LETTERS

A transiting giant planet with a temperature between 250 K and 430 K

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Of the over 400 known[1] exoplanets, there are about 70 planets that transit their central star, a situation that permits the derivation of their basic parameters and facilitates investigations of their atmospheres. Some short-period planets[2], including the first terrestrial exoplanet[3,4] (CoRoT-7b), have been discovered using a space mission[5] designed to find smaller and more distant planets than can be seen from the ground. Here we report transit observations of CoRoT-9b, which orbits with a period of 95.274 days on a low eccentricity of 0.11 ± 0.04 around a solar-like star. Its periastron distance of 0.36 astronomical units is by far the largest of all transiting planets, yielding a 'temperate' photospheric temperature estimated to be between 250 and 430 K. Unlike previously known transiting planets, the present size of CoRoT-9b should not have been affected by tidal heat dissipation processes. Indeed, the planet is found to be well described by standard evolution models[6] with an inferred interior composition consistent with that of Jupiter and Saturn.

CoRoT observed the CoRoT-9 host star for 145 days starting on 15 April 2008, in the target window E1_0651 of the survey-field LRc02 in the constellation Serpens Cauda. Two transit events (Fig. 1) were detected in CoRoT's three-colour photometry, the first one on 16 May 2008. A model fit to the first transit event indicated a Jupiter-sized planet on an equatorial transit (for values, see Table 1). Alerted by this event, two spectra of CoRoT-9 were obtained with the SOPHIE spectrograph[7] on 5 and 25 August 2008, showing a velocity difference of $35 \pm 21\,\mathrm{m\,s^{-1}}$ between both epochs, which is compatible with a giant planet.

Observations of a transit on 1 June 2009 with the Wise Observatory 1 m telescope (Israel) and the IAC 80 cm telescope (Tenerife) confirmed that the event originated on the target star itself. A false alarm from possible nearby eclipsing binary stars, the light of which might have spread into CoRoT's large ($16'' \times 21''$) aperture mask, could therefore be excluded[8]. Radial velocity observations (Fig. 2 and Supplementary Table 1) with the HARPS spectrograph[9] spanning from 21 September 2008 to 20 September 2009 verified a Jupiter-mass planet on a moderately eccentric orbit.

To assign reliable absolute values to the size and mass of the CoRoT-9b planet, a precise characterization of the planet host star is required. Spectra taken at the Thüringer Landessternwarte and with the UVES spectrograph on the Very Large Telescope Unit 2 (ESO) indicated a G3V star of nearly solar metallicity. Its evolutionary age is not strongly constrained, ranging from 0.15 to 8 Gyr. We favour the higher end of the age range, given the quiescent light curve and the absence of chromospheric activity in the spectra. Its rotational velocity of $v \sin i_{\mathrm{rot}} < 3.5\,\mathrm{km\,s^{-1}}$ implies (for a rotational inclination $i_{\mathrm{rot}} \approx 90°$) a slow rotation period of >14 days. Depletion of Li has been noted as a feature of planet-hosting stars[10] and indeed, its doublet at 6,707 Å was not found in our spectra.

The combination of the light curve analysis, the radial velocity data and the determined stellar parameters allows the derivation of absolute values for the planet's mass, radius and density (Table 1). The planet has a radius quite similar to Jupiter, with $R_{\mathrm{p}} = (1.05 \pm 0.04) R_{\mathrm{Jupiter}}$, but a lower mass of $M_{\mathrm{p}} = (0.84 \pm 0.07) M_{\mathrm{Jupiter}}$, leading to a density of $0.90 \pm 0.13\,\mathrm{g\,cm^{-3}}$, or about 68% that of Jupiter.

Tidal heating is expected to play a negligible role in the planet's evolution. The ratio of the rate of energy from tidal circularization (assuming an initial eccentricity similar to that of Jupiter) to that

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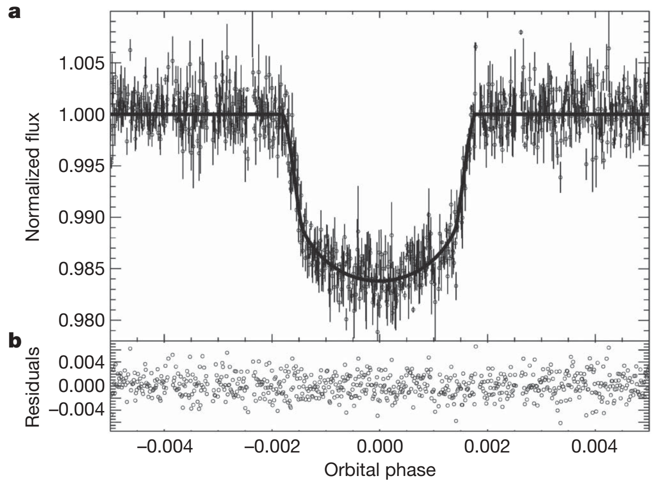

Figure 1 | Light curve and model fit of the CoRoT-9b transit. a, Phase-folded light curve from CoRoT around the first observed transit of CoRoT-9b, with the phase set to zero at mid-transit. The data from the three colour-bands of CoRoT have been summed to a 'white' band and the points have been binned from an original cadence of 32 s to a duration of 96 s; the error bars indicate the dispersion of the points within the bins. The second transit observed by CoRoT is not shown because it was only partially detected; its first 2 h were lost in an instrument interruption. The solid line represents the model fit from which the primary fit-parameters in Table 1 have been derived. They indicate a transit close to the equator, and a stellar limb darkening that is in good agreement with predictions for the CoRoT pass band[21]. This fit was based on the white-light data of the first transit event and included (1) the removal of a 2.5% contaminating fraction of light not originating from CoRoT-9, (2) the generation of a model for the planetary transit[22] assuming a linear relation for the stellar limb-darkening, and (3) the fitting of the model using a heuristic optimization algorithm[23]. The contaminating fraction of 2.5% was determined from pre-launch imagery[24], taken with the INT/WFC on La Palma, after convolving these images with CoRoT's point-spread function, and measuring the contribution of nearby stars within CoRoT's aperture mask. **b**, Residuals after subtraction of the model fit.

Table 1 | Star and planet parameters of the CoRoT-9/9b system

Parameter	Value
ID (CoRoT-Window-Id)	LRc02_E1_0651
ID (CoRoT/Exo-Dat)	0105891283
ID (GSC 2.3)	N1RO059308
Position (J2000)	18:43:08.81 + 06:12:15.19
Magnitudes (ref. 17) *U, B, V, r′, i′*	14.74, 14.55, 13.69, 13.33, 12.86
Results from light-curve analysis	
Planet period, P	95.2738 ± 0.0014 days
Transit epoch, T_0	HJD 24 54603.3447 ± 0.0001
Transit duration, T_{14}	8.08 ± 0.10 h
Relative transit depth, $\Delta F/F_0$	0.0155 ± 0.0005
Radius ratio, R_p/R_s	0.115 ± 0.001
Impact parameter, b	$0.01^{+0.06}_{-0.01}$
Limb-darkening coefficient, u	0.57 ± 0.06
Scaled semimajor axis*, a/R_s	93 ± 3
Orbital inclination*, i	$89.99^{+0.01}_{-0.04}$ °
Stellar density*, ρ_s	1.68 ± 0.20 g cm^{-3}
$M_s^{1/3}/R_s$*	1.06 ± 0.04 (solar units)
Results from radial velocity observations	
Radial velocity semi-amplitude, K	38 ± 3 m s^{-1}
Orbital eccentricity, e	0.11 ± 0.04
Argument of periastron, ω	37^{+9}_{-37} °
Systemic radial velocity	19.791 ± 0.002 km s^{-1}
Mass function, f	$(5.3 \pm 1.3) \times 10^{-10} M_{sun}$
Results from spectral typing of CoRoT-9	
Stellar spectral type	G3V
Stellar surface gravity†, log g	4.54 ± 0.09 c.g.s.
Stellar effective temperature†, T_{eff}	5625 ± 80 K
Metallicity†, [M/H]	-0.01 ± 0.06
Stellar mass, M_{star}	$(0.99 \pm 0.04) M_{Sun}$
Stellar radius, R_{star}	$(0.94 \pm 0.04) R_{Sun}$
Stellar rotational velocity, $v\sin i_{rot}$	≤ 3.5 km s^{-1}
Stellar rotational period, P_{rot}	≥ 14 days
Stellar distance	460 pc
Absolute physical parameters from combined analysis	
Planet mass, M_p	$(0.84 \pm 0.07) M_{Jupiter}$
Planet radius, R_p	$(1.05 \pm 0.04) R_{Jupiter}$
Planet density, ρ_p	0.90 ± 0.13 g cm^{-3}
Planet orbit semi-major axis, a	0.407 ± 0.005 AU
Planet–star distance at transit, a_t	$0.377^{+0.025}_{-0.015}$ AU

* These values take into account the eccentricity as found by the radial-velocity observations.
† These values are based on high-resolution ($R \approx 65{,}000$) spectra taken on 21 and 22 September 2008 with the ESO VLT/UVES in Dic1 mode (390 + 580), a slit width of 0.7 arcsec and analysis with the VWA software[18,19].
The planet's quoted period was determined from the first transit observed by CoRoT and from ground-based photometry of a transit on 5 September 2009, taken with the Euler 1.2 m telescope from La Silla, Chile, and the 2 m LCOGT Faulkes Telescope North at Haleakala Observatory. For the transit duration, the time from first to fourth contact is given. The mass function indicates the ratio $f = (M_p \sin i)^3/(M_p + M_s)^2$ and is given by $f = (1 - e^2)^{3/2} K^3 P/(2\pi\gamma)$, where γ is the gravitational constant. The stellar spectral type is based on data taken with the spectrograph ($R \approx 2{,}100$) at the Thüringer Landessternwarte (Tautenburg, Germany) on 27 July 2008. The value for the stellar surface gravity is determined directly from spectroscopy. An alternative, $\log g = 4.49 \pm 0.04$, can be derived from the stellar density given by the light-curve analysis and a weakly influencing component of $M_{star}^{1/3}$. The stellar mass is derived from StarEvol[20] evolutionary tracks. The stellar radius is derived from the quoted stellar mass and the stellar density from the transit-fit. $R_{Jupiter} = 71492$ km; $M_{Jupiter} = 1.8986 \times 10^{30}$ g. AU, astronomical units.

from insolation[11] is 30 times lower for CoRoT-9b than for HD80606b, and at least 1,000 times lower relative to all other transiting planets. Similarly, we estimate[12] a mass loss rate of about 8×10^6 g s^{-1}, which is the lowest one among the known transiting gas giants; escape processes have therefore not affected the planet significantly since its origin. That CoRoT-9b has a much larger periastron distance than any other known transiting exoplanet also strongly constrains its composition, independently of hypotheses[11,13] on possible missing energy sources and associated radius inflation: An evolutionary model of CoRoT-9b (Fig. 3) shows a good match to the observed radius between 0 and 20 Earth masses of heavy elements, comparable to the composition of giant planets in our Solar System[6].

Effective temperatures of CoRoT-9b have been calculated using a black-body approximation for the host-star emission and a uniform redistribution of absorbed heat energy between the planet's day and night side. Following the planet classification based on temperature regimes in ref. 14, there are two possible outcomes for CoRoT-9b: It may be among class III planets with temperatures >350 K, which have clear atmospheres without cloud cover and low Bond albedos of 0.09–0.12. With such an albedo, CoRoT-9b's temperatures would range from 380 K at apoastron to 430 K at periastron. CoRoT-9b may also be among Class II planets, with much lower temperatures (250–290 K) owing to a significantly higher Bond albedo of ~0.8 from the condensation of H_2O in the upper troposphere. The strong inverse dependency of the albedo on temperatures[14] near 350 K will make it possible to lock the planet into either class II or class III. Transits occur not far from periastron, so temperatures during transit would be only slightly (<30 K) lower than at periastron. Day/night temperature variations are expected to be very small for two reasons. First, from its low tidal dissipation we estimate a timescale for rotational slow-down of the order of 100 Gyr; so its rotation should still be close to the unknown, but probably rapid, primordial rate. Second, the planet's radiative timescale at the photosphere, which is inversely proportional to the cube of the photospheric temperature[15], should be around 50 times longer than for a standard hot-giant planet with a 1,500 K irradiation temperature.

Figure 4 shows a diagram of the eccentricity versus the period for all known planets and for all transiting planets. As can be seen, CoRoT-9b is the first transiting planet among those with longer periods that does not represent a case of extreme eccentricity with associated extreme temperature changes (for example, HD80806b's temperature is estimated to rise from ~800 K to ~1,500 K over a six-hour period near periastron[16]). On the contrary, it is the first transiting planet whose general properties coincide with the largest-known population of planets, those of longer periods and low-to-moderate eccentricities, but which were previously known only from radial velocity surveys.

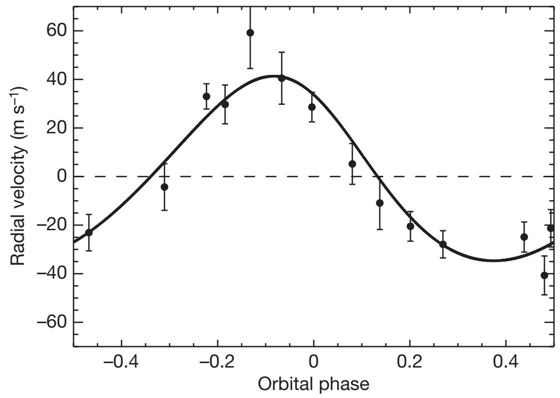

Figure 2 | CoRoT-9 radial velocities. Radial velocity data from the HARPS spectrograph after subtraction of the systemic velocity, versus the orbital phase, set to zero at periapsis. The error bars on individual points are 1-sigma measurement errors, derived from the fit of a cross correlation function to the observed spectra. The solid line is the best-fit elliptical orbital solution; the root-mean-square of its residuals is 6.3 m s^{-1}. This solution was also constrained by the known ephemeris of the planetary transits. An *F*-test comparing a best-fit circular orbit to the adopted elliptic orbit gives 95% confidence for the presence of an ellipticity that is significantly different from zero.

Our results on CoRoT-9b show that these planets may be expected to be rather similar to the giants of our Solar System.

CoRoT-9b's period is about ten times longer than of any other planet discovered through the transit method, which demonstrates the method's potential to find longer-periodic planets. Further observations of such planets will, however, present new challenges. CoRoT-9b's distance from its host-star of ~0.9 milliarcseconds is too close for imaging, and regardless of its actual Bond albedo, its relative secondary eclipse depths will be undetectable, being at the parts per million level in both the visible and the near-infrared regime. The most promising aspect of CoRoT-9b is that it will allow for spectroscopy during primary transits, which may lead to the detection of species at moderate temperatures in the visible and infrared spectra, such as CO_2 at 1.25 μm, CH_4 at 0.95 μm, or H_2O at 6 μm.

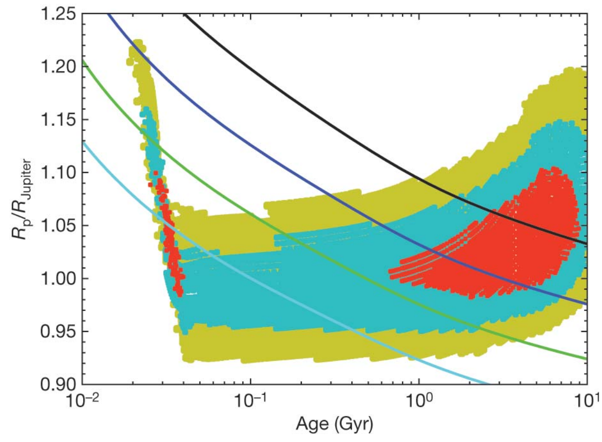

Figure 3 | Evolutionary model for a CoRoT-9b like planet. Constraints on the transit radius of CoRoT-9b for a given age, based on stellar[25] and planetary evolutionary tracks[26]. Its observed radius is $(1.05 \pm 0.05)R_{\mathrm{Jupiter}}$ (Table 1). Red, blue and green dots correspond to models matching the ρ_{star}–T_{eff} uncertainty ellipse within 1σ, 2σ and 3σ, respectively. Planetary evolution models for a planet with a solar-composition envelope and a central dense core of 0, 20, 40 and 60 Earth masses are shown as black, blue, green and light blue lines, respectively. These models assume that the planet is made of a solar-composition envelope over a dense icy/rocky core of variable mass. Their results depend only weakly on the assumed opacities, and uncertainties due to the atmospheric temperature, planetary mass and any tidal dissipation rate are negligible.

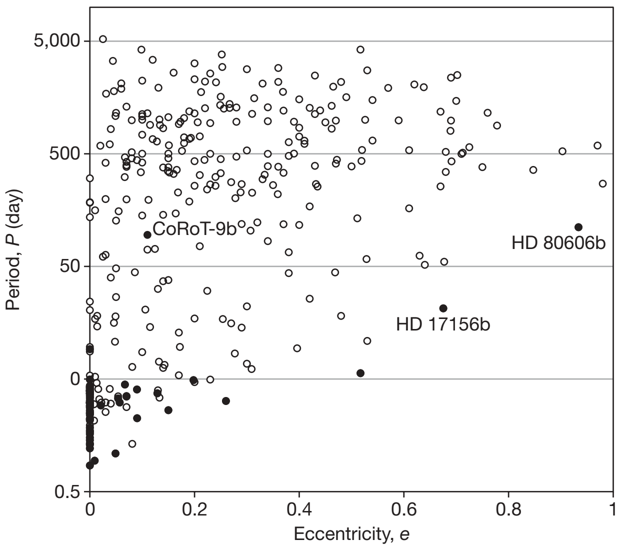

Figure 4 | The orbital parameters of CoRoT-9b among extrasolar planets. The eccentricity and period of all 339 exoplanets for which both values are known as of 1 November 2009. Solid dots are the 58 transiting planets among them—most of them have short periods of less than about 5 days and zero or low eccentricities. Only two further transiting planets have orbital periods longer than ten days; these are HD17156[27] with 21.2 days and HD80806[28–30] with 111.4 days. However, both of them also have the highest eccentricities among planets of similar periods. Open dots represent the remaining exoplanets, known only from radial velocity observations. Data are sourced from ref. 1.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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