PROCEEDINGS OF SCIENCE

CHEOPS (CHaracterizing ExOPlanets Satellite) Mission

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The Characterizing ExOPlanet Satellite (CHEOPS) mission was selected in October 2012 by ESA as the first small mission. It will be a ultra-high precision photometer dedicated to the observation of transits of known exoplanets on bright stars, for which the mass has already been measured via ground-based spectroscopic surveys. Its precision will allow the accurate determination of the planetary radii and, by consequence, the planetary bulk density. CHEOPS will also unveil transiting exoplanets of interest for in-depth characterization, a legacy for future instruments suited to the spectroscopic characterization of exoplanetary atmospheres.

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1. Introduction

In 1995 the discovery of the first planet orbiting a star similar to the Sun was announced [1]. Since then, thousands of extra-solar planets (exoplanets) have been discovered using a variety of techniques. So far, the most effective methods in terms of numbers of discoveries rely on the measurement of dynamical and/or photometric perturbations on the host star induced by the planets. From the dynamical point of view, the radial velocity technique measures the Doppler shift induced by the orbital motion of the planet onto the host star, and it provides a lower limit on the planetary mass. The transit method provides an estimate of the radius of the planet by measuring the apparent dimming of the star when the planet crosses the stellar disk as observed from Earth. Planets investigated by both methods are interesting because both mass and radius, hence the bulk density, can be measured.

In the last twenty years, great improvements have been achieved in the application of the two techniques. As a matter of fact, the CoRoT and Kepler space missions have been dedicated to transit searches, while ground-based radial velocity surveys have benefited from the construction of high-resolution spectrographs specifically designed for the measurement of radial velocities down to the $\sim$1 m/s precision (e.g., ELODIE, HARPS, HARPS-N). Nonetheless, exoplanets with mass lower than $\sim$30 earth masses with precise measurements of mass and radius are limited. This is due to the fact that the CoRoT and Kepler targets are still too faint for the Doppler measurement with current spectroscopic facilities. Thus, there are essentially two populations of exoplanets, one with precise measurement of the mass and the other with precise measurements of the radius, with little overlap between the two.

The goal of CHEOPS is to increase the number of exoplanets for which both mass and radius are measured with good precision, by observing with ultra-high photometric precision the transit of known exoplanets orbiting bright stars and for which the mass has been accurately measured with Doppler techniques. For this purpose, CHEOPS was selected in October 2012 as the first small mission (S-mission) in the ESA Science Programme. Given its photometric accuracy, it will be able to determine accurate radii of exoplanets, either already known or discovered by the next generation transit surveys. CHEOPS will also unveil transiting exoplanets of great interest for deeper characterization of their atmospheres with future spectroscopic facilities.

2. Mission management and organization

In March 2012 the European Space Agency (ESA) issued a call for proposals of small class missions to be developed and launched within 4 years. In October 2012 CHEOPS was successfully selected as the first S-mission, and it will be launch-ready by end-2018.

CHEOPS is implemented in partnership between ESA and a consortium of European countries led by Switzerland [2, 3]. To this purpose, ESA and the CHEOPS Mission Consortium (CMC) jointly coordinate the progress of the mission implementation.

The core science program, which will take 80% of the mission lifetime, is defined inside the CMC, while 20% of the science observation time will be open for projects proposed by guest observers. The core science targets will be selected from the sample of known exoplanets, while

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additional targets will be added as new interesting exoplanets are detected by on-going or future projects.

Open time proposals can be submitted after ESA's announcements: the first call for proposal is expected to be 6 months before launch, with subsequent calls foreseen to be on an annual basis thereafter. A Time Allocation Committee will evaluate and select the proposals, ranking them as a prioritized target list to the SOC. This list will be merged with the the core science program. The Instrument Observer Manual and tools to assist the proposal process will be publicly delivered to the community.

3. Science objectives

The main science goal of the CHEOPS mission is the study of the structure of exoplanets smaller than Saturn orbiting bright stars and for which a precise measurement of the planetary mass is available. CHEOPS will thus allow to set new constraints on the structure, formation and evolution of exoplanets in this mass range.

3.1 Planetary interior structure

The measurement of the radius and the mass of a planet gives the planetary bulk density, which is intimately related to the structure and the composition of the planet. Unfortunately, the determination of planetary structure from bulk density is a highly degenerate problem (e.g. [4, 5]). For instance, for rocky planets the degeneracy arises from the relative amounts of metals in the core (mainly iron), rocks (silicates in the mantle), volatiles and gases. As a matter of fact, a planet made of silicates can have the same mass and radius of another planet made of iron and water. Nonetheless, it has been shown that using the solar abundances as proxy for the planetary bulk composition, the internal structure of Mars, Earth, and Venus can be recovered from the respective masses and radii [5].

The planetary structure is also determined by the size and composition of its gaseous envelope. Given the planetary mass, the maximum planetary radius without atmosphere is the one of a planet made of pure water ice. By consequence, a lower limit to the mass of the atmosphere can be derived assuming a pure-water ice core, a chemical composition of the envelope, and a planetary equilibrium temperature. The characterization of exoplanets with and without atmospheres, in context with their other physical properties, provides constraints on current planet formation theories.

3.2 Constraints on planet formation models

The determination of the structure of exoplanets provides also constraints on planet formation models.

In the core accretion formation model [6], during the first stage of planetary formation the growth of a planet occurs by accretion of planetesimals. When the rocky core becomes massive enough, it also starts to gravitationally capture nebular gas. The accretion of rocks and gas goes on until the rocky core and the gaseous envelope have the same mass. After that, the rate of gas accretion increases, leading to the formation of a massive atmosphere.

From the observational point of view, the critical core mass above which gaseous giant planets are formed can be constrained by measuring the bulk density of exoplanets with similar properties

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(host star and orbital radius, known for all CHEOPS targets). Below the mass of Saturn, planets are expected to have sub-critical cores, thus they should have larger densities compared with planets with super-critical cores. The threshold mass between high and low density planets thus gives an estimate of the critical planetary mass, which can be related to the critical core mass using internal structure models.

On the other hand, there is evidence that planets do not form at the present-day distance from their host stars, but they migrate during their formation spanning a large interval of orbital distances, thus interacting with different regions of the proto-planetary nebula. The history of planet migration thus determines the structure and composition of the atmospheres of giant planets. As a result, the bulk composition and density depends on the path followed by the planet during migration [7, 8]. The comparison of the measured bulk density with theoretical models of planetary migration will thus give an insight on the formation of exoplanets.

3.3 Orbital dynamics and exomoons

If a planetary system is made up of only one planet and its host star, then planetary transits occur at regular time intervals. If the system contains other planets, which does not transit the stellar disc, then it is possible to discover them by measuring the gravitational interactions between the planets. In particular, it is possible to measure the variations of the time interval between transits. The Transit Time Variation (TTV) is thus a powerful technique to discover additional planets [9, 10], by which it is possible to constrain the parameters of the third body. Given the current statistics on exoplanetary systems, these additional planets are expected to be quite common in the CHEOPS sample [11].

The detection and study of moons of exoplanets (exomoons) [12, 13] is something that has not been achieved even by the Kepler and K2 missions. Since the sphere of gravitational influence of a planet shrinks with decreasing orbital distance, the chances to find stable exomoons around close-in exoplanets are small. Nonetheless, simulations show that exomoons larger than the Earth can be stable over 4 Gyr around planets with orbital periods larger than 16 days. To discover these systems, up to five transit observations of such planets will be needed during the CHEOPS mission.

3.4 Targets for future spectroscopic facilities

The true nature of exoplanets requires also the study of their atmospheric properties. In principle, this is possible by analyzing the stellar light filtered by the planetary atmosphere during a transit, or by measuring the flux emitted and reflected by the planet itself. However, these techniques can be applied to transiting planets orbiting stars bright enough to permit high signal-to-noise spectro-photometric observations. This is the case of the planet 55 Cnc e: owing to the brightness of its host star (V=6, K=4), very high signal-to-noise infrared photometry of the planetary occultation (i.e. when the planets passes behind the stellar disk) has been provided by Spitzer, leading to the measurement of the planetary thermal emission [14].

By means of the observation of planetary occultations, CHEOPS will allow us to measure the light reflected by the planet, and will thus provide unique interesting targets for future ground-based (e.g., E-ELT) and space-borne (e.g., JWST) facilities with spectroscopic capabilities.

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4. Science requirements

In order to achieve the objectives presented in Sect. 3, CHEOPS has to satisfy a number of requirements, which are summarized in the following sections.

4.1 Photometric accuracy

CHEOPS will observe transits of known planets with masses between 1 and 30 Earth masses, i.e. super-Earths and Neptunian planets.

For the case of super-Earths orbiting Sun-like stars with magnitude $6 \leq V \leq 9$ mag, the requirement is a photometric precision of 20 part per million (ppm) in 6 hours of observation time. This time interval corresponds to the duration of the transit of a planet with an orbital period of 50 days.

In the case of Neptune-size planets orbiting K-type dwarfs with magnitude $V \leq 12$, the goal is a photometric precision of 85 ppm in 3 hours of integration time, corresponding to the transit duration of a planet with an orbital period of 13 days.

4.2 Target Visibility and Sky Coverage

The design of the telescope is aimed at acquiring the most precise photometry also minimizing the stray light due to the Sun and the reflected light from the Earth and the Moon. Stray light is further minimized by limiting the directions in which the telescope points. In particular, the line of sight of the science observations will have to be:

- more than 120° from the direction to the Sun;
- more than 35° from the direction to any illuminated point on the Earth;
- more than 5° from the Moon.

Despite these restrictions, the CHEOPS mission is designed to maximize the accessible sky fraction. For super-Earths, CHEOPS will be able to access 50% of the sky for 50 cumulative days of observations per year and per target with an observation duration longer than 50 min. This requirement is a trade-off involving the maximum orbital period of the exoplanets the CHEOPS will observe (50 day), which corresponds to an orbit at the inner edge of the habitable zone of K stars.

For Neptune-like exoplanets, the requirement is 25% of the sky, with 2/3 in the southern hemisphere, accessible for 13 cumulative days per year and per target, with observation duration longer than 80 min.

5. Mission design

The CHEOPS instrument is a ultra-high precision broad-band photometer: its passband covers the 0.3 to 1.1 μm wavelength range, the blue and red cut given by the sensitivity of the CCD detector and the optical system. The telescope has a Ritchey-Chretien optical configuration which re-imagine the light onto the CCD. The entrance pupil of the system is located at the primary mirror, which has a diameter of 320 mm and an effective collecting area of 76793 mm^2 (considering the central obscuration of the primary mirror). The effective focal length of the telescope is 1600 mm,

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which gives a focal ratio F/5. The 0.32 degrees field of view is projected with a 1 arcsec/px plate scale onto the detector. The detector selected for the mission is an e2v CCD47-20 (13-μm pixel 1k$\times$1k, AIMO).

CHEOPS will be injected in a dawn-dusk Sun-synchronous orbit, with an altitude of 700 km. The instrument will be installed on top of the platform, behind a fixed Sun-shield. The CCD is nominally operated at the temperature of 233 K, and is passively cooled by a dedicated radiator.

With the chosen Sun-synchronous orbit and the available ground stations, four short contacts per day will be available for telecommand uploading and telemetry downloading between the ground segment and the spacecraft. To reduce the amount of data to be stored on board and the down-linked, only a small 200$\times$200 pixels window centered on the target will be recorded and transfered to the ground. Once the telemetry has been received and checked, the data reduction pipeline will be executed to apply the automatic calibration and corrections to the raw images and to extract the light curves for the specific targets.

To achieve the best photometric accuracy, CHEOPS uses a defocussed stellar point spread function. This is a compromise between the pointing jitter introduced by the pointing performance and the uncertainties introduced by the flat field correction. To reduce the uncertainties introduced by pointing inaccuracies, two important strategies were adopted. First, the star trackers have been designed on the instrument itself to limit the thermo-elastic distortion between them and the line of sight of the instrument. Secondly, the spacecraft pointing system operates with the payload in the loop, i.e. the targeted star is continuously re-centered in the science frames during the operations.

6. Mission lifetime

Assuming 2 days of observation time per target with a 50% on-target visibility, the transit detection on bright stars identified by Doppler surveys will need about a minimum of 600 days of satellite life for 150 targets. For targets from ground-based transit surveys, the faintest ones requiring up to 10 observed transits, a total of 180 days of mission is foreseen, assuming an observing time of 12 hours per transit and an efficiency of 80%. The observations of the reflected light of exoplanets will be possible for a handful of hot Jupiters. It will require 75 days of mission for a sample of 5 hot Jupiters.

Thus, considering all these programs together with some margins for overheads and calibrations, the mission duration is estimated at about 950 days. Adding the 20% open time (Sect. 2) and the commissioning phase of 0.2 years, the total minimum duration of the CHEOPS mission is 3.5 years.

Since the rate of exoplanet discovery is high enough to expect new interesting exoplanets within the next 5 years (e.g., TESS will operate simultaneously with CHEOPS), and since no other mission similar to CHEOPS is planned in this time frame, an extension of the mission lifetime to 5 years will allow to significantly enhance the science impact of the mission.

7. Conclusions

The CHEOPS mission will target approximately 500 targets of interest in its nominal 3.5 year lifetime. The main objectives of CHEOPS are:

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- to determine the mass-radius relation for super-Earths and exoplanets;
- to identify significant atmospheres of planets with different masses, orbital distances, and stellar parameters;
- to constrain models of planet formation and evolution;
- to study the energy transport from the day side to the night side of exoplanets;
- to provide unique targets for future ground-based and space-borne facilities with spectroscopic capabilities;
- to offer 20% of open time to the community.

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