Transiting circumbinary planets Kepler-34 b and Kepler-35 b

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Most Sun-like stars in the Galaxy reside in gravitationally bound pairs of stars2–3 (binaries). Although long anticipated4–9, the existence of a ‘circumbinary planet’ orbiting such a pair of normal stars was not definitively established until the discovery10 of the planet transiting (that is, passing in front of) Kepler-16. Questions remained, however, about the prevalence of circumbinary planets and their range of orbital and physical properties. Here we report two additional transiting circumbinary planets: Kepler-34 (AB)b and Kepler-35 (AB)b, referred to here as Kepler-34 b and Kepler-35 b, respectively. Each is a low-density gas-giant planet on an orbit closely aligned with that of its parent stars. Kepler-34 b orbits two Sun-like stars every 289 days, whereas Kepler-35 b orbits a pair of smaller stars (89% and 81% of the Sun’s mass) every 131 days. The planets exhibit large multi-periodic variations in incident stellar radiation arising from the orbital motion of the stars. The observed rate of circumbinary planets in our sample implies that more than ~1% of close binary stars have giant planets in nearly coplanar orbits, yielding a Galactic population of at least several million.

The new planets were identified using 671 days of data from the NASA Kepler spacecraft10, as part of its mission11 to detect Earth-like planets via the transit method. Kepler is monitoring more than 2,000 eclipsing binary stars12,13. From these, we selected a sample of 750 systems with orbital periods ranging from 0.9 to 276 days, and for which eclipses of both stars occur. For each system, we measured the eclipse times for both stars and searched for departures from strict periodicity, as would be produced by gravitational perturbations from a third body.

All 750 systems were searched by eye for planetary transits, with particular attention being paid to a subset (18% of the total) that exhibited significant differences between the periods derived from the deeper primary eclipses, and those derived from the shallower secondary eclipses (for details, see Supplementary Information). (Here ‘primary eclipse’ indicates the eclipse of the primary star by the secondary star.) This led to the discovery of Kepler-34 and Kepler-35, and a candidate system KOI-2939. KOI-2939 (Kepler Input Catalog12 number 05473556) exhibited a single transit at BJD (barycentric Julian date) 2,454,996.995 ± 0.010 of duration 2.5 h and depth 0.18%. The transit duration constrains the size and velocity of the third body and is consistent with a Jovian planet transiting the secondary star, but we cannot verify its planetary nature. We defer discussion for a future investigation.

The stars of Kepler-34 (denoted A and B, where A is the brighter, more massive primary star) have an orbital period of 28 days, with a period difference between primary and secondary eclipses of 4.91 ± 0.59 s. Three transits were detected (Fig. 1), with the first and second being transits of the primary star, while the third is of the secondary star. Notably the transit durations are all different, ruling out the most common type of ‘false positive’, a background eclipsing binary. Circumbinary transits naturally vary in duration as a consequence of the changing velocity of the stars. The Kepler photometry was supplemented by spectroscopic observations of the radial-velocity variations of both stars (Fig. 11), in order to determine the orbital scale and sizes of all three bodies. The photometric and spectroscopic data were fitted with a model14–16 that accounts for the three-body gravitational dynamics and the loss of light due to eclipses and transits (see Supplementary Information). The model fit confirms that the transiting body is a planet with 22% of the mass of Jupiter (69 Earth masses) and 76% of the radius of Jupiter (8.6 Earth radii). The primary and secondary stars are similar to the Sun. Using the spectra, we also measured the effective temperature and abundance of heavy elements (metallicity) of both stars. The observed stellar parameters match the Yongsei-Yale theoretical models of stellar evolution18 for an age of 5–6 Gyr. The parameters and uncertainties are given in Table 1, with details in Supplementary Information.

The stars of Kepler-35 (A and B) have an orbital period of 21 days, with a period difference between primary and secondary eclipses of 1.89 ± 0.48 s. Four transits were detected (Fig. 2b–e). The first, second and fourth events are transits of the primary star, and the weaker third

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doi:10.1038/nature10768
Figure 1 | Observations of Kepler-34. a, A portion of the normalized light curve, showing the relative brightness versus time (in units of barycentric Julian days, BJD). Low-frequency variations and instrumental drifts have been removed (Supplementary Information). The blue points show the primary eclipses (star B eclipses star A), orange points show the secondary eclipses, red points show the primary transits (planet transits star A), and green shows the secondary transit. The times of each event are indicated by the arrows. Owing to gaps in the observations, one primary and one secondary eclipse were missed. b–d, Close-up views of the three transit events. The solid curve is the photometric-dynamical model. Variations in transit widths are mainly due to differences in the transverse velocity of the stars during transit. The large drop before the transit in c is due to a primary eclipse. e, Close-up views of the phase-folded primary and secondary eclipses plotted versus orbital phase (time modulo the orbital period P, where P = 27.795794795 d and the time of periasterion is BJD 2,455,007.5190). Only Kepler Quarter 4 data are shown. f, Radial velocities of the primary star (blue points), secondary (orange points), and the model curve, versus orbital phase. g, Observed (O) minus computed (C) diagram, showing the deviations between the measured eclipse times and those predicted assuming strict periodicity. Primary eclipses are shown as blue points, secondary by orange points, and the corresponding models by the red curves. A period of 27.79578193 days and an epoch of BJD 2,454,979.72301 were used to compute the primary eclipse times, and a phase offset of 0.6206712 for the secondary eclipse times. The divergence indicates the primary and secondary periods are different. The two vertical bars in the lower left denote the median ±1σ uncertainties of the primary and secondary eclipse times: 0.10 and 0.22 min.

Table 1 | Circumbinary planet system parameters

|                       | Kepler-34 (this work) | Kepler-35 (this work) | Kepler-16 (ref. 9) |
|-----------------------|-----------------------|-----------------------|---------------------|
| **Planetary properties** |                       |                       |                     |
| Mass of planet, $M_p$ ($M_{Jupiter}$) | 0.220 ± 0.011 | 0.127 ± 0.020 | 0.333 ± 0.016 |
| Radius of planet, $R_p$ ($R_{Jupiter}$) | 0.764 ± 0.012 | 0.728 ± 0.014 | 0.7538 ± 0.026 |
| Mean density of planet, $\rho_p$ (g cm$^{-3}$) | 0.613 ± 0.045 | 0.410 ± 0.070 | 0.964 ± 0.047 |
| Planet surface gravity, $g_0$ (cm s$^{-2}$) | 936 ± 52 | 596 ± 98 | 1.452 ± 79 |
| **Properties of the planetary orbit** |                       |                       |                     |
| Reference epoch (BJD) | 2,454,969.20000 | 2,454,965.85000 | 2,455,212.12316 |
| Period, $P$ (days) | 288.822 ± 0.083 | 131.456 ± 0.077 | 228.776 ± 0.020 |
| Semi-major axis length, $a$ (au) | 1.0896 ± 0.0001 | 0.60342 ± 0.000101 | 0.70489 ± 0.0011 |
| Eccentricity, $e$ | 0.182 ± 0.016 | 0.047 ± 0.004 | 0.00685 ± 0.000104 |
| $e \sin(\omega)$ | 0.025 ± 0.007 | 0.036 ± 0.009 | 0.00468 ± 0.00088 |
| $e \cos(\omega)$ | 0.180 ± 0.021 | 0.032 ± 0.0011 | 0.000104 ± 0.00014 |
| Mean longitude, $\lambda = M + \omega$ (deg) | 106.5 ± 0.1 | 90.76 ± 0.12 | 106.51 ± 0.32 |
| Inclination, $i$ (deg) | 0.026 ± 0.018 | 0.99 | 0.00022 ± 0.00023 |
| Relative nodal longitude, $\Omega$ (deg) | 0.16 | 0.33 | 0.0031 ± 0.0013 |
| **Properties of the stars in the binary stellar** |                       |                       |                     |
| Mass of A, $M_A$ ($M_{Sun}$) | 1.0479 ± 0.0033 | 0.8877 ± 0.0051 | 0.6897 ± 0.0035 |
| Radius of A, $R_A$ ($R_{Sun}$) | 1.1618 ± 0.0033 | 1.0284 ± 0.0020 | 0.6489 ± 0.0013 |
| Mass of B, $M_B$ ($M_{Sun}$) | 1.0208 ± 0.0022 | 0.8094 ± 0.0042 | 0.20255 ± 0.00066 |
| Radius of B, $R_B$ ($R_{Sun}$) | 1.0927 ± 0.0032 | 0.7861 ± 0.0020 | 0.22623 ± 0.00053 |
| Flux ratio in the Kepler bandpass, $F_{b}/F_{A}$ | 0.8475 ± 0.0010 | 0.3941 ± 0.0011 | 0.01555 ± 0.00010 |
| **Properties of the stellar binary orbit** |                       |                       |                     |
| Period, $P$ (days) | 27.7958103 ± 0.0000016 | 20.733666 ± 0.000012 | 41.079220 ± 0.000078 |
| Semi-major axis length, $a$ (au) | 0.228822 ± 0.0000019 | 0.17617 ± 0.00003 | 0.224311 ± 0.000077 |
| Eccentricity, $e$ | 0.52087 ± 0.00055 | 0.14211 ± 0.00015 | 0.19944 ± 0.00034 |
| $e \sin(\omega)$ | 0.49377 ± 0.00066 | 0.14181 ± 0.00011 | 0.15840 ± 0.00062 |
| $e \cos(\omega)$ | 0.16782 ± 0.000061 | 0.0086413 ± 0.000000031 | 0.00181481 ± 0.00000044 |
| Mean longitude, $\lambda = M + \omega$ (deg) | 300.1970 ± 0.0009 | 89.1784 ± 0.0011 | 92.3520 ± 0.00011 |
| Inclination, $i$ (deg) | 89.8584 ± 0.0070 | 90.4238 ± 0.0073 | 90.3401 ± 0.0019 |

Results of the photometric-dynamical model for Kepler-34 (KIC 8572936) and Kepler-35 (KIC 9837578). The orbital parameters listed are the osculating Jacobian parameters, that is, the instantaneous Keplerian elements for the listed epoch, in general, unlike the simple two-body Keplerian case, the orbital elements are functions of time. In particular, the orbital period of Kepler-34 varies from 280 to 312 days on secular timescales; the median period is ~291 days. See Supplementary Information for details. For direct comparison, values for Kepler-16 are listed. The mean longitude ($\lambda$) is the sum of the mean anomaly ($M$) and the argument of periasterion ($\omega$).
The mean densities of Kepler-34 b and Kepler-35 b are respectively 0.61 and 0.41 g cm\(^{-3}\), somewhat lower than the 0.96 g cm\(^{-3}\) of radii under the assumption of a common age and metallicity (Supplementary Information). Given the orbital geometry of Kepler-34, Kepler-35 and Kepler-16, the probability\(^{21}\) that a randomly placed observer who sees stellar eclipses would also see planetary transits is approximately 12%, 24% and 21%, respectively (Supplementary Information). If this probability of roughly \(\sim\) 15% were constant across all 750 target systems, then the fraction of binaries with circumbinary gas giant planets at similar periods would be \((3/750) \times (0.15)^{-1}\), or a few per cent. However, this does not account for the period distribution of binaries in our sample, and the search is not complete; consequently a lower limit of \(\sim\) 1% is reasonable. With \(\sim\) 2.6% of all Sun-like stars in Kepler-16 b, but all are consistent with low-density gas-giant planets.}

**Figure 3** | **Orbital configurations.** a, Scale view of the orbits of the Kepler-34 system seen face-on (top) and also as seen from Earth (boxed, bottom). In the face-on view, the stars and planet are too small to be seen relative to their orbit curves, and so are represented as dots and marked with symbols A, B, and b denoting the primary star, secondary star, and planet. This view is correct for a given epoch (BJD 2,455,507.50). Because of the dynamical interactions between the three bodies, this orbital configuration will evolve. For example, the orbits precess, and hence the orbits do not actually close. The line-of-sight view shown in the box depicts the stars and planet with correct relative sizes and orientation. More importantly, the orbits and the orbital tilts are accurately portrayed, showing how transits do not necessarily occur at every conjunction. The grey shaded area in the top panel denotes the limits of the view shown in the expanded bottom panel. As for a, but for Kepler-35 at epoch BJD 2,455,330.60. Note that the relative sizes of the bodies are drawn to scale for each panel (a–c), not just within a panel. c, As for a, but for Kepler-16 at epoch BJD 2,455,213.0.
Figure 4 | Variations in insolation received by Kepler-34 b and Kepler-35 b. 

a. Left panel, the black curve shows the incident flux (insolation) received by Kepler-34 b from its two stars. The insolation is in units of the solar constant \( S \) (solar flux received at a distance of 1 \( \text{au} \); \( S = 1.0 \) for the Sun–Earth system). The contribution from star A is shown in red and the contribution from star B in blue. The most rapid variations are caused by the orbital motion of the stars. The slower variations are due to the orbital motion of the planet. Right panel, a longer timescale view of the insolation. The long-timescale quasi-periodicity is caused by the mutual precession of the orbits of the stars and planet, but is dominated by the precession of the planet. b. As for a, but for Kepler-35 b.

Orbital motion of the central stars causes complex time variations in stellar insolation for circumbinary planets. Figure 4 shows the calculated insolation for Kepler-34 b and Kepler-35 b. The variation is multi-periodic, with changes on the timescales of the stellar orbit, the planetary orbit, and the long-term precession of the orbits due to third-body effects. For Kepler-34 b and Kepler-35 b, the average insolation is (respectively) 2.4 and 3.6 times the Earth’s insolation, with maximum-to-minimum ratios of 250% and 160%. By comparison, for Venus the insolation is 1.9 times the Earth’s with only a 2.7% variation. These highly variable, multi-periodic fluctuations in insolation are unique to circumbinary planets, and can lead to complex climate cycles. It will be interesting to explore the effects of these swings in insolation on the atmospheric dynamics (Supplementary Information), and ultimately on the evolution of life on habitable circumbinary planets.

Received 15 November; accepted 5 December 2011.

Published online 11 January 2012.

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Some of the reported computations were run on the Odyssey cluster supported by the FAS Science Division Research Computing Group at Harvard University. This Letter is based in part on observations made with the Nordic Optical Telescope (operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias), the W. M. Keck Observatory (operated by the University of California and the California Institute of Technology) and the Hobby-Eberly Telescope (HET; a joint project of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Goettingen).

Author Contributions W.F.W. led the research effort on these transiting circumbinary planets (CBPs) and wrote much of the Letter. J.A.O. led the ETVM (eclipse timing variation) investigation, measured O–C, inspected light curves, measured EB (eclipsing binary) properties, measured radial velocities and flux ratios, generated Figs. 1 and 2, and assembled the Supplementary Information. J.A.C. created and used the photometric-dynamical code to model the light curve and RVs (radial velocities), measured system parameters, and generated Table 1 and Fig. 3. D.C.F. produced initial dynamical models to interpret the timing of eclipse and transit events leading to the planet interpretation, and developed criteria for non-eclipsing CBP searches. E.B.F. contributed to interpretation and text, checked long-term stability, and did insolations calculations. J.J.L. contributed to interpretation and text, and initiated study of variations in insolation on CBPs. A.P. measured mass, radii and other properties of the EBs, including contamination and flux ratios. S.N.Q. obtained and analysed spectra, and determined stellar parameters and luminosity ratios. D.R. computed the estimated frequency of CBPs. D.R.S. developed the automated ETV code to measure eclipse times and O–C deviations. G.T. contributed to the discussion of the stellar parameters and carried out the comparison with stellar evolution models. J.N.W. contributed to the text, estimated age via gyrochronology, and contributed to topics related to pseudosynchronicity. L.R.D. contributed to the habitable zone discussion and led the initial search for CBPs. T.N.G. obtained spectroscopic observations using Keck-HIRES. S.B.H. contributed reconnaissance spectroscopy. M.E. contributed HET and McDonald 2.7 m spectra. J.J.F. gathered spectroscopic observations for the RV and spectroscopic parameter determination. C.C. contributed three nights of spectroscopic observations at the McDonald 2.7 m observatory. D.A.C. contributed to calibration of the Kepler photometer and pipeline necessary for data acquisition. J.L.C. supported the science operations to collect and calibrate the Kepler data. D.R.C. coordinated ground-based follow-up observations. W.D.C. obtained the HET spectra, and processed all McDonald 2.7 m and HET spectra. M.E. contributed HET and McDonald 2.7 m spectra. J.J.F. contributed calculations and discussion regarding the characteristics of the planets’ atmospheres. T.N.G. coordinated the Kepler follow-up observation effort. R.L.G. provided mission support and contributed to the text and discussion of results. M.R.H. led the effort to gather, process and distribute the data necessary for this investigation. J.R.H. contributed to the collection, validation and management of the Kepler data used here. M.J.H. contributed to the discussion of the dynamical stability. A.W.H. made spectroscopic observations using Keck-HIRES. S.B.H. contributed reconnaissance spectroscopy. H.I. obtained spectroscopic observations of targets. J.M.J. developed observation/analysis techniques and calibration software that enables the Kepler photometer to operate successfully. T.C.K. led the design and development of the Science Processing Pipeline Infrastructure needed to process the data used here. D.W.L. contributed spectroscopy and preparation of the Kepler Input Catalog. J.L. contributed to the development of the Data Validation component of the Kepler Science Operations Center pipeline necessary to obtain these data. G.W.M. obtained Keck-HIRES spectra. T.M. analysed the beaming effect in Kepler-35 and participated in the discussion of statistical inference and the spectroscopic light ratio. E.V.Q. developed calibration/validation software necessary for the Kepler data in this paper. P.R. contributed ten nights of spectroscopic observations at the McDonald 2.7 m telescope. A.S. contributed ground-based follow-up imaging of the targets. J.H.S. contributed to the text, scope and interpretation. G.W. ran the ETV code, developed tools for analysing O–C variations, and assisted with text. D.G.K. designed major portions of the Kepler photometer that acquired these data. W.J.B. led the design and development of the Kepler mission that acquired these data, and contributed to the text.

Author Information The Kepler light curves used in this work can be downloaded from the MAST (Multimission Archive at Space Telescope Science Institute) at http://archive.stsci.edu/kepler/. 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 this article at www.nature.com/nature. Correspondence and requests for materials should be addressed to W.F.W. (wwf@sciences.sdsu.edu) or J.A.C. (jacarter@cfa.harvard.edu, for questions regarding the photometric-dynamical modelling).