Temperate Earth–sized planets transiting a nearby ultracool dwarf star

Michaël Gillon1, Emmanuel Jehin1, Susan M. Lederer2, Laetitia Delrez1, Julien de Wit3, Artem Burdanov4, Valérie Van Grootel1, Adam J. Burgasser5, Amaury H. M. J. Triaud5, Cyrielle Opitom1, Brice–Olivier Demory6, Devendra K. Sahu7, Daniella Bardalez Gagliuffi4, Pierre Magain1 & Didier Queloz6

TRAPPIST7,8 (the TRansiting Planets and PlanetIsimsals Small Telescope) monitored the brightness of the star TRAPPIST-1 (2MASS J23062298 — 0502285) in the very-near infrared (roughly 0.9 μm) at high cadence (approximately 1.2 minutes) for 245 hours over 62 nights from 17 September to 28 December 2015. The resulting light curves show 11 clear transit-like signatures with amplitudes close to 1% (Extended Data Figs 1, 2). Photometric follow-up observations were carried out in the visible range with the Himalayan Chandra 2-metre Telescope (HCT) in India, and in the infrared range with the 8-metre Very Large Telescope (VLT) in Chile and the 3.8-metre UK Infrared Telescope (UKIRT) in Hawaii. These extensive data show that nine of the detected signatures can be attributed to two planets, TRAPPIST-1b and TRAPPIST-1c, transiting the star every 1.51 days and 2.42 days, respectively (Fig. 1a, b). We attribute the two additional transit signals to a third transiting planet, TRAPPIST-1d, with which we predict the periodicity of the transits of TRAPPIST-1b and TRAPPIST-1c, and the achromaticity of the transits of TRAPPIST-1b as observed from 0.85 μm (HCT) to 2.09 μm (VLT) (Fig. 1a); and second, the agreement between the stellar density measured from the transit light curves, 49.34 ± 4.10 with the density inferred from the stellar properties, (55.3 ± 12.1)ρ⊙ (where ρ⊙ is the density of the Sun).

The masses of the planets, and thus their compositions, remain unconstrained by these observations. The results of planetary thermal evolution models—and the intense extreme-ultraviolet (1–1 000 Å) emission of low-mass stars18—during their early lives make it unlikely that such small planets would have thick envelopes of hydrogen and/or helium gases19. Statistical analyses of sub-Neptune-sized planets detected by the Kepler spacecraft indicate that most Earth-sized planets in close orbit around solar-type stars are rocky20,21. Nonetheless, the paucity of material in the inner region of the protoplanetary disk of an ultracool dwarf would seem to challenge the idea of rocky planets the size of Earth6, favouring instead compositions dominated by ice-rich material originating from beyond the ice line2. Confirming this hypothesis will require precise mass measurements.

1Institut d’Astrophysique et de Géophysique, Université de Liège, Allée du 6 Août 19C, 4000 Liège, Belgium. 2NASA Johnson Space Center, 2101 NASA Parkway, Houston, Texas, 77058, USA. 3Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA. 4Center for Astrophysics and Space Science, University of California San Diego, La Jolla, California 92093, USA. 5Institute of Astronomy, Madingley Road, Cambridge CB3 OHA, UK. 6Astrophysics Group, Cavendish Laboratory, 19 J J Thomson Avenue, Cambridge, CB3 OHE, UK. 7Indian Institute of Astrophysics, Koramangala, Bangalore 560 034, India.

© 2016 Macmillan Publishers Limited. All rights reserved.

LETTER

DOI:10.1038/nature17448

12 MAY 2016 | VOL 533 | NATURE | 221

© 2016 Macmillan Publishers Limited. All rights reserved.
measuring the transit timing variations (TTVs) caused by their planets. Alternatively, the planets’ masses could be constrained by Doppler signatures (of one-half to a few metres per second) of the high-precision infrared velocimeters able to measure the low-amplitude silicates and ice\textsuperscript{22}. This should be made possible by next-generation, UKIRT; HAWK-I, high acuity wide field K-band imager on the VLT.

Figure 1 | Transit photometry of the TRAPPIST-1 planets. Each light curve is phased to the time of inferior conjunction (mid-transit time) of the object. The light curves are binned in two-minute intervals for planet TRAPPIST-1b (a), and in five-minute intervals for planets TRAPPIST-1c (b) and TRAPPIST-1d (c). The best-fit transit models, as derived from a global analysis of the data, are overplotted (red lines). The light curves are shifted along the y axis for the sake of clarity. For the HCT/Hanle faint object spectrograph camera (HFOSC) light curve, the data are unbinned and the error bars are the formal measurement errors. For the other light curves, the error bars are the standard errors of the mean of the measurements in the bin. WFCAM, wide-field infrared camera on the UKIRT; HAWK-I, high acuity wide field K-band imager on the VLT.

Figure 2 | Masses of host stars and equilibrium temperatures 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 are at the boundary between planets associated with hydrogen-burning stars and planets associated with brown dwarfs. Equilibrium temperatures are estimated neglecting atmospheric effects and assuming an Earth-like albedo of 0.3. The positions of the Solar System terrestrial planets are shown for reference. The range of possible equilibrium temperatures of TRAPPIST-1d is represented by a solid bar; the dot indicates the most likely temperature. Only the exoplanets with a measured radius equal to or smaller than that of GJ 1214b are included.

so as to break the degeneracy between the relative amounts of iron, silicates and ice\textsuperscript{22}. This should be made possible by next-generation, high-precision infrared velocimeters able to measure the low-amplitude Doppler signatures (of one-half to a few metres per second) of the planets. Alternatively, the planets’ masses could be constrained by measuring the transit timing variations (TTVs) caused by their mutual gravitational interactions\textsuperscript{23}, or by transit transmission spectroscopy\textsuperscript{24}.

Given their short orbital distances, it is likely that the planets are tidally locked—that is, that their rotations have been synchronized with their orbits by tidal interactions with the host star\textsuperscript{25}. Planets TRAPPIST-1b and TRAPPIST-1c are not in the host star’s habitable zone\textsuperscript{8} (within 0.024 to 0.049 astronomical units (au) of the star, as defined by one-dimensional models that are not adequate for modelling the highly asymmetric climate of tidally locked planets\textsuperscript{26}). However, they have low enough equilibrium temperatures that they might have habitable regions—in particular, at the western terminators of their day sides\textsuperscript{27} (Fig. 2 and Table 1). The main concern regarding localized habitability on tidally locked planets relates to the trapping of atmosphere and/or water on their night sides\textsuperscript{26}. Nevertheless, the relatively large equilibrium temperatures of TRAPPIST-1b and TRAPPIST-1c would probably prevent such trapping\textsuperscript{27}. In contrast, TRAPPIST-1d orbits within or beyond the habitable zone of the star, its most likely periods corresponding to semi-major axes of between 0.033 au and 0.093 au. We estimate tidal circularization timescales for TRAPPIST-1d (unlike for the two inner planets) to be more than 1 billion years (see ‘Dynamics of the system’ in Methods). Tidal heating due to a non-zero orbital eccentricity could thus have a significant influence on the global energy budget and potential habitability of this planet\textsuperscript{28}.

The planets’ atmospheric properties, and thus their habitability, will depend on several unknown factors. These include the planets’ compositions; their formation and dynamical history (their migration and tides); the past evolution and present level of the extreme-ultraviolet stellar flux\textsuperscript{29} (probably strong enough in the past, and perhaps even now, to significantly alter the planets’ atmospheric compositions\textsuperscript{29});
Table 1 | Properties of the TRAPPIST-1 planetary system

| Parameter | TRAPPIST-1b | TRAPPIST-1c | TRAPPIST-1d |
|-----------|-------------|-------------|-------------|
| Star       | TRAPPIST-1  = 2MASS J23062928 - 0502285 | TRAPPIST-1  = 2MASS J23062928 - 0502285 | TRAPPIST-1  = 2MASS J23062928 - 0502285 |
| Magnitudes | V = 18.80 ± 0.08, R = 16.47 ± 0.07, I = 14.0 ± 0.1, J = 11.35 ± 0.02, K = 10.30 ± 0.02 | V = 18.80 ± 0.08, R = 16.47 ± 0.07, I = 14.0 ± 0.1, J = 11.35 ± 0.02, K = 10.30 ± 0.02 |
| Distance, d | 12.1 ± 0.4 parsecs (ref. 12) | 12.1 ± 0.4 parsecs (ref. 12) | 12.1 ± 0.4 parsecs (ref. 12) |
| Luminosity, L | (0.000525 ± 0.000036)L☉ (ref. 13) | (0.000525 ± 0.000036)L☉ (ref. 13) | (0.000525 ± 0.000036)L☉ (ref. 13) |
| Mass, M | (0.080 ± 0.009)M☉ | (0.080 ± 0.009)M☉ | (0.080 ± 0.009)M☉ |
| Radius, R | (0.117 ± 0.004)R☉ | (0.117 ± 0.004)R☉ | (0.117 ± 0.004)R☉ |
| Density, ρ | 50.3 ± 7.9ρ☉ | 50.3 ± 7.9ρ☉ | 50.3 ± 7.9ρ☉ |
| Effective temperature, T eff | 2,550 ± 55 K | 2,550 ± 55 K | 2,550 ± 55 K |
| Metallicity, [Fe/H] | +0.04 ± 0.08 (from near-infrared spectroscopy) | +0.04 ± 0.08 (from near-infrared spectroscopy) | +0.04 ± 0.08 (from near-infrared spectroscopy) |
| Rotation period, P rot | 1.40 ± 0.05 days (from TRAPPIST photometry) | 1.40 ± 0.05 days (from TRAPPIST photometry) | 1.40 ± 0.05 days (from TRAPPIST photometry) |

The values and 1σ errors given for the planetary parameters and for the stellar mass (M*), radius (R*), density (ρ*), and effective temperature (T eff) were deduced from a global analysis of the photometric data, including a priori knowledge of the stellar properties (see Methods). BJD2058, barycentric Julian date in the barycentric dynamical time standard. Lm, Mr, Rm, and ρm are, respectively, the luminosity, mass, radius and density of the Sun. R* and S* are, respectively, the radius and irradiation of the planet. R* and S* are, respectively, the radius and irradiation of Earth.

*These are the potential orbital periods of TRAPPIST-1d, derived from non-continuous observations. The value in bold type is the most likely value for the period, as derived from the shape of the transits.

†Values calculated on the basis that P = 18.20175 ± 0.00045 days.

‡The ranges allowed by the set of possible periods.

and the past and present amplitudes of atmospheric replenishment mechanisms (impacts and volcanism). Fortunately, the TRAPPIST-1 planets are particularly well suited for detailed atmospheric characterization—notably by transmission spectroscopy (Fig. 3)—because transit signals are inversely proportional to the square of the host-star radius, the latter being only around 12% of that of the Sun for TRAPPIST-1. Data obtained by the Hubble Space Telescope should provide initial constraints on the extent and composition of the planets’ atmospheres. The next generation of observatories will then allow far more in-depth exploration of the atmospheric properties. In particular, data from the James Webb Space Telescope should yield strong constraints on atmospheric temperatures and on the abundances of molecules with large absorption bands including several potential biomarkers such as water, carbon dioxide, methane and ozone.

Figure 3 | Potential for characterizing the atmospheres of known transiting sub-Neptune-sized exoplanets. The signal being transmitted from each planet is estimated in parts per million (p.p.m.) and for transparent water-dominated atmospheres with a mean molecular weight, μ, of 19. The signal-to-noise ratio (SNR) in transmission (normalized to that of GJ 1214b under the same atmospheric assumptions) is also calculated. The estimated signal and SNR are plotted against equilibrium temperatures, assuming a Bond albedo of 0.3. The black horizontal bar indicates the SNR that will require 200 (or 500) (or 1,000) hours of in-transit observations with the James Webb Space Telescope to yield a planet’s atmospheric temperature with a relative uncertainty below 15% and with abundances within a factor of four in the case of a H2O (or N2) [or CO2]-dominated atmosphere (μ = 19 (or 28) (or 39)). Only the exoplanets with a measured radius equal to or smaller than that of GJ 1214b are included in the figure. The size of the circular symbol for each planet is proportional to the planet’s physical size. For illustration, symbols for planets of one (R⊕) and two (2R⊕) Earth radii are shown at the top right.
1. Kirkpatrick, J. D., Henry, T. J. & Simon, D. A. The solar neighborhood. II. The first list of dwarfs with spectral types of M7 and cooler. Astron. J. 109, 797–807 (1995).

2. Cantrell, J. R., Henry, T. J. & White, R. J. The solar neighborhood XXVI: the habitable real estate of our nearest stellar neighbors. Astron. J. 146, 99 (2013).

3. Andrews, S. M., Wilner, D. J., Hugues, A. M., Qi, C. & Dullemond, C. P. Protoplanetary disk structures in Ori. II. Extension to fainter sources. Astrophys. J. 723, 1241–1254 (2010).

4. Liu, Y., Jorgens, V., Bayo, A., Nielbock, M. & Wang, H. A homogeneous analysis of disk around brown dwarfs. Astron. Astrophys. 582, A22 (2015).

5. Payne, M. J. & Lodato, G. The potential for Earth-mass planet formation around brown dwarfs. Mon. Not. R. Astron. Soc. 381, 1597–1606 (2007).

6. Raymond, S. N., Scalo, J. & Meadows, V. S. A decreased probability of habitable planet formation around low-mass stars. Astrophys. J. 669, 606–614 (2007).

7. Montgomery, R. & Laughlin, G. Formation and detection of Earth-mass planets around low mass stars. Icarus 202, 1–11 (2009).

8. Kopparapu, R. K. et al. Habitable zones around main-sequence stars: new estimates. Astrophys. J. 765, 131 (2013).

9. Gillon, M. et al. TRAPPIST: a robotic telescope dedicated to the study of planetary systems. EPL Web Conf. 11, 06002 (2011).

10. Gillon, M., Jehin, E., Furet, A., Magain, P. & Queloz, D. TRAPPIST-UCDTS: a prototype search for habitable planets transiting ultra-cool stars. EPL Web Conf. 47, 03001 (2013).

11. Liebert, J. & Gizis, J. E. RI photometry of 2MASS-selected late M and L dwarfs. Publ. Astron. Soc. Pacif. 118, 659–670 (2006).

12. Costa, E. et al. The solar neighborhood. XVI. Parallaxes from CTIOPI: final results from the 1.5m telescope program. Astron. J. 132, 1234–1247 (2006).

13. Filippazzo, J. C. et al. Fundamental parameters and spectral energy distributions of young and field age objects with masses spanning the stellar to planetary regime. Astrophys. J. 810, 138 (2015).

14. Gillon, M. et al. The TRAPPIST survey of southern transiting planets. I. Thirty eclipses of the ultra-short period planet WASP-43 b. Astron. Astrophys. 542, A4 (2012).

15. Reiners, A. & Basri, G. A volume-limited sample of 63 M7–M9.5 dwarfs. Mon. Not. R. Astron. Soc. 431, 2063–2079 (2013).

16. Leconte, J. et al. Fundamental parameters and spectral energy distributions of young and field age objects with masses spanning the stellar to planetary regime. Astrophys. J. 810, 138 (2015).

17. Lopez, M. et al. The ultraviolet radiation environment around M dwarf planet host stars. Astrophys. J. 763, 149 (2013).

18. Tian, F. & Ida, S. Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper. Nature Geosci. 8, 177–180 (2015).

Acknowledgements TRAPPIST is funded by the Belgian Fund for Scientific Research (FRS–FNRS) under grant FFC 2.5.944.09.F, with the participation of the Swiss Fund for Scientific Research. The research leading to our results was funded in part by the European Research Council (ERC) under the FP/2007-2013 Grant Agreement 266484. The research leading to our results was supported in part by NASA under contract NNX15GA75G. UKIRT is supported by NASA and operated under an agreement among the University of Hawaii, the University of Arizona, and Lockheed Martin Advanced Technology Center; operations are enabled through the cooperation of the East Asian Observatory. The facilities at the Indian Astronomical Observatory (IAO) and the Consortium for Research Excellence, Support and Training (CREST) are operated by the Indian Institute of Astrophysics, Bangalore. M.G., E.J. and V.V.G. are FRS–FNRS research associates. L.D. and C.O. are FRS–FNRS PhD students. We thank V. Mégervand, the ASTELCO telescope team, S. Sohy, V. Chantry, and A. Furet for their contributions to the TRAPPIST project; the Infrared Telescope Facility (IRTF) operators B. Cabrera and D. Griep for assistance with the SpeX observations; UKIRT staff scientists W. Varricatt & T. Kerr; telescope operators S. Benigni, E. Moore and T. Carroll, and Cambridge Astronomy Survey Unit (CASU) scientists G. Madsen and M. Irwin for assistance with UKIRT observations; the European Southern Observatory (ESO) astronomers A. Smette and G. Hau for providing us with the best possible VLTI data; and the staff of IAO (in Hanle) and CREST (in Hosakote) for making observations with the HCT possible. Ad.B. and D.B.G. are visiting astronomers at the IRTF, which is operated by the University of Hawaii under Cooperative Agreement NNX08BAE38A with NASA’s Science Mission Directorate, Planetary Astronomy Program.

Author Contributions The TRAPPIST team (M.G., E.J., L.D., A.B., C.O. and P.M.) discovered the planets. M.G. leads the exoplanet program of TRAPPIST, set up and organized the ultra-cool dwarf transit survey, planned and analysed part of the observations, led their scientific exploitation, and wrote most of the manuscript. E.J. manages the maintenance and operations of the TRAPPIST telescope. S.M.L. obtained the director’s discretionary time on UKIRT, and managed, with E.J., the preparation of the UKIRT observations. L.D. and C.O. scheduled and carried out some of the TRAPPIST observations. L.D. and A.B. analysed some photometric observations. J.d.W. led the study of the amenability of the planets for detailed atmospheric characterization. V.V.G. checked the physical parameters of the star. A.I.B. checked the spectral type of the star and determined its metallicity. B.-O.D. took charge of the dynamical simulations. D.B.G. acquired the SpeX spectra. D.K.S. gathered the HCT observations. S.M.L., A.H.M.J.T., P.M. and D.Q. helped to write the manuscript. A.H.M.J.T. prepared most of the figures.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to M.G. (michael.gillon@ulg.ac.be).
J2000 equatorial coordinates of TRAPPIST-1 in the 2015 TRAPPIST images, and from space with the Hubble Space Telescope discarded the existence of a companion down to an angular distance of 0.1, suggesting that the object is not a very young brown dwarf, but rather a very-low-mass main-sequence star. This is in agreement with its thick disk kinematics, its relatively slow rotation (projected rotational velocity $v_{\text{sin}i} = 6.2 \pm 1.5 \text{ km s}^{-1}$), its moderate activity, and its reported photometric stability, all of which point to an age of at least 500 Myr (ref. 13).

### Metallcity of the star.

We obtained new, near-infrared (0.9–2.5 μm) spectrographic data for TRAPPIST-1 with the SpeX spectrograph on the night of 18 November 2015 (universal time), during clear conditions and 0.8″ seeing at K-band. We used the cross-dispersed mode and 0.3″ × 15″ slit, aligned at the parallactic angle, to acquire moderate-resolution data ($\lambda/\Delta \lambda \approx 2,000$) with a dispersion of 3.6 Å per pixel, covering the spectral range 0.9–2.5 μm in seven orders. Ten exposures each of 300 seconds were obtained over an air mass ranging from 1.14 to 1.17, followed by observations of the A0V star 67Aqr ($V = 6.41$) at an air mass of 1.19 for telluric and flux calibration, as well as internal lamp exposures. Data were reduced using the SpeXtool package version 4.04 (refs 37, 38). The reduced spectrum has a median signal-to-noise ratio of 300 in the 2.17–2.35 μm region (see Extended Data Fig. 3b; the metallicity-sensitive atomic features of NaI (2.266 μm, 2.209 μm) and CaI (2.61 μm, 2.626 μm, 2.266 μm) are labelled). We measured the equivalent widths of these features and the H$_2$O–K$_2$ index (defined in ref. 39), and used the mid- and late-M dwarf metallicity calibration of ref. 40 to determine [Fe/H] = 0.04 ± 0.02 (measurement) ± 0.07 (systematic) for TRAPPIST-1. The quadratic sum of the two errors resulted in our final value for [Fe/H] of 0.04 ± 0.08.

### Possible binary nature of the star.

High-resolution imaging from the ground and space with the Hubble Space Telescope discarded the existence of a companion down to an angular distance of 0.1″, corresponding to a projected physical distance of 12.2 au at 12 parsecs, and in good agreement with the reported stability of the radial velocity of the star at the ~10 ms$^{-1}$ level over one week, and at the ~150 ms$^{-1}$ level over about ten weeks. We performed spectral binary template fitting to the IRTF/SpeX spectroscopy, and statistically reject the presence of an L- or T-type brown dwarf companion that would be visible in a blended-SpeX spectrum. TRAPPIST-1 can thus, in all probability, be considered to be an isolated star.

### Upper magnitude limits on a background eclipsing binary.

We measured the J2000 equatorial coordinates of TRAPPIST-1 in the 2015 TRAPPIST images, using 29 stars from the UCAC2 catalogue and the Pulkovo Observatory

---

© 2016 Macmillan Publishers Limited. All rights reserved
represent the other astrophysical and instrumental mechanisms able to produce photometric variations. Assuming the same baseline model for all light curves, and minimizing the Bayesian information criterion (BIC)16, we selected a second-order time polynomial as a baseline model to represent the curvature of the light curves due to the differential extinction and the low-frequency variability of the star, and added an instrumental model composed of a second-order polynomial function of the positions and widths of the stellar images.

Stellar metallicity, effective temperature, mass and radius were four free parameters in the MCMC for which prior probability distribution functions (PDFs) were selected as input. Here, the normal distributions $N(0.04, 0.08^2)$ dex, $N(2.555, 85^2)$ K, $N(0.082, 0.011^2)M_☉$ and $N(0.116, 0.006^2)R_☉$ were assumed on the basis of a priori knowledge of the stellar properties (see the section on ‘Basic parameters of the star’). Circular orbits were assumed for all transiting objects. For each of them, the additional free parameters in the MCMC included: (1) the transit depth, $d$, defined as $(R_p/R)^2$, with $R_p$ and $R$ being the planetary and stellar radii, respectively; (2) the transit impact parameter $b = a \cos i / R$, with $a$ and $i$ being the planet’s semi-major axis and orbital inclination, respectively; (3) the orbital period $P$; (4) the transit width $W$ defined as $(P \times R_☉) \left(1 + R_p/R_☉ - b^2 \right)^{1/2} / \pi$; and (5) the mid-transit time (time of inferior conjunction) $T_0$. Uniform prior distributions were assumed for each of these free parameters. At each step of the MCMC, values for $R_p$, $a$ and $i$, were computed from the values for the transit and stellar parameters; values were also computed for the irradiation of the planet in Earth units and for its equilibrium temperatures, assuming Bond albedos of 0 and 0.75, respectively. A quadratic limb-darkening law60 was assumed for the star. For each bandpass, values and errors for the limb-darkening coefficients $u_1$ and $u_2$ were derived from the tables in ref. 62 (Extended Data Table 2), and the corresponding normal distributions were used as prior PDFs in the MCMC. $u_1$ and $u_2$ were free parameters under the control of these PDFs in the MCMC.

We divided our analysis into three phases. The first phase focused on the two inner planets, for which the period is firmly determined. A circular orbit was assumed for both planets. All transit light curves of the two planets were used as input data for this first phase, except the TRAPPIST light curve of 11 December 2015, for which the transit of planet TRAPPIST-1c is blended with a transit of planet TRAPPIST-1d. A preliminary MCMC analysis composed of one chain of 50,000 steps was first performed to estimate the need to rescale the photometric errors41. Then a longer MCMC analysis was performed, composed of five chains of 100,000 steps, whose convergence was checked using the statistical test of ref. 63. The parameters derived from this analysis for the star and its two inner planets are shown in Table 1. We performed a similar analysis assuming a uniform prior PDF for the stellar radius to determine the value of the stellar density constrained only by the transit photometry64. It resulted in a stellar density of $49.3 \pm 1.5 \rho_☉$, in excellent agreement with the density of $55.3 \pm 1.0 \rho_☉$ derived from the a priori knowledge of the star, thus bringing a further validation of the planetary origin of the transit signals.

In the second phase of our analysis, we performed 11 global MCMC analyses of all transit light curves, each of them consisting of one chain of 50,000 steps and corresponding to one of the possible values of the period of TRAPPIST-1d (see Table 1) for which a circular orbit was assumed. We then repeated the 11 analyses under the assumption of an eccentric orbit for TRAPPIST-1d. We used the medians of the BIC posterior distributions to compare the relative posterior probability of each orbital model through the formula $P(1)/P(2) = e^{(BIC_1-BIC_2)/2}$. The resulting relative probabilities are given in Extended Data Table 3. The table shows that our data favour (with a relative probability of >10%) a circular orbit and an orbital period of between 10.4 and 36.4 days—the most likely period being 18.4 days.

In the final phase, we performed individual analyses of the light curves to measure the mid-eclipse time of each transit to support future TTV studies of the system64. The resulting timings are shown in Extended Data Table 4. They do not reveal any signal, which is not surprising given the amplitude of the expected periodicity departures (see below) combined with the limited timing precision of the TRAPPIST photometry.

Extended Data Figs 1 and 2 show the raw and de-trended light curves, respectively; for each of these, the best-fit eclipse plus baseline model is overplotted. The phased-time de-trended light curves are shown for each planet and bandpass in Fig. 1.

**Photometric variability of the star.** We used the TRAPPIST data set to assess the photometric variability of the star at about 900 nm. On a timescale of a few hours—corresponding to the duration of the three 18.4-day cycles—we reveal that the photometric variability is still a reasonable hypothesis when considering the strong anticorrelation of the other astrophysical and instrumental mechanisms able to produce photometric variations. Assuming the same baseline model for all light curves, and minimizing the Bayesian information criterion (BIC)16, we selected a second-order time polynomial as a baseline model to represent the curvature of the light curves due to the differential extinction and the low-frequency variability of the star, and added an instrumental model composed of a second-order polynomial function of the positions and widths of the stellar images.

Stellar metallicity, effective temperature, mass and radius were four free parameters in the MCMC for which prior probability distribution functions (PDFs) were selected as input. Here, the normal distributions $N(0.04, 0.08^2)$ dex, $N(2.555, 85^2)$ K, $N(0.082, 0.011^2)M_☉$ and $N(0.116, 0.006^2)R_☉$ were assumed on the basis of a priori knowledge of the stellar properties (see the section on ‘Basic parameters of the star’). Circular orbits were assumed for all transiting objects. For each of them, the additional free parameters in the MCMC included: (1) the transit depth, $d$, defined as $(R_p/R)^2$, with $R_p$ and $R$ being the planetary and stellar radii, respectively; (2) the transit impact parameter $b = a \cos i / R$, with $a$ and $i$ being the planet’s semi-major axis and orbital inclination, respectively; (3) the orbital period $P$; (4) the transit width $W$ defined as $(P \times R_☉) \left(1 + R_p/R_☉ - b^2 \right)^{1/2} / \pi$; and (5) the mid-transit time (time of inferior conjunction) $T_0$. Uniform prior distributions were assumed for each of these free parameters. At each step of the MCMC, values for $R_p$, $a$ and $i$, were computed from the values for the transit and stellar parameters; values were also computed for the irradiation of the planet in Earth units and for its equilibrium temperatures, assuming Bond albedos of 0 and 0.75, respectively. A quadratic limb-darkening law60 was assumed for the star. For each bandpass, values and errors for the limb-darkening coefficients $u_1$ and $u_2$ were derived from the tables in ref. 62 (Extended Data Table 2), and the corresponding normal distributions were used as prior PDFs in the MCMC. $u_1$ and $u_2$ were free parameters under the control of these PDFs in the MCMC.

We divided our analysis into three phases. The first phase focused on the two inner planets, for which the period is firmly determined. A circular orbit was assumed for both planets. All transit light curves of the two planets were used as input data for this first phase, except the TRAPPIST light curve of 11 December 2015, for which the transit of planet TRAPPIST-1c is blended with a transit of planet TRAPPIST-1d. A preliminary MCMC analysis composed of one chain of 50,000 steps was first performed to estimate the need to rescale the photometric errors41. Then a longer MCMC analysis was performed, composed of five chains of 100,000 steps, whose convergence was checked using the statistical test of ref. 63. The parameters derived from this analysis for the star and its two inner planets are shown in Table 1. We performed a similar analysis assuming a uniform prior PDF for the stellar radius to determine the value of the stellar density constrained only by the transit photometry64. It resulted in a stellar density of $49.3 \pm 1.5 \rho_☉$, in excellent agreement with the density of $55.3 \pm 1.0 \rho_☉$ derived from the a priori knowledge of the star, thus bringing a further validation of the planetary origin of the transit signals.

In the second phase of our analysis, we performed 11 global MCMC analyses of all transit light curves, each of them consisting of one chain of 50,000 steps and corresponding to one of the possible values of the period of TRAPPIST-1d (see Table 1) for which a circular orbit was assumed. We then repeated the 11 analyses under the assumption of an eccentric orbit for TRAPPIST-1d. We used the medians of the BIC posterior distributions to compare the relative posterior probability of each orbital model through the formula $P(1)/P(2) = e^{(BIC_1-BIC_2)/2}$. The resulting relative probabilities are given in Extended Data Table 3. The table shows that our data favour (with a relative probability of >10%) a circular orbit and an orbital period of between 10.4 and 36.4 days—the most likely period being 18.4 days.

In the final phase, we performed individual analyses of the light curves to measure the mid-eclipse time of each transit to support future TTV studies of the system64. The resulting timings are shown in Extended Data Table 4. They do not reveal any signal, which is not surprising given the amplitude of the expected periodicity departures (see below) combined with the limited timing precision of the TRAPPIST photometry.

Extended Data Figs 1 and 2 show the raw and de-trended light curves, respectively; for each of these, the best-fit eclipse plus baseline model is overplotted. The phased-time de-trended light curves are shown for each planet and bandpass in Fig. 1.
suggested that these planets are well suited for astrophysical studies with HST/ WFC3 similar to those previously targeting GJ 1214b (refs 75, 76).

Given published simulations for terrestrial planets16, we estimate that character-
ization of TRAPPIST-1b, -c and -d should require up to 70 hours, 90 hours and 270 hours, respectively, of in-transit observations with the James Webb Space Telescope (JWST), and should yield atmospheric temperatures with relative uncertainties below 15% and abundances within a factor of four. Assuming that the atmospheres of TRAPPIST-1’s planets are not depleted and do not harbour a high-altitude cloud deck, JWST should, notably, yield constraints on the abun-
dances of molecules with large absorption bands such as H$_2$O, CO$_2$, CH$_4$, CO and O$_3$ if their abundances are at or greater than the 10–ppm level.

We also assessed the potential of the cross-correlation technique27 to constrain the atmospheric properties of the TRAPPIST-1 planets, following a published formalism.28 We find that detecting O$_3$ in TRAPPIST-1’s planets should require up to 80 transit observations with one of the next-generation, giant ground-based telescopes. Taking into account the limited fraction of transits visible at low air mass, such an endeavour could be reached in 5 to 15 years.

**Code availability.** Equivalent widths and H$_2$O–K$_2$ index measurements in the SpeX spectra were made using the IDL program created by A. Mann and dis-
tributed at http://github.com/awmann/metcal. Conversion of the UT times for the
SpeX spectra were made using the IDL program created by A. Mann and dis-
tributed at http://github.com/awmann/metal. Conversion of the UT times for the
SpeX spectra was performed using the online program created by J. Eastman and distributed at http://astrolils.astrology.ohio-
state.edu/time/utc2jd.html. The Image Reduction and Analysis Facility (IRAF) software is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation. The MCMC software used to analyse the photometric data is a custom Fortran 90 code that can be obtained upon request.

31. Gisiz, J. E. et al. New neighbours from 2MASS: activity and kinematics at the bottom of the main sequence. Astron. J. 120, 1085–1099 (2000).
32. Bartlett, J. L. Knowing our neighbours: fundamental properties of nearby stars. Publ. Astron. Soc. Pacif. 119, 828–829 (2007).
33. Schmidt, S. J., Cruz, K. L., Bongiorno, B. J., Liebert, J. & Reid, I. N. Activity and kinematics of ultracool dwarfs, including an amazing flare observation. Astron. J. 133, 2258–2273 (2007).
34. Lee, K.-G., Berger, E. & Knapp, G. R. Short-term H$_\alpha$ variability in M dwarfs. Astrophys. J. 708, 1482–1491 (2010).
35. Rayner, J. T. et al. SpeX: a medium-resolution 0.8–5.5 micron spectrograph and imager for the NASA infrared telescope facility. Publ. Astron. Soc. Pacif. 115, 362–382 (2003).
36. Reiners, A. & Basri, G. A volume-limited sample of 63 M7-M9.5 dwarfs. I. Space motion, kinematics and age, and lithium. Astrophys. J. 705, 1416–1424 (2009).
37. Vacca, W. D., Cushing, M. C. & Rayner, J. T. A method of correcting near-infrared spectra for telluric absorption. Publ. Astron. Soc. Pacif. 115, 389–409 (2003).
38. Cushing, M. C., Vacca, W. D. & Rayner, J. T. SpeXtool: a spectral extraction package for SpeX. a 0.8–5.5 micron cross-dispersed spectrograph. Publ. Astron. Soc. Pacif. 116, 362–376 (2004).
39. Rojas-Ayala, B., Covey, K. R., Muirhead, P. S. & Lloyd, J. P. Metallicity and temperature indicators in M dwarf K-band spectra: testing new and updated calibrations with observations of 133 solar neighbourhood M dwarfs. Astrophys. J. 748, 93 (2012).
40. Mann, A. W. et al. Prospecting in ultracool dwarfs: measuring the metallicities of mid- and late-M dwarfs. Astron. J. 147, 160 (2014).
41. Skrutskie, M. F., Meyer, M. R., Whalen, D. & Hamilton, C. The two micron all sky survey (2MASS). Astron. J. 131, 1163–1183 (2006).
42. Cutri, R. M. et al. Vizier online data catalog II/311: WISE all-sky data release. http://vizier.cfa.harvard.edu/viz-bin/VizieR?source=II/311 (2012).
43. Cruz, K. L. et al. Meeting the cool neighbours. IX. The luminosity function of pre-main sequence and main sequence low-mass stars down to the hydrogen-burning limit. Astron. Astrophys. 577, A42 (2015).
44. Siegler, N., Close, L. M., Mamajek, E. E. & Freed, M. An adaptive optics survey of M6.0–M7.5 stars: discovery of three very low mass binary system including two probable Hyades member. Astrophys. J. 598, 1265–1276 (2003).
Extended Data Figure 1 | Raw TRAPPIST-1 transit light curves. The light curves are shown in chronological order from top to bottom and left to right, with unbinned data shown as cyan dots, and binned 0.005-day (7.2-minute) intervals shown as black dots with error bars. The error bars are the standard errors of the mean of the measurements in the bins.

The best-fit transit-plus-baseline models are overplotted (red line). The light curves are phased for the mid-transit time and shifted along the y axis for clarity. For the dual transit of 11 December 2015, the light curve is phased for the mid-transit time of planet TRAPPIST-1c. T1b, TRAPPIST-1b; T1c, TRAPPIST-1c; T1d, TRAPPIST-1d.
Extended Data Figure 2 | De-trended TRAPPIST-1 transit light curves. The details are as in Extended Data Fig. 1, except that the light curves shown here are divided by the best-fit baseline model to highlight the transit signatures.
Extended Data Figure 3 | Near-infrared spectra of TRAPPIST-1.

a, Comparison of TRAPPIST-1’s near-infrared spectrum (black)—obtained with the spectrograph IRTF/SpeX— with that of the M8-type standard LHS132 (red). b, Cross-dispersed IRTF/SpeX spectrum of TRAPPIST-1 in the 2.17–2.35-µm region. Na I, Ca I and CO features are labelled. Additional structure primarily originates from overlapping H₂O bands. The spectrum is normalized at 2.2 µm. F_λ, spectral flux density; f_λ, normalized spectra flux density.
Extended Data Figure 4 | Flare events in the TRAPPIST 2015 photometry. The photometric measurements are shown unbinned (cyan dots) and binned per 7.2-minute interval (black dots). For each interval, the error bars are the standard error of the mean.
Extended Data Figure 5 | Photometric variability of TRAPPIST-1. 

a, Global light curve of the star as measured by TRAPPIST. The photometric measurements are shown unbinned (cyan dots) and binned per night (black dots with error bars (±s.e.m.)). This light curve is compared with that of the comparison star 2MASS J23063445−0507511, shifted along the y axis for clarity. 

b, The same light curve for TRAPPIST-1, folded on the period $P=1.40$ days and binned by 10-minute intervals (error bars indicate ±s.e.m.). For clarity, two consecutive periods are shown.
Extended Data Table 1 | TRAPPIST-1 transit light curves

| Date       | Instrument | Filter | \( N_p \) | \( T_{\text{exp}} \) | Baseline function               | Transit(s)          |
|------------|------------|--------|-----------|-----------------|---------------------------------|---------------------|
| 17 Sep 2015 | TRAPPIST   | I+z    | 163       | 55s             | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1c         |
| 29 Sep 2015 | TRAPPIST   | I+z    | 232       | 55s             | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1d         |
| 27 Oct 2015 | TRAPPIST   | I+z    | 84        | 55s             | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1b         |
| 30 Oct 2015 | TRAPPIST   | I+z    | 77        | 55s             | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1b         |
| 05 Nov 2015 | TRAPPIST   | I+z    | 237       | 55s             | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1b         |
| 07 Nov 2015 | TRAPPIST   | I+z    | 241       | 55s             | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1b         |
| 08 Nov 2015 | TRAPPIST   | I+z    | 231       | 55s             | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1b         |
| VLT/HAWK-I  | NB2090     |        | 207       | 17x1.7s         | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1b         |
| 11 Nov 2015 | TRAPPIST   | I+z    | 140       | 55s             | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1b         |
| 14 Nov 2015 | TRAPPIST   | I+z    | 241       | 55s             | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1b         |
| 18 Nov 2015 | HCT/HFOSC  | I      | 103       | 20s             | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1b         |
| 05 Dec 2015 | UKIRT      | J      | 1312      | 3x2s            | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1b         |
| 06 Dec 2015 | UKIRT      | J      | 1175      | 5x1s            | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1c         |
| 08 Dec 2015 | UKIRT      | J      | 1109      | 5x1s            | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1b         |
| 11 Dec 2015 | TRAPPIST   | I+z    | 158       | 55s             | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1c + d     |
| 28 Dec 2015 | TRAPPIST   | I+z    | 94        | 55s             | \( p(t^2+xy^2+f^2) \)          | TRAPPIST-1c (partial) |

For each light curve, the date, instrument, filter, number of points (\( N_p \)), exposure time (\( T_{\text{exp}} \)), and baseline function are given. For the baseline functions, \( p(t^2) \), \( p(xy^2) \) and \( p(f^2) \) denote, respectively, second-order polynomial functions of time, of the \( x \) and \( y \) positions, and of the full-width at half-maximum of the stellar images.
Extended Data Table 2 | Quadratic limb-darkening coefficients

| Bandpass       | $u_1$   | $u_2$   |
|----------------|---------|---------|
| I (HCT/HFOSC)  | 0.72±0.10 | 0.15±0.11 |
| I+z (TRAPPIST) | 0.65±0.10 | 0.28±0.12 |
| J (UKIRT/WFCAM)| 0.10±0.05 | 0.57±0.02 |
| NB2090 (VLT/HAWKI) | 0.04±0.03 | 0.50±0.03 |

We inferred these values and errors for the quadratic coefficients $u_1$ and $u_2$ for TRAPPIST-1 from theoretical tables, and used the values and errors as a priori knowledge of the stellar limb-darkening in a global MCMC analysis of the transit light curves. The error bars were obtained by propagation of the errors on the stellar gravity, metallicity, and effective temperature.
Extended Data Table 3 | Posterior likelihoods of the orbital solutions for TRAPPIST-1d

| TRAPPIST-1d period (d) | Circular orbit | Eccentric orbit | $a$ (au) | $S_p$ ($S_{Earth}$) |
|------------------------|----------------|-----------------|----------|---------------------|
| 4.551                  | 0.0016         | 0.0017          | 0.023    | 0.98                |
| 5.200                  | 0.0041         | 0.0045          | 0.025    | 0.82                |
| 8.090                  | 0.012          | 0.013           | 0.034    | 0.45                |
| 9.101                  | 0.018          | 0.011           | 0.037    | 0.39                |
| 10.401                 | 0.139          | 0.0067          | 0.040    | 0.33                |
| 12.135                 | 0.243          | 0.0029          | 0.045    | 0.26                |
| 14.561                 | 0.393          | 0.0023          | 0.050    | 0.21                |
| 18.204                 | 1              | 0.0018          | 0.058    | 0.15                |
| 24.270                 | 0.212          | 0.0016          | 0.071    | 0.11                |
| 36.408                 | 0.122          | 0.0014          | 0.093    | 0.06                |
| 72.820                 | 7.5e-5         | 6.8e-8          | 0.147    | 0.02                |

The likelihoods shown for the circular and eccentric orbits are normalized to the most likely solution (that is, a circular orbit of $P = 18.204$ days (d)). For each orbit, the semi-major axis, $a$ (in astronomical units (au)), assuming a stellar mass of 0.08 $M_\odot$ (Table 1), and the mean irradiation, $S_p$ (in Earth units ($S_{Earth}$)) are shown.
**Extended Data Table 4 | Individual mid-transit timings measured for the TRAPPIST-1 planets**

| Planet          | Instrument | Epoch | Mid-transit timing (BJD$_{TDB}$-2,450,000) |
|-----------------|------------|-------|-------------------------------------------|
| TRAPPIST-1b     | TRAPPIST   | 0     | 7322.5161$^{+0.0013}_{-0.0010}$           |
|                 | TRAPPIST   | 2     | 7325.5391$^{+0.0035}_{-0.0013}$           |
|                 | TRAPPIST   | 6     | 7331.5803±0.0013                         |
|                 | TRAPPIST   | 8     | 7334.6038±0.0012                         |
| VLT/HAWK-I      | 8          |       | 7334.60490±0.00020                       |
| TRAPPIST        | 10         |       | 7337.6249±0.0010                         |
| TRAPPIST        | 12         |       | 7340.6474$^{+0.0010}_{-0.0022}$           |
| HCT/HFOSC       | 15         |       | 7345.18011±0.00089                       |
| UKIRT/WFCAM     | 26         |       | 7361.79960±0.00030                       |
| UKIRT/WFCAM     | 28         |       | 7364.82137±0.00056                       |
| TRAPPIST-1c     | TRAPPIST   | 0     | 7282.8058±0.0010                         |
|                 | TRAPPIST   | 21    | 7333.6633±0.0010                         |
|                 | UKIRT/WFCAM| 33    | 7362.72623±0.00040                       |
| TRAPPIST        | 35         |       | 7367.5699±0.0012                         |
| TRAPPIST        | 42         |       | 7384.5230±0.0011                         |
| TRAPPIST-1d     | TRAPPIST   | 0     | 7294.7736±0.0014                         |
| TRAPPIST        | ?          |       | 7367.5818±0.0015                         |

The transit timings shown were deduced from individual analyses of the transit light curves, assuming circular orbits for the planets. The error bars correspond to the 1σ limits of the posterior PDFs of the transit timings.