EPJ Web of Conferences **47**, 03005 (2013)
DOI: 10.1051/epjconf/20134703005

CHEOPS: A transit photometry mission for ESA's small mission programme

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Abstract. Ground based radial velocity (RV) searches continue to discover exoplanets below Neptune mass down to Earth mass. Furthermore, ground based transit searches now reach milli-mag photometric precision and can discover Neptune size planets around bright stars. These searches will find exoplanets around bright stars anywhere on the sky, their discoveries representing prime science targets for further study due to the proximity and brightness of their host stars. A mission for transit follow-up measurements of these prime targets is currently lacking. The first ESA S-class mission CHEOPS (CHaracterizing ExoPlanet Satellite) will fill this gap. It will perform ultra-high precision photometric monitoring of selected bright target stars almost anywhere on the sky with sufficient precision to detect Earth sized transits. It will be able to detect transits of RV-planets by photometric monitoring if the geometric configuration results in a transit. For Hot Neptunes discovered from the ground, CHEOPS will be able to improve the transit light curve so that the radius can be determined precisely. Because of the host stars' brightness, high precision RV measurements will be possible for all targets. All planets observed in transit by CHEOPS will be validated and their masses will be known. This will provide valuable data for constraining the mass-radius relation of exoplanets, especially in the Neptune-mass regime. During the planned 3.5 year mission, about 500 targets will be observed. There will be 20% of open time available for the community to develop new science programmes.

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1. INTRODUCTION

The CHaracterizing ExoPlanet Satellite (CHEOPS) will be the first mission dedicated to search for transits by means of ultrahigh precision photometry on bright stars *already known to host planets* in the super-Earth to Neptune mass range ($1 < M_{planet}/\mathrm{M}_{Earth} < 20$). By being able to point at nearly any location on the sky, it will provide the unique capability of determining accurate radii for a subset of those planets for which the mass has already been estimated from ground-based spectroscopic surveys. The mission will also provide precision radii for new planets discovered by the next generation ground-based transits surveys (Neptune-size and smaller).

While unbiased ground-based searches are well-suited to detect the transits and fix the ephemerids, CHEOPS is crucial to obtain precise measurements of planet radii. Knowing *where* and *when* to observe makes CHEOPS the most efficient instrument to search for shallow transits and to determine accurate radii for planets in the super-Earth to Neptune mass range.

This article focusses on the science objectives and requirements and briefly outlines the current design.

2. SCIENCE OBJECTIVES

The main science goal of the CHEOPS mission will be to study the structure of exoplanets smaller than Saturn orbiting bright stars. With an accurate knowledge of masses and radii for an unprecedented sample of planets, CHEOPS will set new constraints on the structure and hence on the formation and evolution of planets in this mass range. CHEOPS has two main targets: 1) (very) bright stars with a known planet from RV searches, and 2) bright stars with a known transit from ground-based transit searches.

2.1 Mass-radius relation determination

The knowledge of the radius of the planet by transit measurements combined with the determination of its mass through radial velocity techniques allows the determination of the bulk density of the planet. Technically, this quantity provides direct insights into the structure (e.g. presence of a gaseous envelope) and/or composition of the body (see Fig. 1). Although it is well known that the determination of planetary structure from bulk density is a highly degenerate problem, the knowledge of the planet mass and radius provides enough information to derive a number of basic quantities relevant to planet structure and hence to formation and evolution to make them vital measurements for further progress.

Large ground-based high-precision Doppler spectroscopic surveys carried out during the last years have identified nearly a hundred stars hosting planets in the super-Earth to Neptune mass range ($1 < M_{planet}/\mathrm{M}_{Earth} < 20$). As search programs continue, the number is going to increase in the coming years. The characteristics of these stars (brightness, low activity levels, etc.) and the knowledge of the planet ephemerids make them ideal targets for precision photometric measurements from space. The new generation of ground-based transit surveys (e.g. NGTS), capable of reaching 1 mmag precision on $V < 13$ magnitude stars, provide yet another source of targets. By the end of 2017, NGTS will provide a minimum of 50 targets in the sub-Saturn size range.

CHEOPS will determine the mass-radius relation in the planetary mass range from $20\,\mathrm{M}_{Earth}$ down to $1\,\mathrm{M}_{Earth}$ to a precision not achieved before. In particular, CHEOPS will be able to measure radii to a precision of 10% for Neptune-size planets.

By targeting stars located anywhere on the sky (some biases exist towards southern hemisphere, where HARPS operates since 2003), which are bright enough for precise radial velocity follow-up – CHEOPS will not suffer from the limitations in the planet mass determination associated with fainter stars. CHEOPS will provide a uniquely large sample of small planets with well-measured radii, enabling robust bulk density estimates needed to test theories of planet formation and evolution.

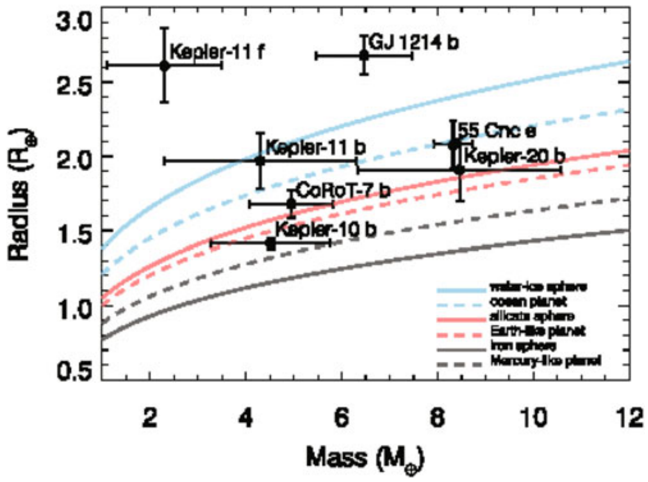

Figure 1. Mass-radius relationship for different bulk composition of the planet (Adapted from [7]) with superimposed known transiting planets where both the mass and the radius of the planet have been measured. The size of the boxes indicates the 1- sigma error on these parameters. So far, in most cases the error bars are too large to obtain an unambiguous measurement of the bulk structure of the planets.

2.2 Identification of planets with atmospheres

In the core accretion scenario, the core of a planet must reach a critical mass before it is able to accrete gas in a runaway fashion. This critical mass depends upon many physical variables, among the most important of which is the rate of planetesimals accretion. The determination of the mean planetary density can provide a lower limit for the mass of the gaseous envelope. For example, a 5-M_{Earth} planet composed of 50% solid terrestrial composition and 50% water vapour has a radius roughly twice as large as the same-mass planet with purely terrestrial composition. In light of recent studies indicating that low density super-Earths with large rocky cores and hydrogen envelopes may survive outgassing, it seems that the presence of a significant H/He envelope would have an even more dramatic effect on the radius due to the reduced molecular weight compared to water. Similar conclusions can be reached assuming that the planetary core is composed of pure water ice. Indeed, for a given mass, the radius of a pure water planet (see Fig. 1) represents an upper limit for the radius of a planet without an envelope. Therefore, a lower limit to the envelope mass can be derived (as a function of assumed envelope composition) by matching the observed radius and mass, assuming a pure water ice core, a composition of the envelope, and a temperature (corresponding to the equilibrium temperature with the stellar flux, an adequate assumption if the planet is not located too close to its star).

CHEOPS will identify planets with significant atmospheres in a range of masses, distances from the host star, and stellar parameters. Using observations of a sample of planets with and without significant gaseous envelopes, CHEOPS will be able to constrain the critical core mass (i.e. identify planets that underwent runaway gas accretion, or those that lost their primordial H-He atmospheres) as a function of the distance to the star and possibly stellar parameters (mass, metallicity). This will be especially true for planets not located extremely close to their stars: if the planet is too close, evaporation could be an issue thus further complicating the analysis.

2.3 Constraints on planet migration paths

It is generally accepted that the envelope masses and compositions of Uranus and Neptune are directly related to their formation in our own solar system. Although forming large cores fast enough is a challenge beyond 10 AU, it is not understood why these two planets did not succeed in accreting larger amounts of gas. Constraining the gas fraction for a large sample of Neptune-like planets, but at various distances to the central star, will shed light on the physical processes that could produce these types of planetary bodies. Yet even observations of planets for which it will be impossible to infer unambiguously the presence of a thick atmosphere (those located below the blue line in Fig. 1) provide strong constraints on formation models in a statistical sense. There is ample evidence that planets are not born where they are observed today but that they have migrated during their formation possibly over large orbital distances. The present day observed location could therefore have been reached following different paths depending upon the growth history of the planet, as well as interactions with the gaseous disc or with other planets. Each of these paths samples different regions of the proto-nebula in varying proportions leading to unique combinations corresponding to the growth history and chemistry appropriate for the amount of time spent at a given orbital radius. As a result, the bulk composition, and hence the mean density, will depend upon which track was followed.

CHEOPS will provide a sufficiently large sample of planets with accurate densities to allow discriminating between common groups of migration paths. In particular, CHEOPS will place constraints on possible planet migration paths followed during the formation and evolution of planets where the clear presence of a massive gaseous envelope cannot be discerned.

2.4 Energy transport in hot Jupiter atmospheres

The detection of the phase curve provides information on planet albedos. These have been well measured for CoRoT-1b [5] and HAT-P-7b [1] with the CoRoT and Kepler missions, respectively. The detailed shape and amplitude of the phase curves represent a powerful tool to study the thermal distribution in the atmosphere (e.g. HD189733b, [3]) and therefore the physical mechanisms and efficiencies of the energy transport from the dayside to the night side of the planet. Since this effect can be seen on any hot Jupiter planet, including non-transiting geometrical configurations, the number of potential targets amongst hot Jupiters detected orbiting bright stars is significant.

CHEOPS will have the capability to detect the phase curve of hot Jupiters in the optical regime, which will provide information on planet albedos. CHEOPS will probe the atmospheres of known hot Jupiters in order to study the physical mechanisms and efficiency of the energy transport from the dayside to the night side of the planet.

2.5 Targets for future spectroscopic facilities

Understanding the true nature of super-Earth planets requires not only precise measurements of their mass and radius, but also a study of their atmospheric properties. This is only possible for transiting planets orbiting bright enough stars to permit high signal-to-noise spectro-photometric observations. This last condition is drastically more stringent for low-mass planets than for gas giants leading to the conclusion that only the few dozens of super-Earths that statistically transit the brightest stars within the solar neighbourhood will ever be suitable for a thorough characterization with future instruments, e.g. [4]. This has been nicely demonstrated in the case of the planet 55 Cnc e. This eight Earth-masses planet is the only one transiting a star visible to the naked eye. First detected by Doppler measurements, transits were later detected by the Spitzer and MOST space telescopes ([2, 6]), revealing a planet with a size of 2.1 Earth radii. Owing to the brightness of its host star ($V = 6$, $K = 4$), very high signal-to-noise occultation photometry was possible with Spitzer, leading to the detection of the thermal emission of this super-Earth planet [2].

Earth-like planets are not expected to bear massive atmospheres. Since the presence of a gaseous envelope (only a few percents in mass) or icy mantle (above 10% in mass) has a large effect on the planet radius and mean density, CHEOPS will be able to discriminate between telluric, Earth-like planets where life as we know it could blossom, from other kinds of Earth-mass planets (hydrogen-rich Earths, ocean-planets), which challenge our understanding of habitability.

CHEOPS will provide unique targets for future ground- (e.g., E-ELT) and space-based (e.g., JWST, EChO) facilities with spectroscopic capabilities. For example, CHEOPS will be able to identify planets that lack an extended envelope, which are prime targets for future habitability studies.

2.6 Astronomical sources variability studies

CHEOPS will have the capability to provide precise differential photometric measurements (photometric time series) of a large number of variable light sources in the Universe. This is regarded as ancillary science for which observing time will be allocated.

3. SCIENCE REQUIREMENTS

Here we briefly summarize the key science requirements of the mission.

3.1 Photometric accuracy

Photometric precision for transit detection (RV targets): CHEOPS shall be able to detect an Earth-size planet transiting a G5 star (0.9 $R_\odot$) of the 9th magnitude in the V band, with a signal-to-noise ratio ($S/N_{transit}$) of 10. Since the depth of such a transit is 100 parts-per-million (ppm), this requires achieving a photometric precision of 10 ppm in 6 hours of integration time. This time corresponds to the transit duration of a planet with a revolution period of 50 days.

Photometric precision for transit characterization (NGTS/ ground based targets): CHEOPS shall be able to detect a Neptune-size planet transiting a K-type dwarf (0.7 $R_\odot$) star of the 12.5th magnitude in the V band (goal: V = 13) with $S/N_{transit} = 30$. Such a transit has a depth of 2500 ppm and last for nearly 3 hours for planets with a revolution period of 13 days. Hence, a photometric precision of 85 ppm is to be obtained in 3 hours of integration time.

3.2 Sky coverage

Stars with planets detected via Doppler velocimetry: 50% of the whole sky should be accessible for 50 days of consecutive observations per year and per target with observation duration longer than 50% of the spacecraft orbit duration (> 50 min for 100-min spacecraft orbital period).

Stars with planets detected via ground-based transit surveys: 25% of the whole sky, with 2/3 in the southern hemisphere, should be accessible for 13 days per year and per target, with observation duration longer than 80% of the spacecraft orbit duration (> 80 min for 100-min spacecraft orbit).

3.3 Temporal resolution

Individual exposures should be short enough to avoid saturation on V $\sim$ 6.5 magnitude stars, but the temporal resolution of the measurement should be 1 minute. Full frame images (addition of shorter images when required) will be recorded (and later downloaded) in 1-minute intervals. The time stamp (UTC) uncertainty on the time of exposure should be smaller than 1s.

3.4 Mission duration

Transit detection on bright stars identified by Doppler surveys will need about 2 days of continuous pointing on target to cope with uncertainties on radial velocity ephemerids of the longest period planet

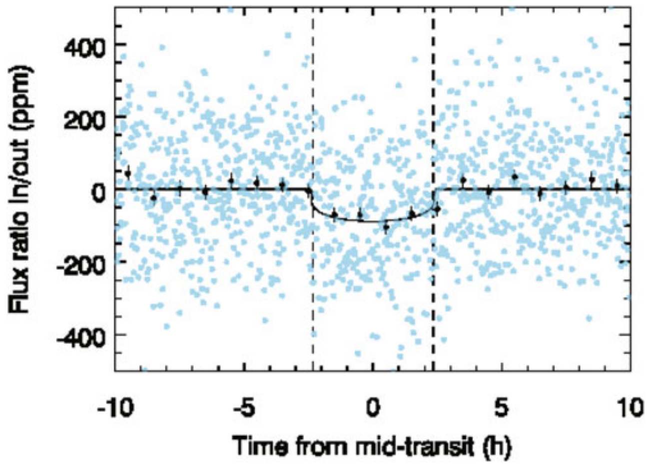

Figure 2. Simulation of a transiting Earth-sized planet with a 50 day period orbiting a G5 dwarf star of the 9th magnitude in the V band, as observed by CHEOPS. Sampling time is 1 minute and photon noise 150 ppm/minute. The black dots indicate 1h-averaged photometry. This light curve illustrates a transit detection with a $S/N_{transit} = 10$.

(about 3–5% of the orbital period). With a minimum of 200 targets and 50% of orbit interruptions, this corresponds to a minimum total of 800 days of satellite life.

For NGTS targets a shorter on-target time is required (12 hours). If one considers 50 targets with a single transit observation and 50 additional targets where 4 transits will be observed and 5 targets where 10 transits may be required we end up with 150 days. With 20% efficiency correction this leads to 180 days of satellite life.

Observations to detect the planets directly in reflected light will be possible for a handful of hot Jupiters. To obtain a reliable measurement, disentangled from possible stellar photometric variability, observations of 3 full planetary orbits are needed. Assuming a typical 5 days orbital period for hot Jupiter, 15 days of continuous observation are required. Estimating a sample of 5 hot Jupiters for which these observations are required, this corresponds to 75 days.

In total these three programs combined require 500 separate target pointings. Assuming 1 hour per pointing, 10% margin on each program, the mission duration is estimated at 1175 days or 3.2 years. Adding to this duration the open time allocation for carrying out ancillary science (up to 20%), the total duration of the CHEOPS mission is estimated to be 3.5 years.

4. MISSION IMPLEMENTATION

To reach its science goals, CHEOPS has to measure photometric signals with a precision limited by stellar photon noise of 150 ppm/min for a 9th magnitude star. This corresponds to the transit of an Earth-sized planet orbiting a star of 0.9 $R_\odot$ in 50 days detected with a $S/N_{transit} > 10$ (100 ppm transit depth). Reaching this ultrahigh photometric stability on the budget of an S-class mission is challenging. Figure 2 shows the simulated light curve of a Earth-sized transiting planet.

4.1 Spacecraft and orbit

The mission will fly a single payload on a small satellite platform and the total mass of the spacecraft (S/C) will be on the order of 200 kg. To obtain high photometric stability, thermal stability of the instrument and straylight suppression from the Earth are design drivers. At the same time, the observable sky should be maximized.

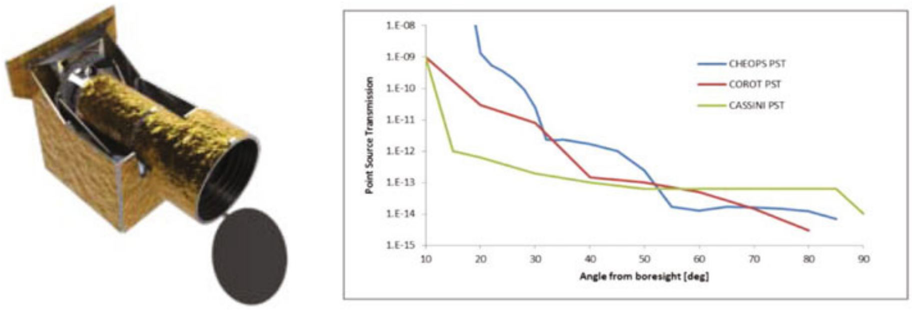

Figure 3. *Left*: rendering of the S/C and payload configuration. *Right*: stray-light performance of the current baffle design in terms of the point source transmission function. CHEOPS is optimized for angles larger 35 degrees.

Table 1. CHEOPS mission summary.

Name	CHEOPS (CHaracterizing ExOPlanet Satellite)
Primary science goal	Measure the radius of planets transiting bright stars to 10% accuracy
Targets	Known exoplanet host stars with a V-magnitude $<$ 12.5 anywhere on the sky
Instrument	33 cm reflective on-axis telescope
Wavelength	Visible range: 400 to 1100 nm
Detector	13 μm pixel 1k $\times$ 1k CCD (baseline: e2v CCD47-20 AIMO)
Total satellite mass	200 kg
Orbit	LEO sun-synchronous LTAN 6 am (or 6 pm), 620 to 800 km
Launch date	2017
Lifetime	3.5 years
Type	s-class

To meet the above requirements, the telescope will be orbiting in a Sun Synchronous Low Earth Orbit (LEO) having a local time of ascending node (LTAN) of 6 am and an altitude in the range of 620 to 800 km (depending on launch opportunities). Hence, the satellite will follow as close as possible the day-night terminator and the target stars will be above the night side of the Earth. This orbit also minimizes eclipses and therefore provides a thermally stable environment. To allow the stringent thermal control of the detector (see next section), the S/C will be 3-axis stabilized but nadir locked. Therefore, the payload radiators can always face away from Earth to cold space. A small sun shield prevents illumination of these radiators by the Sun, therefore providing a thermally stable environment for the payload radiators. This orbit allows to fullfill the science requirements.

In addition to a thermally stable environment, the instrument requires high pointing stability: The telescope line-of-sight must remain stable to 8 arcsec RMS over a 10 hour observing period. This precision can be achieved on a small platform by including the instrument data in the attitude control loop.

The CHEOPS satellite will observe individual target stars in a track and stare mode. Following target acquisition of a single star - which will take less than a minute – the telescope will continuously point at the target for typically 6-12 hours but up to a few weeks if the phase modulation of the planet is measured. The telescope operation will be dominated by many such short pointings, typically only observing a star when the transit is expected to occur. So, from a data point of view, CHEOPS is a simple instrument. We baseline an S-band system for TM/TC and data downlink. The S/C will provide 50 W continuous power for instrument operations and allow for at least 1Gbit/day downlink. See Fig. 3 (left) for a rendering of the S/C.

4.2 Payload

The payload is a single instrument: a 30 cm effective aperture reflecting telescope to observe individual target stars. The major requirement is photometric stability, therefore the detector gain has to be extremely stable and Earth stray light must be supressed to a very high degree.

The optical design is based on a F/8 Ritchey-Chretien style on-axis telescope and a beam shaper to provide a de-focussed image of the target star with a point spread function (PSF) covering an area of 765 px. The detector will be a single frame-transfer back-side illuminated CCD detector. To achieve the required stability, this detector has to be thermally stabilized to 5–15 mK at an operating temperature of -40 C. This is achieved by heating against cold radiators that are not affected by Solar or Earth radiation.

Being in a LEO, Earth reflected light hast to be prevented from reaching the detector: a very strong stray light attenuation is required. An industrial study has led to a suitable optical design, which minimizes stray light onto the detector utilizing a dedicated field stop and a baffling system. This design meets the requirement of < 1 photon/pixel/second stray light onto the detector even in the worst case observing geometry on the baseline orbit (see Fig. 3, right, for the achieved PST).

5. CONCLUSIONS

CHEOPS will fill the gap in transit follow-up capability for bright stars in the sky. It will target approx. 500 targets of interest in its 3.5 year mission. CHEOPS will:

- Determine the mass-radius relation in a planetary mass range for which only a handful of data exist and to a precision never before achieved.
- Identify planets with significant atmospheres as a function of their mass, distance to the star, and stellar parameters.
- Place constraints on possible planet migration paths followed during formation and evolution for planets where the clear presence of a massive gaseous envelope cannot be discerned.
- Detect the phase variations of a handful of known Hot Jupiter in order to study the physical mechanisms and efficiency of the energy transport from the dayside to the night side of the planet.
- Provide unique targets for future ground- (e.g. E-ELT) and space-based (e.g. JWST, EChO) facilities with spectroscopic capabilities. With well-determined radii and masses, the CHEOPS planets will constitute the best target sample within the solar neighbourhood for such future studies.
- Offer up to 20% of open time to the community to be allocated through competitive scientific review. CHEOPS will have the capability to provide precise photometric measurements (light curves) of a large number of variable light sources in the universe.

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