The CoRoT Legacy Book

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V.3

Present and future space missions for ultra-precision photometry

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1. Introduction

We are in a golden era for the study of transiting exoplanets and stellar physics using space-based telescopes. One legacy of CoRoT is that it marked the start of this era. CoRoT was the first to demonstrate the pioneering science that would result from ultra-precise, long duration and continuous space-based photometric measurements. Its two main science programs worked in parallel. One searched for transiting planets among a total of ~100 000 stars. The other performed asteroseismology on 156 bright stars. Kepler shortly followed in CoRoT footsteps. Together they started the space photometry revolution.

CoRoT and Kepler highlighted the advantages of photometry with a space telescope in spite of the higher cost. A ground-based telescope can simply not compete with the exquisite photometric precision and superb sampling of a space based counterpart. The detection of small transiting planets and solar-like oscillations benefit immensely from all these improvements. One can strongly argue that ultra-precision space photometry launched a golden age in both transiting planets and asteroseismology.

Ground-based transit programs such as WASP and HAT-P have had spectacular success at finding almost 200 transiting planets, but these ground-based searches had two large disadvantages. First, they are severely biased towards finding giant planets. Of the exoplanets discovered by these transit searches the smallest planets have a radius of approximately 0.5 $R_{\rm Jup}$. By comparison, CoRoT detected several hundreds of Neptune-size candidates while Kepler detected several thousands, most of these in multiple systems. Clearly, only space-based surveys can get the complete census of the planet population down to the smallest (Earth-sized planets). Gas giants represent only a small fraction of the full planet population.

Second, space photometry is also more efficient at detecting transiting exoplanets. CoRoT discovered a giant planet for roughly every 3000 stars monitored, comparable to that of Kepler. On the other hand the ~200 transiting giant planets discovered by ground-based surveys required the monitoring of many hundreds of thousands if not millions of stars. The detection efficiency of ground-based surveys is roughly a factor of 10–20 worse than those from space.

Although CoRoT and Kepler were spectacularly successful, they suffered from one serious drawback, they generally targeted quite faint ($V > 12$) stars. This made the follow-up observations for both complementary seismology data and the confirmation and characterization of planets through high resolution spectroscopy challenging. For example, CoRoT detected several hundreds of transits with depths consistent with Neptune- or super-Earth-sized planets. However, radial velocity confirmation of these were nearly impossible since most of the targets were in the magnitude range V = 13–16. Only upper limits to the planetary mass could be determined. The brightness of the host stars for the Kepler discovered planets are not much better.

The faintness of the CoRoT and Kepler transit candidates have stressed the telescope resources needed for follow-up observations. The study of the properties (temperature, composition, etc.) of the transiting exoplanet's atmosphere using either in-transit spectroscopy or secondary eclipses is an important next step in the characterization of exoplanets. However, the atmospheric signature of a planet is a million times fainter than the light of the star which means that these measurements can only be made on relatively bright stars. It is for this reason that atmospheric studies have only been performed on a handful of transiting planets. CoRoT and Kepler have discovered a large number of transiting planets, but these are ill-suited for atmospheric studies due to the faintness of the host star.

Space is also the place for stellar oscillation studies. From the ground, the photometric precision is ultimately limited by the atmospheric scintillation noise. Furthermore, the data gaps due to the diurnal cycle of the sun and bad weather makes it challenging and frustrating to acquire sufficient data to detect all oscillation modes. For example, from the ground using coordinated observations from a network of telescopes scattered across the globe, one can detect 10 pulsation modes in a delta-Scuti star using 170 hrs of data (Breger et al. 1995). With 550 hrs continuous observations, the mode count increases to 19 (Breger 1995). In its initial run of just 58 d, CoRoT detected hundreds of pulsation modes in a delta-Scuti star (Poretti et al. 2009). Thanks to space photometry, the largest work load for asteroseismology has shifted from data acquisition to data modeling.

It is beyond the scope of this paper to discuss all the exciting asteroseismic results from CoRoT and Kepler. However, it is worth mentioning the radial and non-radial pulsations in giant stars, first found by CoRoT (De Ridder et al. 2009) and which blossomed into a vibrant sub-field of asteroseismology under Kepler. Without space photometry, asteroseismology would still be in its infancy rather than the mature field it is today.

Asteroseismology is also of immense importance to exoplanet studies. The accurate parameters of planet hosting stars, such as mass and radius, translate into accurate parameters for the planet. The age of exoplanets, important for understanding the evolution of planetary systems, is one of the more poorly known stellar parameters. This is even more difficult for stars lying off the main sequence which can be either very young, or very old. For example, the mass and radius Kepler-423 can be fit by evolutionary tracks with either 25 million years (Myr) or 11 gigayears (Gyr) tracks (Gandolfi et al. 2015). Asteroseismology can deliver accurate values for these important parameters and again space photometry has enabled us to do so.

Also in this respect, CoRoT and Kepler had limitations. CoRoT could perform asteroseismolgy on very few bright planet hosting stars (Escobar et al. 2012), but these were using the bright star seismo-field. The faint star exo-field, which delivered all of CoRoT's planet discoveries, had much fainter stars and with poorer time sampling which made asteroseismic measurements impossible. Kepler was able to perform some asteroseismology on the host stars of its detected planets (e.g. Batalha et al. 2011), but these were only for a few of the stars that were sufficiently bright. Clearly what is needed is a wide-field transit search program for which the asteroseismic measurements are made with the same data used to detect transiting planets.

The upcoming space missions will remedy the limitations of CoRoT and Kepler. Two of these (TESS and PLATO) will perform a wide-angle search for transiting planets, but for stars with $V < 11$. PLATO will have a strong asteroseismic component so that accurate stellar parameters will be obtained. These missions will provide transiting planet candidates for which it will be much easier to perform spectroscopic follow-up measurements. The discovered exoplanets will also provide important targets for characterization studies with the James Webb Space Telescope.

In this paper we give a short description of upcoming space missions, many designed primarily for exoplanet science, but these can also be used to enable a broad range of studies in stellar astrophysics. These include Kepler-K2, BRITE-Constellation, Gaia, CHEOPS, TESS, and PLATO. The Micro-Oscillations of STars (MOST) satellite is still providing ultra-precise photometric data, but this was already presented in Chapter 1 and will not be discussed here.

2. K2: Kepler reborn

The period between November 2012 and May 2013 was a bad time for exoplanet and asteroseismic science. In the space of less than a year, both CoRoT and Kepler experienced hardware malfunctions. For CoRoT it was the loss of the second Data Processing Unit (DPU) in November 2012 that ended its ability to collect data. For Kepler it was the failure of its second reaction wheel in May 2013. The spacecraft could still continue to collect and transmit data, but with only two reaction wheels it was impossible to stabilize the pointing of the telescope in order to obtain ultra-precise light curves. A key science objective of Kepler, to detect Earth-sized planets in the habitable zone of sun-like stars, was thus severely compromised.

Fortunately for the astronomical community, Kepler was able to recover some capabilities and have a new life as the K2 mission. After a careful study NASA determined that by targeting fields along the ecliptic this would minimize the force of the solar wind on the spacecraft. The use of thrusters could compensate for the lost reaction wheel so that the pointing was good enough to continue exoplanet science.

The mission profile of K2 looks very reminiscent of the one for CoRoT. In each target field K2 observes about 10 000 stars for a maximum of about 75 days. This is about twice the number of stars, but for half the observing length of a typical CoRoT field. Figure V.3.1 shows the target fields for the proposed two year K2 mission. Currently, these are 10 fields well spread along the ecliptic. Also shown, for comparison, are the approximate location of the "eyes of CoRoT", regions of the sky that were accessed by CoRoT fields. Keep in mind, though, that one pointing of CoRoT covered approximately one-tenth of the sky of a K2 pointing.

Of particular interest is the fact that K2 fields cover some very important open clusters. Table V.3.1 lists some of the clusters that are in the K2 fields and their estimated ages. These range from a few Myr out to ~4 Gyr for M 67. CoRoT was only able to study one cluster, NGC 2264 (age ~1–4 Myr) in detail (Cody et al. 2014). The original Kepler field had four clusters (NGC 6866, NGC 6811, NGC 6819, and NGC 6791) that have ages >1 Gyr. K2 will thus greatly increase the number of open clusters observed by both CoRoT and Kepler. These clusters will provide important laboratories for a wide range of exoplanet and stellar science. These include:

- the evolution of planetary systems and star-planet interactions. Clusters of well known ages can probe the evolution of planets, hot Jupiters in this case. Young stars tend to be more active which enhances the chance of star-planet interactions.
- the evolution of stellar angular momentum. Angular momentum and its loss via the coupling between the star

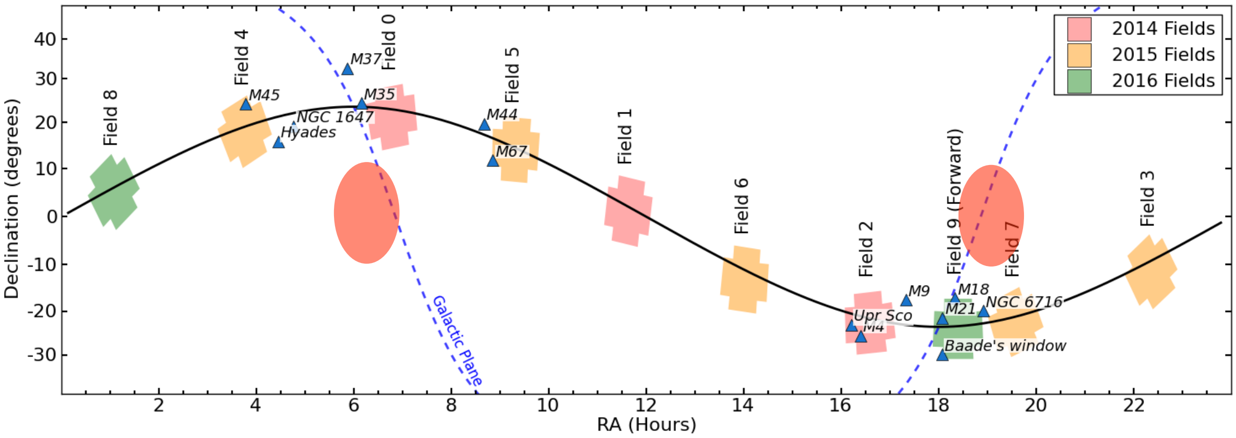

Fig. V.3.1. The designated fields for the 2-yr K2 mission as of October 2015. The red ovals mark approximately the eyes of CoRoT (from `www.keplerscience.arc.nasa.gov/K2/Fields.shtml`).

Table V.3.1. Open Clusters in the K2 Fields.

Cluster	Age
Messier 21	4–8 Myr
Messier 18	32 Myr
NGC 6716	100 Myr
Pleiades	125 Myr
Messier 35	110 Myr
Messier 37	520 Myr
Hyades	625 Myr
Praesepe	625 Myr
Messier 67	4 Gyr

and the accretion disk is a driving force in the early evolution of young stars. This can be better understood by studying clusters with a wide range of ages.

- the evolution of stellar variability and magnetic activity. Ultra-precise stellar light curves enable us to study the magnetic structure of active stars as traced by cool starspots (e.g. Lanza et al. 2009; Fröhlich et al. 2009). K2 can study this as a function of stellar age.
- Asteroseismology of young stellar objects. Asteroseismolgy is the only means of checking the evolutionary status of young stars, probing the internal structure and comparing these to stellar evolutionary tracks (e.g. Zwintz et al. 2014).

Galactic populations will also be studied with K2 both in clusters and in the field. CoRoT and Kepler were able to map out parts of our Galaxy, but K2 will provide stellar masses, radii and ages of red giants over a wider coverage in the Milky Way. Combined with Gaia (see below) and large spectroscopic surveys (see also PLATO in Sect. 6 and references therein) these asteroseismic data will allow us to extend the range of the age-metallicity relations that was started with CoRoT and Kepler. K2 pointings also cover the star forming region Upper Scorpius stellar association with an age of ∼10 Myr. This may give us some early hints as to the early phases of the formation of planetary systems as well as to the occurrence of stellar pulsations in very unevolved stars.

To achieve these science objectives, K2 must demonstrate it can still acquire exquisite data. The dominant factor limiting the photometric precision of K2 is the low frequency motion of the space craft due to the solar wind and the firing of the thrusters which causes a drift of the targets across the detector pixels. In spite of these problems, the precision is quite good. Figure V.3.2 compares the photometric precision of K2 (triangles) to Kepler fine pointing (points) from quiet G-type stars, i.e. the best estimate of the true measurement error Kepler could achieve. We should note that the K2 targets have a wide range of spectral types and intrinsic variability which may be the source of much of the scatter.

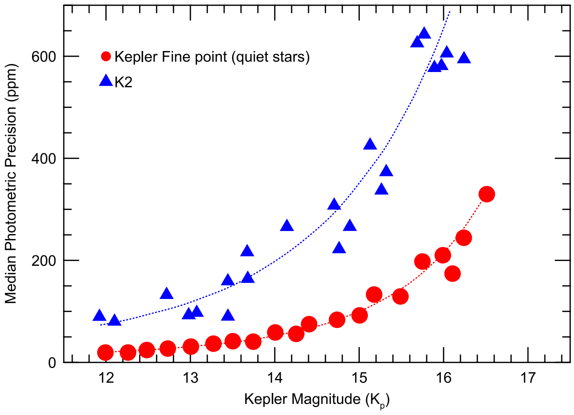

Fig. V.3.2. The photometric precision of K2 compared to Kepler with fine guiding. (Red dots) Kepler photometric precision for the quietest G-dwarfs. (Blue triangles) K2 photometric precision of targets covering a wide range of spectral types and intrinsic stellar variability. Source: NASA (`www.keplerscience.arc.nasa/K2`).

The photometric precision of K2 is 50 parts per million (ppm) for 6.5 hours observation on a 12th magnitude G-type star. This is about a factor of four worse than the best Kepler could do with fine pointing. Overall over the full magnitude range $V = 12$–15, K2 has about four times the photometric error that Kepler could achieve on the quietest stars. As we learn more about the performance of the instrument, astronomers will have better tools for reducing K2 photometry. The photometric performance of K2 is bound to improve.

Despite the diminished pointing performance of K2 with respect to the original Kepler mission, it is capable

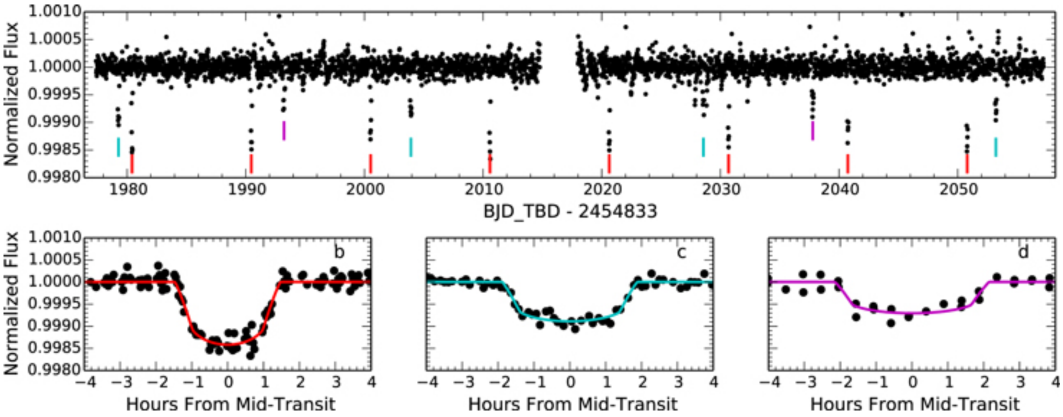

Fig. V.3.3. The K2 photometry of the M dwarf K2-3 (*top*) along with the phase folded light curves and transit fits (*bottom*) of the three transiting super-Earths (from Crossfield et al. 2015) © ApJ.

of ultra-precise photometry as demonstrated by its ability to still detect small transiting planets. Using K2 light curves, Crossfield et al. (2015) discovered three super-Earths around the M dwarf stars K2-3 (Fig. V.3.3). The transit depths were only 0.07–0.15% deep corresponding to planet radii of 1.5–2.1 $M_\oplus$. Orbital periods were 10–44 d. K2 clearly will continue to provide high quality exoplanet science, so long as the two remaining reaction wheels remain operational.

3. BRITE-Constellation

BRITE-Constellation is a group of 6 nanosatellites developed by the Space Flight Laboratory (SFL), Toronto, and devoted to precision photometry of the brightest stars in the sky in two colours (Weiss et al. 2014). The design requirement was an accuracy of at least 1 mmag per orbit for stars with $V \leq 3.5$ mag. However, depending on the individual satellite and observing conditions, also stars as faint as $V = 6$ mag have been observed with comparable accuracy. Frequency spectra with a noise level down to 0.1 mmag and up to 300 d^{-1} have been obtained for bright star data which cover nearly 6 months.

The Austrian BRITEs have been launched into a dusk-dawn orbit, the Polish BRITEs have a sun-synchronous orbit, and BRITE-Toronto a polar orbit with an annual drift of the ascending node of 40 min. These different orbits, a consequence of the required piggy-bag launches, put a severe work load on the mission scientist responsible for optimising the science output of BRITE-Constellation from the technical point of view. Each of the nanosatellites has a size of $20 \times 20 \times 20$ cm^3 and a weight close to 7 kg (Fig. V.3.4). Telecommunication is provided by ground stations in Graz, Toronto, Vancouver, and Warsaw.

The field-of-view is 24 deg × 20 deg and is monitored with a KAI-11002 CCD. An innovative aspect of the BRITE satellites is their 3-axes stabilisation to an accuracy of about 1.5 arcmin, which qualifies them as a pilot small-size space project in astrophysics. The filters were chosen with a central wavelength as different as possible, considering the spectral sensitivity of the CCD detector, and a band width resulting in comparable count rates for BRITE-Constellation main science targets. Figure V.3.5 shows a comparison of BRITE filters with standard photometric filters.

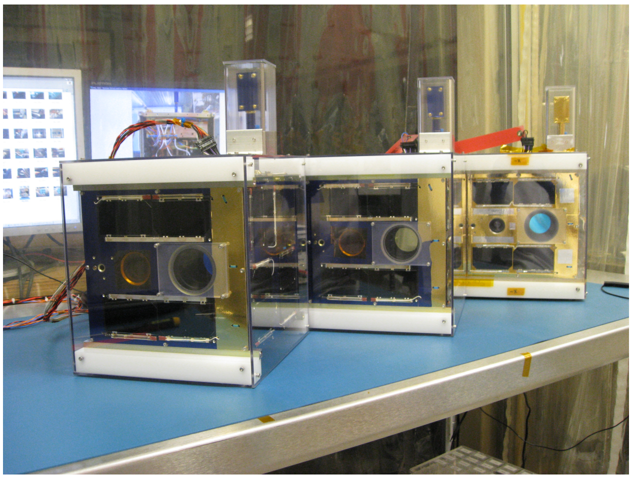

Fig. V.3.4. Three BRITE nanosatellites at SFL, ready for shipment © Space Flight Laboratory, University of Toronto.

Table V.3.2. BRITE-Constellation.

Name	F	Launcher	T0	Orbit km
Austria:				
TUGSAT-1	$\tilde{B}$	PSLV-C20	Feb. 2013	781 × 766
UniBRITE	$\tilde{R}$	PSLV-C20	Feb. 2013	781 × 766
Poland:				
B-Lem	$\tilde{B}$	DNEPR	Nov. 2013	600 × 900
B-Heweliusz	$\tilde{R}$	LM-4B	Aug. 2014	600 × 630
Canada:				
B-Toronto	$\tilde{R}$	DNEPR	Jun. 2014	620 × 770
B-Montréal	$\tilde{B}$	DNEPR	Jun. 2014	620 × 1450†

Notes. F – filter; Launcher (PSLV-C20 from India, DNEPR from Russia, and LM-4B from China); T0 – launch date; Orbit – km above ground; $^{(\dagger)}$ for reasons unknown, BRITE-Montréal did not release from the upper stage of DNEPR.

The "menu card" from which targets can be chosen for BRITE-Constellation is illustrated in Fig. V.3.6. Nearly the entire parameter space of the HRD is populated by stars brighter than $V = 4.5$ mag, and particularly all instability strips currently known, except of WDs and hot subdwarfs, are covered. The BRITE nanosatellites measure

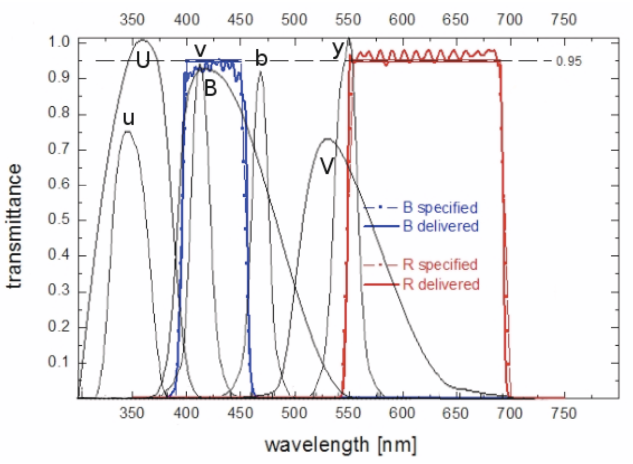

Fig. V.3.5. BRITE filters in comparison to those of the Johnson and Strömgren system.

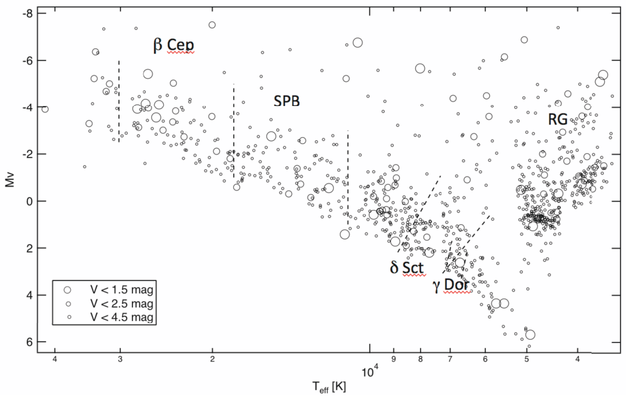

Fig. V.3.6. Hertzsprung-Russell diagram for stars brighter than $V = 4.5$ mag. This is the sample from which the primary BRITE-Constellation targets are drawn. See text for more details.

brightness and temperature variations of the brightest stars on timescales ranging from a few minutes to several months (and perhaps years) via dual-broadband photometry resulting in a continuous precise photometric timeseries.

Stellar groups with V down to 5.5 mag and that are of particular interest include OB (62 stars in Fig. V.3.6), β Cep (29), CP (22), Be (20), EB (12), δ Sct (7), HgMn (7), RR Lyr (3), roAp (1). However, the majority of stellar targets fall into two principal categories:

- *hot luminous H-burning stars.* These O- to F-type stars can contribute to solving outstanding problems such as the efficiencies of convection, mixing and overshooting in massive stars and the influence of rapid rotation on their structure and evolution.
- *cool luminous stars.* Asymptotic Giant Branch (AGB) stars, cool giants and cool supergiants can be used to measure the time scales involved in surface granulation and differential rotation which can constrain turbulent convection models. Though oscillations in solar-type dwarfs have amplitudes of only a few ppm in luminosity, p-mode pulsations in cool giants and g-modes in massive stars and cool giants can have larger amplitudes up to parts per thousand which can be detected by BRITE.

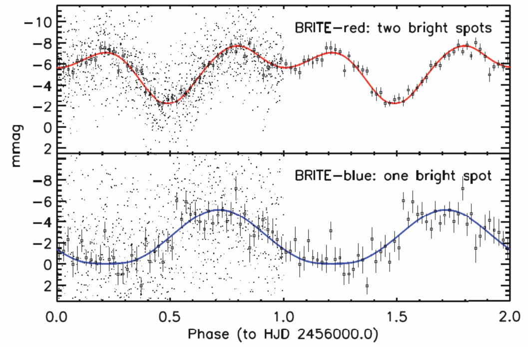

Fig. V.3.7. Rotation ($P_{\rm rot} = 4.4790^d$) of the roAp star α Cir, observed by the red-sensitive (*top*) and blue-sensitive (*bottom*) BRITEs. Phase-binned averages with 1σ errors are given together with the theoretical light curve obtained for a spot model. Phases 0 to 1 show also the phase-binned original BRITE data which latter are only 1-sec exposures, and three per minute.

Constant stars may also teach us much towards understanding stellar variability. BRITE will enlarge the base of stars measured to be constant (within low noise limits) which can serve as photometric standards for other studies.

Last, but not least, there is a chance that BRITE will detect transiting exoplanets (see Passegger 2013; Weiss et al. 2012). Because these transiting planets will occur among the brightest stars, these targets will be amenable to characterization studies of the exoplanet's atmosphere.

We highlight a few of the preliminary results of BRITE in order to illustrate the potential of nanosatellites in general and BRITE in particular. Figure V.3.7 shows the brightness variation of the rapidly oscillating Ap star α Cir ($V = 3.19$, spectral type = A7VpSiCrEu) due to inhomogeneities in its atmosphere (Weiss et al. 2016). This star was also observed at the beginning of the mission with a non-optimised set-up. The brightness varies with the rotational period of 4.48 d. The pulsational variations of 6.8 min have low amplitudes and are not evident in the figure.

HD 201433 is a peculiar B-type star (B9SiMg) that shows rotational modulated light variations with a period of 1.13 d (Catalano & Renson 1998). With a V-mag = 5.7 it is fainter than the typical BRITE targets. B-Toronto observed this star with the red filter (Fig. V.3.8) using a chopping technique implemented in 2015 in order to cope better with CCD radiation damage. We should note that this is a preliminary data reduction developed by R. Kuschnig as a quick operational check. A more refined data reduction should improve the quality of the light curve.

Mainly due to restrictions in telecommunication, BRITE-Constellation observes simultaneously up to 25 stars in its rather large field of view. Figure V.3.9 hows the target fields, as of Fall 2015, containing as many requested and scientifically relevant targets as possible. Targets that have already been observed are marked in red and these were typically observed continuously for up to 180 days.

Due to technical differences, such as star sensors, ageing effects of the CCDs, etc. the data quality depends on the satellite, the filter used and the colour index of a star. Optimisation of the science return of BRITE-Constellation has to take these limitations into account. Figure V.3.10 illustrates the median photometric standard deviation per orbit for stars with different brightnesses that were observed for 147 days during the Centaurus field run in 2014 before

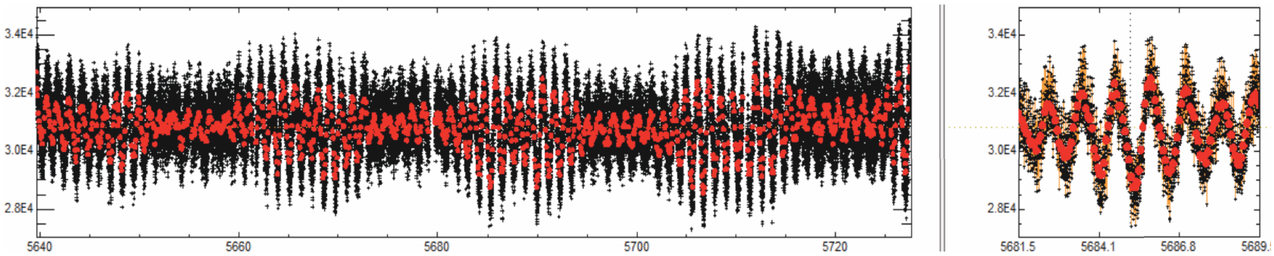

Fig. V.3.8. (*Left*) BRITE-red photometry of HD 201433 (B9V, $V = 5.7$) using a quick-look, preliminary data reduction developed by R. Kuschnig. (*Right*) Zoom into the center of the light curve.

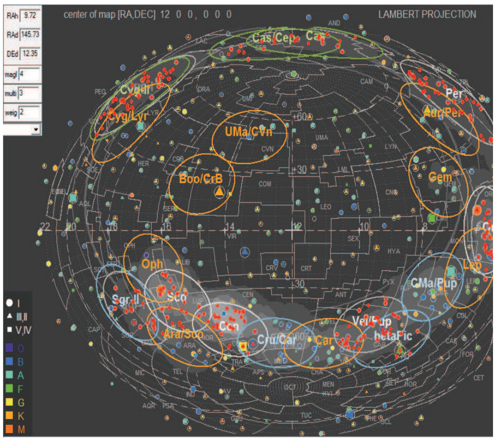

Fig. V.3.9. BRITE sky and target fields presently chosen.

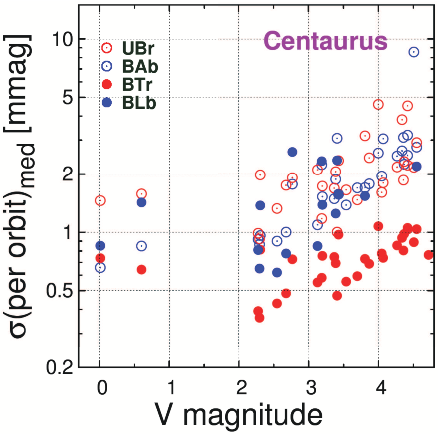

Fig. V.3.10. Median sigma-per-orbits are presented individually for the four BRITEs (TUGSAT-1 (BAb), UniBRITE (UBr), B-Lem (BLb) and B-Toronto (BTr), and for the stars observed in the Centaurus field before chopping has been introduced – Andrzej Pigulski and Adam Popowicz, private communication.

the introduction of chopping (i.e. changing the pointing of a BRITE between two fixed positions on the CCD for every second exposure).

After an observing run has been completed, the data are reduced with tools developed by PHOTT (BRITE Constellation's Photometry Tiger Team) and photometry of individual stars finally distributed to the respective proposers.

Additional information about technical details, programming policy and cooperating teams can be found at the Brite-Constellation website[1].

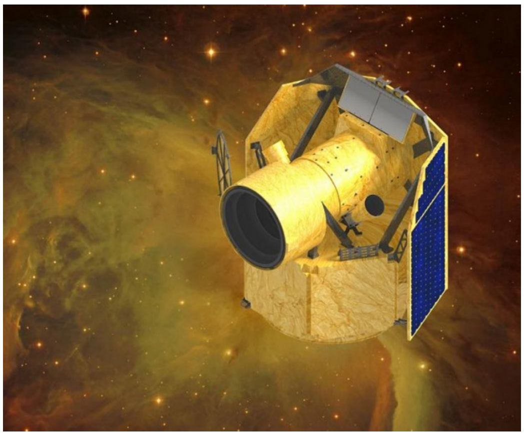

Fig. V.3.11. Artist's rendition of the CHEOPS spacecraft. © ESA.

4. CHEOPS

The first transiting planet, the gas giant HD 209458b (Charbonneau et al. 2000) was first discovered by radial velocity measurements and follow-up photometric measurements later detected the transit. Smaller planets are now relatively easy to detect with radial velocity measurements of bright stars. However, it is very difficult to get the requisite precision using ground-based observations in order to detect possible transits. For example, the RV-discovered transiting hot Neptune, 55 Cnc-e required the space based telescopes MOST (Winn et al. 2011) and *Spitzer* (Demory et al. 2011) to detect the transit. This demonstrated that it is sometimes worthwhile to invest space resources to search for a transit – you sometimes get lucky. However, such a strategy will not work for a large number of RV-detected planets. Space telescopes are general use facilities that are heavily over-subscribed. Time allocation committees may be reluctant to allocate precious telescope time on the ≈90% chance that a transit will not even occur due to an unfavorable orbital inclination. Clearly, a space telescope dedicated for these types of observations is needed and the CHaracterization ExOPlanet Satellite (CHEOPS, see Fig. V.3.11) will fill that role (Fortier et al. 2014).

CHEOPS is different from the CoRoT and Kepler space missions in that it is not an exoplanet discovery mission. Rather, it is dedicated to using ultra-precise photometric measurements to search for transits of bright stars known to host planets from radial velocity measurements. For short period planets there a 10% probability or greater that the planet has an orbital inclination to cause a transit. There will be a chance that CHEOPS will not observe a transit, but if it does, significant science will come out since these

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[1] `http://www.brite-constellation.at`

events will be around relatively bright stars. Furthermore, the mass of the planet is already known from the radial velocity measurements.

CHEOPS is the first of the European Space Agency's (ESA) "small missions" and it is planned for launch in 2018. It will have a 32-cm on-axis Ritchey-Chretien telescope, i.e. roughly the size of the CoRoT telescope. However, because it is targeting single stars, CHEOPS will not have a wide field of view. A dedicated field stop and baffling system will minimize stray light since CHEOPS will be in a low-earth orbit. CHEOPS will build on the experience of CoRoT in terms of the baffling and field stop combination and the mission technology that was already used on CoRoT. Tests indicate that the stray light should be less than 10 ppm. CHEOPS will have a photometric precision of 150 ppm per minute for a $V = 9$ magnitude star

CHEOPS will exploit the fact that the predicted transit times of the planet should be known from the radial velocity orbit. Thus it must only look at the star for a short time, unlike a discovery mission which must collect data continuously over several months. Ground-based surveys are finding more and more low-mass planets in short period orbits, so there will be an ample list of targets for CHEOPS to look at.

The recent radial velocity discovery of the system of four low mass around the bright star ($V = 5.5$) HD 219134 from the HARPS-N Rocky Planet Search Program (Motalebi et al. 2015) demonstrates that CHEOPS will have a good chance of detecting transits around a modest number of RV-discovered exoplanets. The inner planet of HD 219134 orbits the star in 3.98 d. Spitzer observations detected a transit corresponding to a radius of 1.6 $R_\oplus$. A transiting super-Earth around such a bright star is an ideal target for atmospheric studies using in-transit spectroscopy or observations at the secondary eclipse of the planet. CHEOPS should increase the sample size of such interesting targets.

The key science goal of CHEOPS is to detect super-Earth and Neptune-sized objects around bright stars and determine the planetary radius. This, combined with the known planetary mass from radial velocity measurements means we can derive an accurate bulk density of the planet which can be compared to planetary structure models. Because CHEOPS is targeting relatively bright stars, the discovered transiting planets will be ideal for further spectroscopic studies from the ground and the James Webb Space Telescope (JWST) in order to characterize the exoplanetary atmosphere.

Another science aim of CHEOPS is to obtain ultra-precise transit light curves for discoveries made by TESS (see below). It can do so because CHEOPS will have a superior photometric accuracy due to its larger collecting area compared to TESS. CHEOPS will also provide more precise light curves for the Next-Generation Transit Survey (NGTS) that will also target smaller planets compared to previous ground-based transit surveys.

CHEOPS will also be able to do additional science with 20% open to the community through a competitive scientific review.

5. TESS

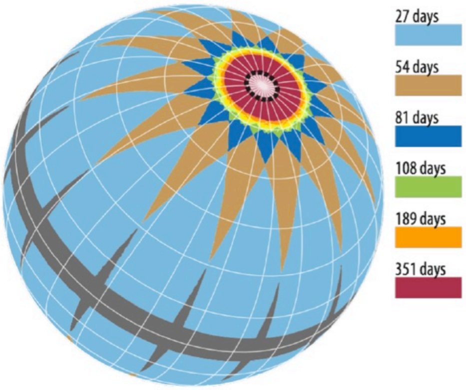

Fig. V.3.12. The duration of observations for TESS targets on the celestial sphere. The dashed black circle at the ecliptic pole represents the JWST continuous viewing zone. (From Ricker et al. 2014).

NASA's Transiting Exoplanet Survey Satellite (TESS) will search for exoplanets transiting bright, nearby stars and is scheduled for launch in 2017. TESS is unique to other space missions in terms of its orbit. It will have a highly elliptical orbit with a perigee of 17 R_{Earth} and an apogee of 59 R_{Earth}. The orbital period of 13.7 d period is in a 2:1 resonance with the lunar orbit. The orbit of TESS will be inclined with the respect to the ecliptic plane which will eliminate long eclipses by the Moon and the Earth. One advantage of this orbit compared to a low-earth polar orbit like that of CoRoT is that it will be above the radiation belts so the flux of high energy particles will be low. This should avoid the loss of data and discontinuities in the light curves caused by the high energy particles. This was often a problem for CoRoT light curves and these may have played a role in the loss of the DPUs.

Since bright stars are distributed throughout the sky, TESS will be the first space-based all sky transit survey. TESS will employ four CCD cameras, each with an aperture of 10.5 cm that will cover an area of the sky 24×20 square degrees. Stars will be monitored for an interval of one month to one year depending on the star's ecliptic latitude. TESS will survey a total of about 200 000 main sequence stars. Figure V.3.12 shows the duration of TESS observations on the celestial sphere. The nominal life of the mission is two years.

The maximum orbital period for a planet that TESS can detect is about 10 d for most stars, but this can be more than 40 d for stars located at the ecliptic poles. Of course TESS will detect single transit events stemming from planets in longer orbits, but the period determination will not be possible. However, a rough estimate of the period will come from the transit duration and since TESS is targeting bright stars, such single transit candidates would be easily monitored by radial velocity measurements.

TESS should reach a precision of 200 ppm in one hour on a star with an I_C magnitude of 10. Saturation occurs for the central pixel at approximately $I_C = 7.5$. This is not necessarily the bright limit for TESS since the excess charge is spread over other CCD pixels and is thus conserved. High precision photometry for brighter targets can still be achieved so long as all the excess charge remains within the aperture. The expected brightness limit for TESS is therefore expected to be $I_C \approx 4$.

Ricker et al. (2014) estimated the expected planet yield of TESS using simulations that included: 1) a realistic

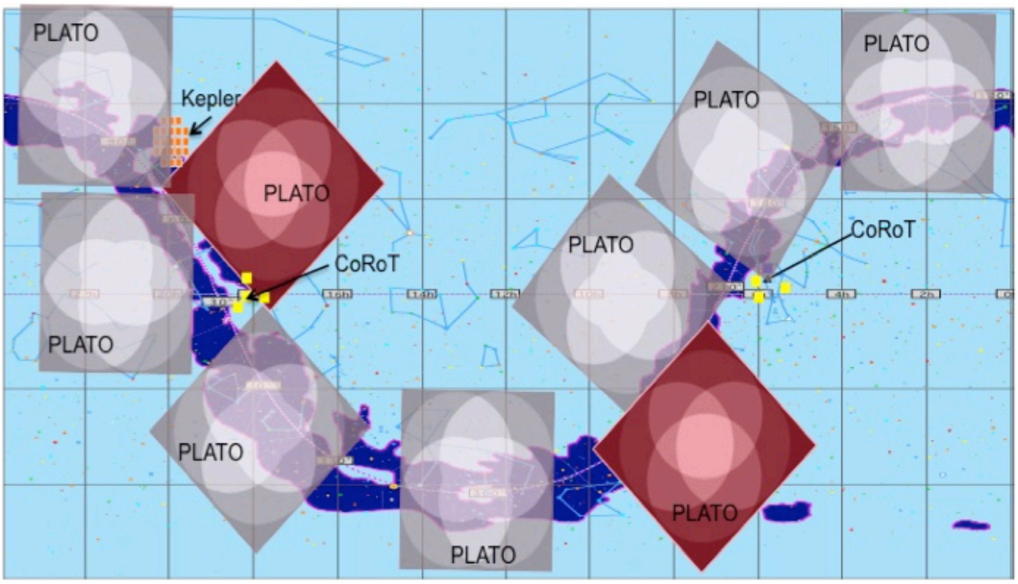

Fig. V.3.13. Schematic comparison of observing approaches. Large squares: approximate size of the PLATO 2.0 field. A combination of short (white squares) and long (red squares) duration pointings is able to cover a very large part of the sky (Rauer et al. 2014). Note that the final locations of long and step-and-stare fields will be defined after mission selection and are drawn here for illustration only. Yellow squares: CoRoT target fields in the galactic centre and anti-centre direction. *Upper left corner*: the Kepler target field.

distribution of stars and eclipsing binaries; 2) occurrence rates and orbital properties based on Kepler results; 3) variations in the background noise due to variations in the stellar surface density and zodiacal light; and 4) variations in the duration of TESS observations. TESS is expected to find thousands of Neptune-sized exoplanets, as well as hundreds of so-called super-Earths in the size range 1.25–2 $R_\oplus$. For Earth-sized planets, the yield is expected to be in the tens.

TESS will be able to perform asteroseismology on a fraction of the target stars, but not to the extent that the PLATO mission will (see below). Asteroseismic measurements are important as they provide accurate stellar parameters such as mass and radius which are important for deriving accurate planetary parameters. TESS is expected to be able to detect p-mode oscillations in about 6000 stars including

- Most stars brighter than $V = 7.5$;
- Approximately 75 stars with spectral types later than the Sun;
- About 2000 upper-main and subgiants;
- Virtually all giant stars.

A more detailed description of the TESS mission can be found in Ricker et al. (2014).

6. PLATO

6.1. Description of the mission

PLATO (PLAnetary Transits and Oscillations of stars) has been selected as ESA's M3 mission in the context of ESA's Cosmic Vision 2015–2025 program, with launch foreseen in 2024 (Rauer et al. 2014). PLATO's main goal is to detect extrasolar planets by photometric transits and to characterize their radius, mass and age. This will be done for a large number of planets in a variety of systems, including planets in the habitable zone of solar-like stars. The PLATO mission will characterize the bulk properties of planets with high accuracy. The goal is to achieve an accuracy of at least 3% for the planet radius and 10% in the planet mass and age for terrestrial planets orbiting a bright solar-like star.

In addition, PLATO core science will be complemented by a significant guest observer program investigating e.g. variable and pulsating stars, stars with mass loss, transient phenomena, and galactic science (see Sect. 6.5.2). With this combination of scientific goals, including exoplanet science in combination with asteroeismology, PLATO builds on the heritage of CoRoT in the European community.

The PLATO satellite will be launched by a Soyuz 2-1b rocket into an orbit around the L2 Lagrangian point. The nominal mission lifetime is 6.5 yr. A baseline observing scenario has been defined for the purpose of mission planning. It includes two "long pointings", staring at target fields for 3 and 2 yr, respectively (see Fig. V.3.13). This phase is followed by a "step-and-stare" phase of 2–5 months observation duration per target field. The long pointings enable PLATO to detect planets out to the habitable zone of solar-like stars. The short pointings widen the sky coverage and will obtain asteroseismic data on a variety of stars that are needed to improve stellar models. This is a pre-requisite to push further the accuracy of our knowledge of stellar parameters and thus planet parameters. The final observing sequence of PLATO will be fixed approximately two years before launch in order to optimize the strategy to the needs of the science community at that time.

The PLATO instrument consists of 34 telescopes with 12-cm aperture each. Of these, 32 telescopes are called "normal" telescopes and are arranged into 4 groups of 8 telescopes each. To widen the area on the sky surveyed for exoplanets, these "normal" telescopes are offset from each other by 9.2° thus providing a total field-of-view of about 2100 square degrees. All "normal" telescopes operate in white light. The telescopes consist of 6 lenses mounted in a tube and protected by a baffle from straylight. The focal plane of each camera consists of 4 CCD detectors with 4510 × 4510 pixels and a plate scale of 15 arcsec per pixel. For the "normal" cameras, these detectors provide a light curve sampling of 25 s for the bright target sample. "Imagettes" are masks around each target star in which the data are readout and sent to the ground for processing. For the larger statistical sample, these lightc urves are processed on board and they will be binned to 600 s time resolution. Two additional so-called "fast" cameras are identical telescopes except that their read-out speed is higher (2.5 s) to support the fine-guidance of the satellite. Furthermore, the "fast" telescopes will be equipped with a red and a blue filter, respectively, to aid in the asteroseismic investigation of variable stars.

Although both are transit search missions, we should note that PLATO differs from TESS in two key points. First, PLATO's pointings will be significantly longer than TESS. This will enable the characterization of transiting rocky planets out to the habitable zone of a solar-like star. It also will find much smaller close-in planets than TESS. Second, PLATO will perform accurate asteroseismic measurements for a significantly larger number of stars than TESS. To reach the required precision in planet radius and mass, it is essential to derive the properties of their host stars with sufficient accuracy. Furthermore, ages of exoplanetary systems can only be derived from the age of their host star. The PLATO core program will therefore combine the detection of photometric transits with asteroseismic analyses of the host stars in order to obtain their precise characterization (see below).

6.2. Exoplanet detection with PLATO

While planetary radii can be derived directly from the satellite photometric light curves, the determination of planet masses requires an extensive ground-based observational follow-up program to measure the radial-velocity (RV) component of the host stars. RV measurements are very time consuming and these stress the available ground-based telescope resources. This is particularly true for small planets which have a small RV amplitude. Realistically, RV measurements on a large scale can only be performed for planets orbiting bright stars. The main target sample of PLATO will therefore focus on stars <11 mag.

To reach the required precision for asteroseismology characterization, a high S/N ratio is needed. The main PLATO target sample will therefore reach 34 ppm in 1 hour for stars <11 mag. This goal can be reached for about 85 000 stars, with 20 000 of them in the two long-pointings. For planets orbiting these stars, the full characterization in terms of accurate radii, masses and ages can be obtained. In addition, PLATO will observe more than 245 000 stars (up to 1 million when we include the step-and-stare phase) with <13 mag. This large sample is still bright enough even to detect a large number of small planets, but it will not allow for RV and asteroseismic measurements. It will therefore be of comparable performance to most of the stellar samples surveyed by Kepler and CoRoT. It will add to the statistical information on planet candidates, increase our understanding of planet formation as a function of location in galaxy, provide inputs to TTV searches, and last but not least it will enable a wide range of additional science.

PLATO will be able to detect transits of thousands of planets in its stellar samples. For more than 100 of the planets detected in the bright stellar sample, highly accurate radii can be combined with accurate masses and ages, including terrestrial planets in the habitable zone of solar-like stars. This estimate assumes resources for ground-based follow-up comparable to those provided by a so-called "large program" at ESO. The resulting sample of terrestrial planets with highly accurate radii, masses and ages at orbital periods beyond 3 months will be a unique contribution of PLATO. Furthermore, many of the well-characterized PLATO planets orbiting bright stars and are key targets for investigations of their atmospheres, e.g. with JWST (see below), or by a dedicated future exoplanet spectroscopy satellite.

The PLATO legacy, that is the final data base of its light curves and derived stellar and planetary parameters, will provide a huge opportunity for science beyond the mission lifetime of PLATO. Together with data from the Gaia satellite, PLATO will provide a wealth of data for stellar science. Also the number of characterized planets from PLATO will increase with time, as teams continue to measure RV data of PLATO planets long after the satellite has stopped operating.

6.3. Asteroseismology with PLATO

The main goals of PLATO asteroseismology program will be to provide precise global parameters of stars hosting planets. This is an accuracy of at most 10% for the stellar mass, 2% for the stellar radius and 10% for the stellar age. Stellar radii will be directly obtained from the combination of effective temperatures (from ground-based high resolution spectroscopy follow-up program and Gaia) and absolute luminosities (from Gaia distance measurements). Asteroseismology then will provide the stellar mean density through the scaling relations, which leads to the precise determination of the stellar mass. The determination of mass and radius is thus essentially independent of stellar modeling.

Ages, on the contrary, require theoretical stellar models in order to fit the observed parameters. This process is thus highly dependent on the physical assumptions used in the model computation. This clearly shows that a better understanding of the physical processes involved in stellar evolution is a key factor to a better knowledge of the planet properties. In particular, the presence of an extra-mixed zone surrounding the convective core in low-mass stars is still a highly debatable question, which involves our poor knowledge (and/or poor numerical treatment) of rotation, convective penetration and convective overshooting. It is, however, of crucial importance since it drastically affects the duration of core hydrogen burning and thus ages of stars.

This important aspect of the interaction of planet finding and host star characterization will benefit from the asterosesimic analyses of a large number of stars of various masses, chemical composition, and ages. This will bring constraints on stellar interiors and more widely, to our understanding of stellar evolution. For that purpose, large

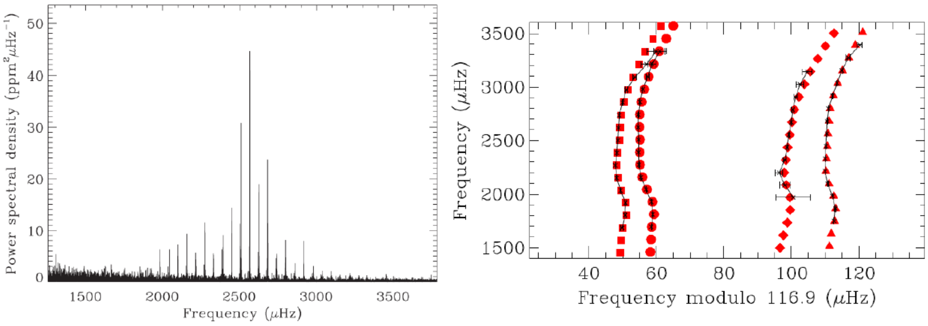

Fig. V.3.14. (*Left*) The p-mode oscillation spectrum of 16 Cyg B derived from three months of Kepler photometry (from Metcalfe et al. 2012). (*Right*)) The Echelle diagram of 16 Cyg B based on the full Kepler time series (from Metcalfe et al. 2015) © ApJ.

grids of stellar models including wide ranges of physical parameters will be used. From a combination of asteroseismic and classical observable constraints, a precision of the order of 10% on the age will be within reach.

6.4. Comparative planetology with PLATO

By combining the asteroseismic data along with the transit results (transit depth, RV orbital curve, etc.) PLATO will enable us to perform comparative exo-planetology to a higher accuracy than is currently available and for a large number of stars. As an example that demonstrates the potential of PLATO we consider the case of Kepler-78b. This is the only Earth-size planet whose mass has been determined via RV measurements. Kepler light curves reveal a planet with a radius of 1.16 ± 0.19 $R_\odot$ in an 8.5 hr orbit (Sanchis-Ojeda et al. 2013). Radial velocity measurements yield a planet mass of 1.69–1.76 $M_\odot$ (Howard et al. 2013; Pepe et al. 2013). This results in an Earth-like density of ≈5.5 $\mathrm{gm\,cm^{-3}}$. However, the planet can have a density as high as 7.9 $\mathrm{gm\,cm^{-3}}$ (Grunblatt et al. 2015) or as low as 2.5 $\mathrm{gm\,cm^{-3}}$ (Hatzes 2014). The difficulty in determining the structure of Kepler-78 b can be traced to the challenge in obtaining precise RV measurements on such a faint target ($V = 11.72$) and the poor knowledge of the stellar parameters.

Figures V.3.14 and V.3.15 demonstrates how PLATO can improve things by providing asteroseismic stellar parameters, and target stars more amenable to precise RVs. The left panel of Fig. V.3.14 shows the p-mode power spectrum of the planet hosting star 16 Cyg B derived from the first 3 months of Kepler photometry (Metcalfe et al. 2012). The right panel shows the so-called Echelle diagram using the full Kepler data set (Metcalfe et al. 2015). These data give a taste of what PLATO could obtain on its brighter targets. Astrometric modeling of the Echelle diagram by Metcalfe et al. (2015) yields a stellar radius of $R = 1.229 \pm 0.008\ R_\odot$ (0.65% error) and stellar mass of $M = 1.08 \pm 0.02\ M_\odot$ (1.85% error).

Figure V.3.15 shows the location of an Earth-like planet (i.e. Kepler-78b-like) in the density versus radius diagram. The tracks show the structure for planets that are Earth-like: iron-core and silicate mantel, Mercury-like: large iron core and thin silicate mantel, and Moon-like: large silicate mantel with small iron core. The error box (large red dotted parallelogram) shows the nominal error based on the errors of the pertinent parameters to Kepler-78b (Sanchis-Ojeda et al. 2013; Grunblatt et al. 2015). Note that Kepler-78 is fainter compared to the core targets of PLATO. The error box is so large that we could not distinguish between the possible structure tracks for this hypothetical short-period planet.

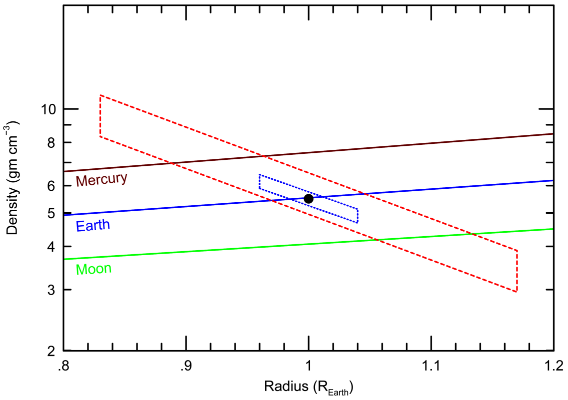

Fig. V.3.15. The density versus radius tracks for planets with a Mercury-like, Earth-like, and Moon-like internal structures. The large red-dashed square shows the error box we would currently have for a Kepler-78-like planet with the radius and density of the Earth (dot). The small blue-dotted box shows the error box we could obtain for a PLATO target,

The smaller blue dotted parallelogram shows the error box assuming that we can derive seismic values for the stellar radius and mass with an accuracy comparable to 16 Cyg B. Since PLATO is targeting stars brighter ($V < 11$ mag) than Kepler-78b, we should be able to achieve a better precision on the velocity amplitude of the host star about the barycenter (3% compared to 15 %). Largely because of the improved accuracy on the stellar parameters and better quality RV measurements we could be able to determine whether such a hypothetical short-period planet has an internal structure like the Earth, Mercury, or the Moon. With current measurements we only would know that an exoplanet like Kepler-78b was a terrestrial planet, but with PLATO we would know what *kind* of terrestrial planet it is. PLATO, because of its use asteroseismology, will enable us truly to perform comparative exo-planetology.

6.5. Complementary program of stellar physics

One major advantage of PLATO over CoRoT and Kepler is its large sky covering, including not only stars in different parts of the Galaxy, but also stellar ensembles, such as binaries and clusters. Stellar physics as well as galactic physics will greatly benefit from such unprecedented investigation. Some examples are given below (see also Rauer 2014).

6.5.1. Stellar structure and evolution

PLATO will be able to investigate several important aspects of stellar structure and evolution.

a) Extra-mixing and chemical profile in stars

Asteroseismology of red giants observed by CoRoT and Kepler have proven to be extraordinary rich in providing constraints on their global properties. Moreover the presence of gravity-dominated modes (from more than 300 days of Kepler data) and the analysis of their period spacings led to the possibility of discriminating between red giants ascending the red giant branch and those quietly burning helium in the so-called red-clump phase (Bedding et al. 2011; Mosser et al. 2012). This additionally brought some unexpected strong constraints on the extent of mixing zones during core helium burning as well as during core hydrogen burning (Montalbán et al. 2013).

Slowly pulsating B (SPB) stars show a frequency spectrum consisting mostly of high-order gravity modes. Their period spacing should therefore be constant, at least for Zero Age Main Sequence (ZAMS) chemically homogeneous models. Once a hydrogen profile develops as a result of the decrease with time of the convective core mass, a periodic component superposes on the constant period spacing. This has indeed been observed in one SPB star (Degroote 2010).

The extent of the mixed core in main sequence massive stars plays a key role in the presence of an intermediate convection zone (ICZ) in post-MS blue supergiants. If the mixed zone is too large, no ICZ can develop at all. Such an ICZ is however essential to allow the excitation of g-modes (detected by MOST in one blue supergiant) in these highly centrally condensed stars (Saio 2006; Godart et al. 2009; Moravveji et al. 2012).

Hot B subdwarfs (sdB) and white dwarfs present frequency spectra that are also very sensitive to their chemical profiles. These are not attainable through direct observations and still poorly constrained by theory. Asteroseismology is thus the only reliable tool to understand better the structure of these stars.

The detailed frequency spectrum of a huge number of such stars of very different types that will be observed by PLATO can thus bring invaluable constraints on the mixing processes affecting the chemical profile in stars and thus their lifetimes.

b) Angular momentum transport

An important question in stellar modeling is the internal rotation profile as a function of the evolutionary phase. From Kepler data, it has been possible to estimate the rotation frequency difference between the core and the envelope in red giants (Beck et al. 2012) and to show that an important angular momentum coupling between core and envelope was absent from stellar modeling (Eggenberger et al. 2012; Marques et al. 2013). A possible clue to this problem could be brought by internal gravity waves, which could transport angular momentum and affect the rotation profile (Shiode et al. 2013).

This very important aspect of stellar evolution, which requires a precise determination of rotational splittings in the frequency spectra, is well within the reach of PLATO.

c) Probing stellar evolution with clusters

The possibility offered by PLATO to observe young open clusters as well as globular clusters is an invaluable gift to stellar evolution. Young open clusters will provide pre-main sequence stars as well as pre-supernova massive objects while globular clusters will bring their amount of MS, red giants and white dwarf stars to this work. Asteroseismic analyses of all these targets will undoubtedly and drastically increase our knowledge of stellar evolution.

6.5.2. Structure and evolution of our Galaxy

The chemical enrichment of our Galaxy has left its imprint in the distribution of stars of different masses, ages, and chemical composition. The key point in drawing a reliable picture of these imprints is our ability to measure distances and ages for stars at different directions and locations in the Galaxy.

One of the greatest successes of the CoRoT mission came from the realization that asteroseismic analyses of red giants could indeed provide a powerful tool to study this enrichment. Masses and radii of red giants are direct outputs of the scaling relations while their period spacings allow us to specify their evolution state, either ascending the red giant branch, or burning helium in the red clump.

With the additional knowledge of the effective temperature and of the chemical composition, intrinsic luminosities, and hence distances, and ages can be readily determined, with a 15% uncertainty for the ages (Miglio 2012, 2013). Data from thousands of red giants taken by the limited pointings of CoRoT and Kepler have already been used to draw a partial 3D map of our Galaxy (see Fig. V.3.16). The first hints at a new age-metalicity relation are starting to appear which could help discriminating between different scenarios for the formation of our Galaxy (Chiappini 2006).

To reach these objectives, spectroscopic analyses of huge numbers of stars are required. In particular metalicity is crucial not only in the stellar modeling, but also for the asteroseismic determination of stellar masses and ages. This is at the origin of a large collaboration involving scientists working on the Milky Way, stellar evolution, and asteroseismology with those specialists involved in large spectroscopic surveys. These include the Gaia-ESO Survey (GES), the Apache Point Observatory Galactic Evolution Experiment (APOGEE) and the Galactic Archaeology with Hermes Survey (GALAH).

The large number of red giants that PLATO will observe will result in a nearly complete mapping of the chemical gradient of our galaxy. This may open a new view on its evolution.

7. Other missions

There are two other important space missions worth mentioning, Gaia and the James Webb Space Telescope (JWST). Although these missions do not strictly build on the legacy of CoRoT in terms of taking long time series of

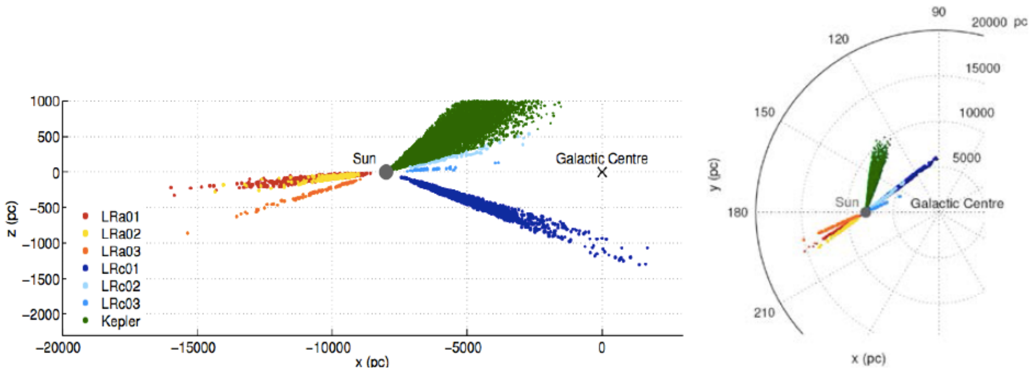

Fig. V.3.16. Spatial distribution of the red giants with asteroseismic characterization observed by CoRoT (six long runs color coded in the graph) and by Kepler (green points). The left panel shows a projection on the x-z plane and the right panel, a projection on the galactic plane. From Miglio et al. (2012).

ultra-precise photometric measurements, they are still important both for exoplanets and stellar physics. In particular, TESS and PLATO will provide important exoplanet targets for JWST.

7.1. Gaia

Gaia is an astrometric mission that is the successor to the Hipparcos mission. It uses the same measurement principles developed with the highly successful earlier mission. Gaia was launched in December 2013 and it began routine observations in August 2014. Gaia's scientific goal is to measure the distances, positions, and space motions of $\sim 10^9$ stars in our Galaxy.

Gaia has an astrometric accuracy that depends on the brightness stars. For bright stars with $V \approx$ 7–12 the astrometric accuracy is $\sim$10 μas and degrades to 20–25 μas for stars at $V \approx 15$. For the faintest stars at $V \approx 20$ the astrometric accuracy should still be 300 μas, significantly better than the $\approx$1000 μm precision Hipparcos achieved on much brighter targets.

Gaia's foremost contribution to stellar physics is that it will obtain a detailed three-dimensional distribution of stars in the Milky Way. This will help us understand its current dynamics, formation, and evolutionary history. Asteroseismic studies will add accurate ages for stars to this study. However, to fully understand the structure and evolution of our Galaxy, we must know the stars' location in the Milky Way and Gaia will provide these.

Besides stellar distances and proper motions Gaia will also provide stellar surface temperatures and RV measurements for a large number of stars. The RV precision varies from 1 $\mathrm{km\,s^{-1}}$ to 15 $\mathrm{km\,s^{-1}}$ depending on the brightness of the star. Stellar radii can be derived by combining the distances, absolute luminosities and stellar temperatures.

Gaia will also have an impact on exoplanet science. One significant contribution of Gaia to exoplanets is that it will be able to derive the true mass of the radial velocity discovered planets. For these only a minimum mass is derived since an orbital solution only yields the mass multiplied by the sine of the orbital inclination. Gaia's astrometric measurements will give of us the orbital inclination and thus true mass of most of the exoplanets discovered by the radial velocity method.

Gaia will also discover a large number of giant planets. Perryman et al. (2014) made an assessment of this number using the estimates of planet occurrence and the current performance of Gaia. They estimate that almost 17 000 planets will be detected around host stars with r-magnitude <17.5. The detected masses will be in the range of 0.12–15 M_{Jup} and the orbital semi-major axes, a, in the range 0.037–6.87 AU. Thus Gaia will fill an important region of the exoplanet mass versus semi-major axis parameter space that is not covered by transit search missions.

A significant fraction of these will be in multiple systems. Casertano et al. (2008) estimate that $\sim$1000 multiple-planet systems will be detected and measured by Gaia. Astrometric measurements of the giant planet υ And c made with the Fine Guidance Sensor of the Hubble Space Telescopes indicate a mutual inclination of the two planets of 30° (McArthur et al. 2010). It will be of interest to see how frequent such misaligned systems are. Gaia should be able to perform co-planarity tests of $\sim$150 systems (Casertano et al. 2008).

7.2. The James Webb Space Telescope

JWST is the successor to the Hubble Space Telescope (HST). With a mirror diameter of 6.5 m, it will be the largest astronomical reflecting telescope flown in space. It will orbit at the L2 Lagrange point where continuous observations are possible without significant blocking of the Earth. It is scheduled for launch in late 2018. The design is for a 5-yr mission life, but with a goal of 10 yr.

JWST will play a significant role in the characterization of exoplanetary atmospheres. Owing to its large aperture, it is supremely suited for studying the absorbed light of transiting exoplanets during the primary (in-transit spectroscopy), or the radiated light near secondary eclipse (Clampin et al. 2009). JWST will observe at wavelengths of 0.6–28.5 μ. This is in contrast to the 0.1–2.5 μ wavelength range of HST which had one-seventh of the collecting area of JWST.

There are several instruments that are particularly important for atmospheric studies of transiting planets. The Near InfraRed Camera (NIRCam) will provide photometric capabilities and low resolution spectroscopy. Pick-off optics separate the light into a short (0.6–2.3 μm) and a long (2.4–5.0 μm) wavelength path. NIRCam has a grism in the long wavelength channel that will provide spectroscopy at a resolving power, $R = \lambda/\delta\lambda \sim 2000$.

The Near InfraRed Spectrograph (NIRSpec) will operate in the wavelength range 0.6–5.0 μm and is ideally suited for measuring the transmission spectroscopy of an exoplanet during the transit. A prism will provide low resolution ($R = 100$) over 0.7–5.0 μm. Three gratings will cover the 1–5 μm at $R = 1000$, and another three the same wavelength band, but at higher resolution ($R = 2700$).

The Mid-Infrared Instrument (MIRI, Wright et al. 2004) will provide a wealth of information for exoplanet occultations (secondary eclipse). The instrument covers the wavelength range 5–28 μm where the occultation contrast is maximized. MIRI will provide direct imaging capabilities for producing a mid-IR secondary eclipse light curve as well as slitless low resolution spectroscopy at $R \sim 100$. Medium resolution spectroscopy ($R = 3000$) is possible in four spectral regions: 4.96–7.77 μm, 7.71–11.90 μm, 11.90–18.35 μm, and 18.35–28.30 μm.

Deming et al. (2009) investigated the capabilities of JWST for the characterization of exoplanet atmospheres using the predicted sensitivities of the respective instruments. JWST instrumentation can be used to detect the spectra of super-Earths and such features such as carbon dioxide as well as the secondary eclipse of of exo-Neptunes.

JWST will be able to perform follow-up studies of the TESS discoveries. If it achieves its goal of a 10-yr mission life, then it should be able to perform atmospheric studies of the first PLATO discoveries.

8. Summary

The next 10–20 yr promises to be exciting times for exoplanet science, astroseismology, and stellar astrophysics. At the end of the future missions described here we will have light curves for well over one million stars using ultra-high precision space-based photometry. We can anticipate tens of thousands of new planets and transiting systems. We will also have astroseismic data for tens of thousands of stars and measurements of the stellar rotation periods and activity cycles for countless others. And of course, we will find new phenomena. For the discovered exoplanets a significant fraction of these will be around relatively bright stars which means, we will have accurate planetary radii, masses, and bulk densities.

PLATO will build on the CoRoT experience and exploit synergy of stellar and exoplanetary science. Using accurate bulk parameters of planetary mass, radius, and bulk density which is only possible because of the use of asteroseismic tools, scientists will be able to perform accurate comparative exo-planetology. This will give us a better understanding of diversity of planet densities and thus internal structures of exoplanets as a function of stellar mass, orbital distances, and planetary age. Thanks to its complementary program, PLATO will increase our understanding of stellar structure and evolution, essentially in constraining still poorly understood transport processes. With thousands of red giants observed in a wide galactic covering, it will also be in the front row of a new vision of the evolution of our Galaxy.

Spectral features have been detected in the atmospheres of only a handful of exoplanets. This will change with the discoveries from TESS and PLATO and the launch of JWST. The rough chemical composition, atmospheric temperature profile, and possible cloud features, etc. will be known for many explanets down to the super-Earth range ($R = 2$–$4\ R_{\oplus}$, $M = 2$–$5\ M_{\oplus}$).

We have only discussed the approved space missions at the time of this writing. A mission dedicated to the study of the atmospheres of transiting planets, Ariel, has been proposed as an M-class mission to ESA. Although it will have a smaller aperture (1.1-m) compared to JWST, all the telescope time will be dedicated to transit studies. This is unlike JWST where the exoplanet scientists will have to compete with the rest of the astronomical community for the precious telescope time. Not so for a mission like Ariel. The number of exoplanets for which we have characterized their atmospheres may well go from the tens to hundreds.

The Gaia mission will provide us with a better understanding of the structure and evolution of our Galaxy, but this requires accurate measurements of stellar ages. This can only come from asteroseismic measurements that will be provided by PLATO.

In short the next 10–15 yr promises to be an exciting journey for exoplanet and stellar researchers. One can well argue that CoRoT marked the start of this wonderful journey.

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