An extrasolar planet that transits the disk of its parent star

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Planets orbiting other stars could in principle be found through the periodic dimming of starlight as a planet moves across—or 'transits'—the line of sight between the observer and the star. Depending on the size of the planet relative to the star, the dimming could reach a few per cent of the apparent brightness of the star. Despite many searches, no transiting planet has been discovered in this way; the one known[1,2] transiting planet—HD209458b—was first discovered using precise measurements[2,3] of the parent star's radial velocity and only subsequently detected photometrically. Here we report radial velocity measurements of the star OGLE-TR-56, which was previously found to exhibit a 1.2-day transit-like light curve[4,5] in a survey looking for gravitational microlensing events. The velocity changes that we detect correlate with the light curve, from which we conclude that they are probably induced by an object of around 0.9 Jupiter masses in an orbit only 0.023 AU from its star. We estimate the planetary radius to be around 1.3 Jupiter radii and its density to be about 0.5 g cm^{-3}. This object is hotter than any known planet (~1,900 K), but is still stable against long-term evaporation or tidal disruption.

The advent of high-precision Doppler and timing techniques in the past decade has brought a rich bounty of giant planets[6–8] as well as smaller, terrestrial-mass pulsar planets[9]. Over one hundred extrasolar giant planets have so far been found by different groups using precise radial velocity measurements[8]. Photometric observations of transiting planets, when combined with radial velocities, yield entirely new diagnostics: the planet size and mean density[1,2]. Transits supply the orbital inclination and a precise mass for the planet, and in addition they enable a number of follow-up studies[10–13]. Hence, a large number of transit searches are already planned or underway[14]. However, photometry alone cannot distinguish whether the occulting object is a gas giant planet (~1–13 Jupiter masses), a brown dwarf (~13–80 Jupiter masses) or a very late type dwarf star, because such objects have nearly constant radius over a range from around 0.001 to 0.1 solar masses. This critical parameter, the mass of the companion, can be determined from the amplitude of the radial velocity variation induced in the star.

One of the most successful searches to date is the Optical Gravitational Lensing Experiment (OGLE), which uncovered 59 transiting candidates in three fields in the direction of the Galactic Centre (OGLE-III)[4,5], with estimated sizes for the possible companions of about 1–4 Jupiter radii. The large number of relatively faint ($V = 14$–18 mag) candidates to study led to our strategy of a preliminary spectroscopic reconnaissance to detect and reject large-amplitude (high-mass) companions, followed by more precise observations of the very best candidates that remained. Of the 59 OGLE candidates, 20 were unsuitable: one is a duplicate entry, four have no ephemeris (only one transit was recorded), eight show obvious signs in the light curve of a secondary eclipse and/or out-of-eclipse variations (clear indications of a stellar companion), and seven were considered too faint to follow up. We undertook low-resolution spectroscopy of the other 39 candidates in late June and

Table 1 **OGLE-TR-56 radial velocities**

Date (MJD)	Radial velocity (km s^{-1})	Error (km s^{-1})
52480.4239	−49.26	0.20
52481.4011	−49.44	0.08
52481.4178	−49.24	0.09
52483.3984	−49.60	0.06
52483.4152	−49.78	0.11

The velocities (reduced to the solar system barycentre) and formal errors are given for each of our individual spectra of OGLE-TR-56. The data indicate a significant variation; a flat line fit gives $\chi^2 \simeq 20$ with 4 degrees of freedom (0.06% false-alarm probability), which is considerably worse than a fit to a keplerian orbit model with a fixed ephemeris ($\chi^2 \simeq 5$ with 3 degrees of freedom; 17% probability). Having shown, as a check, that the velocities from separate exposures on the same night (originally intended for cosmic ray removal) are not significantly different, we have adopted the nightly averages for subsequent use. A similarly high significance is found for the conclusion that the average velocities are not well fitted by a flat line (99.3% confidence level). MJD, modified Julian day.

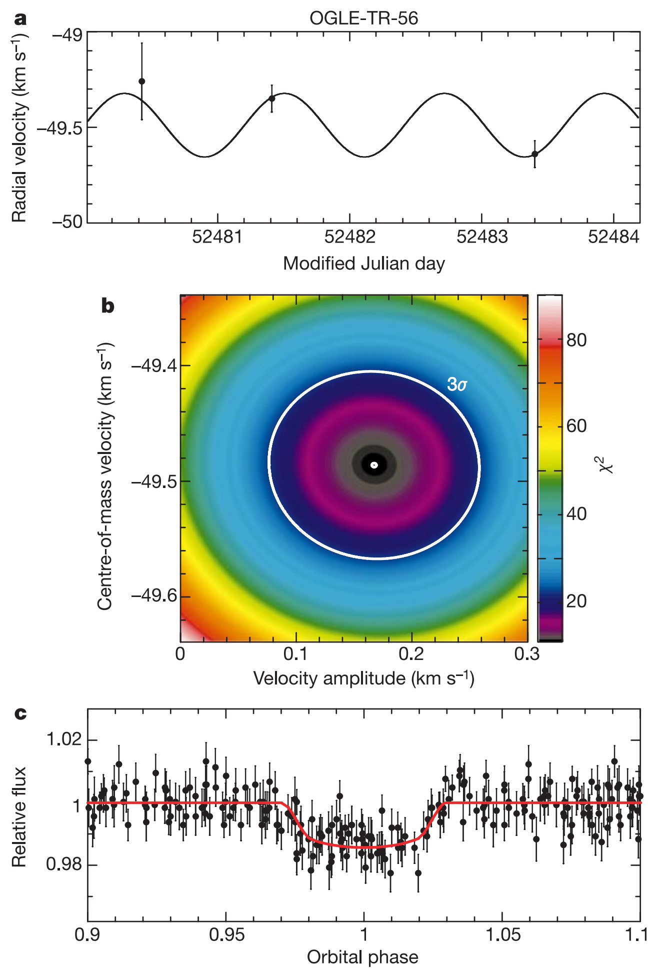

Figure 1 Spectroscopic and photometric observations. **a**, Our radial velocity measurements for OGLE-TR-56 (nightly averages). Note the good agreement with a curve whose only free parameters are the amplitude and systemic velocity; the period and transit epoch are fixed from the OGLE-III photometry. The curve assumes a circularized orbit ($e = 0.0$), as is theoretically expected, and the line thickness corresponds to the phase uncertainty. **b**, χ^2 surface showing the confidence region for our determination of the velocity amplitude and centre-of-mass velocity. The detection of a change in velocity (non-zero velocity amplitude) is formally significant at 6σ, where σ is one standard deviation (see also Table 2). **c**, The photometric transit light curve of OGLE-TR-56 from ref. 5. The transit has an extended flat bottom, and its 1.2%-depth points to a Jupiter-size body (given our determination of a Sun-like primary). The solid red line represents our fitted solution to derive the system parameters. The light curve shows no evidence of other variations or of a secondary eclipse (the hallmark of a strongly blended stellar binary).

mid-July 2002 on the Tillinghast 1.5-m telescope at the F. L. Whipple Observatory (Arizona) and the 6.5-m Magellan I Baade telescope at Las Campanas Observatory (Chile). These spectra were used to eliminate stellar binaries, which can produce shallow, planet-like eclipses caused by blending with light from another star, grazing geometry, or the combination of a large (early-type) primary and a small stellar secondary, but are betrayed by large, easily detected velocity variations (tens of $\mathrm{km\,s^{-1}}$). We found 25 of the 39 candidates to be stellar binaries, and eight to be of early spectral type. Only six solar-type candidates remained with no detected variations at the few $\mathrm{km\,s^{-1}}$ level (G.T., D.D.S. and S.J., manuscript in preparation).

Subsequently, we used the high-resolution echelle spectrograph (HIRES)[15] on the Keck I 10-m telescope at the W. M. Keck Observatory (Hawaii) on the nights of 24–27 July 2002, to obtain spectra of five of these candidates and measure more precise velocities. OGLE-TR-3 turned out to be the result of grazing eclipses and blending (with even a hint of a secondary eclipse present in the light curve), and the data for OGLE-TR-33, OGLE-TR-10, and OGLE-TR-58 are as yet inconclusive and require further measurements. OGLE-TR-33 exhibits a complex spectral line profile behaviour and could also be a blend. OGLE-TR-10 shows insignificant velocity variation, which is consistent with a sub-Jovian mass planetary companion; OGLE-TR-58 is still inconclusive because of the uncertain ephemeris (M.K., G.T., D.D.S. and S.J., manuscript in preparation). Only OGLE-TR-56 showed clear low-amplitude velocity changes consistent with its 1.21190-day photometric variation[5], revealing the planetary nature of the companion. With only one bona fide planet (or at most three) among the $39 + 8$ objects examined spectroscopically or ruled out on the basis of their light curves, the yield of planets in this particular photometric search has turned out to be very low: at least 94% (possibly up to 98%) of the candidates are 'false positives'. This is likely to be due in part to the crowded field towards the Galactic centre, which increases the incidence of blends.

We report here our results for OGLE-TR-56 ($I \approx 15.3$ mag). Radial velocities were obtained using exposures of a Th–Ar lamp before and after the stellar exposure for wavelength calibration, and standard cross-correlation against a carefully matched synthetic template spectrum (see Table 1). Our nightly-averaged measurements rule out a constant velocity at the 99.3% confidence level, and are much better represented by a keplerian model of an orbiting planet (Fig. 1a, b). Note that the period and phase of the solid curve are entirely fixed by the transit photometry, as the ephemeris is constrained extremely well by the 12 transits detected so far (A. Udalski, personal communication). The only remaining free parameters are the amplitude of the orbital motion (the key to establishing the mass of the companion) and the centre-of-mass velocity, both of which can be accurately determined from our velocity measurements. The properties of the planet and the star are summarized in Table 2, and Fig. 1c shows a phased light curve of the transit together with our fitted model.

We performed numerous tests to place limits on any systematic errors in our radial velocities and to examine other possible causes for the variation. These are crucial to assess the reality of our detection. On each night we observed two 'standards' (HD209458 and HD179949) which harbour close-in planets with known orbits[3,16]. We derived radial velocities using the same Th–Ar method as for OGLE-TR-56, and also using the I_2 gas absorption cell to achieve higher accuracy than is possible for our faint OGLE candidates. In Fig. 2 we show that the measured velocity difference between our two standards (HD209458 minus HD179949) is similar for the Th–Ar and I_2 techniques, and more importantly, that both are consistent with the expected velocity change. This indicates that we are able to detect real variations at a level similar to those we see in OGLE-TR-56.

We can rule out the possibility that OGLE-TR-56 is a giant star eclipsed by a smaller main-sequence star, both from a test based on the star's density inferred directly from the transit light curve[17], and from the very short orbital period. We also examined the spectra for sky/solar spectrum contamination from scattered moonlight; a very small contribution from this source was removed using TODCOR, a two-dimensional cross-correlation technique[18]. The separation between the sky lines and the stellar lines is large enough ($\sim 30\,\mathrm{km\,s^{-1}}$) that the effect on our derived velocities is very small.

Blending of the light with other stars is the most serious concern[19,20] in a crowded field such as toward the Galactic centre. We have examined the profiles of the stellar spectral lines for asymmetries and any phase-dependent variations that can result from blending. Very little asymmetry is present, and no correlation with phase is observed. In addition, we performed numerical simulations to fit the observed light curve, assuming OGLE-TR-56 is blended with a fainter eclipsing binary. Extensive tests show that with a photometric precision similar to the OGLE data

Table 2 **Derived stellar and planetary parameters**

Parameter	Value
Velocity amplitude	$0.167 \pm 0.027\,\mathrm{km\,s^{-1}}$
Centre-of-mass velocity	$-49.49 \pm 0.02\,\mathrm{km\,s^{-1}}$
Orbital period	1.21190 ± 0.00001 days
Reference transit epoch (MJD)	52072.185 ± 0.003
Star mass	$(1.04 \pm 0.05)M_\odot$
Star radius	$(1.10 \pm 0.10)R_\odot$
Limb darkening coefficient (*I* band)	0.56 ± 0.06
Orbital inclination	86 ± 2 deg
Planet distance from star	0.0225 AU
Planet mass	$(0.9 \pm 0.3)M_J$
Planet radius	$(1.30 \pm 0.15)R_J$
Planet density	$0.5 \pm 0.3\,\mathrm{g\,cm^{-3}}$

The physical properties of the star were derived by modelling the high-resolution spectra with numerical model atmospheres. We find that OGLE-TR-56 is very similar to the Sun, with a temperature of $T_{\mathrm{eff}} \approx 5{,}900$ K. The star's mass and radius were computed from our stellar evolution tracks[22]. Combining the stellar parameters with the OGLE-III *I*-band photometry yields the planetary radius and orbital inclination. The uncertainties shown for the orbital elements are formal errors; the errors for the planet mass and radius additionally reflect our conservative estimate of systematic uncertainties. $M_\odot$, $R_\odot$, mass and radius of the Sun; M_J, R_J, mass and radius of Jupiter.

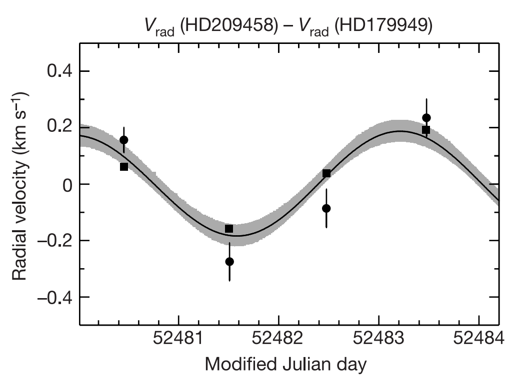

Figure 2 Tests for systematic errors. Predicted radial velocity difference between HD209458 (ref. 3) and HD179949 (ref. 16), our two standard stars with known planets (solid line). We compare these differences with measurements on each of our four observing nights in July 2002. The filled circles are our Th–Ar velocity differences (HD209458 minus HD179949, from the blue echelle orders beyond the iodine spectrum cut-off) with a typical internal uncertainty of about $100\,\mathrm{m\,s^{-1}}$. These differences should be independent of the wavelength solution itself, and should reveal only the real difference in the Doppler shifts of the stars as well as any systematic problems of an instrumental nature. For comparison, our more precise iodine-cell velocity differences for the same stars (squares) have typical uncertainties of $20\,\mathrm{m\,s^{-1}}$. The uncertainty introduced by errors in the orbital elements of the standards is indicated by the shaded area. The graph shows that we have succeeded in measuring small changes in velocity on different nights using the standard Th–Ar technique, which indicates the excellent stability of the HIRES instrument. The same technique was applied to our observations of OGLE-TR-56. V_{radial}, radial velocity.

($\sigma \approx 0.003$–0.015 mag), almost any transit-like light curve can be reproduced as a blend, and only with spectroscopy can these cases be recognized. For each trial simulation, the relative brightness and velocity amplitude of the primary in the eclipsing binary can be predicted. Although a good fit to the photometry of OGLE-TR-56 can indeed be obtained for a model with a single star blended with a fainter system comprising a G star eclipsed by a late M star, the G star would be bright enough that it would introduce strong line asymmetries (which are not seen), or would be detected directly by the presence of a second set of lines in the spectrum. Careful inspection using TODCOR[18] rules this out as well. Therefore, based on the data available, a blend scenario seems extremely unlikely.

This is the faintest ($V \cong 16.6$ mag) and most distant ($\sim$1,500 pc) star around which a planet with a known orbit has been discovered. The planet is quite similar to the only other extrasolar giant planet with a known radius, HD209458b, except for having an orbit which is almost two times smaller. Thus its substellar hemisphere can heat up to about 1,900 K. However, this is still insufficient to cause appreciable planet evaporation (with a thermal root-mean-square (r.m.s.) velocity for hydrogen of around 7 km s^{-1} compared to a surface escape velocity of around 50 km s^{-1}). The tidal Roche lobe radius of OGLE-TR-56b at its distance from the star is about 2 planet radii. The planet's orbit is most probably circularized ($e = 0.0$) and its rotation tidally locked, but the star's rotation is not synchronized ($v \sin i \approx 3$ km s^{-1}). Thus the system appears to have adequate long-term stability. Interestingly, OGLE-TR-56b is the first planet found in an orbit much shorter than the current cut-off of close-in giant planets at 3–4-day periods ($\sim$0.04 AU)[8]. This might indicate a different mechanism for halting migration in a protoplanetary disk. For example, OGLE-TR-56b may be representative of a very small population of objects—the so-called class II planets, which have lost some of their mass through Roche lobe overflow[21] but survived in close proximity to the star; a detailed theoretical study of OGLE-TR-56b will be presented elsewhere (D.D.S., manuscript in preparation). These observations clearly show that transit searches provide a useful tool in adding to the great diversity of extrasolar planets being discovered. □

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Long-distance teleportation of qubits at telecommunication wavelengths

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Matter and energy cannot be teleported (that is, transferred from one place to another without passing through intermediate locations). However, teleportation of quantum states (the ultimate structure of objects) is possible[1]: only the structure is teleported—the matter stays at the source side and must be already present at the final location. Several table-top experiments have used qubits[2–7] (two-dimensional quantum systems) or continuous variables[8–10] to demonstrate the principle over short distances. Here we report a long-distance experimental demonstration of probabilistic quantum teleportation. Qubits carried by photons of 1.3 μm wavelength are teleported onto photons of 1.55 μm wavelength from one laboratory to another, separated by 55 m but connected by 2 km of standard telecommunications fibre. The first (and, with foreseeable technologies, the only) application of quantum teleportation is in quantum communication, where it could help to extend quantum cryptography to larger distances[11–13].

Since the first article presenting the concept[1] (Fig. 1), quantum teleportation has received much attention. On the conceptual side, it has been proved to be a universal gate for quantum computing[14]. In particular, together with quantum memories, it offers the possibility of realizing quantum repeaters with unlimited range[15]. But it is fair to say that the fundamental meaning of quantum teleportation for our understanding of quantum nonlocality (and of the structure of space and time) may still be awaiting discovery. On the experimental side, progress in demonstrating the concept has been surprisingly fast. In 1997, two groups—one in Rome, one in Innsbruck—presented results of quantum teleportation using qubits. The Italian group[2] teleported a qubit carried by one of the

