lifetimes, cadence, and coverage, ground-based monitoring of hot exoplanets remain being necessary. We propose here monitoring of transiting hot and warm exoplanets to search for hints of long-term variability in the transit signals, with primary transit and occultation photometry observations with the SSO and LCOGT observatories.

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Instrument Information

Instrument/Telescope	Req. Time	Min. Time	Req. Dates	Moon?
SPECULOOS	31 nights	17 nights	(see below)	Any
LCOGT 0.4m	100 hours	60 hours	Time critical	Any

SCIENTIFIC AIM AND RATIONALE

Now, with more than three decades of discoveries, the exoplanetary science has evolved from the finding of systems towards their characterization. The current population of exoplanets shows a huge diversity of systems, including a large number of systems with characteristics very different from the ones we find in our own Solar System. Among this diversity, we can find a large population of exoplanets orbiting very close to their host stars (the so-called hot-exoplanets) or the numerous exoplanets with radii larger than that of our Earth and smaller than that of Neptune (the so-called sub-Neptunes and super-Earths), all of them absent from our own Solar System. Among this large population, transiting exoplanets represent an important population of objects where the planetary radius and mass can be inferred, thus providing access to their bulk composition. Since the first discovery of a transiting exoplanet (Charbonneau et al. 2000), several dedicated surveys started the quest to unveil most of the population of systems that can be reached from Earth. Now, by combining both ground- and space-based telescopes the current number of confirmed transiting planets is close to 4,000, which is large enough to perform studies of the whole population itself.

Transiting exoplanets also allows to determine some properties of their atmosphere. On the first hand, if we determine the depth of the transit at different wavelengths, we will be probing the changes in optical depth as a function of wavelength, due to the atmospheric composition and structure. These transmission photometry/spectra have been quite successful in determining the presence of several species in exoplanetary atmospheres. On the second hand, transiting exoplanets are very likely to present secondary eclipses (a.k.a. occultations) if their eccentricity is small. When observing the occultation of an exoplanet we can compare the light of the star-planet system before and during the secondary eclipse, thus determining the amount of light emitted from the planet. This emission spectrum can arise from light originating from the star and reflected on the planet's atmosphere/surface and/or the thermal emission from the day-side of the planet. By analyzing this occultation signal at different wavelengths we can infer some properties of the atmosphere like the brightness temperature, structure, recirculation efficiency, dominant composition (e.g. CO, H_2O, CH_4), as well as the presence of clouds/hazes, high opacity compounds like TiO/VO, and thermal inversions. Moreover, the time at which the occultation occurs represents one of the best constraints on the factor $e\cos\omega$. With this, occultations represent a fundamental complement to primary transit observations (i.e. transmission photometry or spectroscopy), as they allow us to understand those properties not accessible from the primary transits.

The large number of systems detected at very high SNR with current spaced-based facilities like TESS and CHEOPS, which adds to the previous exquisite photometry from Kepler, has revealed a wealth of extremely rich information to exploit. However, even like these facilities have proven to be extremely useful, they have limitations because of the limited cadence and coverage of the space-based missions. It is here where ground-based facilities play a relevant role as they can perform long-term follow-up, without the restrictions inherent to the space observations.

For the wealth of hot exoplanets currently known (i.e., $P < 5\,\mathrm{d}$), there are still some open questions that can be addressed with transit monitoring with ground-based telescopes. For instance, for short-period planets, transit timing variations (TTVs) have been mostly ruled out for most of the hot Jupiters (e.g., Ivshina et al. 2022), while TTVs have been detected in lower mass systems. Transit duration variations have also been detected in a few systems (e.g., Mislis & Schmit 2009; Szabo et al 2014; Eyken et al. 2012; Damiani & Lanza 2011). Transit photometric observations at different wavelengths can also allow to access the transmission spectrum, which may provide being useful depending on the bandwidth of the used filters. For instance, comparing blue and red filters can allow us to determine the strength of the Rayleigh scattering component of the atmosphere, while some spectral features are more sensitive to the presence of high-opacity compounds in the high atmosphere. Similarly, a hypothetical detection of occultations of exoplanets may lead to the determination of apsidal precession and on changes in the atmospheric emission properties. Precession is important as it could explain the unconfirmed long-term changes in the TTVs of a few systems, attributed to orbital decay (e.g., Harre et al. 2022).

As the current data available in the literature comes from a variety of sources, it is difficult to compile the information in a homogeneous way and the joint analysis is not guaranteed to be free from systematics that could originate from different photometric calibrations, time standards definitions, analysis tools, etc. As the amplitude of systematics can easily overcome the strength of the signals in high-precision photometry of transits, it is important to have a homogeneous sample to look for this variability in the transits. It is in this context that we propose to perform a large survey of transits of well-known hot exoplanets to look for variations in the transits, in a homogeneous way. We will use SSO to perform this experiment as this observatory has been designed to look and monitor transits of exoplanets.

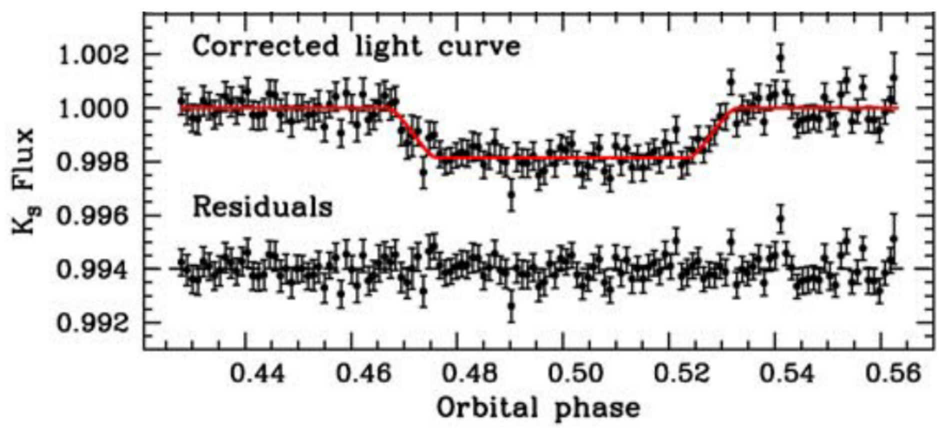

Figure 1: A high-precision light curve of the secondary eclipse of the exoplanet WASP-4b obtained by our team. This light curve shows an r.m.s. similar to the one requested in this proposal, which is necessary to characterize transits of Earth-like exoplanets with SSO (adopted from Caceres et al. 2011). This light curve shows we can achieve a sub-mmag precision with the proposed observations.

The main goal of this proposal is to provide new constraints to the variability of selected transiting systems, including ephemeris, orbital parameters, and with a lower probability, atmospheric parameters. We have defined a pool of exoplanets with transit depths suitable to be detected with SSO to focus this monitoring. We aim at observing at least 2 transits of each target per semester.

Depending on the dates of the granted nights (see Technical Description), we will select a set of planets to follow up from the list of planets in the NASA Exoplanet Archive hosted at IPAC. For the specific case of extremely hot Jupiter planets (excluding those in the protected list of targets provided by SSO), and in the case that the IR camera SPIRIT in Callisto gets available during the requested semester, we will also use some time to attempt the detection of the occultation of a couple of high amplitude currently known occulters (e.g., WASP-4b, WASP-12b, among others). If successful, these experiments will allow constraining the eccentricity and changes in ω, which is important to explain some of the variability found in these systems. Given the currently available filters it is unlikely that we will be able to constrain the Bond albedo of these planets, but it is within the possibilities.

We would like to note that, while this is not formally a student proposal, we will use the acquired datasets to train BSc students in data reduction techniques and in the analysis of transit light curves, especially those that are involved with the PI of this proposal.

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Table 1. Requested and preferred nights for SPECULOOS

Date (night of) yyyy-mm-dd/dd	Telescope Name	Preference? yes/no
2024-04-17	Ganymede	no
2024-04-18	Ganymede	no
2024-04-25	Callisto	yes
2024-04-26	Callisto	yes
2024-05-03	Io	no
2024-05-04	Io	no
2024-05-27	Callisto	yes
2024-05-28	Callisto	yes
2024-06-03	Io	no
2024-06-04	Io	no
2024-06-27	Callisto	yes
2024-06-28	Callisto	yes
2024-07-05	Io	no
2024-07-06	Io	no
2024-07-13	Europa	no
2024-07-14	Europa	no

Date (night of) yyyy-mm-dd/dd	Telescope Name	Preference? yes/no
2024-07-21	Ganymede	no
2024-07-22	Ganymede	no
2024-07-29	Callisto	yes
2024-07-30	Callisto	yes
2024-08-22	Ganymede	yes
2024-08-23	Ganymede	yes
2024-08-30	Callisto	yes
2024-08-31	Callisto	yes
2024-09-01	Callisto	yes
2024-09-07	Io	yes
2024-09-08	Io	yes
2024-09-15	Europa	yes
2024-09-16	Europa	yes
2024-09-23	Ganymede	no
2024-09-24	Ganymede	no

TECHNICAL DESCRIPTION

We propose to obtain time-series photometry to detect the transit signal due to the planet with SSO. This facility has been designed for this purpose, so it is particularly well suited for transit monitoring. We aim at obtaining ∼0.1% accuracy or S/N>1000 per image, for reliable detection of the transits. Depending on the nature of the systems, we will use the minimum DIT of 10s for the brightest targets and we will increase this value to a maximum of 120s for the faintest ones. If the IR camera SPIRIT gets available during the semester, we request to use it for exploring secondary eclipse monitoring of ultra-hot Jupiters in the zYJ bands or any longer-wavelength filter if available in the near future. In this case, then the minimum time will be DIT=7s. For any of the 4 VIS telescopes, we will use g', r', i', or z' for the brightest targets or $I+z'$ for the faintest ones. The transit of the targeted hot planets lasts ∼1-4 h, and we expect to obtain during the transit >100 exposures, so the theoretical S/N of the transit depth measurement will be boosted by another order of magnitude, but it is well known that at this levels of precision systematic effects dominate such observations (e.g. Caceres et al. 2009, A&A, 507, 481; 2011, A&A, 530, 5; 2014, A&A, 565, 7). Another important requirement is to monitor the star out-of-transit for longer than the transit itself, to ensure the baseline observations do not contribute much to the total error budget. Given the uncertainties in the ephemeris and possible transit-time-variations (Liu et al. 2017), we will need, as a *minimum*, 3-5 hr per transit per telescope, but given the constraints from SSO, we request full nights which is helpful because longer plateau helps to characterize better the systematics and allow to get more transits per night.

Considering at least two transits per target per semester, we request an ideal minimum of 17 preferred nights with SSO (most of them with Callisto to allow NIR observations with SPIRIT if available). Our ideal request is for the 31 nights in Table 1, selected from the ones offered by SSO for the Chilean slot. We define there which dates are preferred (17 nights) in case not all the requested time could be offered.

We also request LCOGT 0.4m (both SBIG and QHY) to cover important targets from out list during the nights SSO is not offered. For this purpose we request 100h (60h minimum) to allow to monitor 15-20 transit events per semester. As the transits occurs at specific times and the network works in queue mode, instead of selecting specific nights we request in this proposal *time-critical mode* for these LCOGT observations. The specific requirements are similar than those of SSO, but scaled down to the 0.4m aperture, implying we will also set minimum time of 10s, and we will adjust it to aim to get a SNR of ∼500. We will use the g', r', i', or z' filters, depending on the SpT of the target.

For the whole time request, we would like to note that any amount is acceptable, and a reduced time would impact on the total number of targets being monitored.

For each target and for all telescopes, we will center the field in a way that the target as well as several reference stars are included. This will be used to perform differential photometry. Also, we will use stare-mode for both, the VIS and the NIR imaging if possible, as it has been shown that changes in the position of the targets (like nodding or trends in the tracking) introduce strong systematic effects that are very difficult to remove.

For the analysis we have created ad-hoc calibration and analysis pipelines based on `astropy`, the `MOTEred` pipeline, to facilitate the fast and homogeneous analyses we require for this campaign.

CURRENT STATUS OF THE PROJECT

This is a starting project in terms of science. One semester of nights has been gathered so far, with an overall success rate of 17n/28n = 60%. As it is a monitoring project, we are still in the process of reducing this initial dataset, but so far we can say that most of our targets have been observed only once, and a few others 2 or more times (see Fig. below). The initial semester sets the baseline of objects for the posterior photometric monitoring, and thus, the request for new nights is crucial for the variability monitoring aimed at in this proposal.