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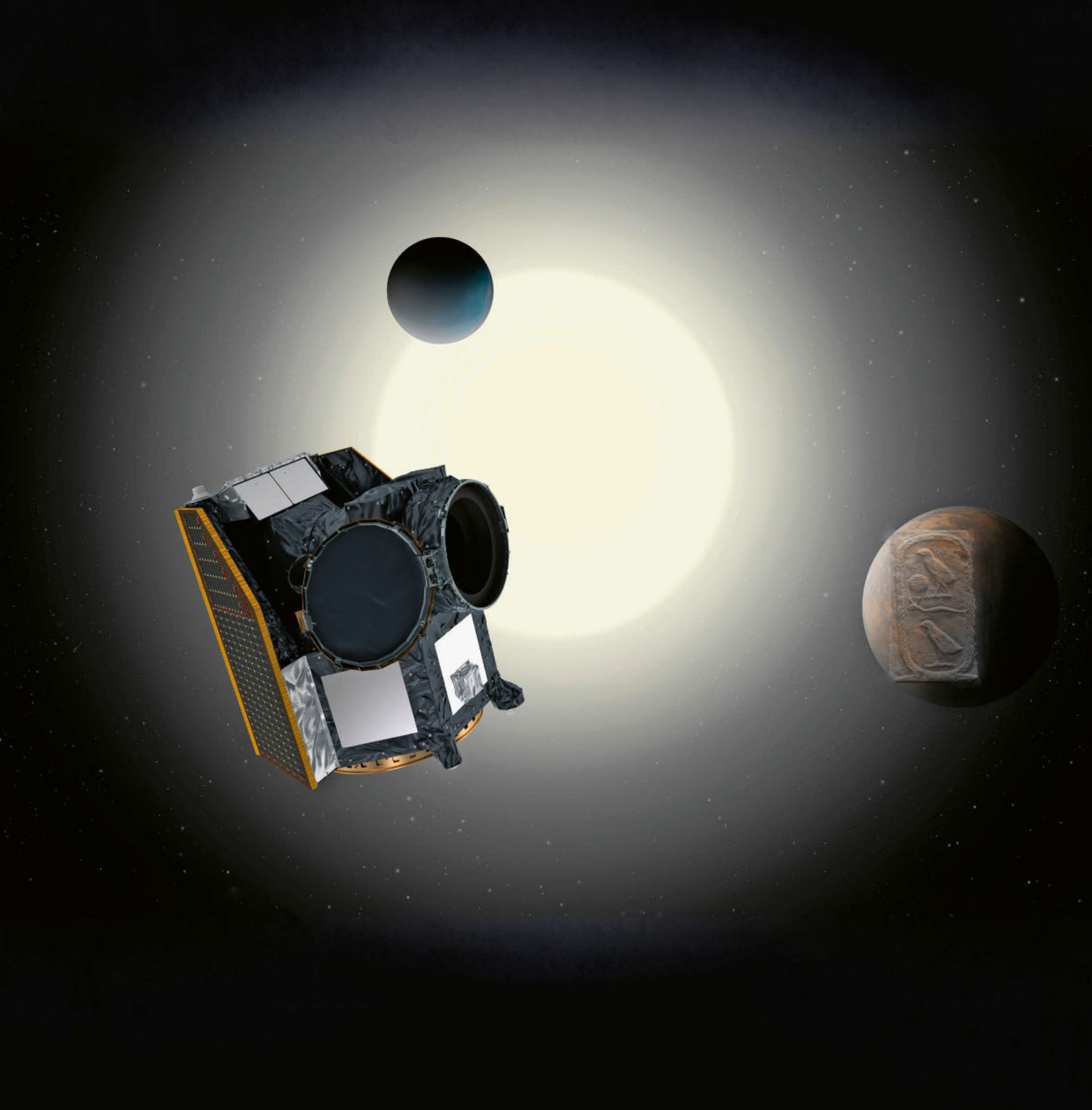
CHEOPS



Editorial

Surely most of us are aware that we live on a very particular planet in extremely unusual conditions and surroundings. Still, the question of whether there could be similar environments somewhere in the Universe has been of great interest to mankind since long. This "somewhere" would be preferably in the accessible (at least by some information-transferring wavelengths) range of the world … How else would we know?

The search for and study of planetary systems beyond our solar system is one of the fastest growing field in astrophysics. Moreover, it even might have acquired the status of a good "Swiss tradition".

The planet hunt is one thing, complicated enough, but after a discovery the real work and study starts – a planet has been found, what are its characteristics? What can we learn about its formation and evolution? How does it fit into our current models and theories of planet formation in general – does it fit at all? Do we need to revise or at least update our view on the physics of planetary systems?

Several issues of the *Spatium* series have already been dedicated to the topic of exoplanets and their detection. This issue, however, is describing CHEOPS, the special mission to further investigate previously detected systems and to provide more details about the host star and its companions than pure detection missions can deliver. Its scientific instrument has been developed and built at the University of Bern, in cooperation with other Swiss and mainly European universities. It is a consequent step forward in the study of planetary systems, and it shows that small and dedicated missions with rather limited budgets can deliver spectacular results and greatly help in advancing science. The content of the actual *Spatium* is based on a talk given by Dr. Andrea Fortier on 20 January 2021 in the pro ISSI lecture series. Dr. Fortier, from University of Bern, has been the CHEOPS Instrument Scientist since 2013 and contributed significantly to the success of this Swiss-lead mission that was conducted as a follow-on in the tradition of planet detection and study at Swiss science institutes.

Anuschka Pauluhn
Mönthal, September 2021

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Title Caption
Artist's view of CHEOPS deciphering signals from a planetary system.
The image is based on a file by ESA/ATG medialab.

CHEOPS

By Dr. Andrea Fortier, Center for Space and Habitability, University of Bern

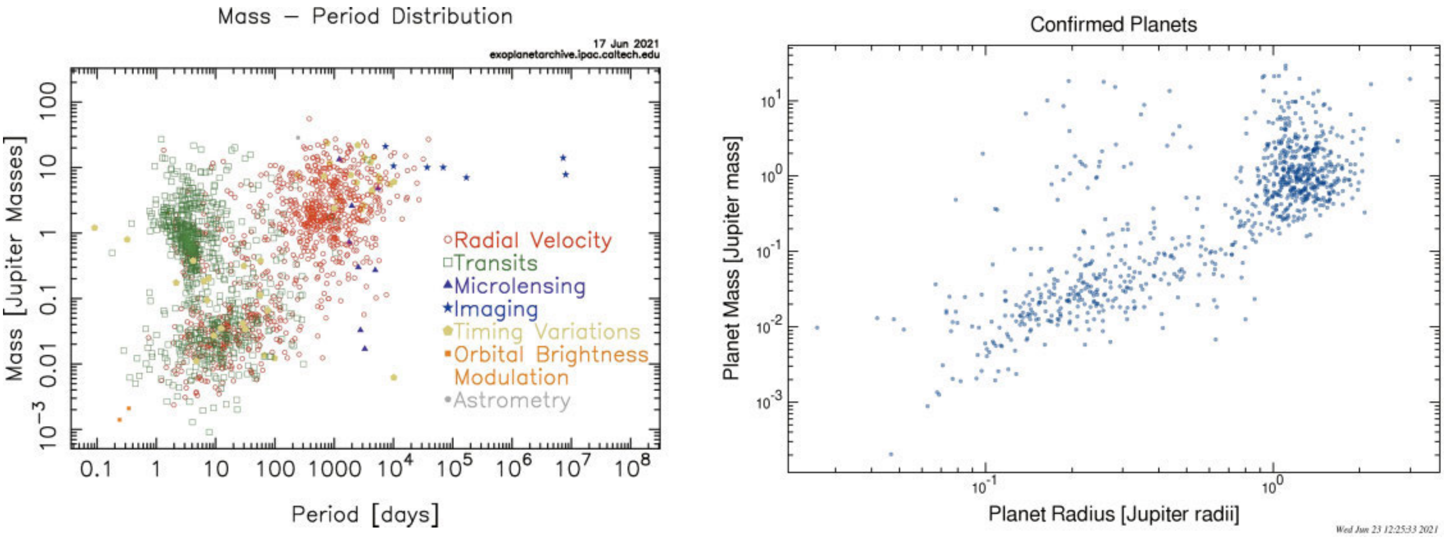
1. Planets – the Earth is not alone

The search for planets beyond the solar system, exoplanets for short, has become a well-established part of astrophysics. Since the first agreed-on discovery of a spectacular example of this species by Michel Mayor and Didier Queloz from the University of Geneva in 1995, honoured by the physics Nobel Prize in 2019, the quest of finding companions of stars other than our Sun has sky-rocketed. The number of confirmed detections at the time of writing is surpassing 4700 (cf., **Figure 1**).[1]

Detection alone, although not trivial, is not enough, a characterisation of planetary systems via dedicated observations is necessary to foster improved understanding of the dynamics and evolution. Interesting questions concern the planet formation and how planets "find their orbits", moreover, how their characteristics vary with their orbits. Of course, the discovery and description of planets orbiting solar-type stars at periods of hundreds of days in regions of "habitable" conditions is of particular interest, as those would potentially resemble Earth-type planets. The planets' density, magnetic field, and atmosphere are of fundamental importance in this respect.

It is on this side of more detailed studies where the CHaracterising ExOPlanet Satellite (CHEOPS) mission delivers its contributions. CHEOPS is an ESA mission implemented in partnership with Switzerland, through the Swiss Space Office. The University of Bern leads a consortium of eleven ESA Member States contributing to the mission and participating in the CHEOPS Science Team.

Figure 1: Diagrams of confirmed planet detections with the various detection methods ***(left)***, and ordered to show the planetary mass in multiples of the Jupiter mass vs. the planetary radius, also referenced to Jupiter ***(right)***.
(Source: The NASA Exoplanet Archive, operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program, https://exoplanetarchive.ipac.caltech.edu.)



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[1] The current count, together with the respective detection methods and customised figures can for example be viewed at the nicely maintained site http://exoplanet.eu.

2. The science

The hunt

Before the confirmed detection of the "Hot Jupiter" 51 Pegasi b by Mayor and Queloz, only the planets orbiting the Sun were known with certainty, with Mercury being the closest, orbiting with a period of 88 days, and Pluto the most outward, at that time still regarded as a planet, orbiting with 248 years. Today, Neptune is considered the farthest solar planet, orbiting at a period of 165 years. The four inner planets Mercury, Venus, Earth and Mars, have dense, rocky compositions, and are called terrestrial planets. The four outer ones are the two gas giants Jupiter and Saturn and the two ice giants Uranus and Neptune.

Afterwards, and more than 4700 planets later, a multitude of planets and planetary systems have been found, several in the so-called habitable zone[2] of their host stars (cf., for example, the *Spatium* issues 30 and 36).

The various ways to detect planets around stars other than our Sun have already been described earlier, for example in the *Spatium* issues 41 and 47.[3]

To summarise, the main methods are:

direct imaging

- It is suitable for large planets that are distant enough from the host star.
- It needs a coronagraph to block the host star's light.

radial velocity measurements

- It uses Doppler spectroscopy measuring changes in the radial movement of the host stars.
- The real orbital inclinations and the true masses of the planets are generally unknown. The method provides only lower limits of the planetary mass.

transit measurements

- This method records the light-curve of the host star when eclipsed by a passing object.
- It allows the determination of the planet's size.

gravitational microlensing

- The light of far-away sources is bent differently when passing stars with planet(s) or even moons than when passing a star without companions (see, e.g., *Spatium* 32 and 45).

timing methods

- It is applicable for pulsars as host stars: their regular pulsar frequency is changed due to a companion.

astrometry

- This method uses measurements of tiny changes in a star's position as it moves around the common centre of mass of its planetary system. ESA's Gaia mission is using this technique.

Not all methods can provide the same information, and whenever possible a combination is preferred. In the following, we will enlarge on the *radial velocity method* and on the *transit method,* which have so far been employed in the vast majority of detections. The latter is used by the CHEOPS mission.

The *radial velocity method* can provide estimates of the planetary mass. An exoplanet causes its host star to move in a small orbit around the centre of mass of the star-planet system. This "wobble" can be observed if the radial velocity of the star is sufficiently high, which of course works better for larger planetary companions. A graph of measured radial velocity versus time will give a characteristic curve (in the case of a circular orbit this will have the form of a sine curve) of higher velocities if the star is moving towards the observer, and of lower velocities for movement away from the observer.

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[2] A possible definition of a "habitable zone" is the range of orbits around a star within which a planetary surface can support liquid water given sufficient atmospheric pressure. However, the attribute "habitable" per se is hard enough to define, meaning habitable by life, as we know it.

[3] Nice summaries and visualisations can also be found on the ESA and NASA webpages https://sci.esa.int/web/exoplanets/-/60655-detection-methods, https://www.esa.int/Science_Exploration/Space_Science/How_to_find_an_extrasolar_planet, https://exoplanets.nasa.gov/alien-worlds/ways-to-find-a-planet (visited Sept. 2021).

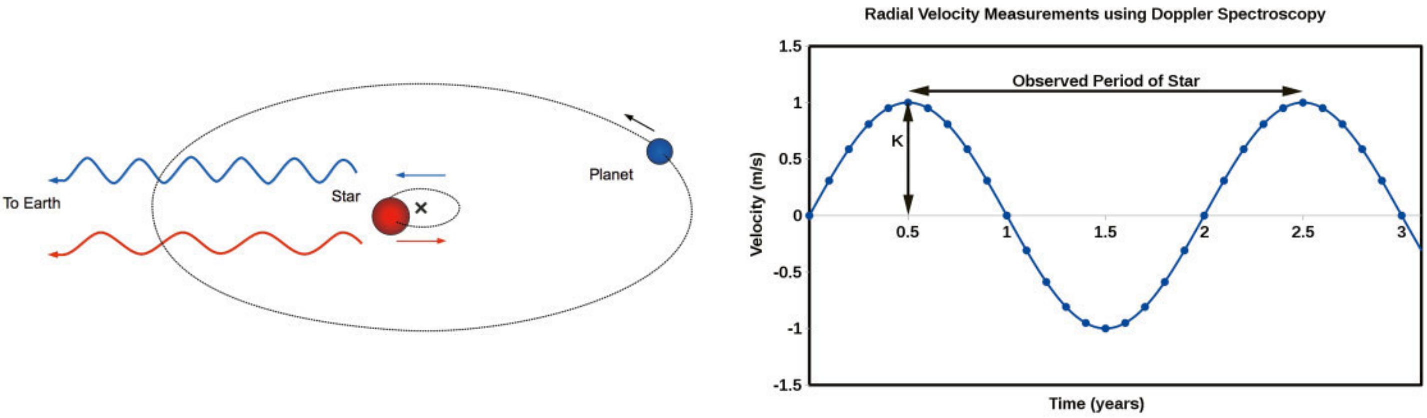

Figure 2: Radial velocity principle: Due to its motion in the star-planet system determined by the mutual gravitational forces, the spectrum of the star, measured for example at Earth, appears shifted. From the shifts of the spectral lines in the star spectrum with respect to the theoretical (undisturbed) spectrum the radial velocity can be determined. The period and amplitude of its variation are used to determine the lower limit of the planet mass. (Source: Wikipedia, under the Creative Commons Universal Public Domain Dedication.)

These velocities are determined from the Doppler shifts in the spectra of the star. The amplitude and period of the curve will allow the minimum mass of the planet to be calculated using Kepler's third law[4]. A sketch of the method is depicted in **Figure 2.**

The major limitation with Doppler spectroscopy is that it can only measure movement along the line-of-sight, and so depends on a measurement (or estimate) of the inclination of the planet's orbit to fully determine the planet's mass. If the orbital plane of the planet happens to line up with the line-of-sight of the observer, then the measured variation in the star's radial velocity is the true value. However, if the orbital plane is tilted away from the plane tangential to the celestial sphere, then the true effect of the planet on the motion of the star will be greater than the measured variation in the star's radial velocity, which is only the component along the line-of-sight. As a result, the planet's true mass will be greater than measured.[5]

The real orbital inclinations and thus the true masses of the planets are generally unknown.

Moreover, the expected changes in radial velocity are very small – Jupiter causes the Sun to change velocity by about 12.4 m/s over its orbital period of 12 years, and the Earth's effect is only 0.1 m/s over a period of 1 year – meaning that long-term observations by instruments with a very high resolution are required. Consequently, the method is best at detecting very massive objects close to the host star, which have the greatest gravitational effect on the parent star, and thus cause the largest changes in its radial velocity. Observation of many spectral lines simultaneously and many orbital periods allows to increase the signal-to-noise ratio, increasing the chance of observing smaller and more distant planets, but planets like the Earth remain undetectable with current instruments. Of course, stability of the spectra and the instruments is required.

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[4] Kepler's third law describes the motion of two bodies around a common centre of mass: it relates the orbital period (the time it takes to complete one full orbit) with the distance between the two bodies (the orbital separation), and the sum of their masses.

[5] The minimum-mass measurement is: $M_{min} = M_{true} \sin i$, $M_{true} = M_{min} / \sin i$, where i is the inclination, i.e., the angle between the orbital plane of the planet and the plane of the observer.
An inclination of 0° or 180° corresponds to a face-on orbit (which cannot be observed by radial velocity), whereas an inclination of 90° corresponds to an edge-on orbit (for which the true mass equals the minimum mass).

The *transit method* uses photometric measurements to record transits of companions in front of their host star's disk. If a planet crosses and obscures part of the star, the observed visual brightness drops, the measured lightcurve shows a "dip". From the transit method, the physical size of the planet passing the host star can be determined. Most transit signals are rather weak, e.g., a Jupiter-sized planet transiting a Sun-like star would generate a dimming of 1 %, Neptune would generate 0.1 %, and Earth 0.01 %. An observed lightcurve of a star with a transiting planet is shown in **Figure 3.**

Figure 3: Transit photometry: the CHEOPS-measured light curve of KELT-11b (Benz et al 2021). Shown are the observed light curve and the model fit. In the lower panel, the residuals (observation - model) are depicted.

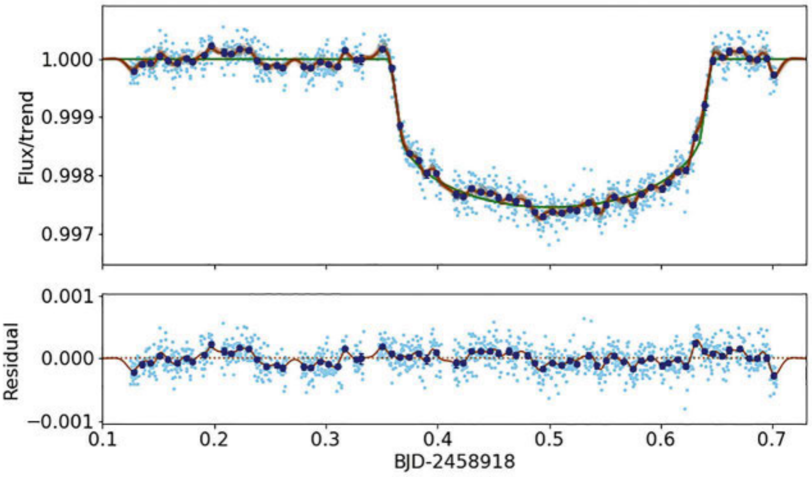
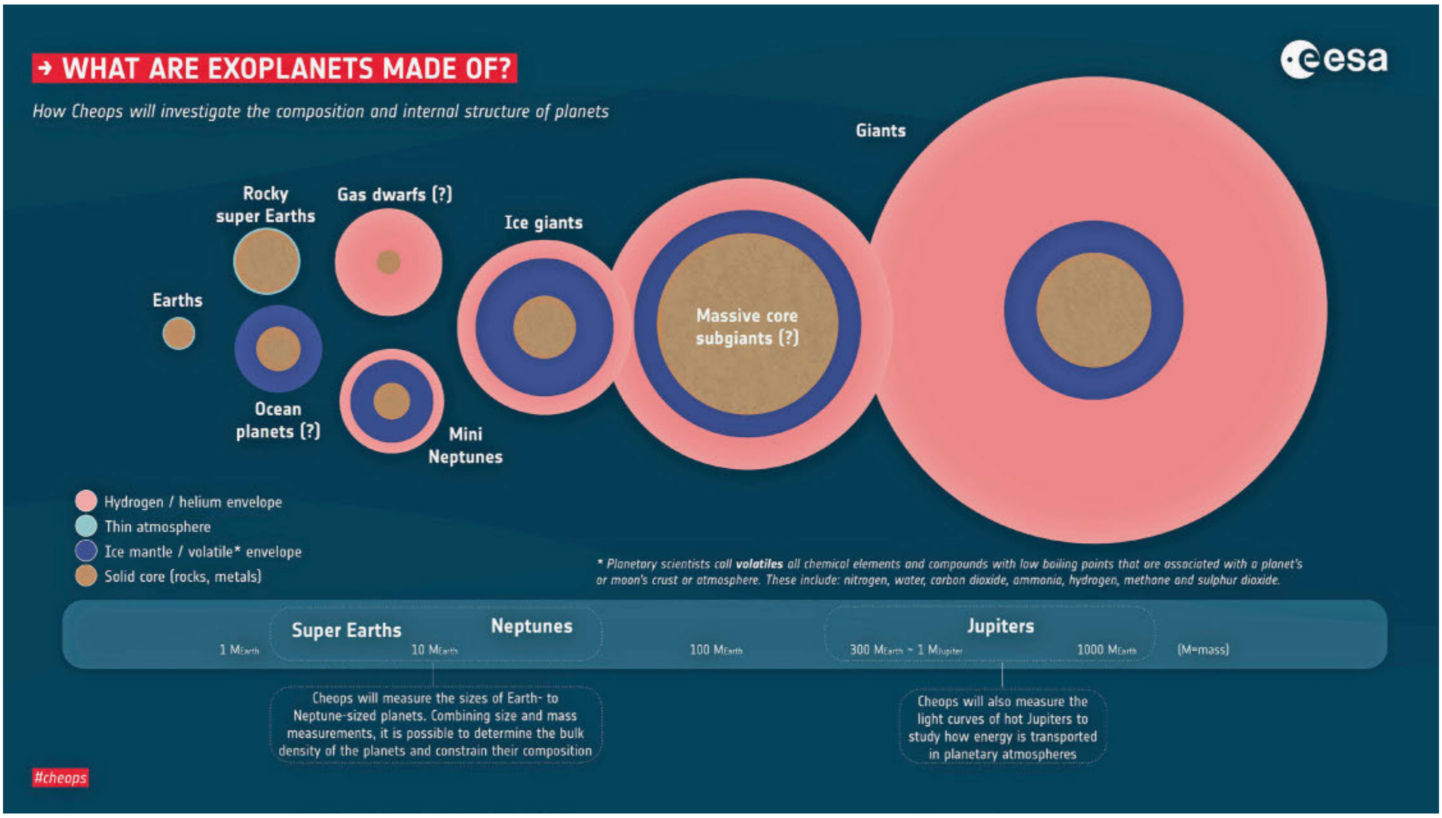


Figure 4: Exoplanets – what can we know? (Credit: ESA.)



** Planetary scientists call **volatiles** all chemical elements and compounds with low boiling points that are associated with a planet's or moon's crust or atmosphere. These include: nitrogen, water, carbon dioxide, ammonia, hydrogen, methane and sulphur dioxide.*

Cheops will measure the sizes of Earth- to Neptune-sized planets. Combining size and mass measurements, it is possible to determine the bulk density of the planets and constrain their composition

Cheops will also measure the light curves of hot Jupiters to study how energy is transported in planetary atmospheres

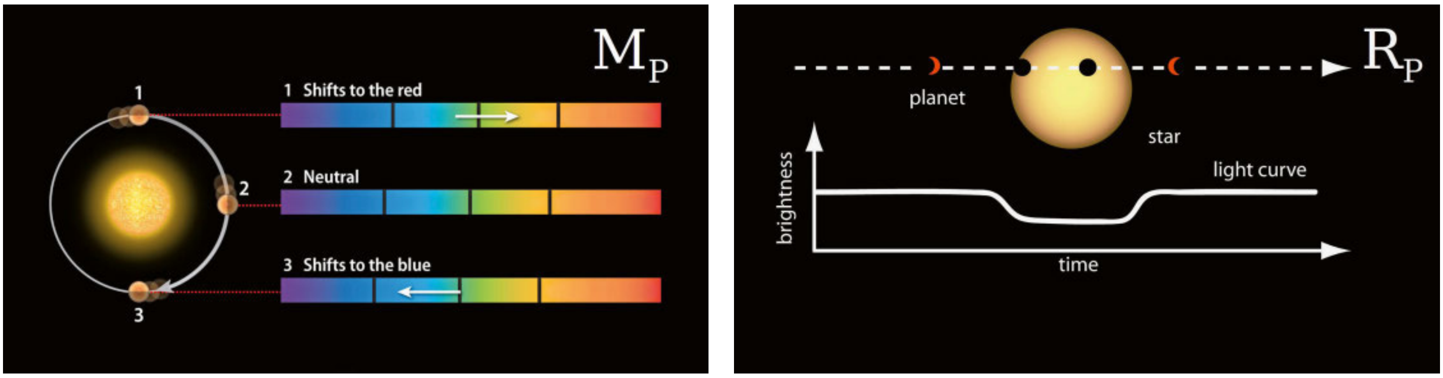


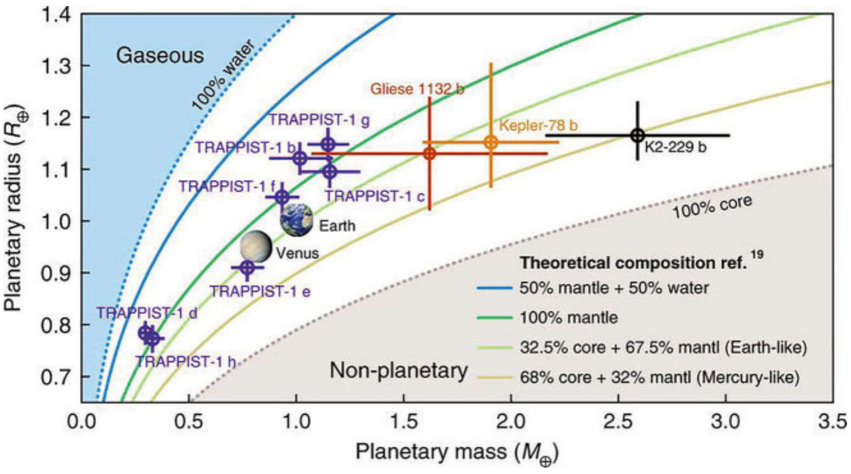
Figure 5: Radial velocity measurements ***(left)*** and transit photometry ***(right)*** – a combination of measurements is needed to characterise a planet.

... and the study

Hunting for exoplanets is not done for the mere fun of it. After a detection the job is not finished, in fact the real work starts from there. As already described in *Spatium* 41, the ultimate goal of these discoveries is to learn something about the entire history of the planets, about the evolution from the formation process up to the state they are today. What are they made of? Their mass and size are the parameters that can tell us something about their composition. From mass and radius the bulk density[6] can be deduced, and it can be determined whether they are likely to be gaseous, rocky or icy planets. **Figure 4** gives an idea how to order the observations according to their composition.

Few exoplanets to date have highly accurate measurements for both mass and radius, limiting the ability to study the variety in bulk density that would provide clues as to what materials they are made of and their formation history. It soon became clear that there was a need for specialised missions dedicated not to detection, but to thorough study and characterisation of the objects already discovered by the missions and campaigns designed for planet hunt. Combining the methods is the path to further understanding, as illustrated in **Figures 5** and **6.**

Figure 6: The uncertainty in the radius determination can dominate the uncertainty in the estimated mean density. (From Santerne et al 2018.)



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[6] The bulk density is the apparent or volumetric density, given as the mass of many particles divided by the volume they occupy. The term is used for powders, granules, soils and other solids consisting of various constituents.

Now – here comes CHEOPS! Its primary goal is the accurate measurement of the size (radii) of exoplanets for which for example ground-based spectroscopic surveys have already provided mass estimates and to further characterise these transiting exoplanets orbiting bright host stars. The very special mandate of the mission is clear – to have a closer look at the pre-selected objects. Consequently, the design had to be optimised for exactly that purpose. CHEOPS has been built as the most efficient instrument to search for shallow transits and to determine accurate radii for known exoplanets in the super-Earth to mini-Neptune mass range (around one to six times the Earth radius).

Where to search, then?

The detectives of promising targets are the ground-based telescopes and spectrometers, such as, for example, HARPS[7] and ESPRESSO[8] at the VLT, and the space missions CoRoT, Kepler/K2 and TESS[9]. Especially the latter missions had been explicitly designed for the search for exoplanets in surveys. On the contrary, CHEOPS has been optimised to perform high-cadence and high-precision photometric observations of a single star at a time.

The terms "Super-Earth" or "Mini-Neptune" are no exact definitions – but rather some guidelines when describing planets.

Super-Earth: The term "Super-Earth" only refers to the mass of a planet; it does not imply anything about its surface conditions or habitability. In general it denotes planets heavier than Earth and yet lighter than ice giants like Neptune or Uranus. Super-Earths are likely of rocky composition. Sizes range between two times and ten times the size of Earth.

Mini-Neptune: A "Mini-Neptune" is a planet less massive than Neptune which resembles Neptune (the third-most massive planet of the Solar System, 17 times the mass of Earth) in that it has a thick hydrogen–helium atmosphere, probably with deep layers of ice, rock or liquid oceans (made of water, ammonia, a mixture of both, or heavier volatiles).

3. The mission – small is beautiful

Organised as a partnership between the European Space Agency (ESA) and the Swiss Space Office, CHEOPS was selected in October 2012 from among 26 proposals as the first S-class ("Small") space mission in ESA's Cosmic Vision programme 2015 to 2025. The mission was formally adopted in early February 2014, and was successfully launched on 18 December 2019. S-class missions have a much smaller budget than Large- and Medium-class missions and a much shorter time from project start to launch. The ESA mission cost had been capped to 50 million Euro. The project is led by the Center for Space and Habitability at the University of Bern, Switzerland, with contributions from other Swiss and European universities. ESA has been responsible for the spacecraft and launch.

1. The spacecraft

Based on previous expertise and as a kind of natural continuation of the successful history in the fields of exoplanets, the CHEOPS mission baseline relies completely on components with flight heritage.

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[7] High Accuracy Radial velocity Planet Searcher

[8] Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations

[9] Transiting Exoplanet Survey Satellite

This applies for the platform as well as for the payload components. For the latter, the team could exploit significant heritage from the CoRoT mission, minimising both cost and risk. The dimensions are compact, a weight of 273 kg and roughly 1.5 m × 1.5 m × 1.5 m spatial extension.

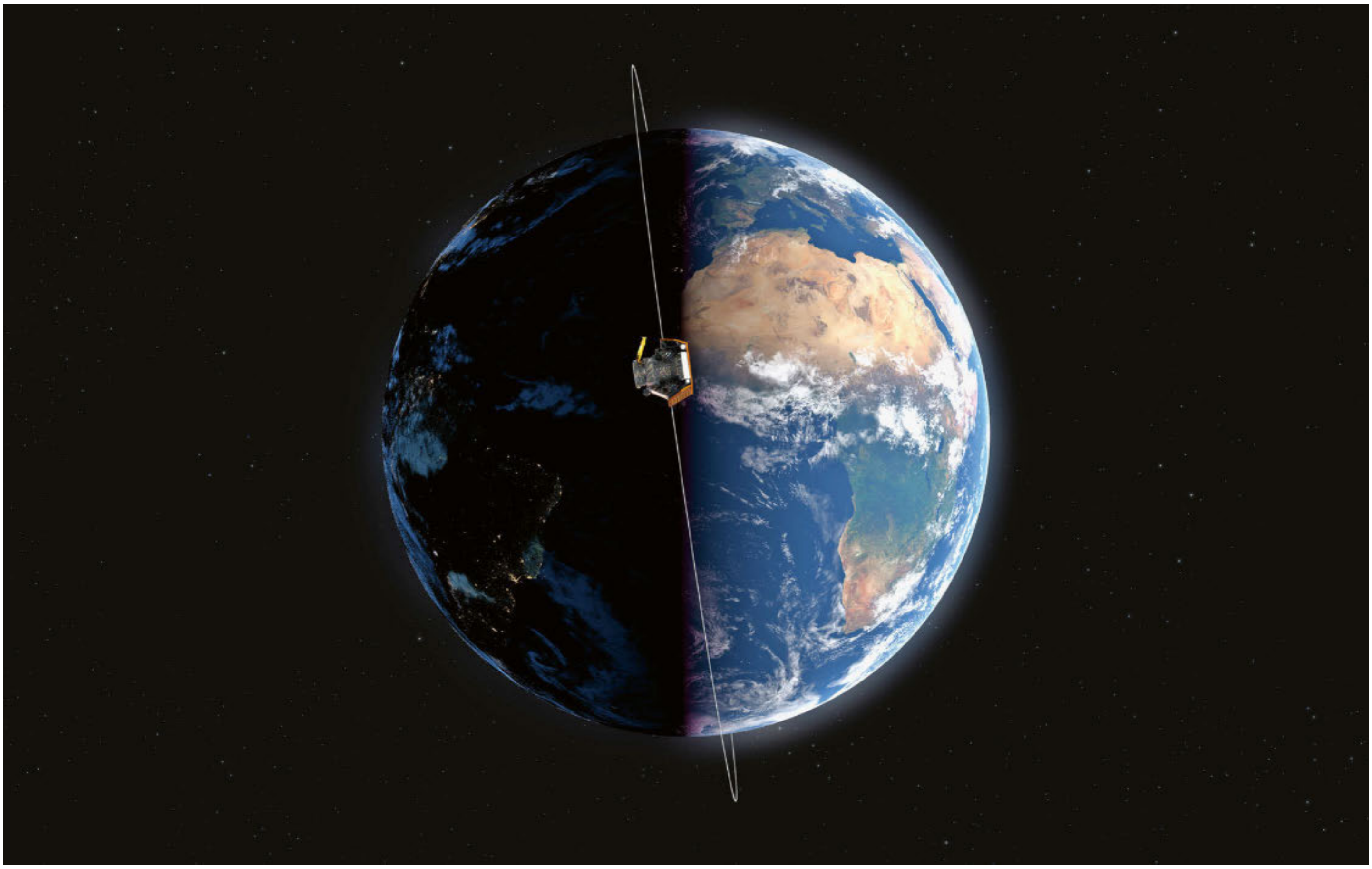

Figure 7: CHEOPS orbit, day-night terminator.

2. The orbit

The baseline orbit satisfying the science requirements is a Sun-synchronous orbit (SSO)[10] at an altitude of 700 km (Low Earth Orbit, LEO), with a mean local time of the ascending node of 6 a.m. The orbit is called a dusk/dawn orbit when the local mean solar time of passage for equatorial latitudes is around sunrise or sunset; so that the satellite rides the terminator between day and night, see **Figure 7.** This choice optimises uninterrupted observations and keeps thermal variations of the spacecraft and stray light on the satellite to a minimum. CHEOPS' orbital period is 98.6 min with an observing cadence of 1 min or better.

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[10] A Sun-synchronous orbit, also called a heliosynchronous orbit, is a nearly polar orbit around Earth, in which the satellite passes over any given point of the terrestrial surface at the same local mean solar time. It precesses through one complete revolution each year, so it always maintains the same orientation with respect to the Sun.

3. The instrument

The telescope is of Ritchey-Chrétien type, which is a special kind of Cassegrain telescope that has a hyperbolic primary mirror and a hyperbolic secondary mirror in order to minimise the off-axis optical focussing errors (coma). The aperture is 30 cm. Care has been taken in the design of the baffle system to reduce the direct as well as the scattered light. The field of view is 17 arcmin times 17 arcmin.

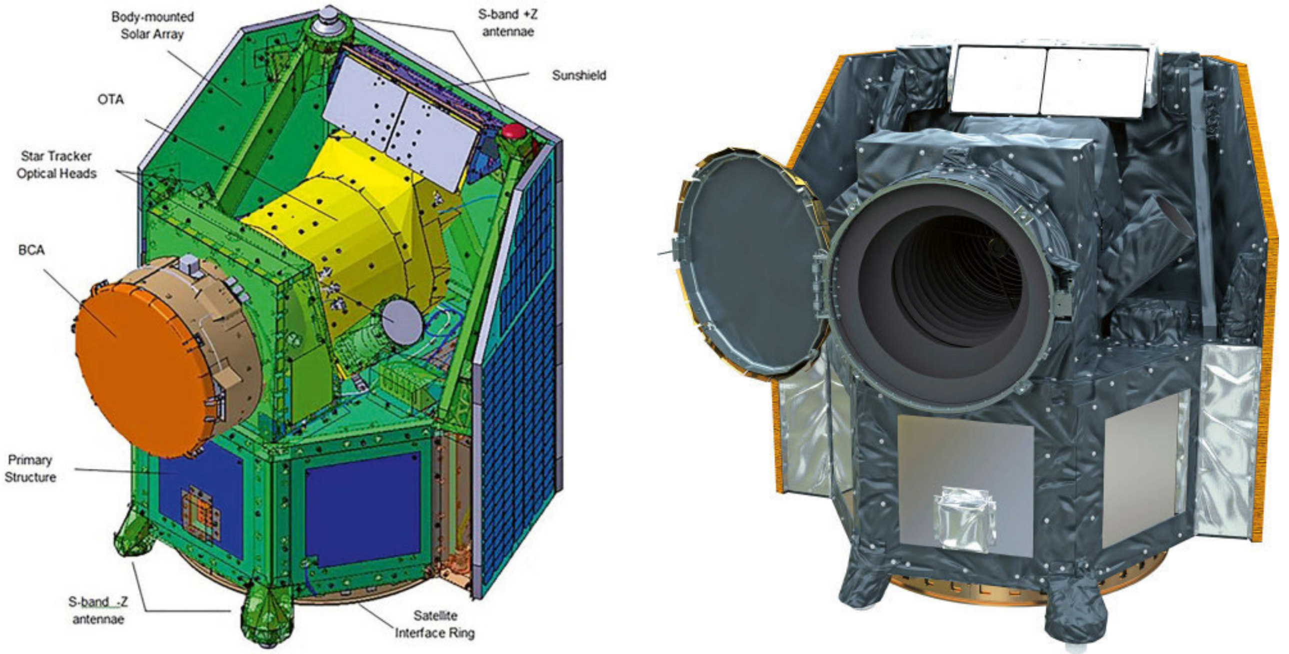
The images are recorded by a back-side-illuminated CCD detector with 1024 × 1024 pixels and a pixel size of 13 μm. The CCD is mounted in the focal plane of the telescope, and is passively cooled to 227 K (−45 °C), with a thermal stability of 2 mK.

The wavelength band reaches from 0.33 μm to 1.1 μm (330 nm to 1100 nm), i.e., from the near infrared to the near ultraviolet range. The data download rate of the instrument is 1.2 Gbit/d. The CHEOPS design model is shown in **Figure 8.**

4. Ultra-high precision: what does that mean?

A particular trick to better capture the incoming photons has been to deliberately defocus and thus spread out the image over more detector pixels than with a focused system. Additional lenses are used to defocus the image of the target star on the detector, spreading the light over a larger detector area. The so-called point spread function has been stretched to a radius of approximately 16 pixels, covering 800 pixels in total.[11] This makes the measurements of stellar photon flux more precise, as they are much less sensitive to small differences in the response of individual pixels in the CCD and to variations in the telescope pointing. The deliberate defocusing is at the core of the mission's observing strategy.

Figure 8: The CHEOPS design model. OTA: optical telescope assembly, BCA: baffle and cover assembly.



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[11] The point spread function (PSF) radius has been defined as the region where 90% of the total energy flux received from the star (in the corresponding wavelength band) is being deposited.

CHEOPS can observe various types of stars of different magnitudes. However, requirements on photometric precision and stability have been derived for magnitudes ranging from 6 to 12 in the V band (the wavelength band centred around 540 nm, see insert). While stars brighter than magnitude 6 and fainter than 12 can in principle be observed by CHEOPS, no precision nor stability requirements have been imposed on the measurements of these stars.

For bright stars (V-band magnitudes in the range $6 \leq V \leq 9$ mag), the requirements have been set so that CHEOPS should be able to detect Earth-size planets transiting G5 dwarf stars (stellar radius of 0.9 $R_\odot$). Since the depth of such transits is 100 parts-per-million (ppm)[13], this requires achieving a photometric precision of 20 ppm (the ultimate goal would be to reach 10 ppm) in 6 hours of integration time (at least, signal-to-noise ratio of 5). This exposure time corresponds to the transit duration of a planet with a revolution period of 50 days.

For faint stars (V-band magnitudes in the range $9 < V \leq 12$ mag), CHEOPS was required to be able to characterise Neptune-size planets transiting K-type dwarf stars (stellar radius of 0.7 $R_\odot$) with V-band magnitudes as faint as $V = 12$ mag (goal: $V = 13$ mag) with a signal-to-noise ratio of 30. Such transits have depths 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.

As photometric stability it has been requested that CHEOPS should maintain its photometric precision for the duration of an observation, which can last as long as 48 h.

The first photometric calibration measurements resulted in photometric precision of

1) 15.5 ppm for bright stars compared to the request of 20 ppm in 6 hours of integration, and
2) 75 ppm for a $V = 11.9$ magnitude star, compared to the request of 85 ppm.

In summary, measurements taken during commissioning have demonstrated that CHEOPS meets the photometric precision requirements on both the bright and faint stars. The determination of the actual detailed photometric performances of CHEOPS is ongoing work that will be carried out based on the analysis of actual science targets by the CHEOPS Science and Instrument Teams over the coming months, more refinement is expected.

Photometry measures light in the visible spectral region from 360 nm to 830 nm. In particular, and this is how it is used in astronomy, the term photometry means the technique to measure the photon flux emitted by astronomical objects. This light is measured through a telescope using a photometer, which converts light, i.e., photons, into electric current, e.g., by the photoelectric effect. When calibrated against so-called "standard" stars (or other light sources) of known intensity and colour, photometers can measure the brightness or **apparent magnitude** of celestial objects (if the spectral responsivity function of the instrument is known).

The magnitude is a historical notation for brightness dating back to the ancient astronomer Ptolemaios, whose star catalogue listed stars from 1st magnitude (brightest) to 6th magnitude (dimmest). The modern scale has been defined in a way to closely match this historical system. The brighter an object is, the lower its magnitude number. The scale is reverse logarithmic; a difference of 1.0 in magnitude corresponds to a brightness ratio of $\sqrt[5]{100}$, or about 2.512.

For example, a star of magnitude 2.0 is 2.512 times brighter than a star of magnitude 3.0, 6.31 times brighter than a star of magnitude 4.0, and 100 times brighter than one of magnitude 7.0.

Photometric measurements are made in the ultraviolet, visible, or infrared wavelength bands using standard passband filters belonging to photometric systems such as the UBV system[12].

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[12] The UBV (Ultraviolet, Blue, Visual) system, with the passbands centred around 364 nm, 442 nm, and 540 nm.

[13] One part per million (ppm) denotes one part per 1 000 000 (10^6) parts, which is a value of 10^{-6}. It is equivalent to about 32 seconds out of a year or 1 mm of error per km of distance traversed.

4. Early adventures

The timeline of the mission has been extremely tight, and CHEOPS has managed the ambitious schedule from first selection to operational mission in slightly less than eight years. CHEOPS launched as secondary payload along several other "passengers" on board of a Soyuz-Fregat rocket on 18 December 2019 at 08:54:20 UTC from Centre Spatial Guyanais in Kourou, French Guiana. The spacecraft separated after 2 hours and 23 minutes from lift-off.

The cover of the telescope was opened on 29 January 2020 and CHEOPS took its first-light image. The image was centred on the star HD 70843, a yellow-white star located around 150 light years away, selected because of its brightness and position. The first-light images were better than it had been expected from tests in the laboratory. The images were smoother and more symmetrical, which pointed to less noise caused by the detector and the spacecraft than assumed.

Not quite one year after launch, and right amidst a critical observation campaign, CHEOPS had another test to pass.

Space debris increasingly threatens rockets, the International Space Station and satellites in Earth orbits. Such encounters can be extremely dangerous, because objects in that orbit shoot through space at many times the speed of a bullet. If a piece only 1 cm in diameter collides with another object, the energy of an exploding hand grenade is released. ESA's Space Debris Office keeps track of thousands of pieces of debris flying around uncontrolled in Earth orbits. If one piece comes close to an active satellite or space capsule, the office issues a warning and proposes an orbit correction, in general three to seven days in advance. Although nowadays this scenario is included in mission planning (for CHEOPS it was assumed that there would be a maximum of three collision warnings per year requiring an effective orbit correction), the ESA warning came at an early phase in the mission operation and on rather short notice. On 30 September at 15 h, ESA's Space Debris Office informed the CHEOPS team that a piece of space debris was on a collision course with the CHEOPS space telescope. Just two days later, the piece of junk from the faulty Chinese satellite Fengyun 1C, of about the size of a milk carton, was to rush past the ESA satellite. The operation team quickly decided on an orbit correction and CHEOPS could avoid any damage and resume operation with only one day of operation time lost.

Figure 9: The characteristics of the WASP-189 system, one of the first targets observed with CHEOPS.

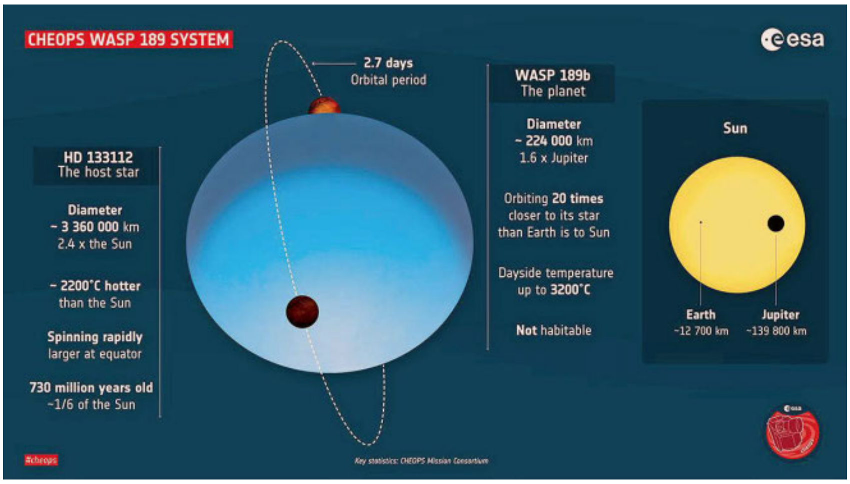
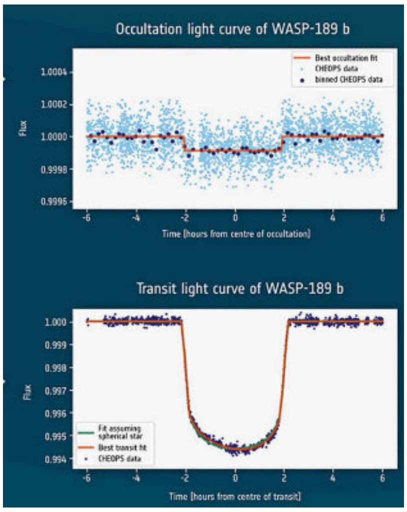


Figure 10: The asymmetric light-curves of exoplanet WASP-189b orbiting its host star.



5. First results … and more to come

During the first regular observation campaigns, already several interesting discoveries could be made that led to a couple of published papers. It was shown that after the first months of operation the expected precision of the instruments has been met. As mentioned before, so far it has been shown to surpass the required 20 ppm and reach a precision of 15.5 ppm in 6 h of integration.

An ultra-hot Jupiter

Among the first observed targets was the exoplanet named WASP-189b – a rather exotic star companion, belonging to the ultra-hot Jupiter class. It is a gas giant orbiting the star HD 133112, one of the hottest stars known to have a planetary system, 322 light years away and located in the constellation Libra (see **Figure 9**). However, this gas giant is significantly different from the gas giants Jupiter and Saturn; it is orbiting within less than three days at rather short distance, its own rotation taking the same time, thus always facing the star with the same side. Its hot dayside temperature has been determined to 3200 °C.

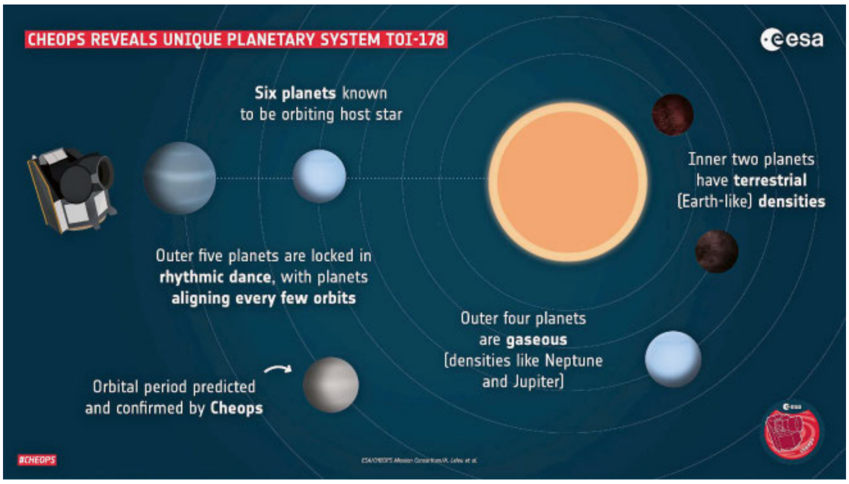


Figure 11: The planetary system TOI-178. (Credit: ESA.)

CHEOPS could provide significant improvements in precision of the parameters for this already known system. The planet WASP-189b was found to be larger than estimated before. Its transit curves have asymmetric shapes, suggesting that the host star features brighter and darker zones on its surface (see **Figure 10**). This hints to gravity darkening of the star due to its high rotation rate.[14] Gravity modifies the light emission differently at the star's poles and the equator, the star appears slightly flattened. Its shape resembles an ellipsoid rather than a sphere (Lendl et al 2020).

Planetary symphony – resonances and extras

A real spectacular discovery was made by re-observing a planetary system that TESS had measured in September 2018 (TOI-178). Initially, three planets had been detected, initiating further observations with ground-based systems, like, e.g., the ESPRESSO spectrograph at the European Southern Observatory(ESO)'s Paranal Observatory in Chile. After several days of CHEOPS observation, signals of more planets than initially expected had been found, moreover, for most of them their orbiting times being commensurable, which means that their times needed to circle the host are in some integer-number relation.

Altogether, six planets could be detected, and five of them were found to be in resonance, with orbital periods such that planet g was orbiting 2 times around the host while planet c performed 12 orbits (the planets g, f, e, d, c being in resonance 2:4:6:9:12). Although planet f had not been directly observed

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[14] When a star is oblate, it has a larger radius at its equator than at its poles, and a higher surface gravity there. This oblateness can be caused by enhanced rotation velocity, as the centrifugal force creates additional outwards pressure, also on the gas in the equatorial region, which becomes less dense and cooler.

before, from the resonance relation its presence was suspected. CHEOPS was pointed there – and found it. This planetary system has thus been found to harbour at least six planets in a most interesting configuration (**Figures 11** and **12**). The resonant condition of their orbits suggests that no significant disturbance like a collision or scattering has taken place since their formation. Moreover, the density of the planets is far from changing monotonously with distance from the host star; instead, the amount of gas of neighbouring planets varies significantly within the Super-Earth to Mini-Neptune range. These results leave a lot to do for the study of the formation and evolution of planetary systems and suggest a valuable target for upcoming missions like the James Webb Space Telescope (JWST).

Figure 13: Lightcurves of CHEOPS observations of HD 108235 (Bonfanti et al 2021).

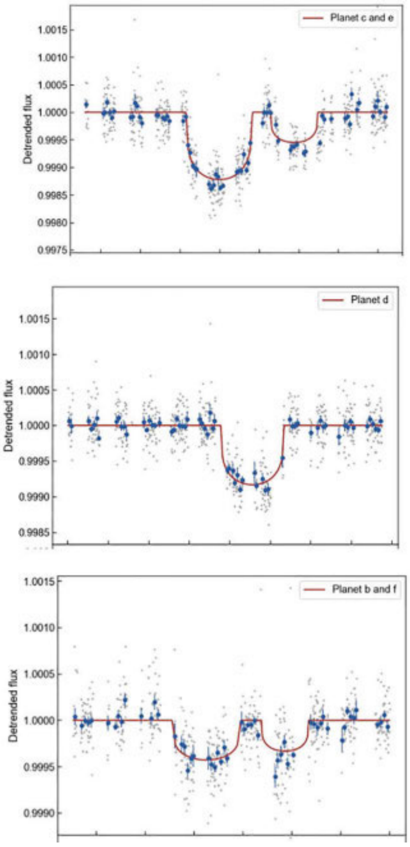
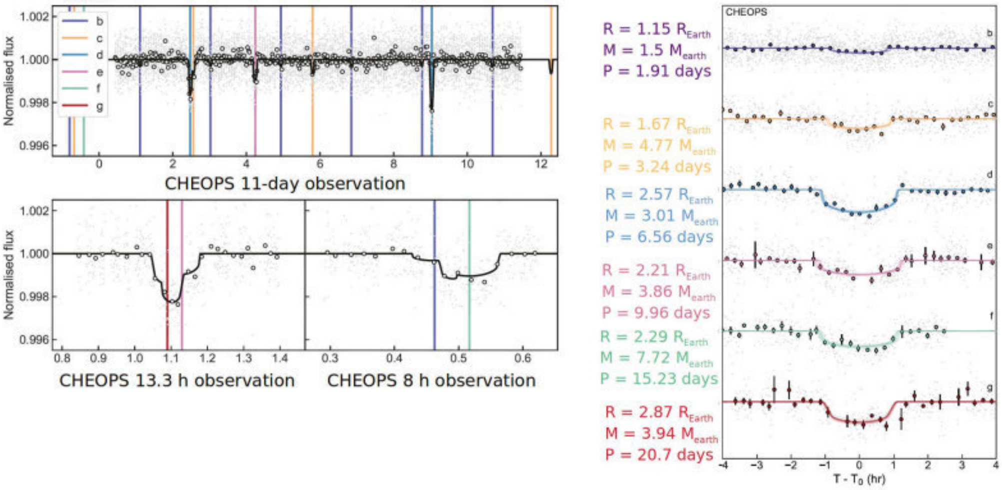


Figure 12: Transits observed by CHEOPS in the system TOI-178: Super-Earths and Mini-Neptunes. Planets c, d, e, f, g form a resonance chain 12:9:6:4:2.



Another system with more planets than seen before

Another TESS follow-up observation with CHEOPS, this time of the star HD 108235 and its planetary system, could, by CHEOPS' high-precision photometry, significantly improve the ephemerides and planetary radii that had been estimated before. Moreover, the system of the Sun-like star and its four companions, a Super-Earth and three Mini-Neptunes, could be extended by another planet. Measured lightcurves of this system are shown in **Figure 13.**

Given its overall objectives and the fact that it is targeting stars already known to host planets, CHEOPS can be thought of as a follow-up mission. However, as the only exoplanet mission of this sort (one single star targeted at a time), it is truly unique and a lot of firsts are involved: apart from being ESA's first S-class mission and the first mission explicitly dedicated to characterise already known planets, it is exploring many planetary configurations in detail for the first time. The planets observed by CHEOPS will, on the one hand, provide fundamental new insights regarding the formation and evolution of planetary systems and, on the other hand, become the prime targets for any future facility with spectroscopic capabilities. Forthcoming missions for which CHEOPS then can suggest observation campaigns are for example NASA's JWST and ESA's Plato and Ariel (see **Figure 14**), as well as future ground-based large observatories.

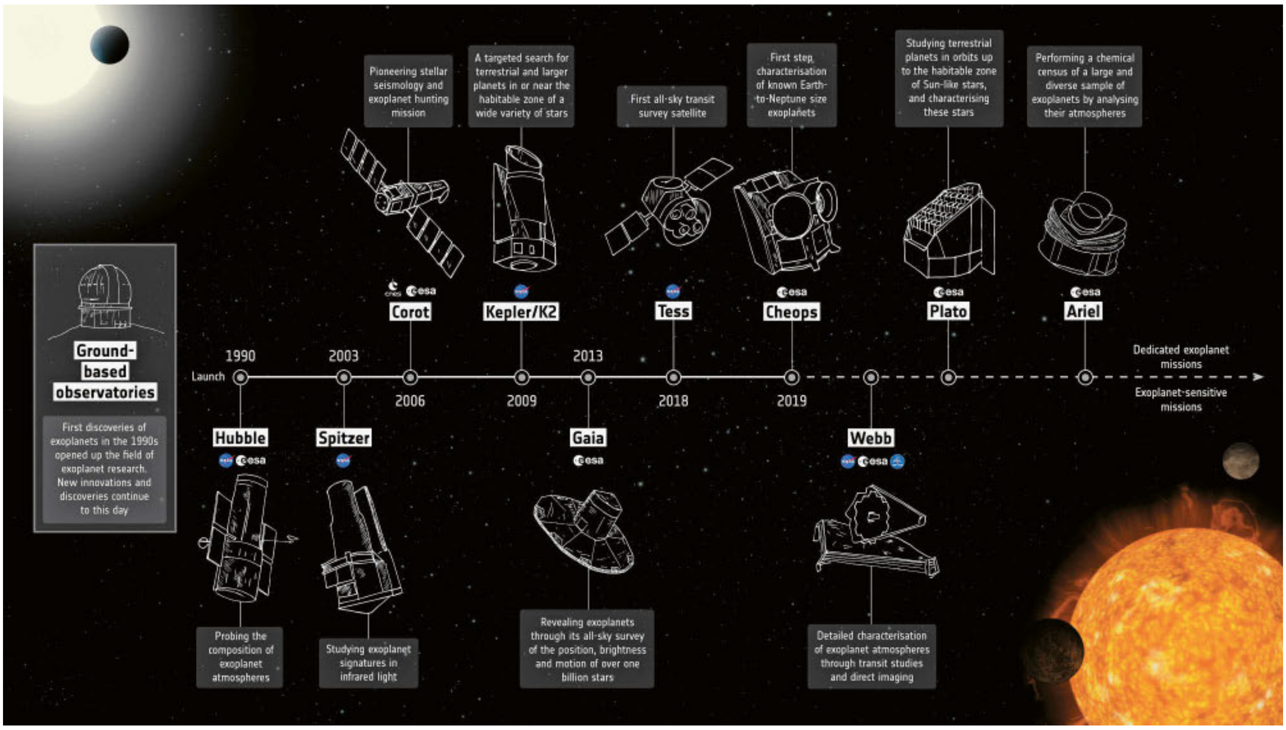


Figure 14: How CHEOPS fits into the timeline of exoplanet missions. (Credit: ESA.)

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Web resources

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SPATIUM

The Author

In 2009 Andrea Fortier received her PhD in Astronomy at the Facultad de Ciencias Astronómicas y Geofísicas de La Plata in Argentina. Already her thesis work was concerned with giant planet formation models. She continued research in planet and planetary systems study as a postdoc at the University of Bern, where she became the CHEOPS instrument scientist in 2013. In this position she was coordinating the CHEOPS project from the beginning, as interface between the engineers and the scientists while building the instrument as well as in the organisation of various science team working groups. Andrea was also in charge of the planning and coordination of CHEOPS' in-orbit commissioning campaign. Currently, she is responsible for the characterisation and monitoring of the CHEOPS instrument performance.