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 Earth-sized planets around these objects is drastically increased compared to Earth-Sun analogs. Furthermore, only a terrestrial planet transiting a nearby UCD would be amenable for a thorough atmospheric characterization, including the search for possible biosignatures, with near-future 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 SPECU-LOOS ground-based transit survey, that will search for Earth-sized planets transiting the nearest UCDs, as well as its prototype survey on the TRAPPIST telescopes. We conclude by discussing the prospects offered by the recent detection by this proto-

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type survey of a system of seven temperate Earth-sized planets transiting a nearby UCD, TRAPPIST-1.

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 three thousand of such exoplanets have been detected at an ever increasing rate (Schneider et al. 2011; Han et al. 2014). The present exoplanets 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 giant 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 the 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 most promising facility for such atmospheric characterizations. All these studies agree on the fact that the best suitable target for biosignatures detection would be an 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 Earthsized exoplanets, allowing us to detect and study in great depth such small planets.

What are ultracool dwarfs?

UCDs are traditionally defined as dwarf stars and brown dwarfs having effective temperatures $T_{eff} < 2700$ K, luminosities $L \le 10^{-3}$ 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 (H₂O, CO, TiO, VO, CH₄, NH₃, CaH, 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_☉, 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/cm³ (Burrows and Liebert 1993). These dense interiors may sample 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 20 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 $T_{\rm eff}\approx250~{\rm K}$ 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 $M_{\odot} < {\rm mass} < 0.5 ~{\rm M}_{\odot}$), but are more abundant than solar-type FGK stars in the immediate solar neighbourhood (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 $T_{\rm eff}$ reduce 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 hours and rotational vsini measurements as high as 80 km/s (Blake et al. 2010; Metchev et al. 2015).

Ultracool dwarfs and planets

Despite 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 Earthsized planets of TRAPPIST-1 (Gillon et al. 2017, see below), the $\sim 3 \, \mathrm{M_E}$ planet MOA-2007-BLG-192Lb and $\sim 1.3~M_{\rm E}$ planet OGLE-2016-BLG-1195Lb detected by microlensing around a distant UCD stars (Kubas et al. 2012; Shvartzvald et al. 2017). This microlensing planets are very interesting, because it demonstrates that UCDs can form planets more massive than the Earth, despite the low mass of their protoplanetary discs. 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 ~ 50 UCDs targeted by the SPECU-LOOS 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_⊕ is lower than $67 \pm 1\%$.

These planet detections are consistent with the growing observational evidence that young UCDs are commonly surrounded by protoplanetary discs (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 pre-planetary formation: evidence of disc accretion, circumstellar disc 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).

Nearly unconstrained 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 discs 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 one 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, the 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 Earthsized planets transiting putative M0 to 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 \sim L2.5, Dieterich et al. 2014). The numbers of UCD stars in the close solar neighbourhood (< 8 pc) are well known (e.g. Reid et al. 2008, 2007), 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 Earthsized 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-size 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). Secondly, 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 (Search for habitable Planets EClipsing ULtra-cOOl Stars). The project is led by the University of Liège (Belgium) in collaboration with the Cavendish Laboratory of the University of Cambridge (UK) and the King Abdulaziz University (Saudi Arabia).

The SPECULOOS Southern Observatory

We decided to initiate SPECULOOS first in the southern hemisphere, with a facility composed of four robotic Ritchey-Chretien (F/8) telescopes of 1-m diameter (see Fig. 1) currently being installed at ESO Paranal Observatory in the Chilean Atacama desert. The name of this facility is the SPECULOOS Southern Observatory¹. Each telescope is equipped with an Andor Peltier-cooled deeply depleted 2K × 2K CCD camera with a 13.5 μ m pixel size. The field of view of each telescope is 12 $^{\prime}$ × 12 $^{\prime}$ and the corresponding pixel scale is 0.35". This set-up is optimized to observe, in good seeing conditions (median seeing < 1.2''), with optimal sensitivity in the verynear-IR (700 to 1000 nm), UCDs with J-magnitude up to 14, and to obtain for them light curves with 0.1% photometric precisions for a few minutes sampling times. In survey operations, each telescope will observe continuously one target during an average period of 10 nights (fine-tuned as a function of the spectral type). This duration of the observation sequence is optimized to explore efficiently the HZ of UCDs for transiting planets. To observe 500 targets in the southern hemisphere, a total of 12000 nights are needed, what can be done in 5 years considering realistic observations with four telescopes. All four telescopes are expected to be operation by the end of 2017.

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 the whole night. This continuous monitoring optimizes the capacity to detect 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 prolongating 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

¹ https://www.eso.org/public/teles-instr/paranal-observatory/speculoos/



Fig. 1 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.

wavelengths, to assess the achromaticity of the eclipses and confirm their planetary origins (Gillon et al. 2016).

We are currently preparing a northern counterpart to the SPECULOOS Southern Observatory which should be operational in 2019. Its location is not decided yet.

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 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 it 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 precisions. 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 in the Atacama Desert in Chile (see Fig. 2). It is equipped with a near-IR optimized $2K \times 2K$ CCD camera with a 0.64 "/pixel scale, offering excellent quantum efficiencies from 300 to > 900 nm. This SPECULOOS prototype survey targets 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 is to monitor in a wide near-IR filter (transmission > 90% from 720 nm) each UCD during at least 100 hours 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.



Fig. 2 Left. The dome of the TRAPPIST-South telescope at ESO La Silla Observatory (Chile). **Right.** TRAPPIST-South telescope. Credit: E. Jehin.

Since mid-2016 a northern extension of the prototype survey for SPECULOOS is 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 sudden increase of a few percents of the measured brightness, followed by a gradual decrease back or close to the normal level. The whole process takes only 10 to 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 \sim 9.5 hours (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 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, low humidity). This conclusion was recently strengthened by our detection of Earth-sized exoplanets transiting one of the TRAPPIST-South UCD target, 2MASS J23062928-0502285 (TRAPPIST-1, Gillon et al. 2016, 2017). The detection - and even the very existence - of this planetary system fully demonstrates the instrumental concept and the scientific potential of SPECULOOS.

The TRAPPIST-1 planetary system

The TRAPPIST-1 planetary system is composed of at least seven planets with sizes and initial mass estimates similar to the Earth transiting an UCD star 39 light-years away (Gillon et al. 2017). The host star is a moderately active M8 \pm 0.5 dwarf star (V=18.80, R=16.47, I=14.02, J=11.35, K=10.30). Its mass, radius and temperature are estimated to be 0.0802 \pm 0.0073 M_{\odot} , 0.117 \pm 0.0036 R_{\odot} , and 2559 \pm 50 K, respectively. Fig. 3a shows the transit light curves of the planets as observed at 4.5 μ by Spitzer, while a representation of their orbits is shown in Fig. 3b. These seven planets form a unique near-resonant chain such that their orbital periods (1.51, 2.42, 4.04, 6.06, 9.21, 12.35 and 18.76 days) are near-ratios of small integers (Gillon et al. 2017; Luger et al. 2017). Transit Time Variation (TTV) signals from a few tens of seconds to more than 30 minutes indicate significant mutual interactions between the planets (Agol et al. 2005; Holman and Murray 2005; Fabrycky 2010). By analysing TTV signals, we could determine initial mass estimates for the six inner planets, along with upper limits on their orbital eccentricities (e < 0.085).

As shown in Fig. 4a, the stellar irradiations of the planets cover a range from \sim 4.3 to \sim 0.14 S_E (S_E = Solar irradiation at 1 au), which is very similar to the range seen in the inner Solar System (Mercury = 6.7 S_E, Ceres = 0.13 S_E). The equilibrium temperature of the outermost detected planet, TRAPPIST-1h, is 170 K (assuming

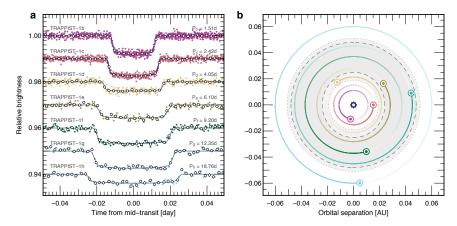


Fig. 3 Panel a. Period-folded transit light curves for the seven planets of TRAPPIST-1, resulting from the nearly-continuous observation of the star by the Spitzer space telescope from 19 September to 10 October 2016. The individual transits were corrected for the measured TTVs to produce this figure. Coloured dots show the unbinned measurements, whereas the open circles depict binned measurements for visual clarity. The 1-sigma error bars of the binned measurements are shown as vertical lines. The best-fit transit models are shown as coloured lines. **Panel b.** Representation of the orbits of the 7 planets. The same colour code as in panel a is used to identify the planets. The grey annulus and the two dashed lines represent the habitable zone of the star based on different theoretical assumptions (see Gillon et al. 2017 and Luger et al. 2017 for details).

a null albedo), placing it at the snow line of the system (Luger et al. 2017). The derived planets' orbital inclinations are all very close to 90°, indicating a dramatically coplanar system seen nearly edge-on. This architecture, combined with the fact that the planets form a near-resonant chain, suggests that they formed farther from the star and migrated inward through interactions with the disc (e.g. Cresswell and Nelson 2006; Papaloizou and Szuszkiewicz 2005; Terquem and Papaloizou 2007). Planets TRAPPIST-1e, f, and g are firmly in the HZ of the star (as estimated following Kopparapu et al. 2013, see Fig. 3b). They are thus prime targets for the search of potential atmospheric biosignatures with the next generation of telescopes and instruments.

Characterization of TRAPPIST-1 planets: present and future

The transiting configuration of the TRAPPIST-1 planets, combined with the small size (0.12 R_{\odot}), low luminosity (0.0005 L_{\odot}), and infrared brightness (K = 10.3) of their host star, provides the extraordinary opportunity to thoroughly study their atmospheric properties with present-day and future astronomical facilities. Our *a priori* knowledge about their atmospheric compositions is very limited as they are the first transiting planets detected around a UCD. Theoretical predictions span the entire atmospheric range, from extended H/He-dominated to depleted atmospheres

(Owen and Wu 2013; Jin et al. 2014; Johnstone et al. 2015; Luger and Barnes 2015; Leconte et al. 2015; Owen and Mohanty 2016). A cloud-free H/He-dominated atmosphere should yield prominent spectroscopic signatures of H₂O and/or CH₄ in the near-infrared, readily detectable with current space-based instrumentation through transit transmission spectroscopy. Reconnaissance observations of the innermost planets b and c during transit conjunction with HST/WFC3 ruled out this scenario for these two planets (de Wit et al. 2016), but still allow for many cloudy and/or denser atmospheres, such as H₂O-, N₂-, or CO₂-dominated atmospheres. Similar observations have been obtained to assess the atmospheres of planets d, e, f, and g as well (de Wit et al. submitted). Further spectroscopic transmission observations of the TRAPPIST-1 planets in the infrared will allow for progressively higher mean molecular weight atmospheres to be probed, before their in-depth characterization with JWST (Barstow and Irwin 2016) and the next-generation of ground-based extremely large telescopes (E-ELT, GMT, and TMT).

Efforts are also ongoing to characterize the high-energy radiation environment of the planets, which is a key factor in assessing their atmospheric stability and potential habitability. XMM-Newton observations showed that TRAPPIST-1 is a relatively strong and variable coronal X-ray source with an X-ray luminosity similar to that of the quiet Sun, despite a much lower bolometric luminosity (Wheatley et al. 2017). The Ly- α line of TRAPPIST-1 was also recently measured using HST/STIS and was found to be much fainter than expected from the X-ray emission, which may suggest that TRAPPIST-1 chromosphere is moderately active compared to its transition region and corona (Bourrier et al. 2017). Still, TRAPPIST-1 Ly- α line is bright enough to perform transit spectroscopy and search for signatures of planetary hydrogen escape. Hydrogen exospheres could indicate the presence of water-vapor being photo-dissociated in the upper atmospheres and replenished by evaporating water oceans, thus hinting at large water reservoirs on the planets (Jura 2004). Theoretical models predict that the total XUV irradiation derived from the XMM-Newton and HST/STIS data could be strong enough to strip Earth-like atmospheres and oceans from planets b and c in approximately 1 and 3 Gyr, while the same process would take between 5 and 22 Gyr for planets d to g (Bolmont et al. 2017; Bourrier et al. 2017). However, the observed high-energy fluxes are highly variable and these first observations may not provide a complete picture of the highenergy radiation environment of the TRAPPIST-1 planets, making it necessary to gather additional measurements.

Precise mass determinations and the resulting constraints on their compositions (e.g. Zeng et al. 2016) are critical for a thorough understanding of these planets, as well as for the optimal exploitation of future atmospheric observations (de Wit and Seager 2013). Assessment of the planets' potential habitability makes it also necessary to measure their orbital eccentricities, to constrain the impact of tidal heating on their total energy budget, but also on their geological activity that could be able to counterbalance atmospheric erosion through volcanism. The current mass estimates for the six inner planets broadly suggest rocky compositions (see Fig. 4b), but are at present too uncertain to constrain the fraction of volatiles in the planets' compositions, except for planet f, whose low density suggests a volatile-rich composition.

We also find small but non-zero eccentricities, resulting in significant tidal heating: all planets except f and h have a tidal heat flux higher than Earth's total heat flux (Luger et al. 2017). However, this global dynamical solution is preliminary and may not correspond to a global minimum of the parameter space, as several solutions fit equally well our currently limited dataset. Additional precise transit timings for all seven planets will be key in constraining further the planet masses and eccentricities and in isolating a unique, well defined, dynamical solution.

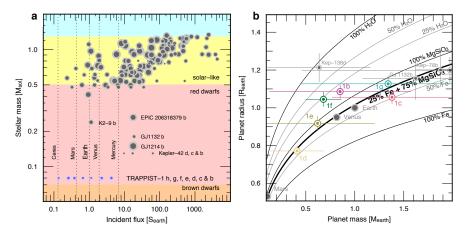


Fig. 4 Panel a. Masses of host stars and incident fluxes of known sub-Neptune-sized exoplanets. The size of the symbols scales linearly with the radius of the planet. The background is colour-coded according to stellar mass (in units of the Sun's mass). The TRAPPIST-1 planets, shown in blue, are at the boundary between planets associated with hydrogen-burning stars and planets associated with brown dwarfs. The positions of the Solar System terrestrial planets and Ceres are shown for reference. Only the exoplanets with a measured radius equal to or smaller than that of GJ 1214b are included. **Panel b.** Mass-radius diagram for terrestrial planets. The coloured circular symbols with error bars represent the TRAPPIST-1 planets. The solid lines are theoretical mass-radius curves for planets with different compositions from Zeng et al. (2016). Figure from Gillon et al. (2017).

The TRAPPIST-1 system is a rich laboratory for exploring the factors relevant to exoplanet habitability and a blueprint for investigations of the many planetary systems expected to be found by SPECULOOS. Observations of these systems with JWST and other upcoming facilities will open the era of detailed characterization of temperate terrestrial planets, and will provide us with first opportunities to detect chemical traces of life beyond our Solar System.

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