Exoplanet detections have revolutionized astronomy, offering new insights into solar system architecture and planet demographics. While nearly 1,900 exoplanets have now been discovered and confirmed, none are still in the process of formation. Transition disks, protoplanetary disks with inner clearings, are natural laboratories for the study of planet formation. Some transition disks show evidence for the presence of young planets in the form of disk asymmetries or infrared sources detected within their clearings, as in the case of LkCa 15 (refs 8, 9). Attempts to observe directly signatures of accretion onto protoplanets have hitherto proven unsuccessful. Here we report adaptive optics observations of LkCa 15 that probe within the disk clearing. With accurate source positions over multiple epochs spanning 2009–2015, we infer the presence of multiple companions on Keplerian orbits. We directly detect Hα emission from the innermost companion, LkCa 15 b, evoking hot (about 10,000 Kelvin) gas falling deep into the potential well of an accreting protoplanet.

We observed LkCa 15 using the high-contrast imaging technique of non-redundant masking (NRM)11, at the Large Binocular Telescope (LBT) in Ks (λc = 2.16 μm) and L′ (λc = 3.7 μm; see Extended Data Table 1). We detect two components, LkCa 15 b and c, in both bands, with consistent positions across wavelength given the uncertainties (see Table 1, Extended Data Fig. 1). We detect a faint, third component, LkCa 15 d, at L′ only. Since d is significantly fainter than b and c, and not detected at Ks, we focus on the other two sources in the following analysis, but include discussion of the putative third companion where relevant.

We also observed LkCa 15 in Hα (λc = 655.8 nm) using the Magellan Adaptive Optics System (MagAO) in Simultaneous Differential Imaging (SDI) mode (see Methods). We detect LkCa 15 b in these data, at a signal-to-noise of 6.4 and a position that agrees with the LBT observations (see Table 1, Extended Data Figs 2–5, Extended Data Table 2). LkCa 15 c was not detected in Hα, perhaps owing to higher extinction along the line of sight or lower accretion rates at the time of the observations. Both b and c lie well within the disk clearing (Fig. 1), which extends to a stellocentric radius of 56 au14.

We compare the positions of LkCa 15 b and c to the infrared signal seen in 2009–2010 NRM observations. As shown in Fig. 2, orbital fits (fixed to the outer disk plane: inclination i = 50°, position angle θ = 150°) suggest distinct orbits, with b moving faster (semi-major axis, a = 14.7 ± 2.1 au) than c (a = 18.6 ± 2.5 au). Taking the semimajor axis uncertainties into account and requiring that these orbits be stable, b and c must have masses lower than 5–10 times that of Jupiter (Mj)15,16, with masses over 5 Mj allowed only in the case of a 2:1 resonance. For completeness, we performed a series of four-body simulations to show that stable orbital solutions exist including LkCa 15 d, with three planet masses ≤0.5MJ (see Methods, Extended Data Figs 6, 7) and higher masses for b and c allowed with a less massive d.

We calculate infrared fluxes for LkCa 15 b and c, and compare them to circumplanetary accretion disk models17,18 and hot-start19 models of sub-stellar mass companions shortly after accretion has ceased (see Fig. 3). From the LkCa 15 A magnitudes (2MASS Ks = 8.1620 and IRAC m1.6 = 7.6121), we derive fluxes of 1.4 ± 0.7 mJy at Ks and 2.5 ± 1.2 mJy at L′.

Table 1 | Model and experimental results

| Component | Date       | Instrument | λ           | PA (°) | t (mas) | Δt (mag) | M (mag) | M/ΔM | ΔM/Δt | a (au) |
|-----------|------------|------------|-------------|--------|---------|----------|---------|-------|-------|--------|
| LkCa 15 b | 15 Nov 2014 | MagAO      | Hα = 655.3 nm | –104 ± 3 | 93 ± 8  | 5.2 ± 0.3 | 15.8 ± 0.3 | 3 × 10^-6 | 14.7 ± 2.1 |
| LkCa 15 b | 5–7 Feb 2015 | LBT        | Ks = 2.18 μm | –86 ± 26 | 125 ± 35 | 6.0 ± 0.5 | 14.2 ± 0.5 | 10^-5   | 14.7 ± 2.1 |
| LkCa 15 b | 15 Dec 2014 | LBT        | L′ = 3.8 μm | –100 ± 11 | 106 ± 19 | 5.4 ± 0.5 | 13.6 ± 0.5 | 10^-5   | 14.7 ± 2.1 |
| LkCa 15 c | 5–7 Feb 2015 | LBT        | Ks = 2.18 μm | –48 ± 22 | 85 ± 15  | 5.5 ± 0.5 | 13.7 ± 0.5 | 10^-5   | 18.6 ± 2.5 |
| LkCa 15 c | 15 Dec 2014 | LBT        | L′ = 3.8 μm | –44 ± 15 | 68 ± 22  | 4.8 ± 0.3 | 12.9 ± 0.3 | 10^-5   | 18.6 ± 2.5 |
| LkCa 15 d | 15 Dec 2014 | LBT        | L′ = 3.8 μm | 14 ± 3 | 87 ± 17  | 5.9 ± 0.3 | 14.1 ± 0.3 | 5 × 10^-6 | 18.0 ± 6.4 |

* Position angle measured east of north.
† Stellocentric separation.
§ Absolute magnitude.
¶ Planet mass times accretion rate.
© Best fit orbital semi-major axis.
at L′ for b, and 2.3 ± 1.1 mJy at Ks and 2.5 ± 1.2 mJy at L′ for c. These are consistent with accretion disks having inner radii \( R_{\text{in}} = 2R_\text{J} \) and planet mass times accretion rate \( M_\text{J} \dot{M} = 10^{-5} M_\text{J}^2 \text{yr}^{-1} \). However, changing \( R_{\text{in}} \) affects both the total disk flux and its colour. The large uncertainties on fluxes and colours allow us to constrain \( R_{\text{in}} \) only to within a factor of ~2, translating to a factor of ~2–3 uncertainty in \( M_\text{J} \dot{M} \) (for example, a \( R_{\text{in}} = 1R_\text{J} \), \( M_\text{J} \dot{M} \approx 3 \times 10^{-6} M_\text{J}^2 \text{yr}^{-1} \) disk can also reproduce the observations).

While the hot-start model shown in Fig. 3 can approximately produce the Ks and L′ emission for b and c, the observations are best explained by an accretion disk model. The hot start model can only match a previously established 1.55 μm upper limit on the contrast of the structure within the disk gap (\( \Delta H \approx 7 \text{ mag} \)) if the extinction is significantly higher than inferred towards the star. Moreover, even a highly extincted hot-start model cannot reproduce the strong emission at 4.7 μm (contrast of \( \Delta M \approx 3.5 \text{ mag} \)). Emission from an accretion disk increases from L′ to M band, while the hot-start model produces little M band emission. Finally, a cooling photosphere produces no Hα emission, firmly ruling out the hot-start model as the source of LkCa 15 b.

Since LkCa 15 b is detected at Hα, an accretion tracer22–24, its nature as an accreting protoplanet is clear. LkCa 15 b’s Hα contrast, corrected for A′s Hα excess and assuming equal extinction to A (\( A_{\text{Hα}} = 0.75 \text{ mag} \)), corresponds to a line flux of ~6 × 10^{-5} L⊙. Assuming similar accretion luminosity (\( L_{\text{acc}} \)) scalings to low-mass T Tauri stars12,23 gives \( L_{\text{acc}} \approx 4 \times 10^{-4} L_\odot \), yielding \( M_\text{J} \dot{M} \approx 3 \times 10^{-6} M_\text{J}^2 \text{yr}^{-1} \) for a 1.6R_\text{J} planet26 (\( R_\text{J} \), Jupiter radius). Previous observations showed that low-mass, accreting objects may emit a higher fraction of accretion luminosity at Hα22; assuming similar accretion scalings as T Tauri stars may overestimate \( L_{\text{acc}} \). Extinction towards b is also uncertain; while we assume equal extinction to A and b, localized extinction can alter the numbers quoted above. While the uncertainties are large, this \( M_\text{J} \dot{M} \) is consistent with that estimated from the infrared fluxes.

Previous investigators posited a single protoplanet in LkCa 15, accreting material from its co-orbital surroundings8. While the semimajor axis uncertainties do not formally rule out b and c (and d, see Extended Data Fig. 6) being co-orbital, physical arguments show that they cannot be gravitationally bound. The size of the previously reported emission (several AU) is larger than a Hill radius (~1.8 AU for a 10 M_\text{J} planet (M_\text{J}, Jupiter mass orbiting a 1 M_\odot star at 10 AU), and much larger than the maximum possible size of a circumsolar disk (~1/3 the Hill radius27). Thus the sources cannot be part of a bound, accreting system, and an alternative scenario is required to explain the observations.

We argue further that it is difficult to explain LkCa 15 b and c (and d) with an orbiting clump of gravitationally unbound dust within the disk gap, emitting thermally or in scattered light. At a distance of ~10 AU, neither LkCa 15 A nor a companion with a contrast of ~5 magnitudes can heat dust sufficiently to emit at 2–4 μm. Assuming isotropic single scattering, we calculate that an optically thin spherical clump of dust, perhaps resulting from a recent planetesimal collision, could produce the contrast observed at a single wavelength.

**Figure 1** | Composite Hα, Ks, and L′ image. a, The coloured image shows Hα (blue), Ks (green), and L′ (red) detections at the same scale as VLA millimetre observations29 (greyscale). b, Zoomed in composite image of LBT and Magellan observations, with b, c, and d marked.

**Figure 2** | Position evolution. a, LkCa 15 b position angle and separation (inset) evolution, showing Hα (blue), Ks (green), and L′ (red). The earliest three points indicate previous observations3; others show fits to our data. Coloured and black 1σ error bars are from a nonlinear algorithm and a grid, respectively (see Methods). The yellow shading spans the 1σ allowed parameters from orbital fitting. Solid and dotted curves show stable orbits for 0.5 M_\text{J} and 1.0 M_\text{J} planets, respectively. b, Same as a, for LkCa 15 c. Stable orbits for 0.5 M_\text{J} (solid) and 1.0 M_\text{J} (dotted) planets. mas, milliarcsecond.

**Figure 3** | Spectral energy distributions. Symbols indicate fluxes for LkCa 15 b, c (squares), and d (diamonds), showing Hα (dark blue), Ks (green), and L′ (red). The light and dark blue arrows mark previously-published H-band and 3μ 642 nm upper limits for LkCa 15 b, respectively. The lines show accretion disk and hot-start models. The disk models are simple combinations of blackbody spectra17, a suitable approximation for the case of a cool (T < 1,500 K) stellar atmosphere where dust opacity dominates. The \( M_\text{J} \dot{M} \) calculated from the Hα flux agrees with that inferred from the infrared measurements (see text).
However, observing this clump before it sheared out would be a priori unlikely, since the viscous timescale at 10 AU is just ~3% of the age of the system.

Observations argue strongly against this explanation as well. Scattering cannot cause increasing emission from H to M band, since dust opacity decreases with increasing wavelength. Furthermore, since dust opacity is equal between Hα and the nearby continuum, scattering signals have equal contrast in both narrowband filters. Scaling the continuum image by the LkCa 15 A Hα-to-continuum flux ratio and subtracting it from the Hα image should only lead to an Hα detection if scattering is not the emission mechanism. Indeed, this yields a LkCa 15 b detection with signal-to-noise of 4.8. While the Wollaston beam splitter in MagAO’s SDI mode could lead to contamination by polarized light, the visible polarized scattered light intensity at b’s position is less than ~7% the Hα source flux. It could not cause the Hα detection. This leaves the multiple-planet scenario as the most natural explanation for the data.

Both the infrared and Hα observations show that we are unambiguously witnessing planet formation in LkCa 15. The data offer evidence that giant protoplanets undergo a period of high infrared and Hα luminosity during their accretion phase. In the near future, ALMA’s sensitivity and angular resolution should enable us to detect submillimetre emission from circumplanetary disks. Additionally, while the LBT data published here were taken in single-aperture mode (baselines up to ~8 m), non-redundant masking using the co-phased LBTI will provide 23-m baselines, allowing us to place tight constraints on the companion orbits and to resolve structure at smaller separations. Continued monitoring of accretion tracers from LkCa 15 b will probe whether the accretion is steady or stochastic. This young system provides the first opportunity to study planet formation and disk–planet interactions directly.

Online Content Methods, along with any additional 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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Author Contributions This work merged two independently acquired and analysed data sets. S.S. led preparation of the manuscript, the orbital fits, and the acquisition and analysis of the LBT data while K.B.F. led the acquisition and analysis of the MagAO data, development of the MagAO SDI pipeline, and drafted MagAO manuscript sections. S.S., K.B.F., J.E., L.C., P.H., A.S., J.M., and K.M. contributed to one or both observing proposals. J.E. modelled circumplanetary disk and hot-start scenarios, developed the NRM mode at LBT, and supervised the effort of S.S.; L.C. carried out Hα luminosity calculations and oversaw the MagAO effort. P.H. led LBTI development and support, and helped commission the NRM mode at LBT. K.K. carried out orbital stability analysis. J.M. developed the KLIP code used in MagAO data analysis. P.T. helped develop the NRM mode at LBT. B.M. supervised the effort of K.B.F., S.S., K.B.F., J.E., L.C., and K.K. contributed key aspects of the manuscript. A.S., V.B., D.D., E.S., and A.V. supported the LBT observations. J.M., K.M., T.R., and A.W. supported the MagAO observations.
METHODS
LBT observations and data reduction. We observed LkCa 15 using non-redundant masking (NRM)\(^1\) with LBT/LMIRCam\(^{26,31}\) in December 2014 and February 2015. NRM transforms a conventional telescope into an interferometric array through the use of a pupil-plane mask, providing better point-spread function (PSF) characterization and resolving angular scales even within \(\lambda/D\). We used LMIRCam’s 12-hole mask in single-aperture mode, yielding 1.4–7.0 m baselines. We broke up the observations into “visits,” each consisting of an identical set of integrations on LkCa 15 and an unresolved calibrator star (Extended Data Table 1). We used three calibrators to lessen the possibility of contamination by a binary calibrator, and included one calibrator, GM Aur, from those observed previously at Keck\(^6\). We let the sky rotate throughout the observations, facilitating calibration of quasi-static speckles. At Ks and \(\lambda’\) we observed LkCa 15 at parallactic angles between \(-37^\circ\) and \(65^\circ\), and \(-65^\circ\) and \(65^\circ\), respectively.

The NRM images show the interference fringes formed by the mask, the Fourier transform of which yields complex visibilities. Sampling the complex visibilities, we calculated squared visibilities (power versus baseline) and closure phases (sums of phases around three baselines forming a triangle). Closure phases eliminate atmospheric phase errors, leaving behind the sum of the intrinsic source phases. The LBT raw closure phase scatter was \(-3^\circ\), significantly lower than the uncertainties in previous NRM observations\(^8\) (\(-4^\circ\)).

For each closing triangle, we fitted a polynomial to all calibrator closure phases as a function of time. We sampled the polynomial at the time of each target observation and subtracted it from each target closure phase. We calibrated using a variety of functions; of these, polynomials up to 2 order in time provided the lowest-scalar calibrated closure phases, with standard deviations of \(1.7^\circ\) at Ks and \(1.9^\circ\) at \(\lambda’\). We calibrated the squared visibilities similarly, dividing by the calibrator rather than subtracting. We calibrated the mask baselines using the observed power spectra and knowledge of the filter bandwidth and plate scale\(^3\).

LBT image reconstruction, model fitting, and parameter error estimation. We fitted models directly to kernel phases\(^33,34\), linearly independent combinations of closure phases, to search for companions. We modelled the central star as a delta function and each companion as another delta function located a distance \(s\) from the star, at position angle \(\alpha\), and with contrast \(\Delta\). We sampled the synthetic complex visibilities at the same baselines and parallactic angles as the data, and performed a grid fit, using a \(\Delta^\alpha\) to determine our parameter confidence intervals. Due to a known degeneracy between companion separation and contrast\(^35\), brighter companions at smaller separations provide equally good fits as those fainter and farther out. We thus performed fits to individual wavelengths to verify that the positions of \(b\) and \(c\) agreed across wavelength, then calculated a best fit where the companions coincided at Ks and \(\lambda’\) (see Table 1). The model grids in this study required \(-50,000\) CPU hours to generate, but were computed in a reasonable amount of time using the University of Arizona’s El Gato supercomputer.

We also reconstructed images from the closure phases. To produce cleaner images, we re-calibrated the closure phases towards the best-fit \(Ks + \lambda’\) model using an optimized calibrator weighting technique applied in previous NRM studies\(^6\). This calibration is similar to the locally optimized calibration of images (LOC\(^{36}\)) technique applied in direct imaging. Since this scheme can remove signal and underestimate errors, we applied it only to produce images (see Extended Data Fig. 1), using the polynomial calibration to estimate companion parameters. As a consistency check, we reconstructed images using both the BiSpectrum Maximum Entropy Method (BSMEM)\(^37\) and the Monte-Carlo Markov Chain IMager algorithm (MACIM)\(^38\). The companion positions agree between the two algorithms, although BSMEM produces more compact emission towards each component.

Companion parameter error estimation for previously-published Keck data. Orbits derived from parameter errors for previously published\(^9\) Keck observations and the LBT observations to be consistently estimated. The published errors for the 2009–2010 companion parameters were generated using the nonlinear algorithm MPFIT\(^{40}\). While nonlinear fitters are often employed for computational expediency, the Levenberg–Marquardt algorithm can easily fall into a local minimum and underestimate parameter errors. The LBT grid \(\chi^2\) surfaces show local minima for both two- and three-companion fits, rendering MPFIT unreliable unless the starting parameters were very close to the global minimum. We compared MPFIT and grid-based parameter errors for the LBT data, and found that MPFIT significantly underestimated the errors (Fig. 2).

To create a “typical” error bar for each Keck companion, we estimated the error bar dependence on contrast using the LBT fits. Errors increased with decreasing companion flux, which we parameterized as a square root dependence. For a given Keck companion we thus scaled our LBT errors by the square root of the LBT-to-Keck flux ratio. We inflated the Keck error bars by a factor of 1.3, the ratio of the uncalibrated closure phase scatter in the Keck data (\(-4^\circ\)) to that for the LBT data (\(-3^\circ\)). We capped the separation upper limits at 30 μm, where D is Keck’s telescope diameter, 10 m, so that the largest LBT upper limit was at nearly 30 μm, and companions at those distances are no longer subject to the separation-contrast degeneracy.

MagAO data reduction and analysis. We observed LkCa 15 on November 15 and 22, 2014, as part of the Giant Accreting Protoplanet Survey (GAPP\(^{39}\)), a visible-wavelength survey of bright transition disks. GAPP\(^{39}\) stars are imaged simultaneously in Hα (0.656 μm, \(\lambda = 6 \text{ nm}\)) and the nearby stellar continuum (0.642 μm, \(\lambda = 6 \text{ nm}\)) using the S85–actuator Magellan Adaptive Optics (MagAO) camera\(^{42,43}\). The continuum channel provides a sensitive, simultaneous probe of the stellar PSF, allowing for effective removal of residual starlight and isolation of Hα emitting sources\(^{42,43}\). The observations used new single-substrate narrowband Hα and continuum filters, a significant improvement over the previous VizA SDF filters, which suffered from ghost images\(^2\).

Seeing during the November 2015 observations was better than the site median (0.56 ± 0.06′), winds were low (3.6 ± 0.9 mph), and humidity was typical of the season (37.0 ± 2.8%). Strehl ratio was low (<10%), and difficult to measure meaningfully. We characterized image quality using the stellar full-width at half-maximum (FWHM), 0.07′ (at 0.65 μm over 30 integrations), a significant improvement over the seeing. We collected 316 30-s closed AO-loop images, with a total of 156 min of integration time and 48.6° of sky rotation. We selected the 149 LkCa 15 images with the lowest residual wavefront error (~50°), equivalent to 74.5 min of exposure time. This image subset had 47.6° of sky rotation, with the rotational space well sampled.

The November 22 data were not of sufficient quality to recover LkCa 15 b, due to lower sky rotation (27.0°), shorter total integration (91 min), and shallower individual exposures (15 s). Injected positive planets with the same separation as LkCa 15 b were only recoverable with S/N > 3 at contrasts > 5 × 10\(^{-4}\) (~ nearly an order of magnitude brighter than the measured November 15 LkCa 15 b contrast). For this reason, we discuss only the November 15 data set in the rest of the paper.

Images were first bias-subtracted, registered, and aligned via cross-correlation. The Hα flat field image showed very little non-uniformity across the field (<1%), so a flat field was not applied. We masked CCD dust spots visible in the flat field wherever they affected the image throughput by more than 2%.

We processed the aligned data using angular differential imaging (ADI\(^{46}\), comparing the “classical” method of using a single median PSF for all images (cADI\(^{46}\)) to the Karhunen–Loève image processing (KLIP\(^{48}\)) algorithm, which calculates a least-squares optimum PSF for each image. LkCa 15 b was detected in the Hα channel via both methods, as shown in Extended Data Fig. 2. The planet was not detected in continuum with either method, so continuum images were used as a probe of PSF residuals and scattered light emission from the inner disk. Subtraction of the processed continuum images from the Hα images (‘ASDI’) left behind only true Hα emission\(^2\).

MagAO cADI reductions. We constructed the stellar PSF by median combining images in 0.5° rotational bins and then median combining again to produce a PSF evenly sampled in rotational space. We subtracted the stellar PSF from the individual images, rotated them to a common on-sky orientation and combined them. Given the small separation between LkCa 15 A and b, the planet moved by only 1.5 FWHM over the course of the observations, resulting in self-subtraction and decreasing the FWHM of the processed planet PSF to 4–5 pixels in azimuth. MagAO KLIP-ADI reductions. KLIP reductions were carried out using a well-tested custom IDL code\(^47\). To optimize reduction parameters, we maximized the signal to noise of injected planets (with the same separation and contrast as LkCa 15 b) inserted after using a negative planet to erase the LkCa 15 b signal. Planets were placed at position angles distant from known artefacts, and east or west of the star to avoid the noisier north/south region of the PSF, corresponding to the wind direction during the observations.

To limit self-subtraction, the library from which KLIP builds the stellar PSF is limited to images where a planet would have rotated away from its original position. We explored the size of this exclusion region (“rotational mask”) systematically through fake planet injection, and found that a 5° mask (~1 pixel at \(r = 11\) pixels) produced the highest signal-to-noise recoveries of injected planets. Given the stellar FWHM of 0.07, this resulted in azimuthal self-subtraction, with a processed planetary PSF of 2 pixels in azimuth.

Noise in the KLIP processed images was mostly Gaussian when images were divided into several independently-optimized radial zones, indicating efficient removal of speckles. Dividing these zones azimuthally provided no additional advantage. The final KLIP reductions shown in Extended Data Fig. 2 reflect a PSF divided into 50-pixel (0.4′) annuli. Removal of the median PSF radial profile for the entire image set aided significantly in attenuating the stellar halo, improving the ability of the KLIP algorithm to match residual speckles and enhancing contrast close to the star.
MagAO LkCa 15 b photometry and astrometry. We estimated photometry and astrometry by minimizing residuals after injecting a negative planet at the location of LkCa 15 b. The cube of registered and aligned Ha channel images was scaled by the chosen contrast value, multiplied by \(-1\), and injected into the raw images before KLIP processing. Using the full Ha image cube rather than its median combination simulated variability of the PSF between images.

We generated error bars by injecting false positive planets with similar separations and contrasts to LkCa 15 b after using a negative planet to eliminate the true signature. Planets were placed at position angles away from the wind direction, and spaced by at least 75\% of the measured stellar FWHM. We computed the centroid and peak pixel using a 5-pixel aperture around each planet, and assigned the standard deviations in recovered flux and position as our 1\(\sigma\) photometric and astrometric uncertainties, respectively (see Extended Data Table 2 and Extended Data Fig. 3).

Signal-to-noise of the MagAO H\(\alpha\) detection. To create signal-to-noise ratio (SNR) maps, we calculated a radial noise profile using the standard deviation of 1-pixel-wide annuli and divided it into the raw images. In the raw maps, LkCa 15 b has SNR \(\approx 3\)–4. Smoothing by a Gaussian with a 2-pixel FWHM maximized the SNR of injected fake planets, so we applied this smoothing to the final science images, resulting in peak SNRs of 4.4 and 6.8 in the KLIP Ha and ASDI images, respectively. However, directly-imaged exoplanets at small separations suffer from small number statistical effects\(^{48}\). The underlying speckle distribution is difficult to probe given the small number of independently sampled noise regions. In an annulus at the distance of LkCa 15 b (1.3 FWHM), seven noise regions exist, leading to corrected\(^{48}\) SNRs of 4.1 and 6.4 for the Ha and ASDI images, respectively. The ASDI detection corresponds to a false positive probability of \(3 \times 10^{-4}\) using the Student’s \(t\)-distribution with 6 degrees of freedom.

Comparing the LkCa 15 b SNR to the distribution of values in the ASDI SNR map (Extended Data Fig. 4), shows that it is a clear outlier. Comparison of the peak pixel in an aperture centred on b to those in the surrounding noise apertures (Extended Data Figs 4, 5) further demonstrates b’s statistical significance.

In addition to the high SNR, low false positive fraction, and the statistics presented in Extended Data Fig. 4, the Ha detection is significant because it occurs at the same location as the independent LBT detection. This further reduces the probability of a false positive detection in the MagAO data, since speckles have no preferred location.

Fidelity of the MagAO LkCa 15 b detection. Neither the existence of LkCa 15 b nor its derived parameters are dependent on our choice to include only the top 50\% of raw images. The planet appears at the same location and with the same approximate brightness when processing all 316 images, as well as only the top 25\% of images. An excess with SNR > 3 appears at LkCa 15 b’s location with a wide range of KLIP zone geometries and rotational masks, when any number of KL modes from 2 to 100+ are removed, and whether or not the median radial profile of the PSF is subtracted before processing.

Limits on MagAO LkCa 15 b continuum flux. We used simulated planet detections to place an upper limit on LkCa 15 b’s continuum flux. We injected planets into the raw continuum channel images with a range of contrasts and at positions near LkCa 15 b. We then measured the SNR of each simulated detection to determine the confidence at which we could detect a given contrast. As above, we applied a small number statistical correction\(^{48}\) to the SNR of each recovered planet. The simulations suggest that we would have detected an excess with a corrected SNR of 3 (false positive fraction of \(10^{-2}\)) for a continuum source with contrast greater than 5 \times 10^{-3}. Since LkCa 15 A is 1.8 times brighter at Ha than continuum, this corresponds to an Ha-to-continuum flux ratio lower limit of 2.7.

Limits on MagAO LkCa 15 c Ha contrast. We established limits on the LkCa 15 c Ha contrast using false planet injections, first using a negative planet to eliminate the LkCa 15 b signal. We injected planets with a range of contrasts at positions near LkCa 15 c. We then measured the SNR of each simulated detection to determine the confidence at which we could detect a given contrast. As above, we applied a small number statistical correction\(^{48}\) to the SNR of each recovered planet. The simulations suggest that we would have detected an excess with a corrected SNR of 3 (false positive fraction of \(10^{-2}\)) for a continuum source with contrast greater than 5 \times 10^{-3}. Since LkCa 15 A is 1.8 times brighter at Ha than continuum, this corresponds to an Ha-to-continuum flux ratio lower limit of 2.7.

Stability analysis with LkCa 15 d. We ran a series of orbit integrations to demonstrate that stable solutions exist for b, c, and d at separations within the inner region of the PSF, leading to decreased sensitivity; here contrasts of 6 \times 10^{-3} peaks near c’s location boost the SNRs for recovered planets.

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Extended Data Figure 1 | Image reconstructions. a–d. Images reconstructed from closure phases, showing $K_s$ polynomial (a) and LOCI-like (b) calibrations, and $L'$ polynomial (c) and LOCI-like (d) calibrations. Both calibrations yielded reconstructed images with at least two distinct components. The LOCI-like calibration moved each companion within the position errors derived from the grid $\chi^2$ surface.
Extended Data Figure 2 | KLIP and ADI Hα SNR maps. a–c, Final KLIP SNR maps for Hα (a), continuum (b) and the difference between the two (ASDI, c). d–f, Final cADI SNR maps in the same order. Dividing by the radial noise profiles to create these maps should normalize the noise distribution at all radii within the speckle-dominated regime.

The presence of dark holes in the maps suggests that we are speckle-dominated out to the AO control radius at $r \approx 20$ pixels (white, dashed circles). LkCa 15 b's separation is 11.6 pixels. The yellow keystones indicate the $2\sigma$ range of allowed astrometry for the KLIP ASDI point source (upper right) based on negative simulated planet injection.
Extended Data Figure 3 | False positive planet SNR maps. a, LkCa 15 final ASDI SNR map. b, ASDI SNR map with LkCa 15 b removed. c–h, ASDI SNR maps of false positive planets injected at a radius of 11 pixels and contrast of $8 \times 10^{-3}$. Recovered parameters for these planets are given in Extended Data Table 2 and were used to determine $1\sigma$ astrometric and photometric uncertainties.
Extended Data Figure 4 | Ha detection noise statistics. a, Histogram of noise (non-planet) pixel values in the SNR map within the speckle dominated regime (black line) compared to a Normal distribution (red line). The black arrow denotes the location of the peak SNR value for LkCa 15 b. b, Histogram of the peak values in all noise apertures (see Extended Data Fig. 5) within the control radius (black line) compared to a Normal distribution (red line). The black arrow shows the peak pixel value in the LkCa 15 b aperture.
Extended Data Figure 5 | Noise apertures. Noise apertures (black circles) surrounding LkCa 15 A used to calculate the statistics presented in Extended Data Fig. 4. Colour indicates SNR.
Extended Data Figure 6 | LkCa 15 d position angle and separation versus time. Evolution of position angle and separation (inset) for LkCa 15 d. Green and red points indicate Ks and L′ data, respectively. In both panels, the earliest three points correspond to previously published Keck observations, and the most recent points show best fits to our data. The coloured error bars are derived using the nonlinear algorithm MPFIT, which significantly underestimates the parameter errors compared to the more robust grid, Δχ² (black error bars; see Methods). The yellow shaded region spans the position angles and separations allowed at 1σ by the multi-epoch observations, which have semi-major axes between 12.6 and 24.7 au. Solid curves show the best-fit orbit (18.0 au), and dashed curves show an orbit (24.7 au) that is stable for a 0.5 MJ planet exterior to LkCa 15 b and c. Lower mass planets or resonant configurations permit stable orbits for LkCa 15 d at smaller stellocentric radii.
Extended Data Figure 7 | Orbital integration results. a, Stable orbits for LkCa 15 b, c, and d over a 10 Myr integration. b, Osculating eccentricity. The planets are each 0.5 $M_J$ with initial semi-major axes of 12.7, 18.6, and 24.7 au, initial eccentricities of order $10^{-5}$, and relative inclinations of <1°. After a 10 Myr integration, the eccentricities of c and d have increased to only a few percent.
Extended Data Table 1 | Summary of observations

| Target | Right Ascension (hh mm ss.sss) | Declination (dd mm ss.ss) | \( t_{\text{ex}} \) (s) | \( N_{\text{frames}} \) * | \( N_{\text{visits}} \) † | Total Time (h) | Average Seeing (asec) |
|--------|---------------------------------|--------------------------|-----------------|-----------------|-------------------|-----------------|-----------------|
| **2014 Nov 15: \( \text{H} \alpha \) and 642 nm continuum** | | | | | | | |
| LkCa 15 | 04 39 17.796 | +22 21 03.48 | 30 | 316 | 1 | 2.63 | 0.56 |
| **2014 Nov 22: \( \text{H} \alpha \) and 642 nm continuum** | | | | | | | |
| LkCa 15 | 04 39 17.796 | +22 21 03.48 | 15 | 364 | 1 | 1.52 | N/A ‡ |
| **2014 Dec 15: L′** | | | | | | | |
| LkCa 15 | 04 39 17.796 | +22 21 03.48 | 10 | 40 | 15 | 1.67 | 0.76 |
| HD284668 | 04 42 09.686 | +22 13 55.82 | 10 | 40 | 5 | 0.56 |
| HD284581 | 04 40 32.495 | +22 31 32.88 | 10 | 40 | 4 | 0.44 |
| GM Aur | 04 55 10.983 | +30 21 59.54 | 10 | 40 | 5 | 0.56 |
| **2015 Feb 5-7: Ks** | | | | | | | |
| LkCa 15 | 04 39 17.796 | +22 21 03.48 | 20 | 20 | 19 | 2.11 | 0.95 |
| HD284668 | 04 42 09.686 | +22 13 55.62 | 20 | 20 | 7 | 0.78 |
| HD284581 | 04 40 32.495 | +22 31 32.88 | 20 | 20 | 7 | 0.78 |
| GM Aur | 04 55 10.983 | +30 21 59.54 | 20 | 20 | 6 | 0.67 |

* Number of frames in each visit.
† Each visit consists of all images taken before switching between target and calibrator.
‡ The seeing monitor was unavailable during the 22 November observations.
### Extended Data Table 2 | False planet injection results

| P.A. * (°) | $X_{\text{in}}$ † (pix) | $Y_{\text{in}}$ ‡ (pix) | $X_{\text{rec}}$ § (pix) | $Y_{\text{rec}}$ ¶ (pix) | $\Delta \text{P.A.}$ ‥ (°) | $\Delta s$ # (pix) | Peak SNR |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|---------|
| -77        | 135.2           | 127.0           | 136.0           | 127.3           | -0.53           | -0.85           | 8.9     |
| -44        | 132.1           | 132.4           | 132.8           | 132.8           | 1.11            | -0.78           | 6.2     |
| 38         | 117.7           | 133.2           | 116.2           | 134.3           | -2.25           | -1.80           | 4.3     |
| 73         | 114.0           | 127.7           | 112.3           | 127.8           | -1.81           | -1.66           | 4.6     |
| 108        | 114.0           | 121.1           | 113.9           | 122.0           | 4.67            | 0.15            | 5.5     |
| 143        | 117.9           | 115.7           | 118.1           | 116.7           | 2.50            | 0.91            | 4.7     |
| Simulated Planet Means |                |                |                |                | 0.62            | -0.67           | 5.7     |

#### LkCa 15 b Fit Results

| Parameters | $X$ | $Y$ | P.A. | $s$ | Peak SNR |
|------------|-----|-----|------|-----|----------|
|            | 135.8 | 121.8 | -103.4 | 11.6 | 6.8      |

| 1σ Errors |                             |                             |                             |     | ±30%     |
|-----------|-----------------|-----------------|-----------------|-----|----------|
|           | ±2.7            | ±1.0            | ±1.0            |     | ±30%     |

*Input false planet position angle.
†Input false planet X location.
‡Input false planet Y location.
§Recovered false planet X location.
¶Recovered false planet Y location.
‖Recovered minus input false planet position angle.
#Recovered minus input false planet separation.