SPECULOOS Exoplanet Search and Its Prototype on TRAPPIST

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Abstract

One of the most significant goals of modern science is establishing whether life exists around other suns. The most direct path towards its achievement is the detection and atmospheric characterization of terrestrial exoplanets with potentially habitable surface conditions. The nearest ultracool dwarfs (UCDs), i.e., very-low-mass stars and brown dwarfs with effective temperatures lower than 2700 K, represent a unique opportunity to reach this goal within the next decade. The potential of the transit method for detecting potentially habitable

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H. J. Deeg, J. A. Belmonte (eds.), *Handbook of Exoplanets*,
https://doi.org/10.1007/978-3-319-30648-3_130-3

Earth-sized planets around these objects is drastically increased compared to Earth-Sun analogs. A terrestrial planet transiting a nearby UCD could be an exquisite target for a thorough atmospheric characterization, including the search for possible biosignatures, with facilities such as the James Webb Space Telescope. In this chapter, we first describe the physical properties of UCDs as well as the unique potential they offer for the detection of potentially habitable Earth-sized planets suitable for atmospheric characterization. Then, we present the SPECULOOS ground-based transit survey that is searching for Earth-sized planets transiting the nearest UCDs, as well as its prototype survey on the TRAPPIST telescopes.

Introduction

Confined for centuries to the rank of a pure speculation, the existence of life outside our solar system is now at the edge of gaining its status of a testable scientific hypothesis. Since the first discoveries of planets orbiting other stars than the Sun (Wolszczan and Frail 1992; Mayor and Queloz 1995), more than five thousand of such exoplanets have been detected at an ever-increasing rate (Akeson et al. 2013; Schneider et al. 2011; Han et al. 2014). The present exoplanet harvest is not only composed of gas and ice giants but also includes a steeply growing fraction of small, potentially terrestrial planets. In parallel to this galore of detections, many projects aiming to characterize exoplanets have reached success in the last decade, bringing notably first pieces of information on the atmospheric properties of exoplanets. Nearly all of these atmospheric studies have been made possible by the transiting configuration of the probed planets. Indeed, the special geometrical configuration of transiting planets offers the detailed study of their atmosphere without the cost of spatially resolving them from their host stars (Winn 2010). The first atmospheric studies of transiting "hot Jupiters" performed with space- and ground-based instruments have provided initial glimpses at the atmospheric chemical composition, vertical pressure-temperature profiles, albedos, and circulation patterns of extrasolar worlds (Deming and Seager 2017). On paper, exporting the techniques developed for these pioneering first studies of transiting gas giants to the atmospheric characterization of terrestrial planets orbiting in the habitable zone (HZ, Kopparapu et al. 2013) of their host star looks like a promising path to search for life outside our solar system in the near future. The relevance of this approach relies on the discovery of suitable transiting planets, i.e., HZ terrestrial planets transiting a host star bright and small enough to lead to adequate signal-to-noise ratios (SNRs) for spectroscopic detection of biosignatures (Seager et al. 2016), assuming realistic observational programs with current and upcoming astronomical facilities. Most studies in this domain have focused on the James Webb Space Telescope (JWST) (Seager et al. 2009; Kaltenegger and Traub 2009; Belu et al. 2011; de Wit and Seager 2013; Barstow and Irwin 2016), because its orbit, large aperture, and infrared (IR) sensitivity make it a priori the best facility for such atmospheric characterizations. All these studies agree on the fact that the best suitable target for biosignatures detection would be a potentially habitable terrestrial planet transiting one of the nearest ultracool dwarfs (UCDs). Indeed, UCDs are so small and faint that they do not drown out the signals of Earth-sized exoplanets, allowing us to detect and study in great depth such small planets.

What Are Ultracool Dwarfs?

UCDsare traditionally defined as dwarf stars and brown dwarfs having effective temperatures T_{eff} <2700 K, luminosities $L \leq 10^{-3}\ L_{\odot}$, and spectral types later than M6, including L, T, and Y dwarfs (Kirkpatrick 2005; Cushing et al. 2011). In these conditions, the atmospheres of UCDs are rich in molecular gases (H_2O, CO, TiO, VO, CH_4, NH_3, CaH, and FeH) and condensed refractory species (mineral and metal condensates, salts, and ices), producing complex spectral energy distributions, strongly influenced by composition and chemistry, that peak at near- and mid-IR wavelengths. UCDs have masses below $\approx 0.1\ M_{\odot}$, extending below the hydrogen-burning minimum mass (HBMM) of $0.07\ M_{\odot}$, into the realm of non-fusing brown dwarfs (Kumar 1962, 1963; Hayashi and Nakano 1963). Supported from gravitational collapse primarily by electron degeneracy pressure, these objects are the most compact and dense hydrogen-rich bodies in the galaxy, with radii reaching a minimum of $R \approx 0.08$–$0.10\ R_{\odot}$ near the HBMM and core densities potentially as high as 1000 g/cm^3 (Burrows and Liebert 1993). These dense interiors may show exotic states of matter (e.g., metallic and crystalline hydrogen) and make UCDs fully convective and well-mixed in their interior composition. Convection, coupled with their low fusion rates, implies lifetimes of tens of trillions of years for stellar UCDs, while substellar UCDs persist indefinitely but with ever-decreasing temperatures and luminosities.

While few UCDs were known prior to the mid-1990s, the proliferation of red optical and near-IR surveys over the past 25 years has dramatically increased the size of the known population, including recent discoveries of some of the nearest systems to the Sun: the L dwarf plus T dwarf binary Luhman 16AB at 2.0 pc (Luhman 2013), the Y dwarf WISE 0855-0714 with $T_{eff} \approx 250$ K at 2.3 pc (Luhman 2014), and the M dwarf plus T dwarf binary WISE 0720-0846, which passed within 50, 000 AU of the Sun in the past 100,000 years (Burgasser et al. 2015; Mamajek et al. 2015). Overall, UCDs appear to be less numerous than more massive M stars ($0.1\ M_{\odot}$ < mass < $0.5\ M_{\odot}$) but are more abundant than solar-type FGK stars in the immediate solar neighborhood (e.g., >5:1 UCDs:G dwarfs in the 8 pc sample; Kirkpatrick et al. 2012).

There are a number of unique characteristics of UCDs that are relevant to understanding exoplanet companions that warrant mention. First, their low T_{eff} reduces the coupling of photospheric gas to internally generated magnetic fields, resulting in a general decline in the relative strength and incidence of optical (H-alpha, Ca II) and X-ray nonthermal emission, particularly among the L and T (and presumably Y) dwarfs (Gizis et al. 2000; Berger 2006; Pineda et al. 2016). This makes the immediate environment around UCDs somewhat more benign than active M dwarfs. Nevertheless, flaring emission (in some cases dramatic, Schmidt et al.

2014) persists in these objects, as does nonthermal radio emission, both indicating the presence of strong magnetic fields. The reduction in magnetic coupling reduces angular momentum loss so that UCDs are generally rapidly rotating bodies with periods as short as 1–2 h and rotational v*sin*i measurements as high as 80 km/s (Blake et al. 2010; Metchev et al. 2015).

Ultracool Dwarfs and Planets

Despite that UCDs represent a significant fraction of the galactic population, their planetary population is still a nearly uncharted territory. As of today, only nine bona fide planets have been found in orbit around UCDs, the seven transiting Earth-sized planets of TRAPPIST-1 (Gillon et al. 2017, see "*TRAPPIST-1 and its compact system of temperate rocky planets*"), the $\sim$3 $M_\oplus$ planet MOA-2007-BLG-192Lb, and $\sim$1.3 $M_\oplus$ planet OGLE-2016-BLG-1195Lb detected by microlensing around distant UCDs (Kubas et al. 2012; Shvartzvald et al. 2017). These microlensing planets are very interesting, because they demonstrate that UCDs can form planets more massive than the Earth, despite the low mass of their protoplanetary disks. On their side, the Earth-sized planets transiting TRAPPIST-1 indicate that compact systems of small terrestrial planets are probably common around UCDs, as TRAPPIST-1 is one of only $\sim$50 UCDs targeted by the SPECULOOS prototype survey ongoing on the TRAPPIST-South telescope since 2011 (see below). First limits on the occurrence rate of short-period planets orbiting brown dwarfs were reported by He et al. (2017), who found that within a 1.28 d orbit, the occurrence rate of planets with a radius between 0.75 and 3.25 $R_\oplus$ is lower than $67 \pm 1\%$. More recently, Sestovic and Demory 2020 inferred an occurrence rate of mini Neptune (2–4 R⊕) in ultracool stars of $20\% + 0.16 - 0.11$ within orbital periods of $1-20$ days. For super-Earths (1–2 R⊕) and ice or gas giants (4–6 R⊕) within 1–20 days, they found occurrence rate <1.14 and <0.29, respectively.

These planet detections are consistent with the growing observational evidence that young UCDs are commonly surrounded by protoplanetary disks (e.g., Luhman et al. 2007) which, while containing less mass, appear to persist longer as compared to solar-type stars (Luhman 2012). Furthermore, young UCDs also exhibit the hallmarks of preplanetary formation: evidence of disk accretion, circumstellar disk excess, accretion jets, and planetesimal formation (e.g., Muzerolle et al. 2000; Klein et al. 2003; Whelan et al. 2005; Pascucci et al. 2011; Ricci et al. 2013).

Still poorly constrained by direct observations for objects below $\sim$0.2 $M_\odot$, planetary formation models agree on the fact that UCDs should be able to form mostly terrestrial planets (Payne and Lodato 2007) but disagree on their typical mass and chemical composition. For instance, Raymond et al. (2007) predicted systems of short-period inhospitable metal-rich terrestrial planets that rarely exceed the mass of Mars, while Montgomery and Laughlin (2009) predicted systems of more massive volatile-rich planets that should be better suited for the emergence of life. Alibert and Benz (2017) predict Earth-sized planets that are volatile-rich if protoplanetary disks orbiting low-mass stars are long lived.

When combined with the observational evidence that short-period low-mass planets are common around solar-type stars and tend to be found in nearly coplanar closely packed multiplanetary systems (e.g., Figueira et al. 2012; Ballard and Johnson 2016; Muirhead et al. 2012, 2015), and with the discovery of the TRAPPIST-1 system, all these considerations lead to the expectation that the typical planetary system around UCDs should be reminiscent to the Jovian system, with (water-rich or not) terrestrial planets replacing the Galilean moons. If this prediction is valid, most UCDs should have terrestrial planets within or close to their HZ. Indeed, due to their small sizes and low temperatures, the HZs of UCDs are located very close by, at just a few percent of 1 au (Bolmont et al. 2011; Kopparapu et al. 2013) or even less for brown dwarfs. If systems of terrestrial planets were confirmed to be common around UCDs, then the archetypical terrestrial planet in our galaxy would not be Venus, Earth, or Mars but rather a tidally locked red world like those of TRAPPIST-1.

SPECULOOS: Seizing the UCDs Opportunity

Because of the low luminosities and small sizes of UCDs, and the resulting large planet-to-star flux and size ratios, expected SNRs on the detection of spectroscopic signatures in the atmosphere of a transiting habitable Earth-sized planet are more favorable for UCDs than for any other host. Kaltenegger and Traub (2009) derived SNR expectations for atmospheric biosignatures measured with JWST for Earth-sized planets transiting putative M0–M9 dwarf stars at 10 pc. Scaling these SNRs with the distance to the Earth and considering SNR = 10 as an absolute lower limit to constrain properly the atmospheric composition, one can derive the following upper limits on the distance (and on the corresponding J-band magnitude) for the different spectral types of UCD stars: 30 pc (J = 12.6) for the M7, 34 pc (J = 13.3) for the M8, 40 pc (J = 14.0) for the M9, and latter (the spectral type range of UCD stars extends down to ~L2.5, Dieterich et al. 2014). The numbers of UCD stars in the close solar neighborhood (<8 pc) are well known (e.g., Reid et al. 2007, 2008), and the corresponding number densities for the different spectral types can be coupled to the distance limits derived above to estimate the number of possible targets as 800 UCD stars. Because of the proximity of the HZ for these UCD stars, the relatively small number of them being bright enough for JWST is balanced by a strongly increased geometric transit probability. Assuming that each of these 800 nearby UCD stars has a terrestrial planet in its HZ leads indeed to an expected sample of about 20 habitable planets waiting to be studied by JWST and other future facilities, to which one should add the planets orbiting outside the HZ. In addition to these 800 UCD stars, about 200 brown dwarfs are nearby and bright enough to enable the study of the atmospheric composition of short-period transiting Earth-sized planets with JWST (e.g., Belu et al. 2011). In total, there are thus about 1000 opportunities in the sky (800 stars + 200 brown dwarfs) to detect Earth-sized planets well suited for detailed atmospheric characterization—including biosignatures detection—with current and near-future technology.

From a transit search perspective, UCDs provide two important observational advantages. First, their small size leads for Earth-sized planets to have transit depths from a few 0.1% up to >1%, similar to the typical transit depths for the dozens of Jupiter-sized planets detected around solar-type stars by wide-field ground-based surveys like WASP (Collier Cameron et al. 2007) and HATNet (Bakos et al. 2007). Second, the proximity of their HZ makes the transits of habitable planets have periodicities of a few days similar to gas giants in close orbit around solar-type stars, which translates into a required photometric monitoring of much smaller duration than for bona fide Earth-Sun twin systems. This means that a transit search targeting the 1000 nearest UCDs could be done within a few years with a realistically small number of telescopes, despite that it should monitor each target individually, as nearby UCDs are spread all over the sky. This is the goal and concept of our project SPECULOOS (**S**earch for habitable **P**lanets **EC**lipsing **UL**tra-c**OO**l **S**tars). The project is led by the University of Liège (Belgium) in collaboration with the Cavendish Laboratory of the University of Cambridge (UK), Massachusetts Institute of Technology (USA), University of Bern (Switzerland), University of Birmingham (UK), and the University of Zurich (Switzerland).

SPECULOOS Prototype on TRAPPIST

Before the discovery of the TRAPPIST-1 planetary system, the relevance of a dedicated transit search targeting nearby UCDs could have been a priori questioned. The need for the individual monitoring of each UCD makes it necessary being able to detect a *single* transit event to prevent booking one telescope to one UCD for unrealistically long durations and thus puts the strongest constraint on the required photometric precision. Related to this point, UCDs are faint and emit most of their light in the IR, a priori suggesting the need for expensive large telescopes and IR detectors. SNR computations convinced us that this was not the case and that telescopes of relatively modest sizes (60 cm to 2 m) equipped with near-IR-optimized CCD cameras should reach the required high photometric precision. This had to be demonstrated. In addition to their intrinsic faintness, late M dwarfs are commonly considered as active objects (Goldman 2005; Reid and Hawley 2005). This activity could be a big issue, as it could strongly limit the ability to detect low-amplitude transits (e.g., Reid and Hawley 2005). Another possible barrier to the relevance of the SPECULOOS project concept could have come from the Earth's atmosphere itself. Indeed, in the very-near-IR, the water molecule and OH radical contribute to a number of absorption bands, as well as significant emission for OH (airglow). This brings unavoidable important levels of red noise in photometric time series (e.g., Berta et al. 2011). For all these reasons, a thorough assessment study based on a prototype survey was mandatory.

In 2011, we initiated such a prototype survey for SPECULOOS with the robotic telescope TRAPPIST-South (**TRA**nsiting **P**lanets and **P**lanetes**I**mals **S**mall **T**elescope; Gillon et al. 2011; Jehin et al. 2011). It is a 60-cm (F/8) Ritchey-Chretien telescope installed by the University of Liège in 2010 at ESO La Silla Observatory

Fig. 1 Left. The dome of the TRAPPIST-South telescope at ESO La Silla Observatory (Chile). Right. TRAPPIST-South telescope. (Credit: E. Jehin)

in the Atacama Desert in Chile (see Fig. 1). It is equipped with a near-IR-optimized 2 K × 2 K CCD camera with a $0.64''$/pixel scale, offering excellent quantum efficiencies from 300 to >900 nm. This SPECULOOS prototype survey targeted 50 among the brightest southern UCDs, with J-magnitude between 5.4 and 12 (mean $J = 11.3$), and uniformly distributed in terms of spectral type and sky position. Its concept was to monitor in a wide near-IR filter (transmission >90% from 720 nm) each UCD during at least 100 h spread over several nights. Its initial goals were to assess the typical photometric precisions that can be reached for UCDs on nightly timescales, the resulting detection thresholds for terrestrial planets, and to identify the astrophysical and atmospheric limitations of the SPECULOOS concept.

Since mid-2016, a northern extension of the prototype survey for SPECULOOS has been conducted with the TRAPPIST-North telescope, installed at the Oukaïmeden Observatory in Morocco. This telescope is a twin brother of the TRAPPIST-South telescope and operated in collaboration with the Cadi Ayyad University of Marrakesh.

Almost 40 UCDs were observed by TRAPPIST-South in the period from 2011 to 2016. Half of the observed UCDs show "flat" light curves, i.e., stable photometry on the night timescale. Some of the other UCDs ($\sim$20%) show clear flares in some light curves. These flares are seen in near-IR light curves as a sudden increase of a few percent of the measured brightness, followed by a gradual decrease back or close to the normal level. The whole process takes only 10–30 min. In the context of a transit search, it is easy to identify and discard the affected portions of light curves. Furthermore, their frequency is relatively small (1 flare per 3–4 nights on average). Finally, about 30% of the observed UCDs show some rotational modulation (and more complex variability) with up to 5% amplitude.

Within the framework of this prototype survey, we also monitored the nearby brown dwarf binary Luhman 16AB for nearly a fortnight, right after its discovery was announced in February 2013 (Luhman 2013). The quality of our photometric data allowed us to reveal fast-evolving weather patterns in the atmosphere of the coolest component of the binary, as well as to firmly discard the transit of a two-Earth radius planet over the duration of the observations and of an Earth-sized planet on orbits shorter than ∼9.5 h (Gillon et al. 2013).

From intense simulations based on the injection and recovery of synthetic transits of terrestrial planets in actual TRAPPIST-South UCD light curves, we have reached the conclusion that the variability of a fraction of UCDs (flares and rotational modulation) does not limit the ability to detect transits of close-in planets. The reached photometric precisions are globally nominal. There is no hint of an extra amount of correlated noise, except for the small fraction (∼10%) of the observations performed in high humidity conditions. Nominal sub-mmag precisions can thus be reached for UCDs from a suitable astronomical site (good transparency and low humidity). This conclusion was strengthened by our detection of Earth-sized exoplanets transiting one of the TRAPPIST-South UCD targets, 2MASS J23062928-0502285 (TRAPPIST-1, Gillon et al. 2016, 2017). The detection—and even the very existence—of the TRAPPIST-1 (=SPECULOOS-1) planetary system fully demonstrates the instrumental concept and the scientific potential of SPECULOOS.

The SPECULOOS Observatories

The SPECULOOS network consists of three nodes. Four telescopes are installed at the ESO Paranal Observatory (Atacama Desert, Chile) and they compose the SPECULOOS South Observatory (SSO, Delrez et al. 2018; Jehin et al. 2018; Murray et al. 2020; Sebastian et al. 2021), which has been operational since January 2019. The second node is the SPECULOOS North Observatory (SNO, Burdanov et al. 2022), which is currently composed of one 1 m-aperture telescope that is located at the Teide Observatory (Canary islands, Spain) and which has been operational since June 2019. The third node is the SAINT-EX (**S**earch **A**nd character**I**zatio**N** of **T**ransiting **EX**oplanets, Demory et al. 2020) telescope in San Pedro Mártir observatory (Mexico), operational since March 2019. Each of these observatories are devoting 70% of their usable observational time to the SPECULOOS survey. In addition, the two 60 cm TRAPPIST robotic telescopes, while not officially part of the SPECULOOS network, have devoted a fraction of their time to supporting the survey and focus on its brightest targets.

Each of the SPECULOOS observatories is composed of identical robotic Ritchey-Chretien (F/8) telescopes of 1-m aperture (see Fig. 2). Each telescope is equipped with an Andor iKon-L thermoelectrically cooled camera with a near-infrared optimized, deep depletion 2 k × 2 k e2v CCD detector (13.5 μm pixel size). The field of view on the sky is 12 × 12 arcminutes, yielding a pixel scale of 0.35 arcseconds/pixel. Exposure control is realized by a mechanical shutter, using overlapping iris blades. Despite the fact that these shutters are generally very durable, they have a limited lifetime. To increase this shutter lifetime, we restrict our remote observations to exposure times longer than 10 s. The camera is

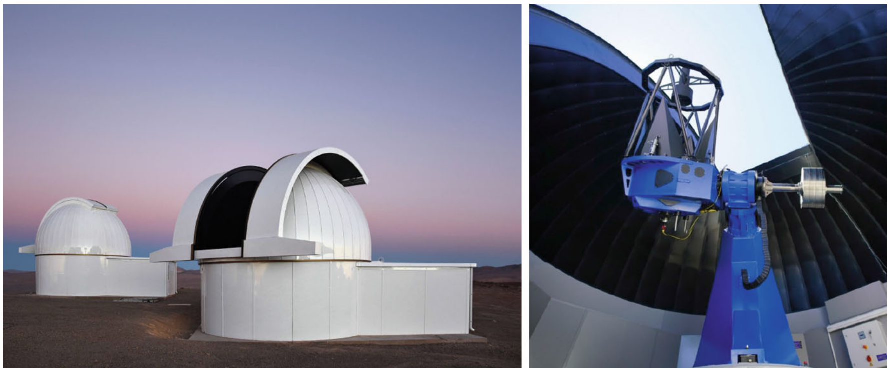

Fig. 2 Left. First two domes of the SPECULOOS Southern Observatory at ESO Paranal Observatory (Chile). (Credit: ESO/G. Lambert). Right. Europa, the first telescope of the SPECULOOS Southern Observatory. (Credit: P. Aniol)

usually operated at –60 °C (via five-stage Peltier cooling) with a dark current of 0.3 electrons/s/pixel. The detector provides high sensitivity in a wide wavelength range (350–950 nm), with a maximum quantum efficiency of 94% at both 420 and 740 nm. Each camera has its own filter wheel providing the Sloan g', r', i', z', and two special exoplanet filters; the near-infrared luminance I + z filter (transmittance >90% from 750 to beyond 1000 nm, which is mostly used for the SPECULOOS core program); and a blue-blocking filter called Exo (transmittance >90% from 500 to beyond 1000 nm).

Each telescope is equipped with a robotic equatorial mount with direct-drive torque motors, which allows fast slewing (up to 20 deg per sec), accurate pointing (better than $3''$), and tracking accuracy better than $2''$ over 15 min without autoguiding and periodic errors.

The observatory is fully robotic and can be controlled from anywhere there is internet access, through a virtual private network (VPN) connection. The human intervention is reduced to a quick status check and manual starting of the night's observing plans. Observing plans, consisting of very simple text files, are submitted daily to the ACP Expert Observatory Control Software installed on the control computer of each telescope.

All telescopes require minimum on-site maintenance. The host observatories provide emergency help in case of technical difficulties as well as regular checkups to ensure continuous robotic operations.

Observation Strategy

The SPECULOOS target list contains a homogeneous selected sample of close-by (<40 pc) low-mass stars and UCDs. The targets have been selected as low-mass dwarfs starting from Gaia DR2 source catalogue (GaiaDR2 reference) crossmatched with the 2MASS point-source catalogue (2-mass reference). During this cross-match, we enforced the agreement between the two catalogues not only in terms of position but also in terms of effective temperatures inferred from different photometric indicators. The final selection of the SPECULOOS target catalogue is based on each target's individual parameters and its match to the SPECULOOS science goals: (i) finding rocky Earth-like planets around close and bright targets that are well-suited for atmospheric characterization with JWST and (ii) to provide a census of the short-period planet population of UCDs. The 40 pc list of late-type targets and SPECULOOS target list are publicly available together with a detailed description of the target selection and survey strategy (see Sebastian et al. 2021).

The SPECULOOS target list is divided into three nonoverlapping programs:

Program 1 (365 targets): Includes all targets that allow transit transmission spectroscopy with JWST for Earth-like planets.
Program 2 (171 targets): Includes all targets that allow a detection of temperate Earth-sized planets, like TRAPPIST-1b, with TESS.
Program 3: Includes 1121 targets with the spectral type M6 and later and aims to explore the planet occurrence rate for ultracool dwarfs within our 40 pc sample.

On average, we observe continuously one or two targets per telescope. Each telescope operates independently and in robotic mode following the plans written by SPECULOOS scheduler `SPOCK`. Our strategy is to observe all targets, reaching an effective phase coverage of up to 80% for temperate planets in Programs 2 and 3 and for planets in the habitable zone in Program 1, resulting in monitoring durations with our SPECULOOS telescope network of 100–200 h, respectively.

The continuous observation of the targets does not only maximize the photon counts; it also improves the photometric detection threshold by letting the telescope keep the stars on the same pixels of the detector during several hours or the whole night. This continuous monitoring optimizes the capacity to detect single low-amplitude transits, which is crucial here as all planetary formation models agree on the fact that UCDs should form small planets (e.g., Montgomery and Laughlin 2009; Raymond et al. 2007). Furthermore, the need for continuous observation is driven by the expected short transit duration (down to 15 min) for planets orbiting at the inner edge of the habitable zone of UCDs (Kopparapu et al. 2013). Once a transit signature is detected in the photometric data, the first follow-up action will be to confirm it by prolonging the SPECULOOS monitoring of the star and possibly by using similar telescopes at other longitudes. Once a transit ephemeris will be secured, larger ground-based telescopes like the VLT, or space facilities like Spitzer (as was done in Gillon et al. 2017), may then be used to gather high-precision transit photometry at different wavelengths, to assess the achromaticity of the eclipses and confirm their planetary origins (Gillon et al. 2016).

Estimating the Planet-Yield of SPECULOOS Through Simulations

To have an assessment of the possible yield of the SPECULOOS survey, we performed Monte-Carlo simulations based on the current target list of 1657 UCDs. We assumed that every target has at least one planet and used mass, radius, and effective temperature as starting points to simulate a planetary system. For each target, we drew a planetary system following Miguel et al. (2020), using their distribution of expected number of planets. We accounted for the period distribution by using two period samples, one between 0.5 and 23 days and a second between 23 and 1800 days. The drawn planets are uniformly distributed with a probability of $p = 0.5$ to be in one of both samples. The planet masses and densities are drawn from a normal distribution based on the TRAPPIST-1 system. We derived the planet parameters and inclinations based on the stellar parameters using the same methods as described in Delrez et al. (2018). Simulated planets are counted as "discovered" if the following criteria are met: (1) a transit has been observed during a simulated SPECULOOS observation run. This assumes a visibility of 4 h per night, a total loss of about 30% due to weather or technical downtime, and a monitoring campaign that is completed after the program-specific number of observing hours has been reached; (2) the S/N of the transit is larger than 5, assuming a floor noise during the transit of 500 ppm.

Our Monte-Carlo simulations lead for the complete SPECULOOS program to 29 ± 4 planets detected after the survey completion. Among these planets, 8 ± 2 orbit within the HZ.

Current Status and Results

We have started observation on ~17% objects of our target list and for ~40% of them, more than 100 h of photometric data have been collected. For ~23% of the program 1 targets the observations have been completed. In parallel, the high S/N TESS light curves of the brightest targets in our programs are being analyzed. Given this synergy, we expect to complete our most time intensive program 1 targets in less than 4 years.

Beside conducting observations of the SPECULOOS core programs, we dedicate 20% of our observing capability to annex programs focused mainly, but not limited to, follow-up observations of planet candidates around late-type dwarfs. We are contributing to the follow-up community as part of the TESS follow-up Observing Program (TFOP) working group, especially in the subgroup 1 dedicated to seeing-limited photometry. Our participation in the TFOP working group has brought interesting planet validation such as the large sub-Neptune TOI-2406b (Wells et al. 2021) or the highly eccentric long-period sub-Neptune TOI-2257b (Schanche et al. 2022). One notable example is the validation of TOI-715b, a 1.55 $R_\oplus$ habitable-zone planet. Additionally, we reveal a second candidate planet in this system, TIC 271971130.02, just inside the outer boundary of the habitable zone, and near a 4:3 orbital period commensurability (Dransfield et al. 2024). Following-up data from K2, using SSO and SNO observatories confirmed the detection of π-Earth (EPIC 249631677b, Niraula et al. 2020), a transiting Earth-sized planet around the mid-M dwarf K2-315b with period ~3.14 days. The follow-up campaign of the TESS transit candidate TOI-1266 was the first exoplanet validation from the SAINT-EX observatory, which revealed a system that hosts a super-Earth and a sub-Neptune around a M3 dwarf (Demory et al. 2020). We also contributed to refining the planetary parameters and transit time variations of known planets (Ducrot et al. 2018). Additionally, we performed follow-up photometry for projects such as NGTS (Günther et al. 2018; West et al. 2019), WASP (Barkaoui et al. 2019; Temple et al. 2019), and CHEOPS (Leleu et al. 2021). Giant planets are still a rarity around cool stars, making their detection an important step towards the understanding of their formation pathway. We developed a joint program between TRAPPIST and SPECULOOS that aims to validate photometrically large candidates around M-dwarf stars, named M-dwarfs Accompanied by Nearby Giant Orbiters (MANGOs, Dransfield et al. in prep.).

The SPECULOOS network is also involved in projects different from planet transit characterization, such as studying ultracool dwarfs magnetic behavior (Günther et al. 2020; Murray et al. 2022) and characterize low-mass eclipsing binaries within the EBLM project (von Boetticher et al. 2019). One notable example is the detection of a novel ultracool system, a young triple brown dwarfs system discovered in SSO photometry (Triaud et al. 2020). This system contains one of the two double-lined eclipsing brown dwarfs known today, providing a valuable benchmark to constrain the masses, radii, and ages of such objects.

In 2022, we discovered a new potentially habitable planet around LP 890-9 (Delrez et al. 2022). The first planet, LP 890-9b (or TOI-4306b), the innermost in the system, was initially identified by TESS. The follow-up observations of LP 890-9 obtained by SPECULOOS have proved fruitful, as they have not only helped to confirm the first planet but have also made it possible to detect a second, previously unknown one. This second planet, LP 890-9c (renamed SPECULOOS-2c by the ULiège researchers), is similar in size to the first one (about 40% larger than the Earth) but has a longer orbital period of about 8.5 days. SPECULOOS-2c is the second-most favorable habitable-zone planet for atmospheric characterization found so far after the TRAPPIST-1 planets.

More recently, the project discovered SPECULOOS-3b, an Earth-sized planet in a 17-hour orbit around an M6.5-type ultracool dwarf located 16.8 parsecs away (Gillon et al. 2024). The planet's high irradiation (16 times that of Earth) combined with its host star's infrared luminosity ($K = 10.5$) and Jupiter-like size ($R = 0.12$ Rsun) make it one of the most promising extrasolar rocky planets for a detailed characterization by emission spectroscopy with JWST.

Cross-References

- ▶ Exoplanet Atmosphere Measurements from Transmission Spectroscopy and Other Planet Star Combined Light Observations
- ▶ Proxima b: The Detection of the Earth-Type Planet Candidate Orbiting Our Closest Neighbor
- ▶ The Habitable Zone: The Climatic Limits of Habitability
- ▶ The Impact of Stellar Activity on the Detection and Characterization of Exoplanets
- ▶ Transit Photometry as an Exoplanet Discovery Method
- ▶ Transit-Timing and Duration Variations for the Discovery and Characterization of Exoplanets
- ▶ TRAPPIST-1 and Its Compact System of Temperate Rocky Planets

Acknowledgments The authors are grateful and thank Adam Burgasser, Amaury H. M. J. Triaud, Catarina S. Fernandes, Julien de Wit, and the rest of SPECULOOS and TRAPPIST teams for the help in the preparation of this chapter. TRAPPIST-South is a project funded by the Belgian Fonds (National) de la Recherche Scientifique (F.R.S.-FNRS) under grant FRFC 2.5.594.09.F, with the participation of the Swiss National Science Foundation (FNS/SNSF). TRAPPIST-North is a project funded by the University of Liège and performed in collaboration with Cadi Ayyad University of Marrakesh. The research leading to these results has received funding from the European Research Council (ERC) under the FP/2007–2013 ERC grant agreement no. 336480 and under the H2020 ERC grant agreement no. 679030 and from an Actions de Recherche Concertée (ARC) grant, financed by the Wallonia-Brussels Federation. This work was also partially supported by a grant from the Simons Foundation (PI Queloz, grant number 327127). L.D. acknowledges support from the Gruber Foundation Fellowship. M.G. and E.J. are F.R.S.-FNRS research associates.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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