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The SPECULOOS Southern Observatory Begins its Hunt for Rocky Planets

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The SPECULOOS Southern Observatory (SSO), a new facility of four 1-metre robotic telescopes, began scientific operations at Cerro Paranal on 1 January 2019. The main goal of the SPECULOOS project is to explore approximately 1000 of the smallest (≤ 0.15 $R_\odot$), brightest (K_{mag} ≤ 12.5), and nearest (d ≤ 40 pc) very low mass stars and brown dwarfs. It aims to discover transiting temperate terrestrial planets well-suited for detailed atmospheric characterisation with future giant telescopes like ESO's Extremely Large Telescope (ELT) and the NASA James Webb Telescope (JWST). The SSO is the core facility of SPECULOOS. The exquisite astronomical conditions at Cerro Paranal will enable SPECULOOS to detect exoplanets as small as Mars. Here, we briefly describe SPECULOOS, and present the features and performance of the SSO facility.

Search for Planets EClipsing ULtra-cOOl Stars (SPECULOOS)

One of the most thrilling questions posed by humankind is whether inhabited worlds similar to Earth exist elsewhere in the Universe. The most direct way of answering this question is through the detection and detailed atmospheric characterisation of terrestrial exoplanets orbiting in the habitable zones of nearby stars. The nearest ultra-cool dwarf (UCD) stars represent a unique opportunity to reach this goal within the next couple of decades. UCD stars are very low mass stars at the bottom of the main sequence, with masses approximately 10% that of the Sun, sizes similar to Jupiter, effective temperatures lower than 2700 K, and luminosities less than one thousandth that of the Sun.

The habitable zones in these systems are very close to the host stars, corresponding to orbital periods of only a few days. This proximity to the host star maximises the transit probability and the likelihood of detecting habitable planets. In addition, an Earth-sized planet transiting a small UCD star produces a 1% transit signal, 100 times deeper than that of an equivalent transit around a Sun-like star, and well within the reach of ground-based telescopes. With these properties, it is possible to characterise the atmospheres of UCD habitable zone planets — including the potential detection of spectroscopic biosignatures — with forthcoming giant telescopes such as ESO's ELT (Rodler & López-Morales, 2014) and the JWST (Kaltenegger & Traub, 2009).

SPECULOOS[1,b] (Principal Investigator: Michaël Gillon) is a new photometric survey based on a network of 1-metre-class robotic telescopes. It aims to seize the opportunity to detect temperate terrestrial planets transiting nearby UCDs that are bright enough in the near-infrared to make possible the atmospheric characterisation of their planets in the near future (see Gillon et al., 2018; Delrez et al., 2018a; Burdanov et al., 2017).

Figure 1. The four 1-metre telescopes Io, Europa, Ganymede, and Callisto (from right to left)[a] of the SPECULOOS Southern Observatory starting the night under Paranal's sky.

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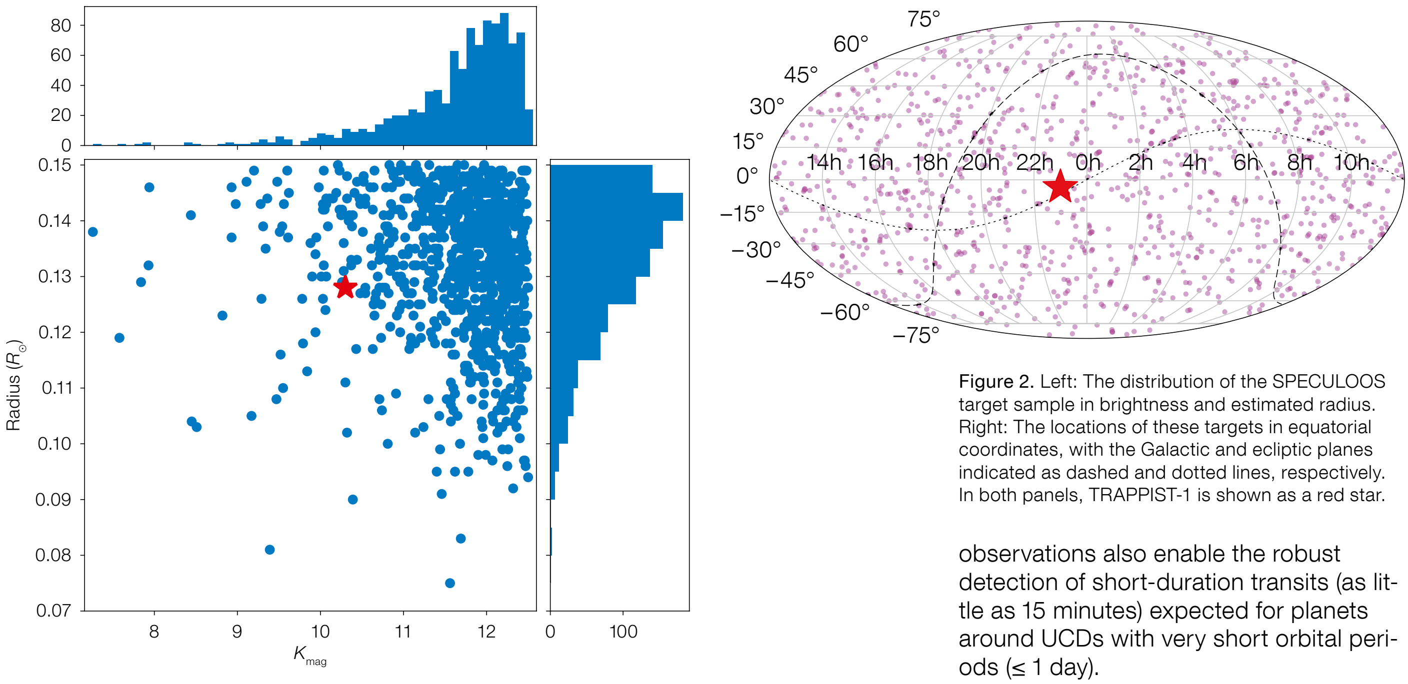

Figure 2. Left: The distribution of the SPECULOOS target sample in brightness and estimated radius. Right: The locations of these targets in equatorial coordinates, with the Galactic and ecliptic planes indicated as dashed and dotted lines, respectively. In both panels, TRAPPIST-1 is shown as a red star.

The target sample and observing strategy

The SPECULOOS target sample includes all UCD stars within 40 pc of the Sun that have a *K*-band magnitude less than 12.5 and an estimated radius less than 15% of the Sun's. These limits in *K*-band and radius correspond to the properties that allow the atmospheric characterisation of temperate Earth-sized planets with JWST. Cross-matching the catalogues from the second data release (DR2) from the ESA Gaia mission with the Two Micron All-Sky Survey (2MASS), we identified about 1000 targets across the sky, of which ~ 90% are very late M-dwarfs and ~ 10% are L-dwarfs.

Our targets are evenly distributed over the sky (Figure 2), which means that they have to be monitored individually. Fortunately, the short orbital periods of planets in the habitable zones of UCDs (~ 1 week) translate into a required photometric monitoring period for each star that is much shorter than the equivalent monitoring period for an Earth-Sun twin (~ 1 year). Consequently, SPECULOOS should complete its extensive transit search for planets around 1000 UCD targets within a 10-year window.

Because of their low temperatures, UCDs are faint in the optical, and their spectral energy distributions peak at near- and mid-infrared wavelengths. Our signal-to-noise analysis demonstrated that 1-metre-class telescopes on a dry site with good seeing, equipped with near-infrared optimised CCD cameras (providing high quantum efficiencies out to 1 μm) would be sufficient to achieve the required photometric precision (< 0.1%). We validated this strategy through a six-year prototype survey that we performed with the southern 0.6-metre telescope of the TRAnsiting Planets and PlanetesImals Small Telescope (TRAPPIST) at ESO's La Silla observatory (Jehin et al., 2011; Gillon et al., 2011). This led to the spectacular discovery of the TRAPPIST-1[2] exoplanetary system (Gillon et al., 2016, 2017).

In addition to high photometric precision, observations of each target must be taken nearly continuously over 10–25 nights to assure the detection of low-amplitude transits from planets orbiting in UCD habitable zones. These continuous observations not only maximise the photon counts but also minimise systematics and improve photometric reliability by allowing us to keep all of the stars in a particular field of view on the same pixels of the detector over the course of an entire night. Continuous observations also enable the robust detection of short-duration transits (as little as 15 minutes) expected for planets around UCDs with very short orbital periods (≤ 1 day).

To observe 1000 UCDs with SPECULOOS over the monitoring periods described above requires a total of ~ 20 000 nights of survey data. This can be achieved in ~ 10 years with a network of two facilities, one in each hemisphere and comprising four telescopes each, assuming a global efficiency of 70% (i.e., a 30% time-loss due to bad weather and technical problems).

These considerations drive the instrumental conceptual design of our survey: a network of ground-based 1-metre-class optical telescopes equipped with near-infrared optimised CCD cameras, monitoring each UCD individually and continuously for a duration long enough to efficiently and thoroughly probe its habitable zone for transiting planets. Whilst we are still in the process of deploying two telescopes in the northern hemisphere, our core facility, the SPECULOOS Southern Observatory (SSO), is now fully operational at Paranal. After a two-year development phase and two years of installation and commissioning, the facility is now starting routine operations.

The SSO site

With its low humidity (80% of nights with < 4 mm precipitable water vapour), Peter Aniol

Figure 3. The SSO is visible to the left. It neighbours the NGTS facility and is downhill from the VISTA peak. The VLT is to the right on top of Cerro Paranal while the basecamp is in the background, in the shade at the middle of the image.

excellent seeing, photometric conditions (78% of nights are photometric), and logistical infrastructure, Paranal was recognised early on as the preferred site for the installation of the SSO. Following discussions with ESO and its Scientific Technical Committee (STC), the agreement for the construction of the SSO at Paranal was signed by the then Director General Tim de Zeeuw on 30 March 2015. After a two-month seeing monitoring campaign to validate the site (seeing was better than 1.5 arcseconds for 90% of the nights), it was decided to install the SSO on a spot (see Figure 3c) below the VISTA peak and close to the Next-Generation Transit Survey (NGTS) — another exoplanet survey facility (Wheatley et al., 2018).

The telescopes and domes

The SSO is composed of four identical robotic 1-metre Ritchey-Chrétien telescopes built by the German ASTELCO company[3]. For each telescope, the 1-metre diameter primary mirror has an *f*/2.3 focal ratio and is coupled with a 28-centimetre diameter secondary resulting in a system with a combined *f*/8 focal ratio. Both mirrors are coated with pure aluminium. The telescopes have a compact and open design with a lightweight optical tube assembly made of steel, aluminium and carbon fibre components (see Figure 4).

This design provides high wind resistance, enabling observations in wind speeds reaching 50 km h^{-1}. The focusing of each telescope is achieved through motorised axial movement of the secondary mirror to an accuracy of 5 µm. Each telescope is associated with a robotic equatorial ASTELCO New Technology Mount NTM-1000. This mount uses direct-drive torque motors, which allows fast slewing (up to 20 degrees s^{-1}), accurate pointing (better than 3 arcseconds) and tracking accuracy better than 1 arcsecond over 10 minutes without an autoguider. A key component of our strategy to achieve high photometric precision is to keep our target stars on the same pixels for an entire exposure sequence. This is done using an updated version of the DONUTS autoguiding system described by McCormac et al. (2013). This technique relies on a reference

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Figure 4. Commissioning of Io and Europa in the ASTELCO assembly hall in Munich.

image of each science field. The reference image is summed along the *x* and *y* directions, creating two 1D reference image projections. A pair of 1D comparison projections is created for each subsequent science image and the guide correction is measured from a pair of cross-correlations between reference and comparison in both *x* and *y* directions. This allows a self-guiding precision better than 0.5 pixels (0.15 arcseconds) root mean square (RMS) over tens of nights for the same target.

Each telescope is enclosed in a 6.25-metre-diameter circular building surmounted by an automated hemispheric wide-slit dome with sliding doors (see Figure 5), made and equipped with an automation system from ASTELCO. The domes are made of aluminium, painted white outside to minimise internal heating during the day, and dark inside to minimise reflections during the night. The dome is slave to the telescope and a complete azimuth rotation takes less than one minute. Each building also includes a small control room that we use for commissioning activities, equipment storage, and the telescope control cabinets and computers. The distance between the domes is optimised to prevent vignetting of any telescope by another, down to 20 degrees above the horizon.

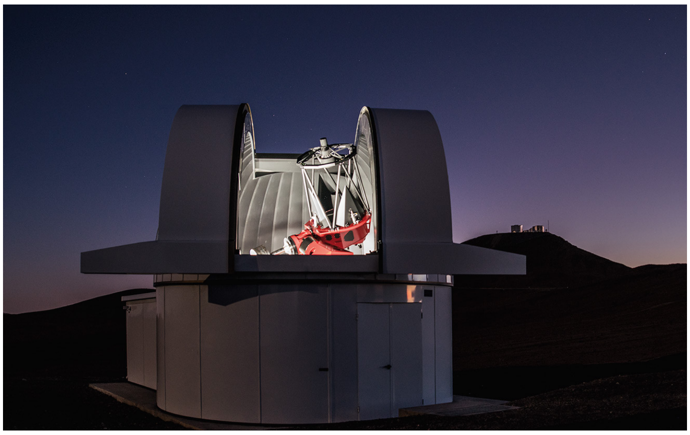

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Figure 5. The Io 1-metre robotic telescope unit in its 6.25-metre dome.

The cameras and filters

Each telescope is equipped with an Andor iKon-L thermoelectrically cooled camera with a near-infrared optimised, deep depletion 2k × 2k 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^{-1}. The camera can be cooled down to – 100° C (via five-stage Peltier cooling) but it is usually operated at – 60° C with a dark current of ~ 0.1 electrons s^{-1} pixel^{-1}. The detector provides high sensitivity from 350 nm (near-ultraviolet) to 950 nm (near-infrared), with a maximum quantum efficiency of 94% at both 420 and 740 nm. The camera also has very low fringing in the near-infrared (< 1%) thanks to both the wedge design of the window and the e2v proprietary fringe suppression technology applied to the detector. There are four readout speeds available, up to 5 MHz, with various gains. The observations at each telescope are performed using the same 1 MHz readout mode, no binning and a gain of about 1.1 electrons ADU^{-1}, which provides a low readout noise of about 6.0 electrons.

Each camera has its own filter wheel from Finger Lakes Instrumentation (model CFW3-10), allowing 10 different 5 × 5 cm filters. A selected set of broad-band filters, all manufactured by Astrodon company, is available on each telescope: the Sloan *g'r'i'z'* filters and two special exoplanet filters; the near-infrared luminance *I+z* filter (transmittance > 90% from 750 to beyond 1000 nm); and a blue-blocking filter called Exo (transmittance > 90% from 500 to beyond 1000 nm). Some of the telescopes also provide broad-band Johnson-Cousins *B*, R_C and *V* filters, the Sloan *u'* filter, and the Hα, S II and O III narrow-band filters.

A robotic and safe observatory

Building on the experience and operational scheme of TRAPPIST (Jehin et al., 2011, Gillon et al., 2011), the SSO is nearly fully robotic and can be controlled remotely via a secure Virtual Private Network (VPN) connection between Paranal and the University of Liège. Observing plans, consisting of simple text files (one for each target) linked to each other, are automatically generated and submitted daily by a scheduling script to the ACP Expert Observatory Control Software[4], which is installed on the control computer of each telescope unit. ACP is the main automation software working in combination with the various subsystems, and it automatically handles every aspect of the observations: startup and shutdown procedures (including flat fields and other calibrations), pointing and centring of the targets, autofocusing, filter wheel management, image setup and acquisition sequences, autoguiding via DONUTS, target chaining, and other operations.

ACP is also in charge of the shutdown of the observatory in case of bad weather. Each telescope unit is independent and is equipped with its own weather station[d], which monitors in real time the cloud cover, sky temperature, wind speed (≤ 50 km h^{-1}), humidity level (≤ 80%), dew point, and the amount of daylight. These weather stations also include a moisture sensor that is able to detect rain and snow. They are connected to ACP and can trigger a clean and automatic termination of observations (closing the dome and parking the telescope) in bad weather conditions. The weather stations are also directly wired to the domes for emergency closure in case ACP does not trigger it. In addition, each dome is equipped with rain and light sensors, working independently from the telescope control computer for redundant safety.

Several IP power sockets are connected to the electrical devices inside the domes to allow remote rebooting (or shutdown) when necessary. Each observatory unit is equipped with an uninterruptible power supply (UPS) that can hold each telescope in operation for about 8 hours. To guarantee safe and optimal operation, one operator initiates the startup procedure before twilight, making sure that

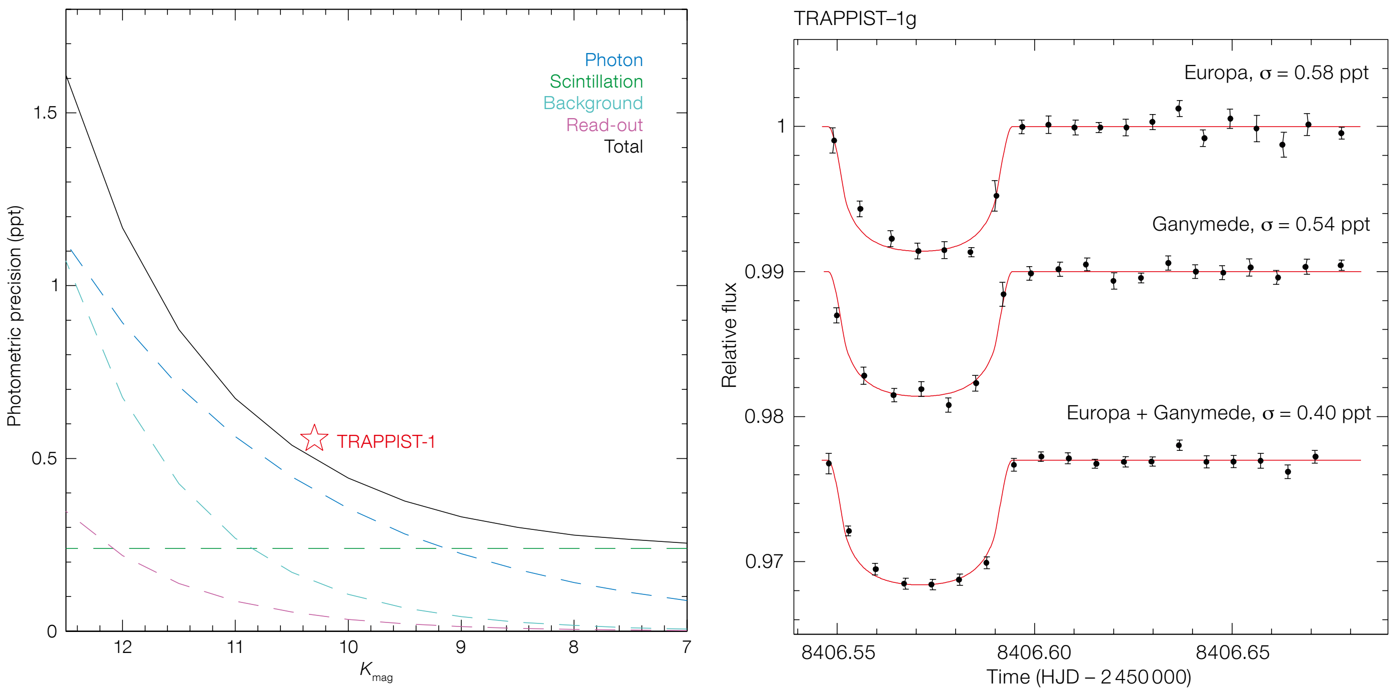

Figure 6. Left: Photometric errors per time bin of 0.005 d (7.2 minutes) computed for an M8-type dwarf observed by one SSO telescope as a function of its *K*-band magnitude. The different contributions to the errors are shown as dashed coloured lines. The photometric precision measured for TRAPPIST-1 is illustrated as a red star symbol. Right: Light curves, binned per 0.005 d, of a transit of the temperate terrestrial planet TRAPPIST-1g observed by Europa (top) and Ganymede (middle), and the combined light curve Europa + Ganymede (bottom).

the weather and telescopes are safe and in working condition after performing diagnostic checks. At the end of the night, the operator makes sure the telescopes are closed and secure. An operational webpage receives live information about the telescopes and the weather status as well as real-time images of the night sky and dome webcams. This setup allows us to easily keep an eye on the observatory.

Dataflow and pipeline

Each telescope generates between 250 and 1000 images per night with typical exposure times of 10–50 s, corresponding to between 4 and 16 Gb of data. The data are saved locally on a dedicated computer for each telescope and are initially processed by a local pipeline. The data are automatically transferred to the ESO archive and then retrieved to be processed by a dedicated pipeline which produces calibrated light curves that are then used to compute differential photometry for the target star.

In addition to producing a unique photometric database for a large sample of nearby UCDs, the SPECULOOS dataset is also valuable for the astronomical community, as it provides densely-sampled photometric monitoring over long periods (10–20 nights) over a total survey field of view of 24 square degrees with excellent spatial sampling in the near-infrared. By agreement with ESO, we will provide public access to the photometric data gathered with the SSO after a one-year proprietary period. Reduced images, as well as extracted light curves of all point-sources detected by our reduction pipeline, will be made available to the community via the ESO archive (under the programme ID 60.A-9009).

Photometric performances

Figure 6 shows the photometric precision expected for each SSO telescope for an integrated exposure of 7.2 minutes (7 exposures of 50 s + overheads) in the "*I*+*z*" filter for M8-type dwarfs with *K*-magnitudes covering the whole range of SPECULOOS targets. Uncertainties take into account the transparency of the sky at Paranal, mirror reflectivity, the quantum efficiency of the CCD cameras cooled to – 60° C, and the transmittance of the filter and of the CCD window. We assume pure white noise (photon noise, dark current, background, scintillation, and readout), an airmass of 1.5, a typical seeing of 1 arcsecond, and a photometric aperture of 2-arcsecond radius.

Figure 6 also shows a transit of TRAPPIST-1g observed by Europa and Ganymede. TRAPPIST-1g orbits around a $K = 10.3$ M8-type dwarf, and our photometric performance calculator predicts a precision of 0.51 ppt[e] for each total integration of 7.2 minutes. Our observed light curves, divided by the best-fit transit models and also binned by 7.2 minutes, have standard deviations of 0.58 and 0.54 ppt — only slightly larger than the predicted value and consistent with a correlated, "red-noise floor" of 0.2–0.30 ppt. Combining the two light curves reduces the standard deviation to 0.4 ppt, scaling by ~ $\sqrt{2}$ as expected. This impressive photometric precision validates the scientific potential of the SSO. Indeed, the transit of a temperate Earth-sized planet should be in the range 3.8–13.5 ppt, and should have a typical duration of 30 to 60 minutes. Figure 6 shows that our photometric precision is sufficient to robustly detect such transits for every star in our UCD sample, irrespective of atmospheric or instrumental red noise. For our brightest and smallest targets, we expect to be able to detect transits of planets as small as Mars (depth of ~ 3 ppt in front of a 0.08 $R_\odot$ star).

A global network of robotic telescopes

SPECULOOS will eventually consist of five nodes, with the SSO being the primary node. The other nodes are: the SPECULOOS Northern Observatory (SNO), which will consist of at least one 1-metre telescope to be installed in Spring 2019 at Teide Observatory in Tenerife (Canary Islands); SAINT-Ex, a new robotic 1-metre telescope that is being installed at San Pedro Mártir Observatory (Mexico), and which will partially contribute to SPECULOOS; and finally, the two 60-cm robotic telescopes TRAPPIST-South (La Silla Observatory, Chile) and TRAPPIST-North (Oukaïmeden Observatory, Morocco), which devote ~ 25% of their time to SPECULOOS, focusing on about 100 of the brightest targets.

The discovery of TRAPPIST-1

The SPECULOOS project started in 2011 as a pilot survey using TRAPPIST-South (Gillon et al., 2011), with a limited target list composed of the 50 brightest southern ultra-cool dwarf stars. The goal of this pilot was to assess the feasibility of the project, but the survey achieved much more than anticipated. It detected a spectacular planetary system that we named TRAPPIST-1[2], which is composed of seven Earth-sized planets in temperate orbits ranging from 1.5 to 19 days (Gillon et al., 2016, 2017). At least three of these planets orbit within the habitable zone of the star, and each of them is particularly well-suited for a detailed atmospheric study with JWST. Thanks to the resonant and transiting configuration of the system, the masses and radii of the planets could be precisely measured (Grimm et al., 2018; Delrez et al., 2018b). The resulting densities suggest that most of the planets have a rocky composition with a volatile content significantly larger than that of Earth.

The detection of TRAPPIST-1 from a target list of only 50 objects, and the apparently low densities of most of its planets, suggest that compact systems of water-rich rocky planets could be very frequent around UCD stars (He, Triaud & Gillon, 2017), in agreement with recent theoretical predictions. Should this be confirmed, it implies that SPECULOOS will find many other TRAPPIST-1-like systems, and eventually produce a catalogue of several dozen temperate rocky planets that are well suited for detailed atmospheric characterisation with the next generation of major astronomical facilities.

Acknowledgements

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Links

[1] The SPECULOOS project: http://www.speculoos.uliege.be/
[2] The TRAPPIST-1 planetary system: http://www.trappist.one/
[3] ASTELCO Systems: http://www.astelco.com/
[4] ACP observatory control software: http://acp.dc3.com/
[5] The TRAPPIST project: http://www.trappist.uliege.be/

Notes

[a] Since we expect the typical planetary systems around UCDs to be scaled-up versions of the Jovian satellite system (with terrestrial planets replacing the Galilean moons), we decided to name the four telescopes Io, Europa, Ganymede, and Callisto.
[b] Speculoos are also delicious cookies that are traditionally baked in Belgium for consumption around St Nicholas's day on 6 December.
[c] The coordinates of the site are: latitude −24°36′56.2″ and longitude −70°23′25.4″
[d] The Boltwood Cloud Sensor II from Diffraction Limited company
[e] ppt: part-per-thousand (i.e., 0.1%)