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ExoSim: a novel simulator of exoplanet spectroscopic observations

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Abstract

ExoSim is a new simulator of exoplanet transit spectroscopy incorporating instrument and detector models. It is designed to capture both random and systematic noise, producing realistic image outputs. It is generic, easily adapted for different instruments, with multiple potential applications, including the design of future instrumentation, planning of observations and validation of previously obtained spectra.

1. Introduction

Chracterisation of exoplanet spectra by transit spectroscopy requires observational precision of the order of 10^{-5} or better. In addition to photon noise from the source and astrophysical backgrounds, such observations will be subject to various other experimental uncertainties including detector and electronic noise, telescope thermal emission, spacecraft jitter and pointing strategy, and other systematics, the ensemble total of which may be difficult to determine analytically. We are developing an observation simulator – ExoSim – that incorporates models of the astrophysical scene, the instrument and the detector as well as multiple noise sources. It builds on the experience of EChOSim [1], but is intended to be more general and versatile in its application.

2. Structure

Using a modular structure (Figure 1), the simulator initially models the astrophysical scene, including the stellar spectrum, the planet-star contrast ratio, and the transit light curve. The telescope and optical channels are modeled and the spectral signal is modulated in multiple ways including by transmission through and emission from optical surfaces and convolution with the psf. A detector module simulates the pixel response function, dark current, quantum efficiency variability and other detector non-idealities.

It is also modulated in time to model either a primary or secondary transit. Various sources of noise are added including photon noise, pointing jitter, and read noise, as well contributions from zodiacal foreground, telescope and instrument emission, and dark current. Different observational modes can be applied and the output images and noise studied. We intend to add a stellar variability capability to simulate star granularity, pulsation and active regions.

3. Applications

Since the simulator will produce spectral images akin to those produced as the primary data product of the instrument being modeled (Figure 2), its output can be utilized generically by different data reduction methods and pipelines to assess the confidence level of retrieved quantities such as chemical abundances, temperature and pressure. It can be used 'predictively' to calculate signal/noise ratio and determine the instrument requirements and observation strategy needed to observe all kinds of transiting planets, including those in the habitable zones of late-type stars. It can be used 'retrospectively' to evaluate results from previous or existing instruments e.g. by performing Monte Carlo simulations, to determine the uncertainties on the emergent spectrum. We are applying ExoSim to future space-borne exoplanet instruments including Ariel, as well as to the Hubble WFC3 infrared instrument, which is currently used for exoplanet transit spectroscopy. Initial results are returning 'white light' photoelectron counts in agreement with those of published results [2].

4. Figures

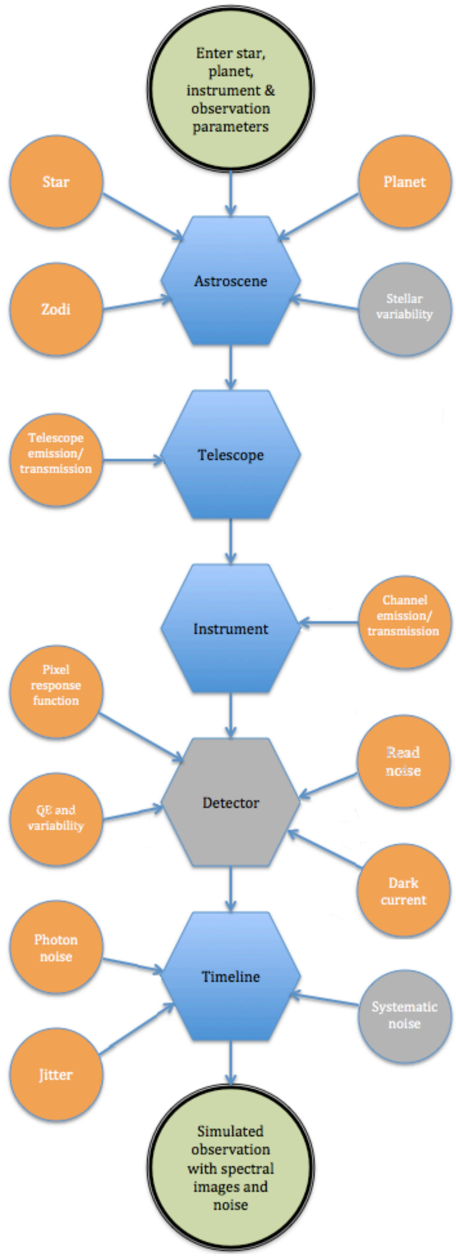

Figure 1: ExoSim architecture. A modular design is utilized and can be adapted for different instruments (grey elements are in the process of implementation).

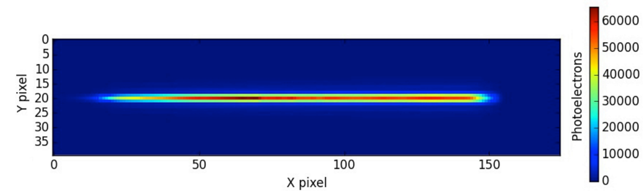

Figure 2: A simulated focal plane array image of the spectrum of GJ1214

5. Summary and Conclusions

We have demonstrated the capability of ExoSim to produce realistic spectral images and noise for two different instrument models, the proposed Ariel telescope and the Hubble WFC3 IR instrument. These simulations can be used for both predictive and retrospective studies. In the future ExoSim can be adapted for other instruments including SPICA and JWST.

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CHEOPS: Characterising ExOPlanet Satellite

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Abstract

CHEOPS (CHaracterising ExOPlanet Satellite) is the first exoplanet mission dedicated to the search for transits of exoplanets by means of ultrahigh precision photometry of bright stars already known to host planets. CHEOPS will provide the unique capability of determining radii to ~10% accuracy for a subset of those planets in the super-Earth to Neptune mass range. The high photometric precision of CHEOPS will be achieved using a photometer covering the 0.4 - 1.1um waveband and designed around a single frame-transfer CCD which is mounted in the focal plane of a 30 cm equivalent aperture diameter, f/5 on-axis Ritchey-Chretien telescope. Key to reaching the required performance is rejection of straylight from the Earth that is achieved using a specially designed optical baffle.

CHEOPS is the first S-class mission in ESA's Cosmic Vision 2015-2025, and is currently planned to be launch-ready by the end of 2017. The mission is a partnership between Switzerland and ESA's science programme, with important contributions from Austria, Belgium, France, Germany, Hungary, Italy, Portugal, Spain, Sweden and the United Kingdom.

In this presentation I will give a scientific and technical overview of the mission, as well as an update on the status of the project.

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Exoplanets characterisation with the JWST and particularly MIRI

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Abstract

The use of the James Webb Space Telescope (JWST) and especially its Mid-Infrared instrument, MIRI, to characterize the atmosphere of exoplanets is discussed. Both transit observations and direct imaging observations are considered.

1. Introduction

The detection of exoplanets, the measurement of their mass and radius, and thus the determination of their mean density, are well on track with several dedicated space and ground-based facilities in operation or planned (TESS, CHEOPS, PLATO,…).

The next step to progress in the field of exoplanets is the study of their atmosphere (chemical composition, vertical structure, two-D map, variability, …). Such a study is interesting to test atmospheric/climate models in a wide range of parameter values. It is also a way to break degeneracies in the determination of exoplanet internal structure from the mean density alone, to provide clues to planet formation (C/O ratio),... Such studies have started with observations from Spitzer and HST, and from ground-based telescopes. Nevertheless, the field is still in its infancy; a breakthrough in the domain is expected thanks to the JWST.

2. The JWST and its instrumental suite

The JWST is an InfraRed (IR) telescope of large diameter (6.5m to be compared to 0.8m for Spitzer) to be launched in October 2018 by an Ariane rocket. It is a NASA program with the participation of the European Space Agency (ESA) and the Canadian Space Agency (CSA). Observations in the 0.6 -28 microns range will be possible thanks to four instruments. Three of the four instruments, NIRCAM (PI. M. Rieke), NIRIS (PI R. Doyon) and NIRSPEC (PI P. Ferruit), are dedicated to imaging, coronagraphic or spectroscopic observations in the near IR (up to 5 microns); one, MIRI (European PI: G. Wright, US PI: G. Rieke), is dedicated to observations in the mid-IR (5-28 microns). For a recent status of the JSWT, see for example [3].

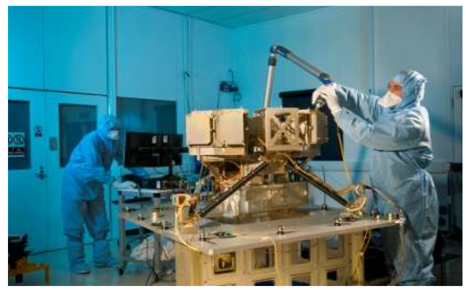

Figure 1: The JWST MIRI instrument in the RAL facility (UK) in 2012. The instrument features two main modules: an integral field spectrometer (on top) and an imager (at the bottom). For information about MIRI see [7]. (Copyright: Stephen Kill, STFC)

3. The JWST and the exoplanets

It should first be pointed out that the JWST is not a mission dedicated to exoplanets. Four science fields have been put forward: *First Light & Reionization, Assembly of Galaxies, Birth of Stars and protoplanetary systems, Planets and Origin of Life.* The JWST is an observatory and observing time will be granted through Time Allocation Committees. We can anticipate that the observing pressure will be high.

The capability of the JWST to observe primary and secondary transits of exoplanets has been recently (March 2014) discussed during a meeting at Passadena and the reader is referred to the paper resulting from the meeting [1] and the references there-in.

Note that the JWST will not do "all" and there is a strong scientific case for a space mission with a 1m class IR telescope dedicated to a statistical study of the atmosphere of hot to warm giant, Neptune like or super-Earth exoplanets ([6] and the Ariel M4 proposal to ESA, see also [4]).

4. MIRI and the exoplanets

Given its wavelength coverage (5 to 28 microns), MIRI is well suited to study exoplanets down to "temperate" one. Several strong molecular features from H_20, CH_4, CO_2, NH_3, HCN, C_2H_2… are present in the mid-IR region. Strong dust features (Silicates) are also present around 10 microns. Two observing techniques will be used: transit (primary and secondary) observations and direct imaging observations. These techniques probe two different classes of exoplanets. Due to observational bias, the exoplanets observed by direct imaging are **young** giant exoplanets orbiting **far** from their host star. The transit technics probe a larger mass range (from Earth mass to giant), but is limited to exoplanet in relatively close orbit around their host star; (the probability of transit decreases with the distance of the planet to the star).

4.1 Direct imaging

Since the beginning of the conception of MIRI, a coronagraphic mode has been included. Thanks to the use of 4 quadrants phase mask, an inner angle as low as Lambda/D is obtained [2]. The observations can be made at three wavelengths (10.65, 11.4 and 15.5 microns), which have been chosen to detect the NH_3 feature at 10.65 microns, which can probe the temperature of the object. MIRI observations will pioneer the field. Indeed no observation of direct imaged exoplanets has been done so far above 5 microns. Spitzer suffers from a lack of angular resolution and ground-based observations suffer from a lack of sensitivity.

The list of imaged planetary mass companions is so far limited, but will rapidly grow, now that GPI on Gemini and SPHERE on VLT are in operation. After the discovery of a planetary mass object on a wide orbit around the Young M3 Star GU Psc [5], the search for similar objects is quite active. For those exoplanets far enough from their host star, slit spectroscopic observations with the Low Resolution Spectroscopic (LRS) mode of MIRI (R about 100 in the 5-12 microns range) can be undertaken to determine the composition of the atmosphere. We are also considering using the Medium Resolution Spectroscopic (MRS) mode to obtain spectra at higher spectral resolution (R about 3000) or at wavelengths longer than 12 microns.

4.2 Transit observations

The observation of exoplanet transits was not foreseen at the beginning of MIRI. In the course of the instrument development, this aspect has been taken into account by adding a new observing mode: slitless LRS observations with only part of the array read to push further away the saturation limit.

5. Summary and Conclusions

The JWST will be a great facility to enter fully in the field of exoplanets atmosphere characterization. The observations will be difficult; for example, some transit observations will require reaching the 10 ppm level. However we can be optimistic as, the JWST in orbit at L2 will be very stable, its jitter will be as low as 7 mas (1 sigma) and a lot of knowledge on the instrument behavior and particularly the detectors, will be acquired prior to launch.

Acknowledgements

POL thanks CNES for financial support.

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The balloon-borne exoplanet spectroscopy experiment (BETSE)

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Abstract

The balloon-borne exoplanet spectroscopy experiment (BETSE) is a proposed balloon spectrometer operating in the 1-5 μm band with spectral resolution of R = 100. Using a 50 cm diameter telescope, BETSE is desgnied to have sufficient sensitivity and control of systematics to measure the atmospheric spectra of representative sample of known hot Jupiters, few warm Neptunes, and some of the exoplanets TESS will soon begin to discover. This would for the first time allow us to place strict observational constraints on the nature of exo-atmospheres and on models of planetary formation. In a LDB flight from Antarctica, BETSE would be able to characterize the atmospheres of 20 planets. If a ULDB flight is available, the combination of a longer flight and night time operations would enable BETSE to ground-breakingly characterize the atmospheres of more than 40 planets. Prior to an LDB or ULDB flight, BETSE would be tested in a 24 hr flight from Fort Sumner, NM, in order to test all subsystems, also observing more than 4 planets with SNR greater than 5.

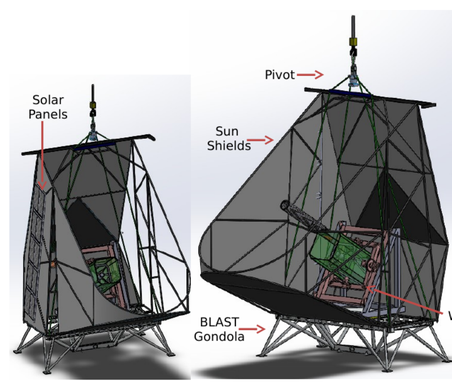

Figure 1: A CAD rendering of the BETSE instrument concept. The main telescope and spectrometerare mounted on the WASP (in red) platform which is held by an A-frame on the BLAST gondola outer frame (Pascale et al. 2008). The gondola outer-frame is connected to the flight chain by a pivot and suspension cables. Sun shields are required for day time operations. The telescope will also be provided with a baffle to further reduce stray light. Solar panels will be mounted on the right, left and back side of the gondola. The CAD shows only one side with solar panels for clarity.

1. Introduction

The Balloon-borne Exoplanet Transit Spectrocopy Experiment (BETSE) is a proposed balloon mission capable to conduct a spectroscopic survey of a statistically representative sample of the atmospheres of transiting extrasolar planets in the 1 to 5μm region of the elecromagnetic spectrum.

More than 1,000 extrasolar systems have been discovered, hosting nearly 2,000 exoplanets with a huge range of masses, sizes and orbits: from rocky Earth-like planets to large giant planets. However, we still know very little about the true nature of these alien worlds beyond their basic physical parameters (orbit, mass, radius) and, for a few, some sparse multiband photometry or near-infrared spectroscopy obtained using the *Hubble Space Telescope (HST)*, *Spitzer* and other ground based instrumentation. What we know is very limited. It appears that there is no clear relation between the nature of the host star and the observed orbital, mass and radius parameters of the orbiting exoplanets. What is the chemical composition of the atmospheres of discovered exoplanets? How is the chemical composition of exoplanet atmospheres linked to the formation environment? What is the role

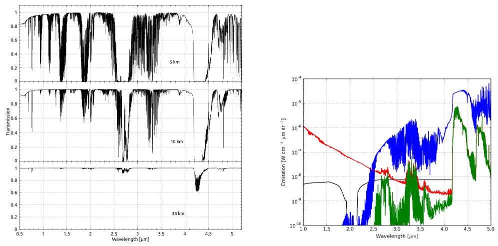

Figure 2: Left panel. Earth's atmospheric transmission for a site located on the Atacama Desert (5 km altitude), at aircraft altitude(10 km) and for the environment available from a stratospheric balloon-borne experiment (38 km). The 1 to 5μm band in its entirety cannot be accessed by ground-based or air-borne instrumentation. Only at balloon altitudes the Earth stratosphere is sufficiently transparent to allow spectroscopy over the whole band. Right panel. The Earth atmosphere emission is simulated at balloon altitude (night flight in green and day flight in red) and for a ground telescope located at Atacama (blue line). Skyglow is also represented by the black line (Leinert 1998).

of the parent star in driving the physics and chemistry of the planet's birth and evolution? BETSE (see Figure 1) will be the first instrument with sufficient sensitivity and control of instrument systematics to address these questions in a systematic way by conducting a volume-limited survey of hot Jupiters and warm Neptunes orbiting nearby stars.

2 Experimental Approach

The near to mid-IR part of the spectrum contains several key molecular signatures. Tinetti et al. (2013) list relevant molecules, and discuss the necessity to measure not one, but several molecular features and their continua to break the degeneracies which would otherwise jeopardise the retrieval process.

Large portions of the near and mid-IR spectral band that is not available to ground-based or air-borne instrumentation (Figure 2). Even at aircraft altitude, several key bands are still saturated. Bands which can be considered sufficiently transparent to be accessible by ground instrumentation are actually affected by atmospheric variations which can easily blind the exoplanet signal or increase the experimental uncertainties severely compromising the detection. As shown in the left panel of Figure 2, the greatly reduced air pressure (about 4 mbar) at balloon altitudes, together

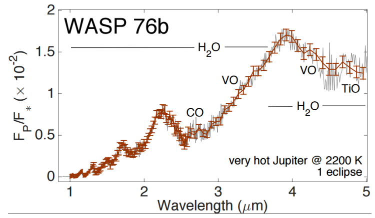

Figure 3: EChOSim simulations of hot Jupiter HD 189733b (left) detection with BETSE. The host star has a k-band magnitude of 8.5. A single secondary eclipse is assumed. The right panel shows simulations of hot Jupiter WASP 76 b observed during a single occultation. The hst star has a k-band magnitude of 5.9. For this class of planets BETSE achieve a detection at a SNR > 7 in a single eclipse observed in day-time (assumed spectrum binned to a constant $\lambda/\Delta\lambda = 100$ grid).

with the stability of the stratosphere, allows exoplanet transit spectroscopy over the whole BETSE band, and enables observations even in daytime. This is important, as a survey experiment will have to be operated in day-time for a LDB campaign, and during both day and night in a ULDB campaign.

A $\sim$ 0.5 m-class telescope, fit with a moderate-resolution spectrometer from 1 to $\sim 5\mu$m is adequate to undertake the first spectroscopic survey of the atmospheres of a significant sample of transiting hot Jupiter and warm Neptune exoplanets. This would result in ground breaking science, particularly since there are currently no alternative facilities to perform spectroscopy of exoplanets over the whole required band. BETSE will be equipped with a moderate resolution spectrometer, and a photometric channel in the visible for stellar monitoring and for the fine pointing system. In Figure 3 we present simulations obtained with EChOSim (Pascale et al., 2014, Waldmann et al., 2014), the end-to-end simulator originally developed for the EChO space mission (Tinetti et al.m 2012) and adapted to include the balloon-specific systematics.

While these simulations also show how effective BETSE is in measuring the spectra of hot Jupiters such as WASP-76b with suficiently high SNR in a single transit, the ability to observe multiple transits and eclipses of the same exoplanets in LDB and ULDB flights allows to stack several observations to increase the SNR on a much larger number of systems. Comparing different transits/occultations of the same exoplanet also allows detailed quantification of experimental uncertainties and systematics.

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Future prospects for radial-velocity searches

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Abstract

Instrumental advances in the last few years have seen the "high frontier" of radial-velocity searches moving towards detection of planets in the few-Earth-mass regime around solar-type stars. A new generation of stable high-resolution infrared spectrometers will soon see a move towards detection of Earth-mass planets in the habitable zones of low-mass stars. The infrared and polarimetric capabilities of the next generation of instruments will also help to combat astrophysical noise from the host stars. In this talk I will survey prospects for realising these ambitions in the face of the challenges presented by instrumental limitations and astrophysical noise originating in the host stars themselves. I will discuss synergies with forthcoming ground-based and space-based transit missions such as NGTS, TESS and CHEOPS, and examine considerations to be taken into account when selecting targets and formulating observation strategies.

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Direct Imaging of Exoplanets, from very large to extremely large telescopes

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Abstract

Presently, dedicated instruments at 8-m class telescopes (SPHERE for the VLT, GPI for Gemini) are about to discover and explore self-luminous giant planets by direct imaging and spectroscopy. In a decade, the next generation of 30m-40m ground-based Extremely Large Telescopes (ELTs) have the potential to dramatically enlarge the discovery space towards older giant planets seen in reflected light and ultimately even a small number of rocky planets.

In order to fulfill the demanding contrast requirements of a part in a million to a part in a billion at separations of one tenth of an arcsecond, the seeing limited PSF contrast must gradually be improved by eXtreme Adaptive Optics (XAO), non-common path aberration compensation, coronagraphy, and science image post-processing. None of these steps alone is sufficient to leap the enormous contrast. High-contrast imaging (HCI) from the ground encompasses all those disciplines which are to be considered in a system approach.

The presentation will introduce the principle of HCI and present the current implementation in the SPHERE, ESO's imager for giant exoplanets at the VLT. It will then discuss requirements and necessary R&D to reach the ultimate goal, observing terrestrial Exoplanets with the next generation of instruments for the ELTs.

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Gaia: Status and Promises

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Abstract

The power of micro-arcsecond (μas) astrometry is about to be unleashed. ESA's Gaia mission, now entering its second year of routine science operations, will soon fulfil its promise for revolutionary science in countless aspects of Galactic astronomy and astrophysics. I will briefly review the Gaia mission status of operations, and the scenario for intermediate data releases. I will then illustrate the potential of μas astrometry for detection and improved characterization of planetary systems in the neighborhood of the Sun.

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The WASP and NGTS ground-based transit surveys

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Abstract

I will review the current status of ground-based exoplanet transit surveys, using the Wide Angle Search for Planets (WASP) and the Next Generation Transit Survey (NGTS) as specific examples. I will describe the methods employed by these surveys and show how planets from Neptune to Jupiter-size are detected and confirmed around bright stars. I will also give an overview of the remarkably wide range of exoplanet characterization that is made possible with large-telescope follow up of these bright transiting systems. This characterization includes bulk composition and spin-orbit alignment, as well as atmospheric properties such as thermal structure, composition and dynamics. Finally, I will outline how ground-based photometric studies of transiting planets will evolve with the advent of new space-based surveys such as TESS and PLATO.

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Exoplanet Science with E-ELT/METIS

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Abstract

METIS - the Mid-infrared E-ELT Imager and Spectrograph - is foreseen as one of the first instruments for the 39-m European Extremely Large Telescope (E-ELT). It will provide diffraction limited imaging and spectroscopy in the L, M, N and Q band and also feature a high-dispersion integral field unit in the L and M band. While being a multi-purpose instrument with a broad and diverse science case, exoplanets are one of the driving science topics for METIS.

In this talk I will highlight a few areas in exoplanet research, where METIS will be uniquely positioned to deliver breakthrough results early in the era of ground-based ELTs. In fact, it might be METIS that takes the first image of a small and possibly rocky planet around a nearby star.

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Habitable Zone Planets: PLATO, and the search for Earth 2.0

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Abstract

The PLATO mission, part of ESA's Cosmic Vision program, will launch in 2024 and will revolutionize the field of transiting exoplanets. By observing a large sample of bright stars, PLATO will discover thousands of terrestrial planets, including hundreds in the habitable zones of their host stars.

The brightness of PLATO targets allows full characterization of both the planets and their host stars, including asteroseismic analysis to precisely determine masses, radii, and ages. Moreover, PLATO host stars will be bright enough to allow atmospheric spectroscopy. Confirmation and characterization of PLATO planets will require a coordinated, ground-based follow-up program to both eliminate false-positives, and derive planetary masses.

I will present an introduction to PLATO, discussing the scientific motivation behind the mission, its aims and goals, and the significant contribution that PLATO will make to the search for a second Earth. I will also talk about the requirements and formulation of the follow-up program, showing that the demands are not as onerous as might be feared.

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ARIEL – The Atmospheric Remote-sensing Infrared Exoplanet Large-Survey

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Abstract

More than 1,000 extrasolar systems have been discovered, hosting nearly 2,000 exoplanets. Ongoing and planned ESA and NASA missions from space such as GAIA, Cheops, PLATO, K2 and TESS, plus ground based surveys, will increase the number of known systems to tens of thousands.

Of all these exoplanets we know very little; i.e. their orbital data and, for some of these, their physical parameters such as their size and mass. In the past decade, pioneering results have been obtained using transit spectroscopy with Hubble, Spitzer and ground-based facilities, enabling the detection of a few of the most abundant ionic, atomic and molecular species and to constrain the planet's thermal structure. Future general purpose facilities with large collecting areas will allow the acquisition of better exoplanet spectra, compared to the currently available, especially from fainter targets. A few tens of planets will be observed with JWST and E-ELT in great detail.

A breakthrough in our understanding of planet formation and evolution mechanisms will only happen through the observation of the planetary bulk and atmospheric composition of a statistically large sample of planets. This requires conducting spectroscopic observations covering simultaneously a broad spectral region from the visible to the mid-IR. It also requires a dedicated space mission with the necessary photometric stability to perform these challenging measurements and sufficient agility to observe multiple times ~500 exoplanets over 3.5 years.

The ESA Cosmic Vision M4 mission candidate ARIEL is designed to accomplish this goal and will provide a complete, statistically significant sample of gas-giants, Neptunes and super-Earths with temperatures hotter than 600K, as these types of planets will allow direct observation of their bulk properties, enabling us to constrain models of planet formation and evolution.

The ARIEL consortium currently includes academic institutes and industry from eleven countries in Europe; the consortium is open and invites new contributions and collaborations.

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What can we expect from near to mid-term direct imaging programs?

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Abstract

Direct imaging for exoplanets has made enormous progress in the last decade owing to the advent of new technologies, efficient algorithms for postprocessing and dedicated observing strategies. A few young giant exoplanets were detected with the previous generation of instruments (beta Pic b, HR8799bcde, HR95086b …). While SPHERE and GPI were conceived with this very purpose, we are thus expecting many more discoveries in the next years. SPHERE comes with a series of facilities to characterize the atmosphere of these planets, from the visible to the near IR, with broad band, narrow band filters, and low to medium resolution spectroscopy as well. It is also a fabulous instrument to study circumstellar disks both in intensity and polarimetry in order to establish the link between planets and their environments. A large survey of 600 targets on a 5 years baseline has been started. The next space telescope, JWST equipped with MIRI and NIRCAM will extend the ability to characterize young giants in the mid IR. No doubt we will learn more about their atmospheres. Finally, by the next decade, very large apertures will become available on the ground. Extremely Large Telescope will have general first light instruments (MICADO, HARMONI), but some programs to image and characterize young giant planets around very distant stars (>100pc) will be feasible. For a much ambitious goal, detecting telluric planets and studying their atmosphere, two paths are now considered either from space (WFIRST AFTA-C is a good candidate) and from the ground with SPHERE-like instruments on ELTs. A review of achievements and perspectives in the context of direct imaging will be presented.