cheops

→ SIZING AND FIRST CHARACTERISATION OF EXOPLANETS

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exploration

exomars
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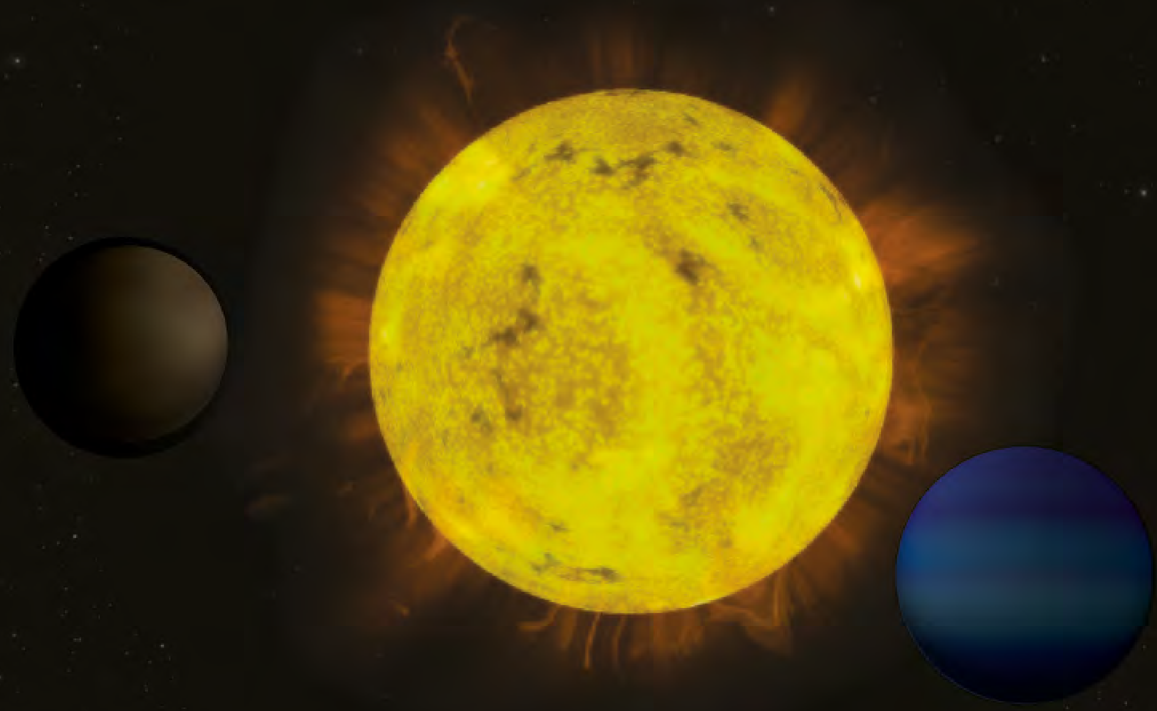


CHEOPS

SIZING AND FIRST CHARACTERISATION OF EXOPLANETS

CONTENTS

→ WHY EXOPLANETS?

"Are we alone in the Universe?" is one of the most profound questions humanity can ask. Humankind has long speculated on the existence of other worlds, with the idea first mooted by the Ancient Greek philosophers and recurring through the Middle Ages and Renaissance.

Searches for exoplanets began in earnest in the mid-20th Century. The first unambiguous discovery of an exoplanet orbiting a star like our Sun, in 1995, completely changed our perspective on the Solar System. A giant planet with a mass of around half that of Jupiter, subsequently named 51 Pegasi b, was found orbiting its host star in just over four days. The presence of such a massive planet in such a short orbit – much closer to its star than Mercury is to our Sun – was completely unexpected and did not fit with our then understanding of planet formation.

Fast forward two decades, and the study of exoplanets is one of the fastest growing areas in astronomy. As of early 2019, nearly 4000 exoplanets have been confirmed: more hot-Jupiters like 51 Pegasi b, and planet types that do not have analogues in our Solar System. There are systems hosting more than one planet, planets orbiting two stars, and planetary systems that may even include planets that have the right conditions for water to be stable on their surfaces, a necessary ingredient for life as we know it.

Studying this diverse range of planets and planetary systems – from the small to the large, from those that appear Earth-like to the profoundly bizarre – will help us learn about how these particular systems formed and evolved, and will provide essential clues towards understanding whether and where life might exist elsewhere in the Universe.

Searching from Earth

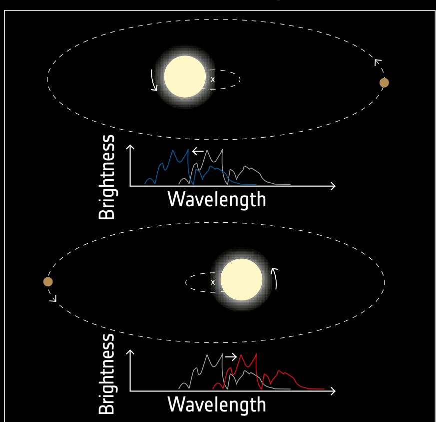
51 Pegasi b was found using a ground-based observatory by spotting 'wobbles' in its star's motion. Such wobbles are caused by the gravitational pull of a planet as the planet and star orbit around a common centre of mass. When viewed from afar, the star appears to move towards and away from the observer. This motion makes the light from the star appear slightly bluer when it is moving towards the observer, and slightly redder when moving away. This shift in frequency is known as the Doppler effect, the same effect as the change in pitch of an ambulance siren as it rushes past you. Most early exoplanet discoveries were made using this so-called **radial velocity** method.

The first detections using **transit photometry** were made in 1999. 'Transiting' exoplanets are detected as they pass in front of – transit – their host star, causing a dip in the starlight as seen from the observer's viewpoint. The transit repeats, with the time interval depending on the time it takes the exoplanet to orbit its star. For example, an observer of our own Solar System would have to wait a year to see a repeat of Earth transiting the Sun.

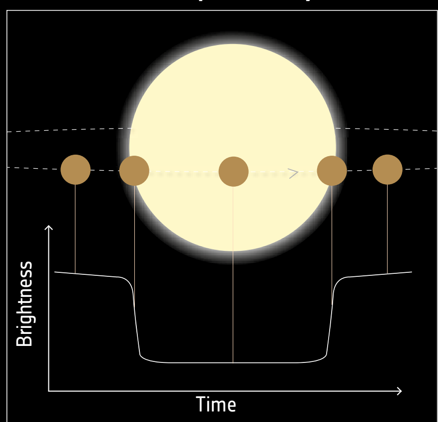
The vast majority of confirmed exoplanets have been discovered using the two methods above. A less common method is **direct imaging**, which relies on measuring light from the exoplanet itself. This is particularly challenging at optical wavelengths, because the relatively dim planet can be lost in the glare of the much brighter host star. However, instruments have been developed that block the light from the star, and more than 40 planets have been detected in this way.

Radial velocity measurements and astrometry tend to uncover heavier planets and allow mass to be determined; transit photometry is sensitive to planets orbiting close to their host star and provides a measure of planet size; direct imaging is biased towards planets orbiting further away from their star; microlensing is the technique least biased to the planet type.

Radial velocity



Transit photometry



What is an exoplanet?

An exoplanet is a planet outside our own Solar System, sometimes referred to as an extrasolar planet.

Microlensing relies on the chance alignment of two stars with an observer. As one star passes behind the other, the closer star acts like a lens, bending the light so that the brightness smoothly increases and decreases. If a planet is present around the closer star, its gravity will also bend the light stream, causing a spike. Over 70 planets have been detected by this method, but detections are unrepeatable.

A few planets have also been found using other techniques, including pulsar timing. By combining the results of observations and surveys using different techniques, we are able to build a representative picture of the diversity of exoplanets and planetary systems.

NASA's 2009 Kepler mission was an exoplanet discovery machine, accounting for almost three-quarters of all exoplanet discoveries to date. It looked at a fixed patch of sky for over four years, monitoring over 150 000 faint stars and discovering thousands of exoplanets. Although it only looked at a small area of the sky, the slew of discoveries gave an indication of the vast number of exoplanets that must exist in our Galaxy.

The most recent addition to the exoplanet-hunting fleet is NASA's Transiting Exoplanet Survey Satellite, Tess, launched in April 2018. It is an all-sky mission with the main goal of detecting small planets with bright host stars.

Moving to space

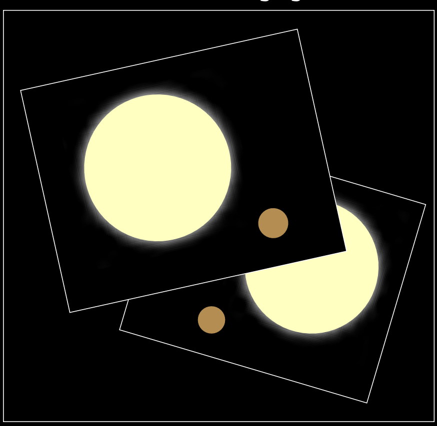
What really opened the floodgates for the discovery of exoplanets was the use of space-based telescopes. In addition to being free of the disturbances caused by viewing through Earth's atmosphere, satellites offer a more continuous line-of-sight visibility to the target star and round-the-clock observations.

One of the first exoplanet-sensitive space telescopes was the CNES-led Convection, Rotation and planetary Transits mission, CoRoT (2006–13). The mission's two objectives were to search for extrasolar planets with short orbital periods (of days or even hours), and to measure oscillations in stars. Using the transit method, CoRoT has uncovered 37 exoplanets to date, including the first confirmed rocky planet (though it was orbiting much too close to its star to be habitable!). More may be discovered during the post-mission data analysis.

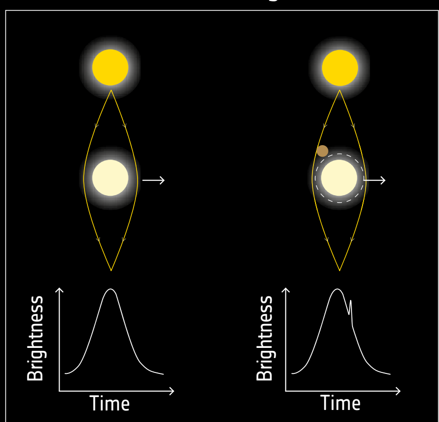
Supporting roles

While not dedicated planet-hunters, space observatories with completely different initial mission goals have also contributed significantly to exoplanet studies. For example, the NASA/ESA Hubble Space Telescope, which was designed and launched well before exoplanets were known to be commonplace, can be used to make transit measurements and can even discern some details of the atmospheres of planets. Similarly, NASA's infrared space telescope Spitzer has contributed, studying changes in infrared light during an exoplanet's transit. ESA's Gaia mission, through its unprecedented all-sky survey of the position, brightness and motion of over one billion stars, is generating a large astrometry databank from which exoplanets will be found, either through observed changes in a star's position on the sky due to planets orbiting around it, or by a dip in its brightness as a planet transits its face.

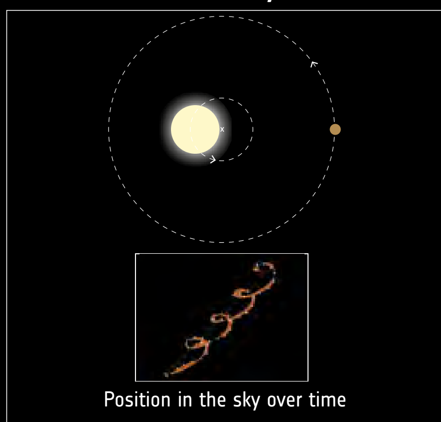
Direct imaging



Microlensing



Astrometry



→ ENTER CHEOPS

Discovering an exoplanet is just the beginning. Dedicated space telescopes are needed to follow up on the ever-growing catalogue and to start characterising these intriguing worlds in order to understand their place in the Universe. To this end, ESA plans to launch three dedicated exoplanet satellites in the next decade, each tackling a unique aspect of exoplanet science: Cheops, Plato and Ariel.

Previous observations have shown that most Sun-like stars host planets, with a very wide range of sizes, masses and orbital parameters, and that small planets are surprisingly ubiquitous: around half of Sun-like stars host at least one planet of a size between that of Earth and Neptune. The large number of small planets orbiting close to their star was not predicted by planet formation theories and this provides a focus for Cheops, ESA's CHaracterising ExOPlanet Satellite.

Unlike exoplanet discovery missions (such as CoRoT, Kepler and Tess), Cheops will observe bright, nearby stars that are already known to host exoplanets, focusing particularly on those with (smaller) Earth- to Neptune-sized planets. The exquisite precision of Cheops, together with the stability with which the telescope will be able to measure the transit depths using the transit method, will enable astronomers to determine the planet sizes both accurately and precisely.

By knowing when and where to point in order to catch transits, Cheops will maximise the time it spends monitoring actual transit events. It will point at stars over most of the sky, returning to observe multiple transits over the course of the mission, thus building up the accuracy of measurement of planet sizes.

For a planet for which we already have a mass measurement, combining this with Cheops data will make it possible to determine the density of the planet, giving us vital clues about its composition and structure. This first-step characterisation of these worlds – many with no Solar System equivalents – is a critical step towards understanding the formation, origin and evolution of these small exoplanets.

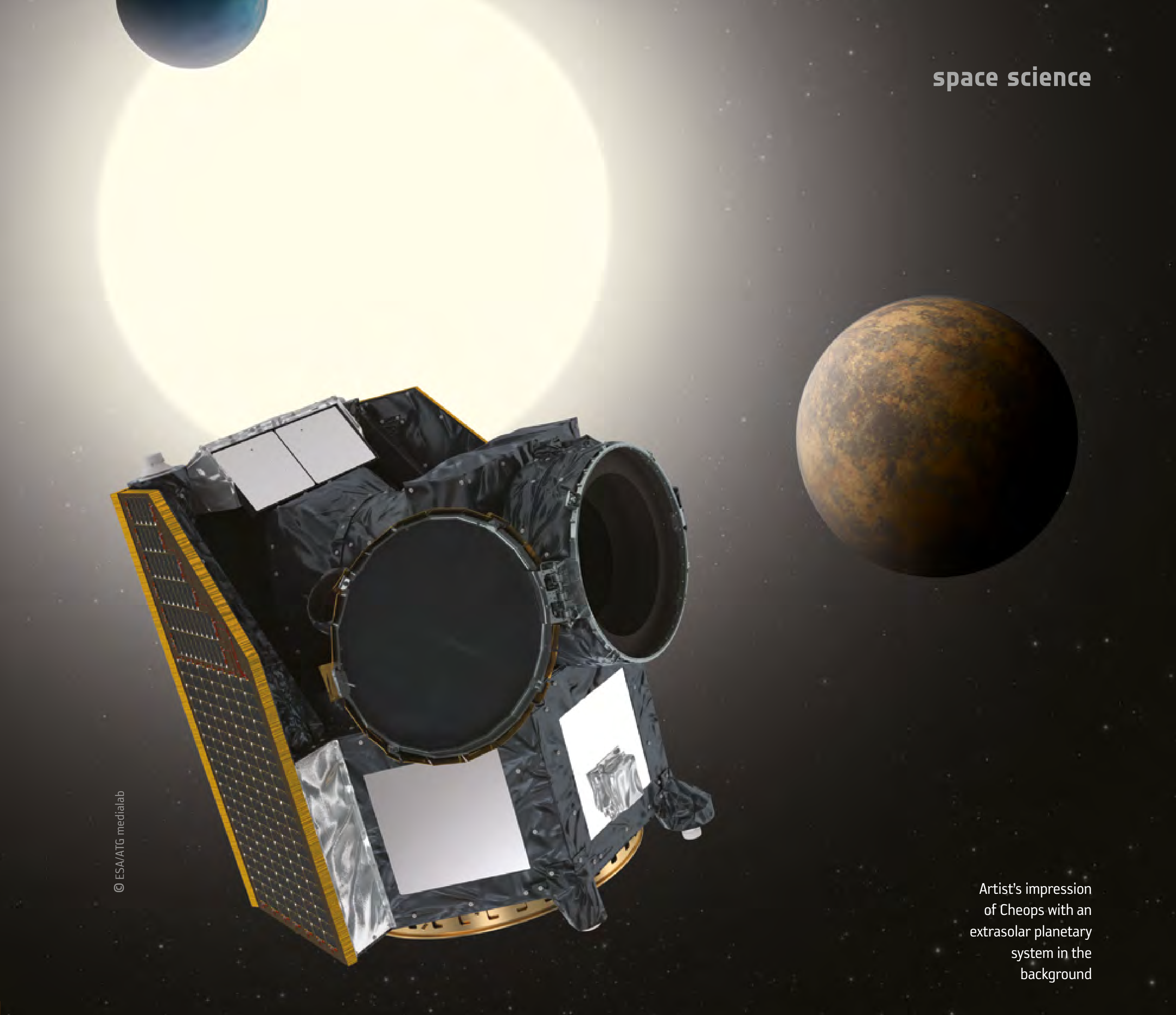
Exoplanet analysers united

Cheops will not only follow up on exoplanets discovered by other missions, but it will also identify the best candidates for detailed study by future missions and observatories. For example, it will provide targets for the international James Webb Space Telescope, which will be used to search for the signatures of water and methane, important elements in our quest for signs of habitability.

Transit depth

The size of the dip in the measured light from a star due to the transit of an exoplanet in front of it

Testing Cheops before launch



Artist's impression of Cheops with an extrasolar planetary system in the background

Plato, the PLAnetary Transits and Oscillations of stars mission, is a next-generation planet hunter with an emphasis on the properties of rocky planets in orbits up to the 'habitable zone' (i.e. where liquid water can exist on the planet's surface) around Sun-like stars, but it will also investigate seismic activity in stars. This will enable precise characterisation of the planet's host star, including its age, providing insight into the age and evolutionary state of the planet system.

Ariel, the Atmospheric Remote-sensing Infrared Exoplanet Large-survey mission, is foreseen to take exoplanet characterisation one step further, performing a chemical census of a large and diverse sample of exoplanets by analysing their atmospheres. This will enable the study of exoplanets both as individuals and, importantly, as populations, in greater detail than ever.

Together with Cheops, these future missions will keep ESA at the forefront of exoplanet research well beyond the next decade, and will build on answering the fundamental question: what are the conditions for planet formation and the emergence of life?

A small mission

Cheops is a small, or S-class, mission in ESA's science programme. It is a partnership between ESA and Switzerland, with a dedicated Consortium led by the University of Bern, and with important contributions from 10 other ESA Member States (see page 11). S-class missions have a much smaller budget than large- and medium-class missions, and a much shorter time from project start to launch. These conditions have made it necessary to use technologies that have already been tried and tested in space, and a number of tasks traditionally undertaken by ESA, such as operations, will be done by the Consortium. Cheops will share the ride into space as a secondary passenger, a choice which has driven a number of aspects of the satellite design.

→ HOW CHEOPS WILL CHARACTERISE EXOPLANETS

Cheops will focus on exoplanets with orbital periods of around 50 days or less, typically ranging from Earth-sized to Neptune-sized planets around a variety of stars. By targeting planets that have short orbits, Cheops will have access to multiple transits over the lifetime of the mission, making it easier to repeat observations in order to build up the precision of the measurement.

Cheops makes use of the technique of 'ultra-high-precision transit photometry' to measure very precisely the sizes of exoplanets. The size of the dip in the light due to the exoplanet transit is known as the 'depth' of the transit, and relates directly to the size of the planet relative to the star: a large planet will block a larger fraction of the light from the star than would a small one. The small planet transits that Cheops will observe mean that it is necessary to measure the variations in the brightness of the star's light over a transit to the level of a few tens of parts per million (ppm).

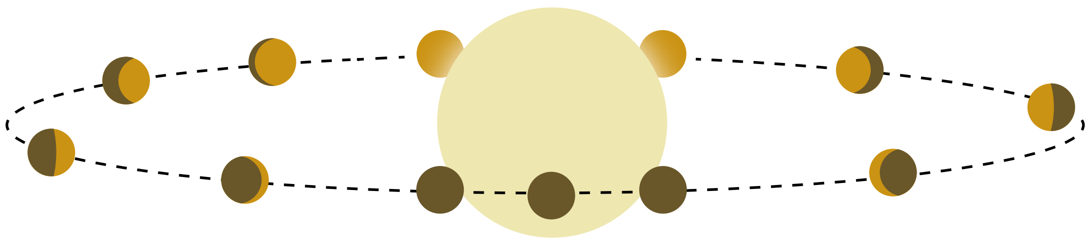
Cheops will be able to take frequent measurements – up to one per minute – making it possible to characterise the light curves in detail. Importantly, this includes detailed measurements of the beginning and end periods of the transit as the planet starts and ends its crossing of the star, which provides key information such as the inclination of the orbit and exact timing of the transit.

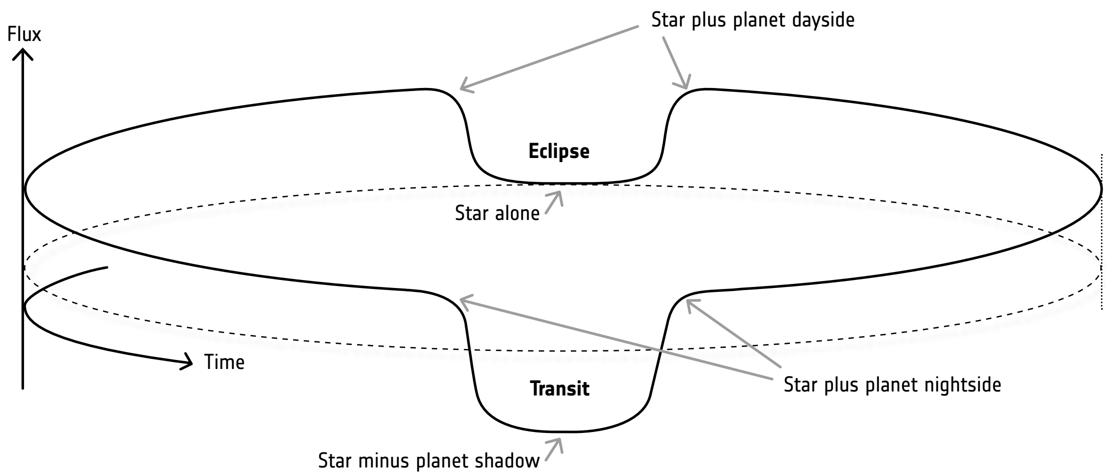
Measurement of the transit depth by Cheops will yield an accurate value for the radius of the exoplanet. Combining this with a planet's known mass yields the bulk density, which constrains its possible composition and structure, indicating for example if it is predominantly rocky or gassy, or perhaps harbours significant oceans. Cheops will also be able to identify whether a planet has a significant atmosphere.

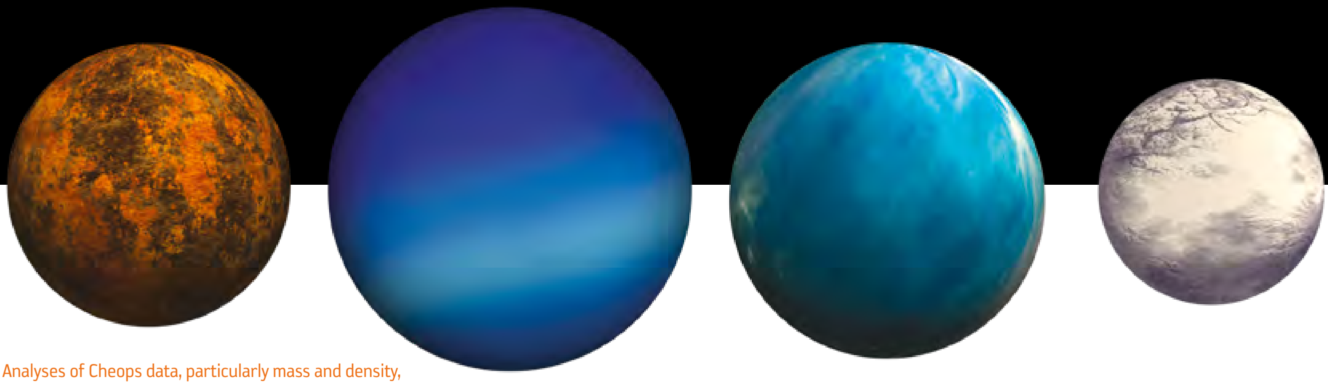
The characteristics determined by Cheops will help astronomers refine their models of the formation and

Phase curves

Studying the reflected light as a planet orbits its star reveals temperature differences between day and night







Analyses of Cheops data, particularly mass and density, will put constraints on the structure and composition of an exoplanet, for example telling us if it is – from left to right – a dense rocky world or rather more gaseous, a water-world, or an ice-rich planet

evolution of small planets, with potential implications for our understanding of the evolution of our own Solar System.

For some planets it will also be possible to detect changes in starlight reflected by the planet as it orbits its host star, in a similar manner to how we experience the phases of the Moon. The resulting **phase curves** – measurements of the changing brightness of the star as the exoplanet moves around its orbit – provide insight into the physical processes that drive the transport of heat from the hot day side to the cooler night side. Analysis of the phase curves also reveals details of the planet's atmosphere, including the presence of clouds, and possibly even hints of the cloud composition.

The precision with which Cheops can measure the light from stars will allow scientists to monitor their activity. It will also enable the measurement of the sizes of much more local, small Solar System bodies such as trans-Neptunian objects (objects outside the orbit of Neptune, like Pluto) as they briefly pass in front of and block light from background stars.

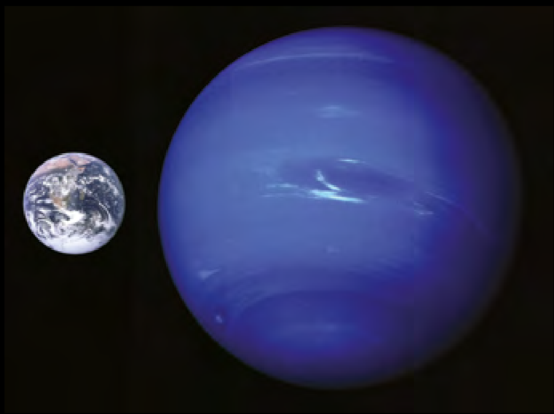
New planets and exomoons?

While it is primarily a follow-up mission to make a first-step characterisation of known planets, Cheops has the capability to discover previously unknown planets by measuring tiny variations in the timing of the transit of a known planet, which can reveal the presence of other planets in the system. Thanks to the very high precision with which Cheops can measure the light from a star, there is the potential to find small planets orbiting close to their star that may have been missed in previous observations due to their shallow transit depths.

Transit photometry can also be used to search for moons orbiting transiting planets, and even asteroids or planetary rings that transit in front of their host star. In October 2018, the Hubble Space Telescope team announced the strongest evidence yet for the presence of an exomoon, none having been discovered earlier despite an extensive search using Kepler. Will Cheops detect more?

What kinds of planets will Cheops study?

- Hot-Jupiters: giant gas planets similar in mass and size to Jupiter, orbiting very close to their host stars
- Terrestrial: rocky planets similar in composition to Mercury, Venus, Earth and Mars
- Super-Earths: rocky planets between two and ten times as massive, or 1–1.75 times as large as Earth
- Mini-Neptunes: icy planets larger than Super-Earths, but smaller than Neptune – up to ten times as massive as Earth, with thick atmospheres
- Neptunes: dense 'ice' giants composed of helium, hydrogen and frozen volatiles, with masses of 10–100 times and sizes of two to six times that of Earth



Earth compared with Neptune, which is nearly four times larger in diameter and 17 times more massive

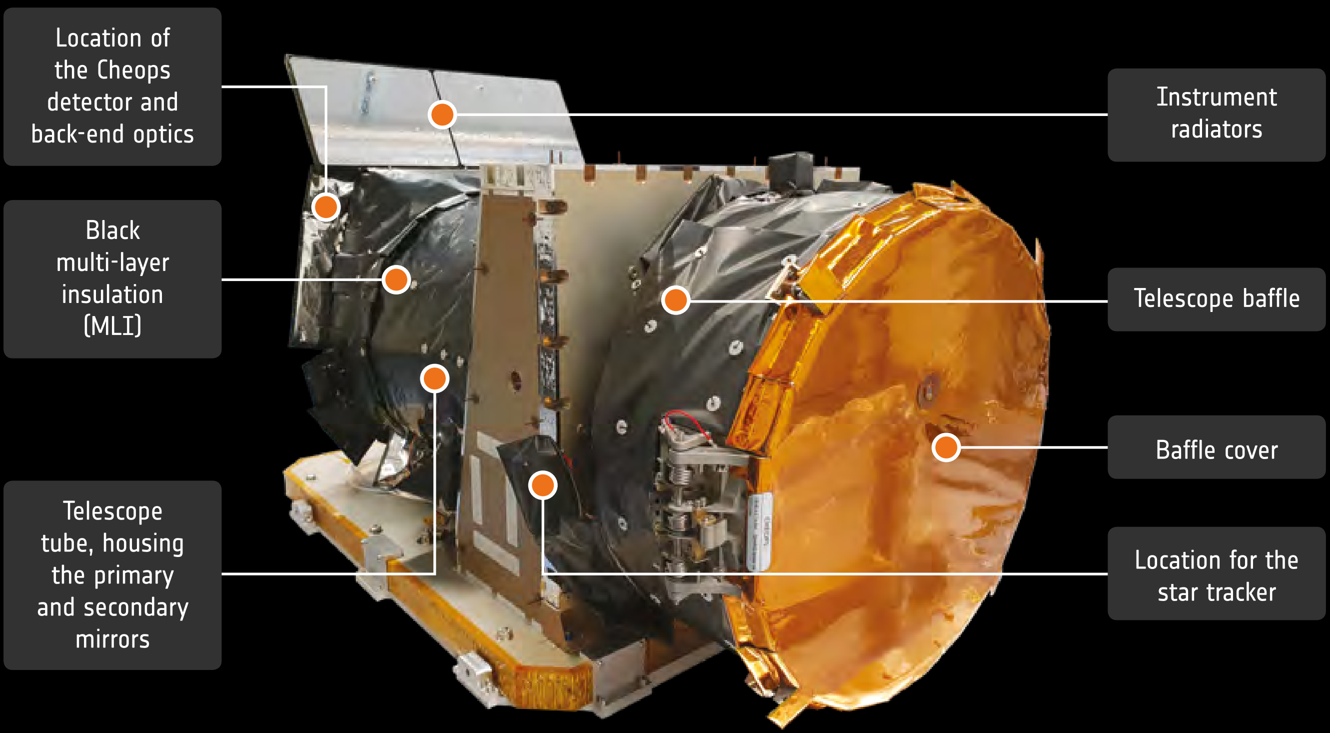
→ DESIGNING A PLANET WATCHER

The design of Cheops was driven by the need to precisely measure the 'signal' from exoplanet host stars. Precision is of particular importance because the transit signal can be extremely tiny for the smallest planets, and noise from the instrument itself can potentially obscure the transit. The instrument therefore needs to be as stable as possible, both in terms of keeping jitter to a minimum while observing the star in 'stare and track' mode, and in keeping cool to avoid thermally-induced noise.

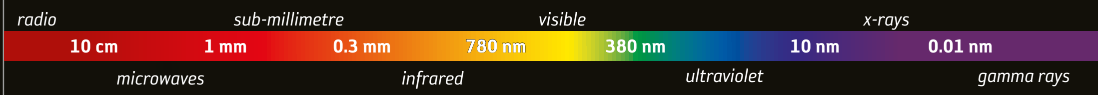
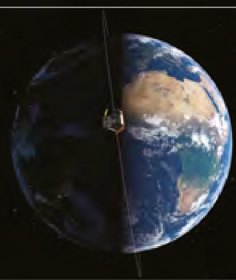
Cheops has a single instrument: a high precision photometer with a 300 mm effective aperture telescope and a single charge-coupled device (CCD) detector covering visible to near-infrared wavelengths. A number of key elements of the Cheops instrument are designed to keep stray light, such as from the Earth and Moon, from entering the telescope. These include a large external baffle, a smaller internal one and vanes inside the telescope. Much as street lights make it harder for us to see the stars, stray light would reduce the observation ability of the telescope. The baffle has a cover to protect the optics from dust and contamination on the ground and during launch. This will be opened once it is in Earth orbit with the telescope pointing away from the Sun.

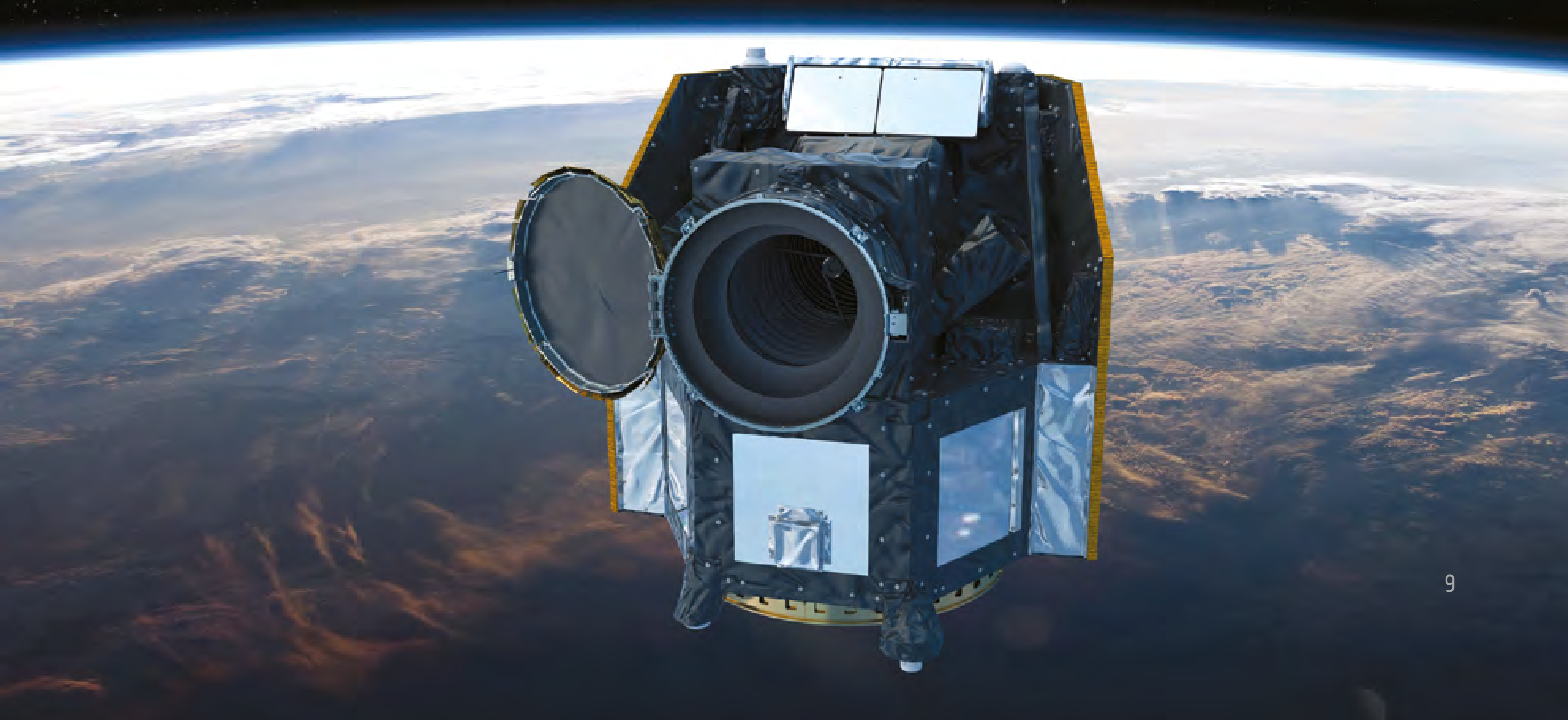
A sunshield keeps the instrument shaded, protecting the two instrument radiators that provide cooling to the detector and electronics. The sunshield also doubles as the structure carrying three solar panels, which are orientated in such a way as to provide sufficient power to operate the spacecraft in the planned pointing direction.

In order to improve pointing stability and minimise misalignment effects, the two spacecraft star trackers are mounted directly onto the instrument. The stability of the spacecraft pointing over time is further improved by feeding back information on the actual position of the target star that is being measured by the Cheops instrument to the spacecraft attitude and orbit control system – the platform system that controls the satellite pointing.



Mission vital statistics

Dimensions	1.5x1.5x1.5 m
Mass	280 kg including propellant (similar to that of a fully fueled, top-of-the-range racing motor bike)
Solar panel area	2.5 m^2
Science instrument	High precision photometer based on a 300 mm effective aperture Ritchey-Chrétien telescope and a single CCD, operating over visible to near-infrared wavelengths (330 to 1100 nm) 
CCD temperature	223K with a stability of 10mK (–40°C with stability of one hundredth of a degree)
Field of view	19 x 19 arcminutes (two-thirds the size of the full Moon)
Pointing directions	60 degree half-cone around the anti-Sun direction
Target stars	Stellar magnitude 6–12 (stars at the bright end are just visible to the naked eye from the darkest sites)
Precision	20 parts per million (ppm) in 6 hours' observing time for the transit depth of an Earth-sized planet orbiting a solar-type star; 85 ppm in 3 hours' observing time for detailed characterisation of the light curves of Neptune-sized planets transiting smaller, cooler stars; to be maintained over 48 hours
Orbit	Sun-synchronous dusk–dawn at an altitude of 700 km (low-Earth orbit) with an inclination of about 98 degrees (a 100-minute polar orbit that crosses the equator at sunset and sunrise) 
Attitude stabilisation	3-axis stabilised (telescope always pointing away from the Sun), with the science instrument used to further improve stability (so-called payload in the loop)
Data downlink	1.2 Gbit/day
Nominal mission	3.5 years



→ A EUROPEAN COLLABORATION

Building

ESA is the mission architect, responsible for procurement and testing of the satellite. The prime contractor for the design and construction of the spacecraft is Airbus Defence and Space in Spain. A Consortium of 11 ESA Member States led by Switzerland provided essential elements of the mission. Of them, six countries were involved in building the instrument: the mechanical structure was built in Switzerland, the focal plane assembly in Germany, the baffle in Belgium, the optics in Italy, the data processing unit in Austria and the radiators in Hungary. ESA also contributed to the instrument development by procuring the focal plane detector (CCD).

Launching

Cheops will be a secondary passenger on a Soyuz-Fregat rocket launching from Europe's Spaceport in Kourou, French Guiana, in 2019. The launcher will deliver Cheops directly to its operational orbit, a Sun-synchronous dusk–dawn orbit 700 km above Earth. This orbit allows the rear of the craft to permanently face the Sun with a minimum number of eclipses, offering a stable thermal environment and keeping stray light to a minimum while the instrument is observing night-side targets in the direction opposite to the Sun.

During each orbit the satellite will slowly rotate around the telescope line of sight to keep the instrument radiators orientated away from Earth and therefore maintain the required detector temperature stability needed for precise measurements.

After the launch and in-orbit commissioning ensures the satellite is functioning correctly, ESA will hand over control to the Consortium mission operations centre located at INTA, in Torrejon de Ardoz, Spain.

Operations

The Consortium science operations centre is located at the University of Geneva, and is responsible for the processing, archiving and distribution of science data. Planning of observations will be carried out there using mission planning software developed in Portugal, and then communicated to the mission operations centre, where commands will be uplinked and data downlinked via ground station antennas at Villafranca and Torrejon (Spain). During the early mission operations, Cheops will make use of the ESA ground station located at Kiruna (Sweden).

Up to 10% of each year will be reserved for activities to monitor the satellite's performance and fix any problems. Observations of a list of exoplanet targets defined by the Cheops Science Team – scientists associated with the institutes within the Cheops mission Consortium – will account for 80% of the science observing time. The remaining 20% will be available to scientists worldwide, who can apply to use Cheops through the ESA-run Guest Observers Programme. Proposals will be selected by an independent committee based on scientific merit and the applicability of Cheops, thus enabling the community at large to capitalise on the unique capabilities of Cheops. All data will be made public through the Cheops archive after a proprietary period.

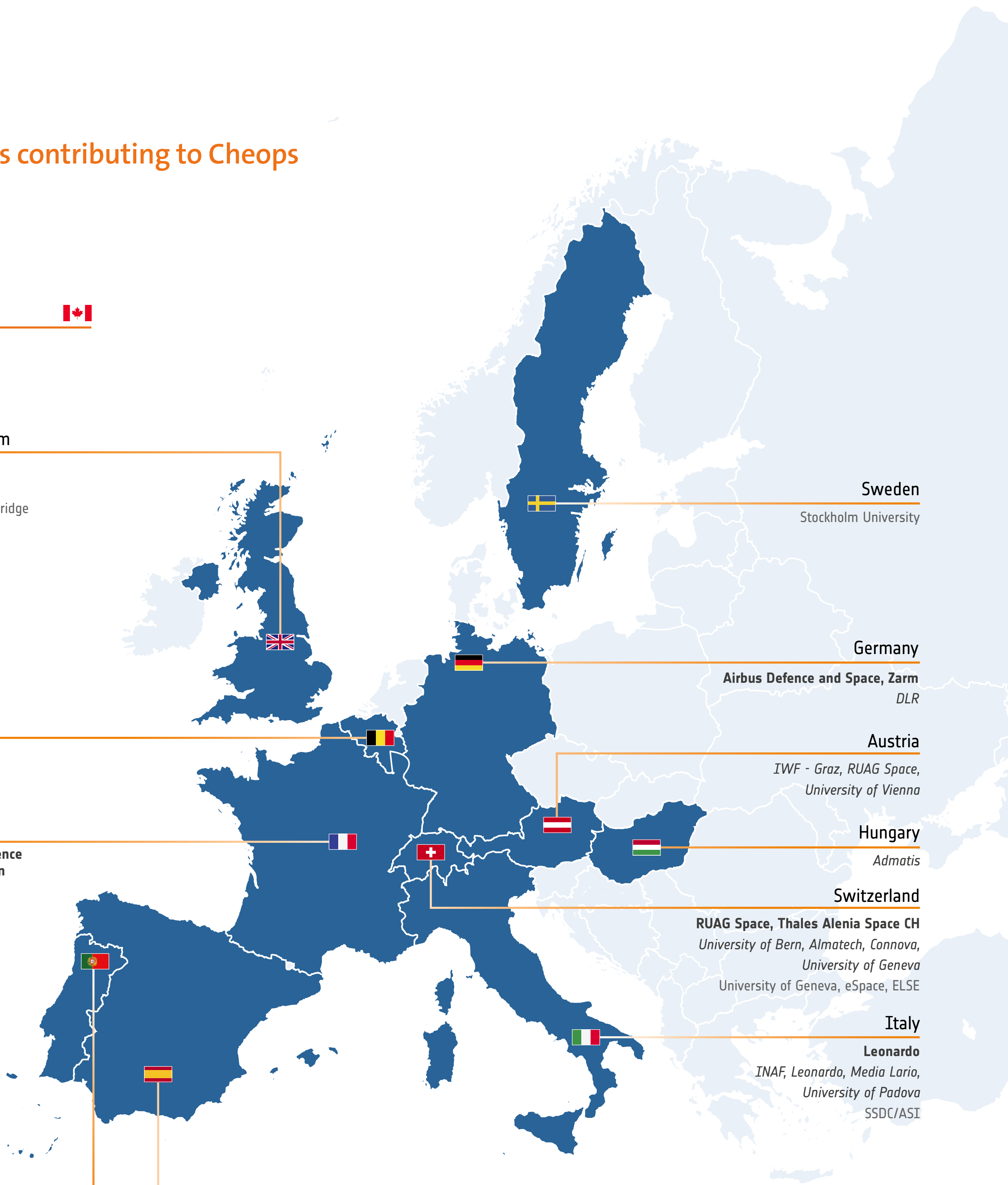
First the raw data from the satellite is processed into usable science data by the Consortium. For example, software from Switzerland will be used to 'unpack' the data that arrives from the ground station, while France is responsible for the software that automatically processes the raw data, with contributions from Portugal. Processed data will be stored in an archive that is also developed in Portugal, with a backup archive hosted by Italy.

The UK is providing 'quick look' software for checking instrument health, while Switzerland has developed software to simulate the behaviour of the instrument in orbit. Sweden has developed software to package data generated by the simulator, which can then be processed in the same way as real spacecraft data and used for testing.

The division of tasks across the various centres spread across Europe reflects the collaborative nature of this European exoplanet mission.

The Kiruna S- and X-band station is located at Salmijärvi, 38 km east of Kiruna, in northern Sweden

Countries contributing to Cheops



Canada
MSCI

United Kingdom
Honeywell
Teledyne e2v
University of Cambridge

Belgium
QinetiQ, CSL

France
SAFT, Airbus Defence and Space, Sodern
LAM

Portugal
LusoSpace
Deimos Engenharia, University of Porto, CAUP

Spain
Airbus Defence and Space, Rymsa Espacio, CRISA, IberEspacio, HV Sistemas
GMV, INTA

Sweden
Stockholm University

Germany
Airbus Defence and Space, Zarm
DLR

Austria
IWF - Graz, RUAG Space, University of Vienna

Hungary
Admatis

Switzerland
RUAG Space, Thales Alenia Space CH
University of Bern, Almatech, Connova, University of Geneva
University of Geneva, eSpace, ELSE

Italy
Leonardo
INAF, Leonardo, Media Lario, University of Padova
SSDC/ASI

Spacecraft
Payload
Ground Segment

→ WELCOME ONBOARD!

Exoplanets fascinate a broad audience, from science fiction authors and film-makers to scientists, and capture the imagination of anyone who has ever pondered whether there might be another Earth out there. To engage and inspire the next generation, two exciting competitions were created in the buildup to launch.

The Cheops Consortium invited schoolchildren to produce drawings that were inspired by the mission. Thanks to the enthusiastic response, Cheops will fly nearly three thousand drawings, which have been shrunk by a factor of 1000 and engraved on two 18 x 24 cm titanium plates attached to the satellite. These creative drawings were submitted by thousands of children sharing their excitement for space; they sketched everything from our own Solar System, starry skies and astronauts, to imaginative illustrations of stars and extrasolar worlds.

You can view the full set via
http://cheops.unibe.ch/campaign-cheops-childrens-drawings

G. Bucher–Bern University of Applied Sciences

Thousands of miniaturised children's drawings, etched on plaques attached to Cheops

University of Bern–A. Moser

The two titanium plates attached to Cheops

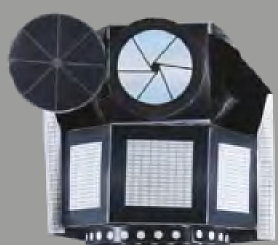
ESA invited early-career graphic artists to submit a design for the mission sticker to be used on the fairing (housing) of the rocket that carries Cheops into space. The colourful winning design, selected from more than 300 entries, was made by 25-year-old graphic designer Denis Vrenko from Slovenia. It captures the scientific essence of the mission, focusing on transiting planets and different star systems.

The winning fairing sticker design

ESA/D. Vrenko

Feeling creative?

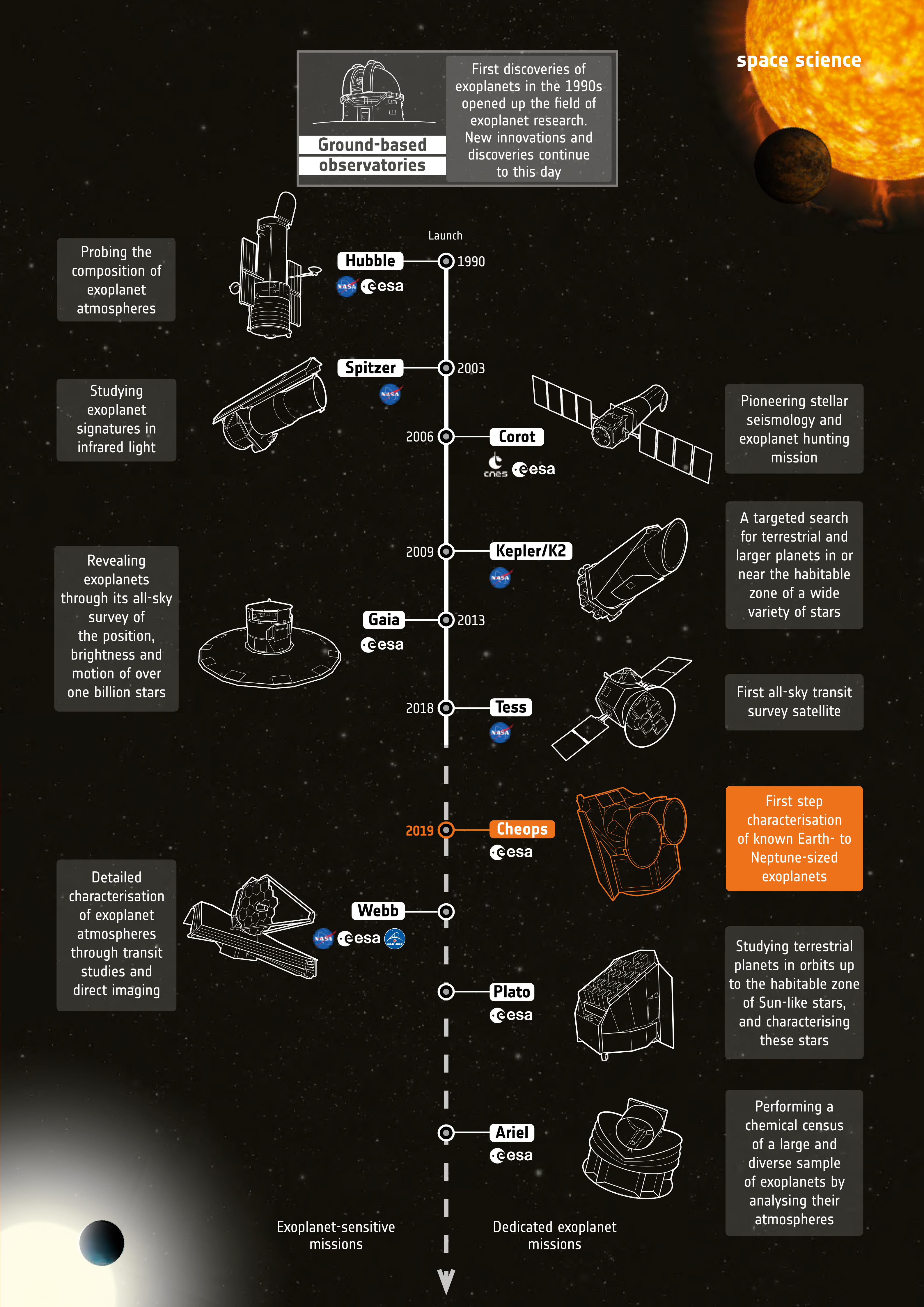
Build your own planet watcher with this paper model! Download the instructions and template by scanning the QR code.



For more information, see:

www.esa.int/cheops

@esascience @ESA_CHEOPS


space science
Ground-based observatories
First discoveries of exoplanets in the 1990s opened up the field of exoplanet research. New innovations and discoveries continue to this day
Launch
Hubble
1990
Probing the composition of exoplanet atmospheres
Spitzer
2003
Studying exoplanet signatures in infrared light
2006
Corot
cnes esa
Pioneering stellar seismology and exoplanet hunting mission
2009
Kepler/K2
A targeted search for terrestrial and larger planets in or near the habitable zone of a wide variety of stars
Gaia
2013
esa
Revealing exoplanets through its all-sky survey of the position, brightness and motion of over one billion stars
2018
Tess
First all-sky transit survey satellite
2019
Cheops
esa
First step characterisation of known Earth- to Neptune-sized exoplanets
Webb
esa
Detailed characterisation of exoplanet atmospheres through transit studies and direct imaging
Plato
esa
Studying terrestrial planets in orbits up to the habitable zone of Sun-like stars, and characterising these stars
Ariel
esa
Performing a chemical census of a large and diverse sample of exoplanets by analysing their atmospheres
Exoplanet-sensitive missions
Dedicated exoplanet missions

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