Space Missions for Exoplanet Science: PLATO

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Abstract

PLATO is the M3 (medium-class) mission in the ESA Cosmic Vision 2015–2025 program, with a planned launch date in 2026. PLATO will carry out transit surveys to detect and characterize planets around bright stars, with special emphasis on small planets orbiting in the habitable zone of solar-like stars. PLATO will allow us to determine the planets' radii with unprecedented accuracy, and, thanks to the brightness of its targets, also the planets' masses through ground-based radial velocity observations. With the asteroseismology analysis of the light curves, it will be possible to characterize the planet host stars and to determine their precise ages, covering a large diversity of planetary systems. The PLATO payload consists of 24 telescopes with CCD-based focal planes, which will monitor stars with $V > 8$ over a wide sky field of view of $2232°^2$ per pointing. Two additional "fast" cameras will be used for stars with *V* 4–8. The nominal duration of the science operations is 4 years.

Introduction

PLATO (PLAnetary Transits and Oscillations of stars) has been selected by ESA as the M3 (medium-class) mission of the Cosmic Vision 2015–2025 program. PLATO is a transit survey mission with the goal of detecting and providing prime planet parameter characterization for new planets and planetary systems around bright stars, including small planets orbiting in the habitable zone of solar-like stars. A Mission Consortium of scientific institutes and universities funded by ESA Member States provides the PLATO payload and elements of the science ground segment. ESA contributes to the payload by supplying the CCDs. PLATO has completed the definition phase (phase B1), and has been adopted by ESA to start its implementation phase.

This chapter describes the scientific objectives of PLATO and gives an overview of the mission concept and the satellite design and its operations. The last sections explain the reference observing scenario and depict the scientific data products that will be available to the community.

Scientific Objectives

PLATO's key science objectives focus on the detection and characterization of exoplanets for their radius, mass, and age as well as characterization of their host stars. PLATO will furthermore address stellar science and provide a large legacy science data set to the exoplanet and stellar science community for years to come. PLATO will answer the following scientific questions (PLATO Definition Study Report, ESA-SCI (2017, 1):

- How do planets and planetary systems form and evolve?
- Is our solar system special or are there other systems like ours?
- Are there potentially habitable planets?

The mission's main objectives are:

- Determine the prime properties (orbit, mass, radius, mean density) of planets in a wide range of systems, including terrestrial planets in the habitable zone (HZ) of solar-like stars
- Analyze the correlation of planet properties and their frequencies with stellar parameters (e.g., stellar metallicity, stellar type)
- Study how planets and planet systems evolve with time
- Study the typical architectures of planetary systems
- Analyze the dependence of the frequency of terrestrial planets on the environment in which they formed
- Study the internal structure of stars and how it evolves with age
- Identify good targets for spectroscopic follow-up measurements to investigate planetary atmospheres

Exoplanet Detection and Characterization

PLATO will achieve its science objectives by detecting planets from photometric transits, surveying a large sample of bright stars in the visible wavelengths range. The main goal of PLATO is to provide a large number of exoplanets which are accurately characterized for their prime parameters:

- **Radius** from analysis of photometric transit light curves obtained by PLATO
- **Mass** from ground-based radial velocity (RV) follow-up spectroscopy
- **Age** from asteroseismic analysis of stars, based on PLATO's photometric light curves

Prime parameters will be provided for all kinds of planets over a wide range of orbits. The main design driver for PLATO, however, is the characterization of terrestrial planets in the habitable zone of bright solar-like stars (dwarfs of spectral type from F5 to K7), although M stars, young, as well as evolved stars will also be observed extensively. See also Rauer et al. (2014) for an overview on PLATO's science goals.

The Core Sample

The characterization of all three prime planet parameters requires to target at bright stars. Figure 1 shows a comparison of planets with known mass or mass lower limit and their detection method (RV or transit) versus the magnitude of their

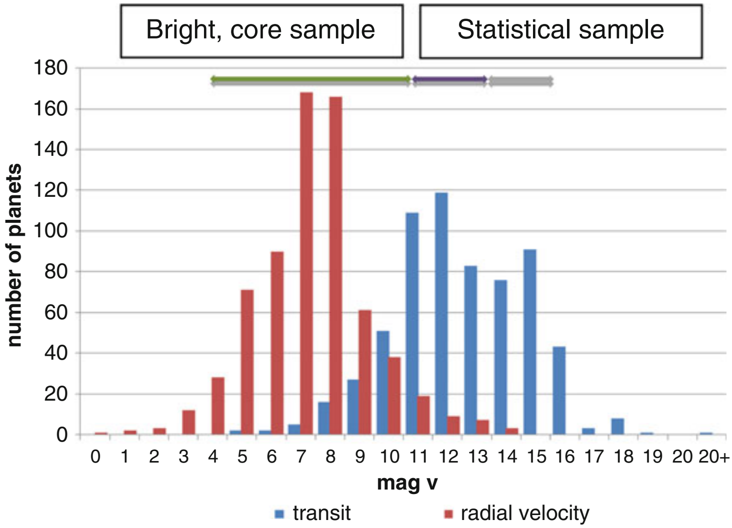

Fig. 1 Histogram of the visual magnitude of stars with known exoplanets. *Red vertical bars* correspond to planets discovered by radial velocity and *blue vertical bars* to exoplanets detected via transits. The magnitude range of PLATO samples is indicated by *horizontal arrows*: *green*: bright core sample (V<11 mag), *purple*: statistical sample (V <13 mag), *grey*: extension for M dwarf targets. The bright PLATO targets overlap well with the detection range of RV surveys

host star. It can be seen that RV observations are most efficient for stars brighter than $V = 11$ mag. The determination of RV masses for fainter targets requires an increasing amount of telescope time, which is unfeasible when observing hundreds to thousands of planets. Such investigations will therefore be limited to especially interesting planets, as was the case for the CoRoT and Kepler missions (e.g., CoRoT-7b, $V = 11.7$ mag (Queloz et al. 2009), or Kepler-10b, $V = 11$ mag (Batalha et al. 2011)). PLATO therefore targets stars brighter than $V = 11$ mag in its core sample to allow for feasible RV measurements for a large number of detected planets (Fig. 1). In practice, a selection of RV follow-up targets will have to be made based on the available ground-based telescope time. In the PLATO core sample, such choices can be made according to scientific merit from a large sample of detected planetary transit signals, all being bright enough for RV observations.

Another key element of the PLATO core sample is the capability to allow for asteroseismic characterization of the planet host stars. The core sample, therefore, requires a noise level of less than or equal to 34 ppm in 1 h, with photon noise being the dominant noise source.

In total about 15,000 stars brighter than or equal to $V = 11$ mag and with the required noise level will be observed in the core sample. We call planets characterized in this sample “accurate”, because not only a high-precision planetary radius and mass can be determined, but also the host star parameters are well determined using asteroseismology methods.

The anticipated accuracy for an Earth-sized planet orbiting a solar-like star of V <10 mag is 3% for its radius, 10% in mass, and 10% for its age. These planets will form "Rosetta-stone targets" for our understanding of planet nature, their formation, and evolution.

In addition, the observations of stars down to V <8 mag in the brightest PLATO sample are essential for the detection of planets that can become main targets for atmospheric follow-up characterization. For these brightest stars, PLATO will provide two color information for additional planet validation, planet atmosphere studies, and complementary stellar science.

The Statistical Sample

Planets detected around stars of fainter magnitudes (V <13 mag for solar-like stars, <16 mag for M dwarfs) will provide a much larger, statistical sample of planet transit detections. This sample still allows for the detection of small, terrestrial planets in the HZ, including Earth-sized planets for solar-like stars with noise levels $\leq$80 ppm in 1 h. However, most of the planets in the statistical sample will have reduced mass (and radius) precisions. Most of their host stars will be too faint for RV follow-up for small planets and also for asteroseismic analysis. Nevertheless, we note that for specifically interesting targets in this sample RV follow-up can be made if willing to invest larger amounts of follow-up time. For planets showing transit-timing variations (TTVs), masses can be derived although with lower precision than from RV data, except for transiting multi-planet coplanar systems which can provide very high-precision planet masses. Ages for planetary systems in this sample must be inferred from classical methods, which should be however much improved by calibration with asteroseismic ages in the PLATO core sample in future.

The "statistical" PLATO sample will include at least 245,000 target stars. Altogether, PLATO will detect transit signals from thousands of planets of all kinds at orbital periods up to 1 AU.

Observing Strategy

To put the expected results into context, PLATO needs to be compared to the current status of exoplanet detection and characterization. The CoRoT and Kepler/K2 missions, together with ground-based transit surveys, have successfully provided more than 2700 confirmed transiting planets and several thousands of planet candidates (e.g., http://exoplanet.eu). These include planets of all kinds, and planetary candidates range down to objects as small as the Earth moon. The statistics of planets characterized for their radius and mass, however, is much smaller since most known planets today orbit stars too faint for RV spectroscopy (see Fig. 1). Planetary masses obtained via TTV analysis are available for a larger number of objects, although usually with lower precision. Today, only about 40 transiting planets of

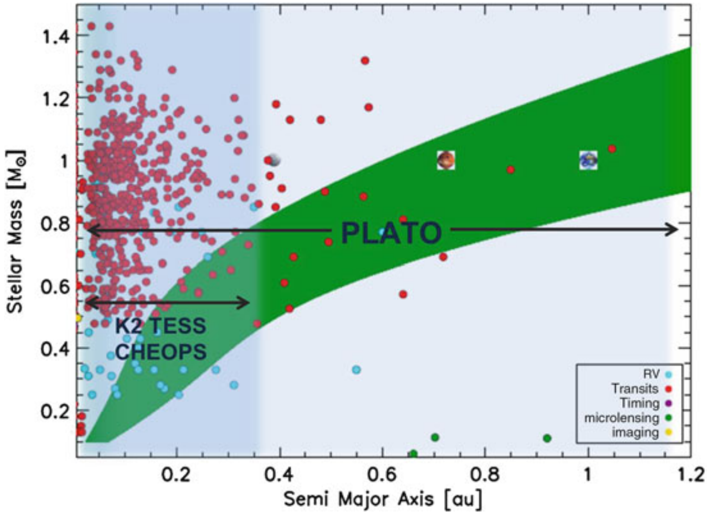

Fig. 2 Schematic illustration of the detection and characterization range of PLATO (*shaded light blue*) in comparison to ongoing and near-future missions (*medium blue*). The *dots* show currently known super-Earth exoplanets ($1< M \leq 10$ $M_{\oplus}$ or $R \leq 3$ $R_{\oplus}$) for different host star masses in comparison with the position of the habitable zone (*green*)

$M < 10$ $M_{\oplus}$ with measured RV masses are known, and none of them is a terrestrial planet in the HZ of a solar-like star. This is the main target range for PLATO.

A comparison to the main detection ranges of K2 (Howell et al. 2014), CHEOPS (Broeg et al. 2013), and TESS (Ricker et al. 2015) is for illustration purposes schematically shown in Fig. 2. K2 and TESS point at their target fields for less than about 3 months and can therefore detect mainly short-period planets. An exception is the continuous viewing zone of TESS, but the number of bright stars in that zone is limited. CHEOPS is a follow-up mission and observes planetary systems detected in other surveys. CHEOPS, K2, and TESS will significantly improve our knowledge of characterized planets in the next 10 years, including the HZ of M dwarf host stars. PLATO's main target range in terms of orbital distances expands this range to solar-like stars, aiming to answer the question whether there are systems similar to ours, including habitable planets. For bright host stars, those planets could be further characterized by spectroscopy for their atmospheres. For M and K dwarfs, the HZ is closer to their star, and PLATO will be able to detect and characterize planets beyond the snow line in those systems.

With a nominal science operation duration phase of 4 years, PLATO is able to detect planets up to about 1 AU. The current operation baseline of two fields observed for 2 years each is chosen to maximize the detection of planets at such intermediate orbits and will provide dozens of signals from transiting terrestrial planets in the HZ of solar-like stars. Those from the bright core sample can be followed by RV spectroscopy observations and are suitable for asteroseismology. RV observations for the most interesting targets will be performed during the mission operation phase, and others will become part of the long-term PLATO science legacy for years to come.

The flexible approach of PLATO also allows for observing scenarios optimized for short-period planets, maximizing the exploration of different regions in the sky. Due to its large field-of-view combined with a step-and-stare observing strategy, the number of close-in small planets around bright stars from PLATO which can be accurately characterized by RV follow-up combined with asteroseismology will exceed the characterized targets from Kepler (Lundkvist et al. 2016) and NASA's mission TESS (Campante et al. 2016) for short-period small planets (<2 $R_{\oplus}$) by up to a factor of 6, if at least six fields are observed for 2 months each (ESA-SCI 2017, 1), in addition to one long pointing. Finally, the design of the mission will allow for operations of up to 8 years total, hence providing the required flexibility to select the observing strategy focusing on the most interesting target parameters in the future.

Planetary Systems

PLATO results will also include planetary systems, such as Kepler-90 (Cabrera et al. 2014), a 7-planet system around a solar-like star, and TRAPPIST-1 (Gillon et al. 2017), a 7-planet system orbiting an M dwarf. Both are surprisingly compact systems. For coplanar systems showing multiple planet transits, accurate mass determinations will be possible based directly on spacecraft data via TTVs. Multi-planet systems around bright target stars will also allow for RV mass determinations. The bright PLATO sample can therefore provide precise planet parameters in many systems. Together with a well-known age of the system from asteroseismic analysis, such systems will be highly interesting objects for studies of planet formation and evolution.

Exoplanet Parameters

Simulated light curves with the expected PLATO instrument performance (ESA-SCI 2017, 1) show that planetary radii can be derived with an accuracy of <3% for a terrestrial planet orbiting a bright G0V star with $V \leq 10$ mag. For the same reference star, ages can be obtained with 10% accuracy using asteroseismic methods. Accurate asteroseismology results from the most suitable targets will be used to calibrate other methods of stellar age determination and therefore increase today's age accuracy also for stars not assessable to asteroseismic analysis. Planetary masses are derived by follow-up RV observations with an accuracy of 10% for terrestrial planets orbiting PLATO's bright target stars. These accuracies are the benchmark cases used as design drivers, and better accuracies are expected for larger planets, smaller hosts, and planets orbiting the brightest stars.

Once accurate planetary radii and masses are known, their mean densities can be derived. Today, observed mean densities of exoplanets span a range of two

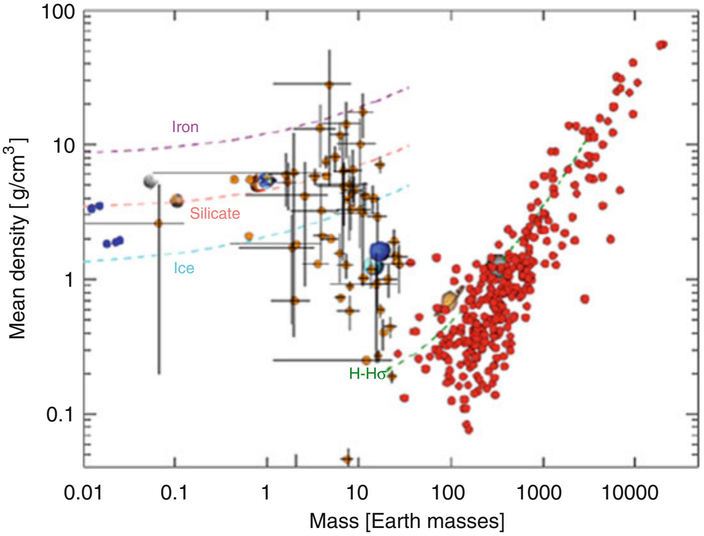

Fig. 3 Mean planet density versus mass with density lines for different bulk compositions (update from Rauer et al. 2014)

orders of magnitudes for the same planetary masses (Fig. 3). This diversity in planet properties requires an explanation by planet formation theories, but also by a better understanding of planet evolution, e.g., including atmospheric loss processes and cloud formation (Lammer et al. 2016). PLATO will provide significant observational constraints to improve our understanding of planet diversity. PLATO will provide precise masses, and therefore mean densities, also for planets at intermediate orbits. Note that less than a dozen of the planets with measured mean densities in Fig. 3 orbit their host star with orbital periods above 80 days. If compared to our solar system, the majority of exoplanets with measured mean density known today would orbit inside Mercury's orbit. Accurately characterized planets at intermediate orbits remain an open parameter range to be filled with PLATO.

Furthermore, today only a handful of known planets have mean densities known to better than 10% accuracy (http://exoplanet.eu). PLATO will provide a large catalogue of planets with well-known radii, masses, and mean densities. The high accuracy of radii and masses will help to classify planets into rocky, icy, or gassy. Gas giant planets cool over long timescales, which means their cooling history needs to be taken into account when determining their heavy element abundance. Therefore, accurate radii measurements need to be combined with a well-known planet age to arrive at meaningful constraints for a planet's core mass. With PLATO accuracies on radii and age, we will be able to study whether gas giants with massive cores are common. Other interesting science questions include, e.g., the orbital distance up to which we find inflated planets or planets with high mass loss rates and how this correlates with stellar type and activity. Furthermore, together with a well-known age determination via asteroseismology, we will be able to constrain the evolution of planets and planetary systems with large samples of observational data. The large number of PLATO-characterized planets will allow us to correlate prime planet parameters with parameters of host stars, e.g., type, metallicity, mass, and age.

Planetary Atmospheres

The PLATO instrument is a photometric camera operating in white light, except for two cameras which are equipped with a red and a blue filter, respectively. Planets detected around bright stars will be subject to follow-up observations by spectroscopic instruments from ground (e.g., VLT, E-ELT) and space (e.g., JWST) to investigate their atmospheres. However, PLATO light curves can also provide information on planetary atmospheres via the reflected stellar light on the planet. Observations of the secondary transit will provide the geometric albedo of a planet, and measurements of the reflected light along the full orbit (phase curves) will provide the spherical albedo, a key ingredient for a planet's energy balance. The red and blue cameras will help to disentangle contributions from thermal emission for the hottest planets observed and also help to identify the dominant inert molecule in an atmosphere. Phase curves in visible light, such as provided by PLATO, allow mapping the brightness distribution over different longitudes of a planet and therefore to study the distribution of clouds and hazes in the atmosphere. In summary, although PLATO is not primarily a mission to investigate planetary atmospheres, it will provide significant data which will complement spectroscopic follow-up observations.

The Evolution with Age

A key element of PLATO is the accurate determination of ages for field stars and hence the age of detected planetary systems. This will allow us to study the correlation of planet and planetary system parameters with age to learn about their evolution processes. An example for such processes is the contraction of gas giant planets after formation which can take up to Gyrs. Among the surprising diversity of exoplanets are gas giants which seem to contain hundreds of Earth masses of in their cores (Cabrera et al. 2010). It will be interesting to learn how frequent such planets are, how they correlate with the host star parameters, and whether they are also found at larger orbital distances. However, when interpreting their planetary radius and mass in terms of heavy element content, the planetary age needs to be well known. With up to 10% accuracy in age for bright host stars, PLATO will help in disentangling this uncertainty.

Atmospheres of terrestrial planets show a strong dependence on age, as we have learned from Venus, Earth, and Mars in our solar system. Terrestrial planet atmospheres are affected by loss processes removing their primary, and in case of

Mars also their secondary (outgassed), atmosphere. Earth has developed a tertiary nitrogen-oxygen-dominated atmosphere from its biosphere. Young planets will be subject to significant loss processes induced by an active host star, emitting strong UV and high-energy radiation which can also affect the habitability on such planets. PLATO will detect terrestrial planets around bright stars and provide some first indications for the possible existence of a dense atmosphere for these planets, helping to identify the best targets for spectroscopic follow-up investigating atmosphere composition. Such follow-up observations combined with the age derived from PLATO will allow investigating whether a correlation of planetary atmosphere compositions with ages can be found in the future.

Planetary systems evolve with age due to migration and scattering processes which can change the distribution of the planetary mass function over orbital distance with time. A better determination of the age of planetary systems, in particular for young systems, will provide better constraints to planet formation and dynamical evolution theories. Improved age determination methods triggered by PLATO observations will be key to better understand such dynamical processes.

Planets Around Different Types of Host Stars

PLATO will detect planets around different types of stars. The solar-like stars forming the main target sample of PLATO have already been discussed above, as well as the M dwarfs which provide planets in the HZ with short orbital periods. The high sensitivity of PLATO will however also allow us to search for the small signal of transiting planets in front of subgiant and giant stars. These systems are of particular interest because they provide information on the planet population around evolved stars. Correlations with stellar properties such as metallicity (e.g., Mortier et al. 2013) will provide further insight into the planet formation processes. Another interesting line of research will be the search for giant planets around white dwarfs, telling us how planets survive the evolution of their host star. Similar arguments hold for post-RGB pulsating stars.

Several circumbinary planets, hence planets orbiting both components of a binary star system, have been found today (e.g., Doyle et al. 2011). PLATO will enlarge this sample and allow us to study correlations with masses, orbital periods, age, and type of host stars.

Disintegrating Planets and Moons

UV transmission spectroscopy of close-in giant planets has shown significant mass loss of such planets. Today, these studies are limited to a few known bright targets (HD209458b, WASP-12b, HD189733b, 55 Cancri b, GJ 436b). PLATO will increase the sample of bright targets for which such follow-up measurements will be possible. Furthermore, mass loss can then also be studied for smaller planets and for planets at larger orbital distances. A larger sample of planets with indications for mass loss will allow us to investigate the dependence of star-planet interactions and mass loss on stellar type, activity, and orbital distance.

The search for exomoons is challenging, and no successful detections have been made so far. Detection is difficult because their signal in photometric transit light curves can be easily mixed with stellar spot crossings or instrumental systematics (Kipping et al. 2015). TTVs induced by moons are small, in the range of seconds. Furthermore, orbits of moons for close-in planets are likely unstable (Namouni 2010), and we need to search them at intermediate and large orbital separations. The long-term photometric light curves of PLATO, obtained with high cadence time sampling for bright stars, will form an ideal data set to continue this challenging search.

Host Star Parameters

Accurate planetary parameters require a precise knowledge of the host star, since planetary radii and masses are measured relative to their respective stellar counterparts. The age of an exoplanetary system can only be derived via the age of the host star, with the reasonable assumption that planet formation is very fast once the host star has formed. The determination of accurate host star parameters is therefore a key element of the PLATO mission and performed via asteroseismology methods.

Asteroseismology studies the global oscillations of stars due to trapped acoustic and gravity waves. The frequency of the oscillations observed depends on the internal radial density distribution and the sound speed of the star. It allows us to derive the stellar bulk parameters as well as the age. The great potential of this technique has been successfully demonstrated by the CoRoT (Baglin et al. 2013) and Kepler (Borucki et al. 2010) missions.

Figure 4 shows an example of the power spectrum of HD52265 obtained with the CoRoT satellite (Gizon et al. 2013). The stellar PLATO core program focuses on stars showing oscillations similar to the Sun and will be able to apply asteroseismology methods to thousands of stars in its bright core sample.

The goal of PLATO is to provide host star parameters with mass precisions of 10%, stellar radii with 1–2%, and ages to 10% precision for a reference solar-like star with $V = 10$ mag.

The PLATO target samples focus on bright stars and therefore can take advantage of a strong synergy with ESA's Gaia mission. Gaia will provide the distances to the target stars and allow us to derive the absolute luminosity of the star. Combined with the effective temperature of the star, the stellar radius can be derived with the required high precision. PLATO will also provide significant input into the calibration of scaling relations, which are used to derive the stellar density and mass (e.g., Huber et al. 2012, Silva Aguirre et al. 2012, White et al. 2015). Data from the brightest stars will allow for analysis via inversion techniques (e.g., Buldgen et al. 2015) and provide a model-independent mass. The derivation of stellar ages requires sophisticated stellar models and has been studied using available CoRoT

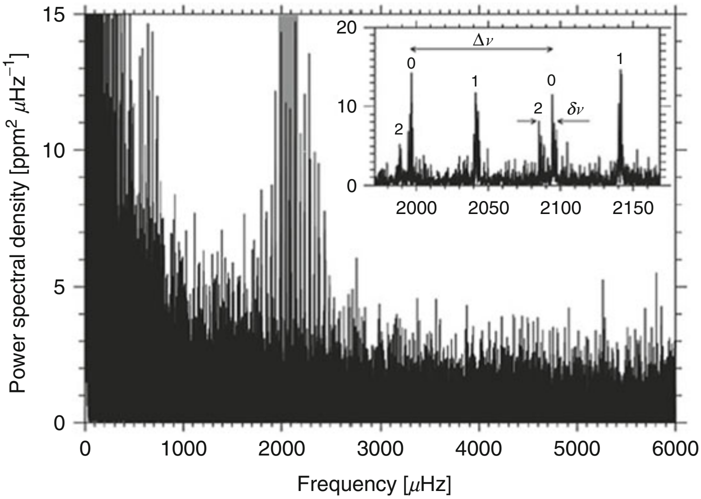

Fig. 4 Power spectrum of HD52265 obtained after 117 days of observations with CoRoT (Gizon et al. 2013). The insert figure shows a zoom of the power spectra frequency range highlighted in *grey*

and Kepler data (e.g., Lebreton and Goupil 2014; Lebreton et al. 2014a,b) to show that high precisions can be reached for bright stars.

The core sample of up to 15,000 solar-like stars is sufficiently bright for asteroseismology (V <11 mag). The observations are obtained with a lightcurve sampling cadence of 25 s. The fainter statistical sample is mainly obtained at a reduced cadence of 600 s, but still includes a few thousand bright targets which can be downloaded with high cadence. Those will have a reduced accuracy compared to the bright sample, but will still provide useful information on stellar characterization. The large number of bright stars observed with PLATO for several years is expected to provide a large catalogue of well-characterized stars with substantially better performance than Kepler, K2, and TESS.

It is interesting to point out that asteroseismic data also provide highly useful information on the dynamical evolution of planetary systems. The existence of planets on oblique orbits, that is, with high angles between the stellar spin and the orbital axis of the planetary system, indicates that scattering processes by the Kozai mechanism must have been important. However, to determine the true spin-orbit angle, the spin angle of the star must be known. It has been demonstrated that the true obliquity can be derived via asteroseismic techniques (Gizon et al. 2013; Chaplin et al. 2013; Benomar et al. 2014; Campante et al. 2016). Such measurements require high signal-to-noise ratios and long-duration data sets, such as those provided by PLATO.

PLATO data will furthermore provide information about the stars that will help to better constrain stellar models. This includes, e.g., the surface helium abundance, the depth of a convective envelope, the internal structure, etc. Crucial here are the high-quality photometric light curves for a large number of stars of different types that will significantly enhance our understanding of stellar evolution. PLATO's long time series will furthermore allow the study of spot decay and magnetic activity cycles.

Complementary Science

PLATO provides data for a large complementary science program, obtained on all kinds of objects. The complementary science targets, which must be located within the PLATO fields, will be proposed by the community through a guest observer program. This program may include, e.g., red giant stars, hot OB subdwarfs, massive stars, white dwarfs, young and evolved stars, stars in clusters, pulsating stars, binaries, and many more. When combining chemical composition from ground-based spectroscopic surveys, distances from Gaia, and ages from PLATO for a large sample of stars, a comprehensive study of chemical gradients and temporal evolution in our galaxy will be possible. This data set will provide a long-term legacy for the scientific community, significantly expanding the exoplanet science case of the mission.

Mission Design

For the observation of planetary transits and the stellar seismic activity, PLATO will perform long (months to years) uninterrupted high-precision photometric monitoring in the visible band of large samples of stars. PLATO must be able to obtain light curves that are precise enough to detect and determine the radius of an Earth-sized planet around a G0V star of $V = 10$ mag with 3% accuracy. Asteroseismology analysis should be able to provide the age and stellar radius of a G0V star of $V = 10$ mag with 10% and 1–2% accuracies, respectively. This translates into light curves with a random signal-to-noise ratio of less than 34 parts per million (ppm) in 1 h and to the requirement that the total residual error in the final light curves, after all corrections applied, remains below one third of the random noise associated with a star of $V = 11$ mag.

The capability to confirm and determine the mass of planets of the same size as the Earth, with 10% accuracy through ground-based observations, is an important element of the PLATO concept. This requires that the stars are bright enough for feasible ground-based observations with the facilities available at the time of the PLATO launch (e.g., ESPRESSO in the VLT). The limiting magnitude of the core PLATO stellar sample has therefore been set to $V = 11$.

Satellite and Payload

The PLATO spacecraft is composed of two main modules:

- The payload module, which consists of the cameras and associated electronics, data processing units as well as the optical bench, supporting structures, and the hardware thermal control.
- The service module, which consists of the platform equipment and the main structure including sunshield that protects the payload from the Sun, as well as generates power via body-mounted solar cells.

The key scientific requirement to detect and characterize a large number of terrestrial planets around bright stars determines the design of the payload module. The payload needs to provide a wide field of view to maximize the number of the sparsely distributed bright stars in the sky with one pointing and allow the satellite to cover a large part of the sky. In addition, it has to provide the required photometric accuracy to detect Earth-sized planets and a high photometric dynamic range, from bright stars (V <11 mag) as well as fainter stars down to $V = 16$ mag.

This performance is achieved by a multi-telescope instrument concept, consisting of 24 "normal" cameras with CCD-based focal planes, with a readout cadence of 25 s. The "normal" cameras, dedicated to monitor stars with V >8, are arranged in four groups of six (see Fig. 5). Each group has the same field of view but is offset by a 9.2° angle from the payload module +Z axis, allowing for a total field of view of about 2232°^{2} per pointing. This arrangement results in different sensitivities over the field, with four parts monitored by 24, 18, 12, and 6 cameras. Two additional "fast" cameras with high readout cadence (2.5 s) will be used for stars with V 4–8 and will act as the fine guidance sensor for the attitude control system. In addition,

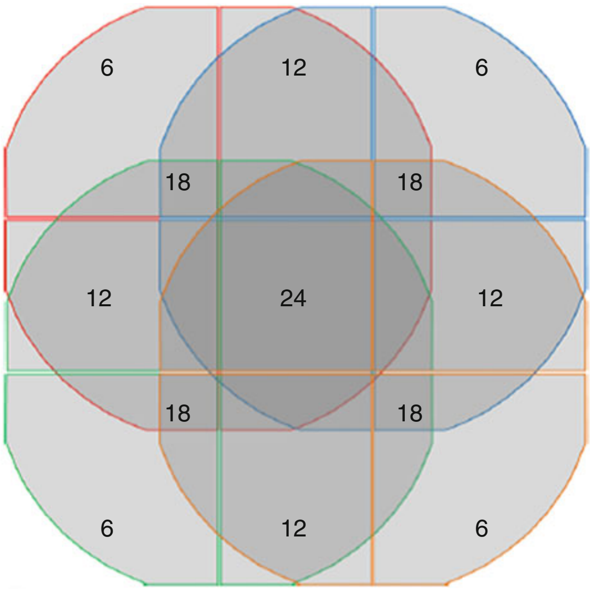

Fig. 5 PLATO field of view indicating the number of cameras covering each area

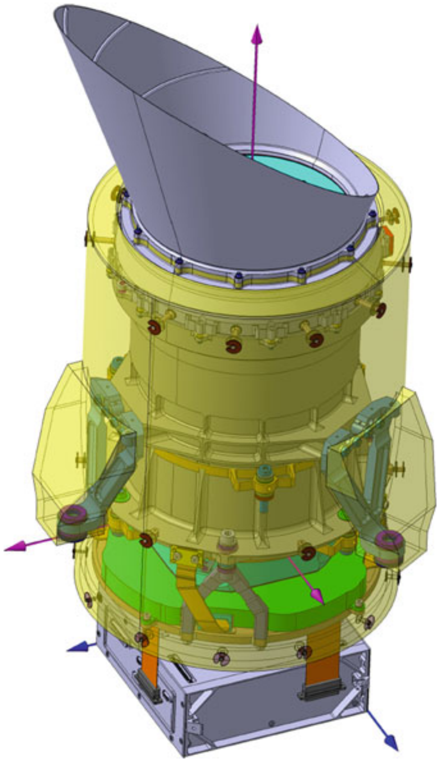

Fig. 6 View of one of the 24 "normal" cameras with multilayer isolation around the telescope. The focal plane assembly is displayed in *green* and the front-end-electronics box in *blue* at the *bottom*

they will allow measurements of stars in two spectral bands. For this purpose one of the "fast" cameras is equipped with a blue, the other one with a red bandpass filter. The ensemble of cameras is mounted on an optical bench. The cameras are based on a fully dioptric design with six lenses. Each camera has a 1037$°^2$ field of view and a pupil diameter of 120 mm and is equipped with a focal plane array of four CCDs, each with 4510×4510 pixels of 18 μm size, working in full frame mode for the "normal" camera and in frame transfer mode for the "fast" cameras. There is one Data Processing Unit (DPUs) per two "normal" cameras performing the basic photometric tasks and delivering a set of light curves, centroid curves, and imagettes to a central Instrument Control Unit, which stacks and compresses the data, then transmits them to the service module for downlink (Fig. 6).

As a result of the PLATO definition study (phase B1), two spacecraft competitive concepts, respectively, led by Airbus DS Ltd. and OHB System AG are currently under consideration. The spacecraft proposed by Airbus is based on a prism-shaped structure with three main panels of 5×2 m with equilateral triangle basis (see Fig. 7, left). The 26 cameras that constitute PLATO's payload are installed horizontally on one of the three vertical panels. The spacecraft proposed by OHB is based on a separation between service and payload modules as illustrated in Fig. 7 (right), to isolate the payload module as much as possible from the service module thermal dissipations and mechanical distortions.

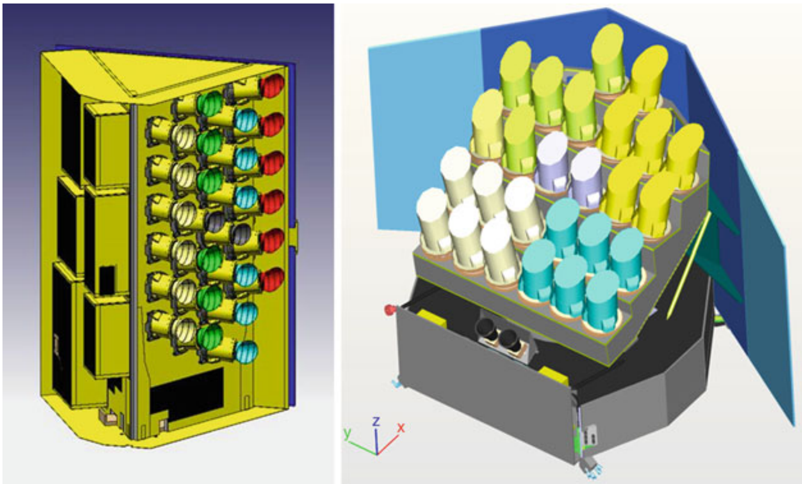

Fig. 7 PLATO satellite designs resulting from the Definition study, from Airbus DS Ltd. (*left*) and OHB System AG (*right*)

The high photometric accuracy and therefore stability depends directly on the performance of the spacecraft attitude system, which is a driver for the satellite design. The key parameter is the mean pointing error (MPE) of each camera, which is constrained by the performance of the attitude and orbit control system (AOCS). The maximum relative pointing error (RPE) of the spacecraft must be limited to 3 arcsec (95% confidence level) over the cycling time of the "normal" cameras, i.e., 25 s. The RPE is driven by the attitude system high-frequency noise mainly caused by reaction wheel friction jumps and by microvibrations.

Data Acquisition and Operations

At the beginning of each sky pointing full images will be transferred to ground to derive the PSF at each target position. To reduce the high data volume produced onboard during operation, each assigned target star will be allocated a CCD window around it from which all the pixel values will be gathered, forming a small image called an "imagette." The size of this window is typically 6×6 pixels, 9×9 pixels for the fast cameras, large enough to contain the whole image of the target star. These imagettes will either be sent as raw data to ground or processed onboard to get centroids and light curves to further reduce the telemetry data volume. The raw imagettes are used on ground to derive the PSF at different positions of the detector, a step which is needed to verify the quality of the photometric and centroiding data. During science operations, a communication session with the nominal ground station will be used several times per week. The expected downlink data volume including compression is 435 Gb per day, which requires data transmission at 36 Mbps in the K-band. In addition, real-time housekeeping data will be transmitted at 26 kbps in X-band via a dual X/K-band high antenna gain.

PLATO is foreseen to be launched in 2026 from Kourou and injected onto a transfer trajectory to the second Lagrangian point of the Sun-Earth system, L2. After a commissioning phase of maximum 3-month duration, a nominal science operations phase of 4 years will be performed. Mission extensions are possible, since the satellite will be designed for an in-orbit lifetime of 6.5 years accommodating consumables for 8 years. During long observations, the spacecraft must maintain the same line of sight toward one field for up to several years. However, to ensure that the solar arrays are kept pointing toward the Sun, the spacecraft is rotated around the line of sight by 90° roughly every 3 months.

Achieving an 80% probability that all transits of a planetary three-transit sequence are observed requires a duty cycle of 93%. This value imposes a strict control of the duration and frequency of observation interruptions due to spacecraft maneuvers and calibrations. Furthermore, gap periodicity must be avoided, because it produces side lobes in the power spectrum of the observational data that make the identification of stellar oscillation modes ambiguous.

The operations of PLATO will be carried out by the following: (i) an ESA-provided mission operations center; (ii) an ESA-provided science operations center; (iii) a PLATO data center, a science management group, and a calibration/operation team, all provided by the Mission Consortium; and (iv) a ground-based observations program team.

Reference Observing Scenario

PLATO has a flexible observing approach. It is designed to carry out observations of the same sky field lasting for several years (long-duration pointings) and to make short observations (from days to months) at different sky locations (step and stare). Long-duration pointings are required to detect planets out to the HZ of solar-like stars. Short pointings would be dedicated to shorter-period planet detections and would address a number of different science cases such as galactic exploration. These strategies complement each other and allow for a wide range of different science cases. Because of the fast development in the exoplanet field, the final PLATO observing strategy will only be decided 2 years before launch. Currently a baseline observation scenario for the nominal science operations has been defined, which assumes two long-duration pointings of different sky fields, lasting 2 years each. An alternative scenario would consist of a long-duration pointing of 3 years and a step-and-stare phase of 1 year. The current mission design constraints the center of the long-duration pointing fields to be at least above 63° or below −63° in ecliptic latitude. The long-duration pointing fields that have been preliminary selected are shown in Fig. 8. A Southern field center is located at $l = 253°$ and $b = -30°$ and a Northern field centered at $l = 65°$ and $b = 30°$.

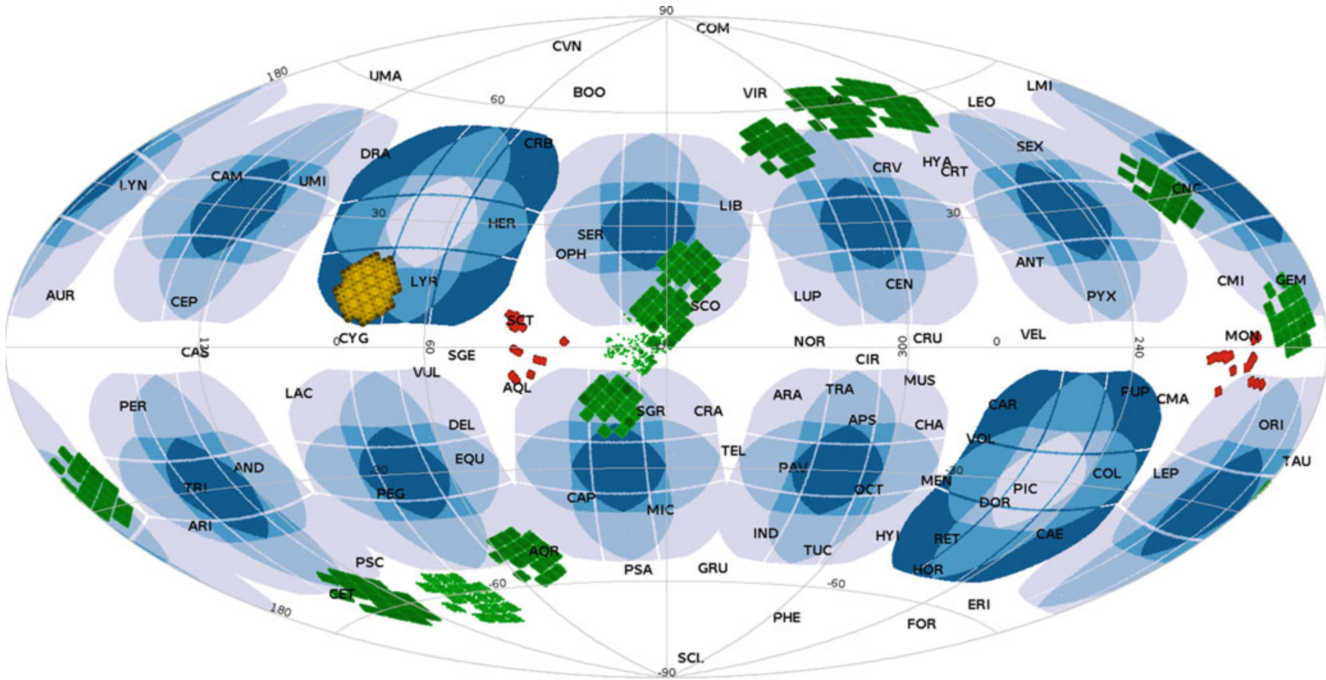

Fig. 8 *Dark blue* areas show the PLATO field of view for two preliminary selected long-duration pointings in galactic coordinates. *Light blue* areas show possible short-duration (or step-and-stare) pointings. The *yellow region* indicates the Kepler mission field; *red* indicates CoRoT target fields and *green*, fields of the K2 mission. Note that the final locations of long-duration and step-and-stare fields will be defined 2 years before launch and are drawn here for illustration only (Figure courtesy of N. Nascimbeni, Univ. Padova).

The PLATO Input Catalogue (PIC) will contain the targets that will be observed in the selected sky fields. Preparatory work on the PIC will serve to select the optimal PLATO fields; select dwarf and sub-giants of spectral type later than F5, and M dwarfs, in each field; and characterize them as much as possible. The PIC will also contain enough information to provide a list of stellar neighbors that contaminate each target star flux. Pre-launch characterization of PLATO targets will provide us with the basis for an initial statistical analysis of planetary system properties on a large scale. The main source for the PIC will be the Gaia catalogue, but it will also require the assembly of information from very different input catalogues on a wide range of targets. For the initial performance estimates of PLATO, Nascimbeni et al. (2016) constructed a catalogue of FGKM dwarfs (UCAC4-RPM) by applying the reduced proper motion technique to the UCAC4 catalogue and using the RAVE spectroscopic catalogue as a calibrator. They found that a merge of the Tycho-2 catalogue at the bright end (V <10 mag) and their UCAC4-RPM at the faint end (10< V <13 mag) was suitable for a preliminary version of the PIC. Considering this early PIC for the two long-duration pointings, performance estimates show that PLATO may observe 13,000 stars with V <11 mag and a random noise of 34 ppm in 1 h and 42,000 stars brighter than this magnitude with a random noise of 80 ppm in 1 h. The total number of stars with V <13 mag in the two fields will be 320,000, of which 80,000 will have light curves with a random noise of 80 ppm being 1 h.

Members of the scientific community may participate in the PLATO mission by becoming Guest Observers (GOs) selected by ESA through calls for proposals. The calls will ask for complementary science programs targeting objects within the PLATO sky fields that have been defined for the core science, therefore not requiring dedicated repointing of the spacecraft. A percentage of up to 8% of the science data rate (excluding calibration data) will be allocated to targets from the GO program.

Data Products

PLATO will provide raw (Level-0) and calibrated (Level-1) light and centroid curves for all observed targets, including those of the GO program. For the targets in the PIC, the Mission Consortium will generate high-level products (Level-2) with stellar characteristics and identification of planetary candidates, as listed in Table 1. Planetary candidates for a subset of targets in the PIC, selected in advance depending on the noise in their light curve, will be followed up with ground-based observations carried out by a dedicated team selected by ESA, in coordination with the Mission Consortium. The follow-up will be aimed at filtering false positives and therefore confirming the planets and at characterizing the planets' orbits and masses through high-precision radial velocity observations. The result will be a catalogue of confirmed planets with mass measurements (Level-3 product). The ground-based observations to confirm and characterize the remaining candidate planets are expected to be carried out by the community at large as part of the PLATO legacy.

Table 1 PLATO data products

Product level ID	Description
Level-0	Validated imagettes, light curves, and centroid curves[a]
Level-1	Calibrated imagettes, light curves, and centroid curves[a]
Level-2	Planetary candidate transits and their parameters
	Asteroseismic mode parameters
	Stellar rotation and activity
	Stellar radii, masses, and ages
	Living catalogue of confirmed planetary systems and their characteristics using light curves and transit time variations
Lg	Follow-up ground-based observations
Level-3	Living catalogue of confirmed planetary systems and their characteristics using new ground-based follow-up observations (Lg)

[a]Calibration, housekeeping, ancillary, and quality products will also be available

Level-0 to Level-3 products will be public in the ESA PLATO archive after the respective proprietary periods have expired. Level-0, Level-1, and Level-2 products for each three-month observing period will be released within a year after the Level-1 product has been validated. ESA will encourage observers to deliver their high-level products so that they can also be made available through the PLATO archive.

Cross-References

- ▶ Ages for Exoplanet Host Stars
- ▶ Characterizing Host Stars Using Asteroseismology
- ▶ ESPRESSO on VLT: An Instrument for Exoplanet Research
- ▶ High-Precision Spectrographs for Exoplanet Research: CORAVEL, ELODIE, CORALIE, SOPHIE, and HARPS
- ▶ Mass-Radius Relations of Giant Planets: The Radius Anomaly and Interior Models
- ▶ Radial Velocities as an Exoplanet Discovery Method
- ▶ The Habitable Zone: The Climatic Limits of Habitability
- ▶ Transit Photometry as an Exoplanet Discovery Method
- ▶ Transit-Timing and Duration Variations for the Discovery and Characterization of Exoplanets

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