A rocky composition for an Earth-sized exoplanet

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Planets with sizes between that of Earth (with radius \( R_{\oplus} \)) and Neptune (about \( 4R_{\oplus} \)) are now known to be common around Sun-like stars1-3. Most such planets have been discovered through the transit technique, by which the planet’s size can be determined from the fraction of starlight blocked by the planet as it passes in front of its star. Measuring the planet’s mass—and hence its density, which is a clue to its composition—is more difficult. Planets of size \( 2-4R_{\oplus} \) have proved to have a wide range of densities, implying a diversity of compositions4,5, but these measurements did not extend to planets as small as Earth.

Here we report Doppler spectroscopic measurements of the mass of the Earth-sized planet Kepler-78b, which orbits its host star every 8.5 hours (ref. 6). Given a radius of \( 1.20 \pm 0.09R_{\oplus} \) and a mass of \( 1.69 \pm 0.14M_{\oplus} \), the planet’s mean density of \( 5.3 \pm 1.8 \text{g cm}^{-3} \) is similar to Earth’s, suggesting a composition of rock and iron.

Kepler-78 is one of approximately 150,000 stars whose brightness was precisely measured at 30-min intervals for four years by NASA’s Kepler spacecraft7. This star is somewhat smaller, less massive and younger than the Sun (Table 1). Every 8.5 hours the star’s brightness declines by 0.02% as the planet Kepler-78b transits (passes in front of) the stellar disk. The planet’s radius was originally measured8 to be \( 1.16^{+0.10}_{-0.09}R_{\oplus} \). Its mass could not be measured, although masses exceeding \( 8M_{\oplus} \) could be ruled out because the planet’s gravity would have deformed the star and produced brightness variations that were not detected.

We measured the mass of Kepler-78b by tracking the line-of-sight component of the host star’s motion (the radial velocity) that is due to the gravitational force of the planet. The radial-velocity analysis is challenging not only because the signal is expected to be small (about \( 1-3 \text{ m s}^{-1} \)) but also because the apparent Doppler shifts due to rotating star spots are much larger (about \( 50 \text{ m s}^{-1} \) peak-to-peak). Nevertheless the detection proved to be possible, thanks to the precisely known orbital period and phase of Kepler-78b that cleanly separated the timescale of spot variations \( (P_{\text{rot}} \approx 12.5 \text{ days}) \) from the much shorter timescale of the planetary orbit \( (P = 8.5 \text{ hours}) \). We adopted a strategy of intensive Doppler measurements spanning 6–8 hours per night, long enough to cover nearly the entire orbit and short enough for the spot variations to be nearly frozen out.

We measured radial velocities using optical spectra of Kepler-78 that we obtained from the High Resolution Echelle Spectrometer (HIRES) on the 10-m Keck I Telescope. These Doppler shifts were computed relative to a template spectrum with a standard algorithm9 that uses a spectrum of molecular iodine superposed on the stellar spectrum as a reference for the wavelength scale and instrumental profile of HIRES.

### Table 1 | Kepler-78 system properties

| Parameter | Value |
|-----------|-------|
| Stellar properties | |
| Name | Kepler-78, KIC8435766, Tycho 3147-188-1 |
| Effective temperature, \( T_{\text{eff}} \) | 5,121 ± 44 K |
| Logarithm of surface gravity, \( \log g \) | 4.61 ± 0.06 |
| Iron abundance, \([\text{Fe/H}]\) | -0.08 ± 0.04 dex |
| Projected rotational velocity, \( V_{\text{sin}i} \) | 2.6 ± 0.5 km s\(^{-1}\) |
| Mass, \( M_{\star} \) | 0.83 ± 0.05\( M_{\odot} \) |
| Radius, \( R_{\star} \) | 0.74 ± 0.05\( R_{\odot} \) |
| Density, \( \rho_{\star} \) | 2.8 ± 0.7 \( \text{g cm}^{-3} \) |
| Age | 625 ± 150 million years |
| Planetary properties | |
| Name | Kepler-78b |
| Mass, \( M_{\text{pl}} \) | 1.69 ± 0.14\( M_{\oplus} \) |
| Radius, \( R_{\text{pl}} \) | 1.20 ± 0.09\( R_{\oplus} \) |
| Density, \( \rho_{\text{pl}} \) | 5.3 ± 2.9 \( \text{g cm}^{-3} \) |
| Surface gravity, \( g_{\text{pl}} \) | 11 ± 2.4 \( \text{m s}^{-2} \) |
| Iron fraction | 0.20 ± 0.33 (two-component rock/iron model) |
| Orbital period, \( P_{\text{orb}} \) (from ref. 6) | 0.3550744 ± 0.0000006 days |
| Transit epoch, \( t_{\text{c}} \) (from ref. 6) | 2454953.99999 ± 0.00013 (BJD\(_{\text{TBD}}\)) |

The stellar effective temperature and iron abundance were obtained by fitting stellar atmosphere models10 to iodine-free HIRES spectra, subject to a constraint on the surface gravity based on stellar evolution models11. We estimated the stellar mass and radius from empirically calibrated relationships between those spectroscopic parameters12. The refined stellar radius led to a refined planet radius. Planet mass and density were measured from the Doppler analysis. The stellar age is estimated from non-detection of lithium in the stellar atmosphere (Extended Data Fig. 1), the stellar rotation period, and magnetic activity. See Methods for details. Parameter distributions are represented by median values and 68.3% confidence intervals. Correlations between transit parameters are shown in Extended Data Fig. 2. Barycentric Julian dates in barycentric dynamical time, BJDTBD.

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(Supplementary Table 1). Exposures lasted 15–30 min depending on conditions and produced radial velocities with 1.5–2.0 m s\(^{-1}\) uncertainties. The time series of radial velocities spans 45 days, with large velocity offsets between nights due to star spots (Fig. 1). Within each night the radial velocities vary by typically 2–4 m s\(^{-1}\) and show coherence on shorter timescales.

We modelled the radial-velocity time series as the sum of two components. One component was a sinusoidal function representing orbital motion (assumed to be circular). The orbital period and phase were held fixed at the photometrically determined values; the only free parameters were the Doppler amplitude \(K\), an arbitrary radial-velocity zero point, and a velocity ‘jitter’ term \(\sigma_{\text{jitter}}\) to account for additional radial-velocity noise. The second component of the model, representing the spot variations, was the sum of three sinusoidal functions with periods \(P_{\text{rot}}/2\), \(P_{\text{rot}}/3\), and \(P_{\text{rot}}/5\). The amplitudes and phases of the sinusoids and \(P_{\text{rot}}\) were free parameters. All together there were ten parameters and 77 data points. Using a Markov Chain Monte Carlo (MCMC) method to sample the allowed combinations of the model parameters, we found \(K = 1.66 \pm 0.40\) m s\(^{-1}\), corresponding to \(M_p = 1.69 \pm 0.41\) M\(_{\oplus}\) (Fig. 1). This planet mass is consistent with an independent measurement using the HARPS-N spectrometer\(^\text{10}\).

Several tests were performed to gauge the robustness of the spot model. First, we varied the number of harmonics, checking at each stage whether any improvement in the fit was statistically significant. The three-term model was found to provide noticeable improvement over one-term and two-term models, but additional harmonics beyond \(P_{\text{rot}}/3\) did not provide significant improvement. Second, we used a different spot model in which the spot-induced variation was taken to be a linear function of time specific to each night. The constant and slope of each nightly function were free parameters. With this model we found \(M_p = 1.50 \pm 0.44\) M\(_{\oplus}\), consistent with the preceding results (see Methods and Extended Data Fig. 3). The larger uncertainty can be attributed to the greater flexibility of this piecewise-linear spot model, which permits discontinuous and probably unphysical variations between consecutive nights.

Kepler-78b is now the smallest exoplanet for which both the mass and radius are known accurately (Fig. 2), extending the domain of such measurements into the neighbourhood of Earth and Venus. Kepler-78b is 20% larger than Earth and is 69% more massive, suggesting commonality with the other low-mass planets (4–8 M\(_{\oplus}\)) below the rock composition contour in Fig. 2b. They are all consistent with rock/iron compositions and negligible atmospheres.

Figure 1 | Apparent radial-velocity variations of Kepler-78. a, The 38-day time series of relative radial velocities (black filled circles) from Keck-HIRES along with the best-fitting model (red line), with short-term variations due to orbital motion and long-term variations due to rotating star spots. Blue boxes identify the eight nights when high-cadence measurements were undertaken. JD, Julian day. b–i, For each individual night, the measured radial velocities (black filled circles), the spot + planet model (solid red lines) and spot model alone (dashed red lines) are shown. j, k, The phase-folded radial velocities after subtracting the best-fitting spot model (j), and after binning in orbital phase and computing the mean radial velocities and s.e.m. for error bars (k). Planetary transits occur at zero orbital phase and solid red lines mark the phased planet model (in j and k). Each radial-velocity error bar in panels a–j represents the s.e.m. for the Doppler shifts of around 700 segments of a particular spectrum; it does not account for additional uncorrected radial-velocity ‘jitter’ from astrophysical and instrumental sources.
We explored some possibilities for the interior structure of Kepler-78b using a simplified two-component model consisting of an iron core surrounded by a silicate mantle (Mg$_2$SiO$_4$). This model correctly reproduces the masses of Earth and Venus given their radii and assuming a composition of 67% silicate rock and 33% iron by mass. Applied to Kepler-78b, the model gives an iron fraction of 20% ± 33%, similar to that of Earth and Venus but smaller than that of Mercury (approximately 60%; ref. 12).

With a star–planet separation of 0.01 astronomical units (1 AU is the Earth–Sun distance), the dayside of Kepler-78b is heated to a temperature of 2,300–3,100 K. Any gaseous atmosphere around Kepler-78b would probably have been lost long ago to photoevaporation by the intense starlight. However, based on the measured surface gravity of 11 m s$^{-2}$, the liquid and solid portions of the planet should be stable against mass loss of the sort that is apparently destroying the smaller planet KIC 12557548b (ref. 15).

Kepler-78b is a member of an emerging class of planets with orbital periods of less than half a day$^{6,16,17}$. Another member is KOI 1843.03 (refs 18 and 19), which has been shown to have a high density (more than about 7 g cm$^{-3}$), similar to that of Earth and Venus but smaller than that of Mercury (approximately 60%; ref. 12).

Figure 2 | Masses and radii of well-characterized planets. Extrasolar planets are denoted by red circles and Solar System planets are represented by green triangles. a spans the full range of sizes and masses on logarithmic axes. The shaded grey rectangle denotes the range of parameters shown in b on linear mass and radius axes. Kepler-78b is depicted as a black filled circle in a and as a distribution of allowed masses and radii with a dotted red ellipse marking the 68% confidence region in b. Model mass–radius relationships for idealized planets consisting of pure hydrogen, water, rock (Mg$_2$SiO$_4$), and iron are shown as blue lines. Green and brown lines denote Earth-like composition (67% rock, 33% iron) and Mercury-like composition (40% rock, 60% iron). Exoplanet masses, radii and their associated errors are from the Exoplanet Orbit Database (http://exoplanets.org; downloaded on 1 September 2013). Planets with fractional mass uncertainties of over 50% are not shown.

METHODS SUMMARY

We fitted Keck-HIRES spectra of Kepler-78 with stellar atmosphere models using Spectroscopy Made Easy to measure the star’s temperature, gravity and iron abundance. These spectroscopic parameters were used to estimate the host star’s mass, radius and density—crucial parameters from which to determine the planet’s mass, radius and density—from empirical relationships calibrated by precisely characterized binary star systems. Using this stellar density as a constraint, we reanalysed the Kepler photometry to refine the planet radius measurement. We observed Kepler-78 with HIRES using standard procedures including sky spectrum subtraction and wavelength calibration with a reference iodine spectrum. We measured high-precision relative radial velocities using a forward model where the de-convolved stellar spectrum is Doppler-shifted, multiplied by the normalized high-resolution iodine transmission spectrum, convolved with an instrumental profile, and matched to the observed spectra using a Levenberg–Marquardt algorithm that minimizes the $\chi^2$ statistic. The time-series radial velocities on eight nights were analysed with several parametric models to account for the small-amplitude, periodic signal from the orbiting planet and the larger-amplitude, quasi-periodic apparent Doppler shifts that are due to rotating starspots. In our adopted harmonic spot model the star-spot signal was modelled as a sum of sine functions whose amplitudes and phases were free parameters. We sampled the multi-dimensional model parameter space with an MCMC algorithm to estimate parameter confidence intervals and to account for covariance between parameters. We found multiple families of models that described the data well and they gave consistent measures of the Doppler amplitude, which is proportional to the mass of Kepler-78b.

Online Content Any additional Methods, Extended Data display items and Source Data are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Supplementary Information is available in the online version of the paper.

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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 A.W.H. (howard@ifa.hawaii.edu) or R.S.-O. (rsanchis86@gmail.com).
METHODS

Stellar characterization. We fitted three Keck-HIRES spectra of Kepler-78 with stellar atmosphere models using Spectroscopy Made Easy (SME)26. The spectra have per-pixel signal-to-noise ratios of 220 at 550 nm. We used the standard 625-nm wavelength intervals, line data and methodology27. Kepler-78 does not have a measured parallax with which to constrain luminosity and gravity. The initial analysis gave an effective temperature $T_{\text{eff}} = 5119 \pm 44$ K, a gravity of $\log(g) (\text{cm s}^{-2}) = 4.751 \pm 0.060$, an iron abundance of $[\text{Fe/H}] = -0.054 \pm 0.040$ dex, and a projected rotational velocity of $V_{\text{sin}i} = 2.2 \pm 0.5$ km s$^{-1}$. These values are the mean of the SME results for the three spectra and the error bars are limited by systematics28. Because this combination of $T_{\text{eff}}$ and $\log(g)$ is inconsistent with the Dartmouth stellar evolutionary model29, we recomputed stellar parameters with $\log(g)$ fixed at the value that is predicted by a stellar model at the value of $T_{\text{eff}}$ from SME, resulting in the stellar parameters in Table 1. We note that the adopted $V_{\text{sin}i} = 2.6 \pm 0.5$ km s$^{-1}$ is consistent with an expectation based on a stellar rotation, size and an equatorial viewing geometry. $V_{\text{sin}i} = V_{\text{eq}} = 2\pi R_{\text{star}}/P_{\text{rot}} = 3.0$ km s$^{-1}$.

We estimated the stellar mass and radius using empirical relationships30 based on non-interacting binary systems that parameterize $M_{\text{star}}$ and $R_{\text{star}}$ as functions of $\log(g)$, $T_{\text{eff}}$ and $[\text{Fe/H}]$. We propagated the errors on the three SME-derived inputs to obtain $M_{\text{star}} = 0.74 \pm 0.05$ $M_{\odot}$ and $R_{\text{star}} = 0.83 \pm 0.05$ $R_{\odot}$. The $M_{\text{star}}$ uncertainty comes from the 6% fractional scatter in the mass–radius relationship31. We adopt an age of 625 million years with an approximate age uncertainty of $\pm 10^{9}$ years. These three ages are self-consistent.

The rotation period of Kepler-78 was previously measured to be $12.5 \pm 1.0$ days32. Using a relationship33 between age, mass and rotation period, we estimate its age to be $750 \pm 150$ million years. The stellar age can also be estimated from the stellar magnetic activity measured by the $S_{\text{11K}}$ index. We computed the spectral-type-independent activity index, $\log(R_{\text{HK}})$, for all HIRES observations of this star and found a median value of $-4.52$ with a 1σ range of $-0.03$. The compilation made use of an estimated broadband photometric colour $B - V = 0.873$, converted34 from $T_{\text{eff}}$. This level of activity is consistent with the value for a 500–700 million-year-old Hyades cluster35. We also constrained the age by searching for the age-sensitive Li I absorption line at 6708 Å. Lithium is depleted relatively quickly in stars of this spectral type by convective mixing. Based on Li I measurements in three clusters with known ages36, our non-detection (Extended Data Fig. 1) suggests an age greater than around 500 million years. These three ages are self-consistent.

We adopt an age of 625 million years with an approximate age uncertainty of 150 million years. We expect a star of this age and activity to have spots that cause radial-velocity variations of $\sim 15$ m s$^{-1}$ (rms).

Transit analysis. Transit parameters are crucial to estimating the planet radius, which in turn affects our ability to estimate the composition of the planet. These parameters were measured previously with the discovery of Kepler-78b (ref. 6). In that study the impact parameter $b$ was nearly unconstrained because the 30-min time sampling of the Kepler long-cadence data cannot resolve the transit ingress time. This leads to an increased uncertainty on transit depth owing to the stellar limb-darkening profile. We constrained the transit parameters using the stellar density ($\rho_{\text{star}}$) obtained from the spectroscopic analysis. Assuming a circular orbit:

$$\rho_{\text{star}} = (3\pi G/P_{\text{rot}}^2)/(a/R_{\text{star}})^3$$

where $a/R_{\text{star}}$ is the scaled semi-major axis, $G$ is the gravitational constant, and $P_{\text{rot}}$ is the orbital period37. This gives us $a/R_{\text{star}} = 2.7 \pm 0.2$, a much tighter constraint than from the transit light curve alone ($a/R_{\text{star}} = 3.0 \pm 0.9$).

Aside from this additional constraint, our transit analysis is similar to the one in ref. 6. In brief, we analysed the Kepler long-cadence data from quarters 1–15 (a total of 3.7 years of nearly continuous observations) to construct a filtered, phase-folded light curve with a final cadence of 2 min. The light curve is modelled with a combination of a transit model38, a model for the out-of-transit modulations and an occultation model. The most relevant transit parameters are the impact parameter, the ratio of stellar radius to orbital distance, and the zero-limb-darkening transit depth. The model is calculated with a cadence of 1 s and averaged over the 30-min cadence of Kepler. In this new analysis, $a/R_{\text{star}}$ is subjected to a Gaussian prior (2.7 $\pm$ 0.2), which leads to a well-measured impact parameter and a reduced uncertainty for the transit depth. We found the best-fit solution and explored parameter space using an MCMC algorithm. The final parameters are $(R_{\text{pl}}/R_{\text{star}}) = 0.175_{-0.010}^{+0.010}$ parts per million, impact parameter $b = 0.68_{-0.03}^{+0.03}$, orbital inclination $i = 75_{-2}^{+3}$ deg, a transit duration of 0.813 $\pm$ 0.014 hours, and $P_{\text{rot}} = 1.20 \pm 0.09_{\text{rms}}$. Error bars encompass 68.3% confidence intervals. Parameter correlations are plotted in Extended Data Fig. 2. These values are compatible with the previous estimate that was not constrained by $a/R_{\text{star}}$ (ref. 6).

Radial-velocity measurements. We observed Kepler-78 with the HIRES echelle spectrometer39 on the 10-m Keck I telescope using standard procedures. Observations were made with the C2 decker (a rectangular opening in the HIRES entrance) (14 $\times$ 0.86 arcsec). This slit is long enough to simultaneously record spectra of Kepler-78 and the faint night sky. We subtracted the sky spectra from the spectra of Kepler-78 during the spectral reduction40.

The HIRES observations span 45 days. On eight nights we observed Kepler-78 intensively, covering 6–8 hours per night. We also gathered a single spectrum on six additional nights to monitor the radial-velocity variations from spots. These once-per-night radial velocities were not used to determine the planetary mass and are shown in Extended Data Fig. 3 but not in Fig. 1.

We measured high-precision relative radial velocities using a forward model where the de-convolved stellar spectrum is Doppler-shifted, multiplied by the normalized high-resolution iodine line transmission spectrum, convolved with an instrumental profile, and matched to the observed spectra using a Levenberg–Marquardt algorithm that minimizes the $\chi^2$ statistic41. In this algorithm, the radial velocity is varied (along with nuisance parameters describing the wavelength scale and instrumental profile) until the $\chi^2$ minimum is reached.

The times of observation (in heliocentric Julian days, HJD), radial velocities relative to an arbitrary zero point, and error estimates are listed in Supplementary Table 1 and plotted in Extended Data Fig. 3. Each radial-velocity error is the standard error on the mean radial velocity of about 700 spectral chunks (each spanning about 2 Å) that are separately Doppler-analysed. These error estimates do not account for systematic Doppler shifts from instrumental or stellar effects. We also measured the $T_{\text{eff}}$ for each HIRES spectrum. This index measures the strength of the inversion cores of the Ca II H and K absorption lines and correlates with stellar magnetic activity42.

We measured the absolute radial velocity of Kepler-78 relative to the Solar System barycentre using telluric sky lines as a reference43. The distribution of telluric radial velocities has a median value of $-3.95$ km s$^{-1}$ and a standard deviation of 0.10 km s$^{-1}$.

Harmonic radial-velocity spot model. Kepler-78 is a young active star, as demonstrated by the large stellar flux variations observed with Kepler. A previous study44 measured $P_{\text{rot}} = 125 \pm 1.0$ days using a Lomb–Scargle periodogram of the photometry. Inspection of the radial velocities measured over one month did indeed show some repeatability with a timescale of about 12–13 days, a sign that star spots are also inducing a large radial-velocity signal (see Extended Data Fig. 3). Using previous work45, we modelled the radial-velocity signal induced by spots with a primary sine function at the rotation period of the star, followed by a series of sine functions representing the harmonics of the stellar rotation frequency. The planet-induced radial-velocity signal is modelled with a sinusoid, assuming zero eccentricity and using a linear ephemeris fixed to the best-fit orbital period and phase46. The final model for the radial velocity at time $t$ is:

$$R V(t) = -K \sin[2\pi(t - t_0)/P] + \sum_{n = 1}^{\infty} a_n \sin [n2\pi(t - t_0)/P_{\text{rot}}]$$

where $K$ is the semi-amplitude of the planet-induced radial-velocity signal, $t$ is a time of transit, $P$ is the orbital period, $t_0$ is an arbitrary radial velocity offset, $i$ runs from 1 to $N$, where $N$ is the number of harmonics used, $P_{\text{rot}}$ is the rotation period, and finally $a_n$ and $\varphi_n$ are the parameters added for each of the $N$ harmonics. The amplitude $a_n$ is always chosen to be positive, and $\varphi_n$ is constrained to be positive and smaller than $2\pi$. The time $t$ was set to zero at 2,456,446 in HJD format. $P$ and $t_0$ were
These values are the median and 68.3% confidence regions of marginalized measurement to the spot model. We found a second family of solutions with descriptors describing the starspots are $(p, s)$ set with three and four consecutive harmonics, giving a best-fit standard deviation on positive and negative values to prevent a bias towards larger planet mass. Our task was to measure the planet's mass given knowledge of its orbit. We used an MCMC algorithm to explore the model parameter space. The best-fit model and randomly selected models from the MCMC chain are shown in Extended Data Fig. 3. The key result is $K = 1.53 \pm 0.45 \text{ m s}^{-1}$, which is consistent with the value from the harmonic spot model. The lower precision of the offset-slope model (3.4$r$ versus 4.1$r$ significance) results from greater model flexibility. The slopes and offsets on nearby nights are not constrained to produce continuous spot variations as a function of time. For this reason we adopted the harmonic spot model.

As an additional test of the sensitivity to model details, we used the offset-slope framework to model a subset of the radial velocities. Within each night, we selected the median values from each group of three radial velocities ordered in time. This selection naturally rejects outlier radial velocities and matches the observing style on nights 2–8 when three groups of three measurements were made as close as possible to orbital quadratures (maximum or minimum radial velocity). (On night 8, the final group of radial velocities has only two measurements; we used the mean of those two radial velocities for this test.) Our MCMC analysis of these median radial velocities gave a similar result, $K = 1.26 \pm 0.38 \text{ m s}^{-1}$, that is consistent with the above results at about the 1$r$ level. We conclude that our detection of Kepler-78 is not strongly sensitive to spot model assumptions or to individual radial-velocity measurements.

We searched for additional $\gamma^2$ minima to assess the sensitivity of our mass measurement to the spot model. We found a second family of solutions with $K = 1.18 \pm 0.45 \text{ m s}^{-1}$, with a slightly larger $\sigma_{\gamma^2} = 2.3 \pm 0.3 \text{ m s}^{-1}$. A model with the first four harmonics gives $K = 1.27 \pm 0.31 \text{ m s}^{-1}$, with $\sigma_{\gamma^2} = 2.2 \pm 0.3 \text{ m s}^{-1}$. Second, we included all of the radial velocities (including the six radial velocities measured on nights without intensive observations) and fitted the complete data set with three and four consecutive harmonics, giving $K = 1.80 \pm 0.43 \text{ m s}^{-1}$ and $\sigma_{\gamma^2} = 2.4 \pm 0.3 \text{ m s}^{-1}$ for the three-harmonics model, and $K = 1.77 \pm 0.41 \text{ m s}^{-1}$ and $\sigma_{\gamma^2} = 2.2 \pm 0.3 \text{ m s}^{-1}$ for the four-harmonics model. Although the coefficients and phases of the sine functions changed with each test, $K$ remained compatible with the value from our adopted model. We also checked that $K$ is not correlated with any other model parameters in the MCMC distribution.

We estimate the probability that radial-velocity noise fluctuations conspired to produce an apparently coherent signal with the precise period and phase of Kepler-78, and therefore establish that the joint occurrence of the two signals is significant. Outlier for a 4$r$ outlier for a normally distributed random variable. We adopted $\gamma^2$ for the fractional error on $K$ is approximately 4. Note that this is not the false alarm probability commonly computed for new Doppler detections of exoplanets. In those cases one must search over a wide range of orbital periods and phases to detect the planet, and also measure the planet's mass. Here the existence of the planet was already well established. Our task was to measure the planet's mass given knowledge of its orbit.

Offset-slope radial-velocity spot model. To gauge the sensitivity of our results to model assumptions, we considered a second radial-velocity model. Like the harmonic spot model, the offset-slope model consists of two components. The Doppler signal from the planet is a sinusoidal function of time with the period and phase held fixed at the values from the photometric analysis. The spot variations are approximated as linear functions of time with slopes and offsets specific to each night, providing much greater model flexibility. This model for the radial velocity at time $t$ on night $n$ is:

$$ RV(t) = -K \sin[2\pi(t-t_n)/P] + \gamma_n + \eta_n(t-t_n) $$

where $\gamma_n$ is a radial-velocity offset, $\eta_n$ is a radial-velocity slope (velocity per unit time), and $t_n$ is the median time of observation specific to night $n$. The other symbols are as defined above. As with the previous model, a radial-velocity jitter term was added in quadrature to the errors and $P$ and $t_n$ were fixed (Table 1). All together, the offset-slope model contains 18 free parameters.

We used an MCMC algorithm to explore the model parameter space. The best-fit model and randomly selected models from the MCMC chain are shown in Extended Data Fig. 3. The key result is $K = 1.53 \pm 0.45 \text{ m s}^{-1}$, which is consistent with the value from the harmonic spot model. The lower precision of the offset-slope model (3.4$r$ versus 4.1$r$ significance) results from greater model flexibility. The slopes and offsets on nearby nights are not constrained to produce continuous spot variations as a function of time. For this reason we adopted the harmonic spot model.
Extended Data Figure 1 | Wavelength-calibrated spectra of three stars near the age-sensitive Li I line (6,708 Å). This line is not detected in the Kepler-78 spectrum, suggesting that lithium has been depleted, consistent with an age exceeding half a billion years for this K0 star. The lithium line is also not detected in the 4.6-billion-year-old Sun. (Gyr, billion years; Myr, million years.) It is clearly seen in the rotationally broadened spectrum of [PZ99] J161618.0-233947, a star whose spectral type (G8) is similar to that of Kepler-78, but that is much younger (about 11 million years)⁴. Additional iron and calcium lines are labelled.
Extended Data Figure 2 | Correlations between model parameters in the transit analysis. Greyscale contours denote confidence levels, with thick black lines highlighting the 1σ, 2σ and 3σ contour levels. The strongest correlations are between transit depth, scaled semi-major axis and impact parameter.
Extended Data Figure 3 | Apparent radial-velocity variations of Kepler-78 for the offset-slope model. The top panel shows the complete 45-day time series of relative radial velocities (red filled circles). Eight grey boxes highlight nights of intensive observations. The measurements from these nights are shown in the eight subpanels. In each subpanel, the radial velocities (red filled circles) and best-fit offset-slope model (solid black line) are shown. The radial-velocity curves for 100 randomly selected models from the MCMC chain are underplotted in grey, showing the range of variation within the model distribution.