A global cloud map of the nearest known brown dwarf

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Brown dwarfs—substellar bodies more massive than planets but not massive enough to initiate the sustained hydrogen fusion that powers self-luminous stars1,2—are born hot and slowly cool as they age. As they cool below about 2,300 kelvin, liquid or crystalline particles composed of calcium aluminates, silicates and iron condense into atmospheric ‘dust’3,4, which disappears at still cooler temperatures (around 1,300 kelvin)5,6. Models to explain this dust dispersal include both an abrupt sinking of the entire cloud deck into the deep, unobservable atmosphere5,7 and breakup of the cloud into scattered patches6,8 (as seen on Jupiter and Saturn9). However, hitherto observations of brown dwarfs have been limited to globally integrated measurements9, which can reveal surface inhomogeneities but cannot unambiguously resolve surface features10. Here we report a two-dimensional map of a brown dwarf’s surface that allows identification of large-scale bright and dark features, indicative of patchy clouds. Monitoring suggests that the characteristic timescale for the evolution of global weather patterns is approximately one day.

The recent discovery of the Luhman 16AB system (also called WISE J104915.57-531906.1AB; ref. 12) revealed two brown dwarfs only two parsecs away, making these the closest objects to the Solar System after the Alpha Centauri system and Barnard’s star. Both of these newly discovered brown dwarfs are near the dust-clearing temperature13,14, and one (Luhman 16B) exhibits strong temporal variability of its thermal radiation consistent with a rotation period of 4.9 hours (ref. 15). Luhman 16AB’s proximity to Earth makes these brown dwarfs the first substellar objects bright enough to be studied at high precision and high spectral resolution on short timescales. We observed both of the brown dwarfs for five hours (about one rotation period of Luhman 16B) using the CRyogenic high-resolution InfraRed Echelle Spectrograph26 (CRIRES) at the European Southern Observatory’s Very Large Telescope to search for spectroscopic variability.

Absorption features from CO and H2O dominate the spectra of the brown dwarfs, as shown in Fig. 1. The two objects have similar spectra but the absorption lines are broader for the B component: it exhibits a projected equatorial rotational velocity of 26.1 ± 0.2 km s⁻¹, versus 17.6 ± 0.1 km s⁻¹ for Luhman 16A. Taking Luhman 16B’s rotation period15 and considering that evolutionary models predict these objects to be 1.0 ± 0.2 times the radius of Jupiter17, Luhman 16B’s rotation axis must be inclined less than about 30 degrees from the plane of the sky; that is, we are viewing this brown dwarf nearly equator-on. If the axes of the two brown dwarfs are closely aligned (like those of the planets in our Solar System) then Luhman 16A rotates more slowly than Luhman 16B and the objects either formed with different initial angular momenta or experienced different accretion or spin-braking histories. Alternatively, if the two brown dwarfs have comparable rotation periods (as tentatively indicated by recent observations18) then the two components’ rotation axes must be misaligned, which would imply either an initially aligned system (like the Solar System) that was subsequently perturbed or a primordial misalignment (in contrast to the close alignment more typically observed for pre-main-sequence stellar binaries29). Measuring Luhman 16A’s rotation period is the best way to determine whether the axes of the brown dwarfs are currently aligned or misaligned.

Our data clearly show spectroscopic variability intrinsic to Luhman 16B, and this brown dwarf’s rapid rotation allows us to produce the global surface map shown in Fig. 2 using Doppler imaging techniques20,21. This produces a map that shows a large, dark, mid-latitude region, a shorter rotation period than did its companion. The gaps in the spectra correspond to physical spaces between the four infrared array detectors. The plotted data represent the mean of all spectra. Luhman 16A’s spectrum has been offset vertically for clarity by 1.5 units. The flux is normalized so that the continuum level (the flux level outside of absorption features, as seen, for example, in the far left regions of the spectra) is unity (1.0).

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brighter area on the opposite hemisphere located close to the pole and mottling at equatorial latitudes.

A natural explanation for the features seen in our map of Luhman 16B is that we are directly mapping the patchy global clouds inferred to exist from observations of multiwavelength variability. If this is true, the dark areas of our map represent thicker clouds that obscure deeper, hotter parts of the atmosphere and present a higher-altitude (and thus colder) emissive surface, whereas bright regions correspond to holes in the upper cloud layers that provide a view of the hotter, deeper interior. This result is also consistent with previous suggestions of multiple stratified cloud layers in brown dwarf atmospheres. Because our mapping is mostly sensitive to CO, the map could in principle show a combination of surface brightness (that is, brightness temperature) and chemical abundance variations. Coupled models of global circulation and atmospheric chemistry, maps obtained via simultaneous observations of multiple molecular tracers and simultaneous Doppler imaging and broadband photometric monitoring could distinguish between these hypotheses.

The high-latitude bright spot could be similar to the polar vortices seen on Jupiter and Saturn and predicted to exist on highly irradiated gas giants in short-period orbits around other stars; in this case, the high-latitude feature should still be visible in future maps of Luhman 16B. Jupiter and Saturn exhibit prominent circumplanetary banding, but (as described in the Methods) our analysis is not sufficiently sensitive to detect banding on Luhman 16B. Furthermore, assuming a mean horizontal wind speed of about 300 m s\(^{-1}\) (as predicted by global circulation models of brown dwarfs at these temperatures) the Rhines relation predicts that Luhman 16B should exhibit roughly ten bands from pole to pole—too many to resolve with our 18-degrees-wide maps.

Long-term monitoring of Luhman 16B suggests that its weather conditions change rapidly but remain at least partly coherent from one night to the next, a result that indicates that the characteristic timescale for evolution of global weather patterns is of the order of one day. In this case, successive full nights of Doppler imaging could observe the formation, evolution and breakup of global weather patterns—the first opportunity for such a study outside the Solar System. Such measurements would provide a new benchmark against which to compare global circulation models of dusty atmospheres and could perhaps measure differential rotation in Luhman 16B’s atmosphere.

Future mapping efforts should reveal whether we are mapping variations in temperature, cloud properties or atmospheric abundances: high-resolution spectrographs with broader wavelength coverage than CRIRES should provide better sensitivity and spatial resolution, perhaps sufficient to search for banded cloud structures. Instruments with broader wavelength coverage will also allows maps to be made at multiple wavelengths and using independent molecular tracers (for example, H\(_2\)O). In addition, a few other variable brown dwarfs may be bright enough for these techniques to be applied. Although the day sides of hot, short-period gas giant planets can also be mapped using occultations under favourable conditions, model degeneracies may prevent these efforts from achieving a spatial resolution comparable to that achievable with Doppler imaging. Thus, Doppler imaging in general, and Luhman 16B in particular, represent the best opportunity to challenge and improve our current understanding of the processes that dominate the atmospheres of brown dwarfs and of giant extrasolar planets.

**METHODS SUMMARY**

We extract and calibrate our spectroscopic data using standard techniques (Extended Data Figs 1 and 2) and look for temporal changes in the mean spectral line profiles. Luhman 16B exhibits strong spectroscopic variability but we see no evidence for similar variations in our simultaneously acquired observations of Luhman 16A (Extended Data Fig. 3). A simplified analysis using a parameterized spot model verifies that our observations are consistent with rotationally induced variations (Extended Data Fig. 4). We then produce our global map of brown dwarf Luhman 16B using Doppler imaging.

The technique of Doppler imaging relies on the varying Doppler shifts across the face of a rotating object and has been widely used to map the inhomogeneous surfaces of many rapidly rotating stars. As darker regions rotate across the visible face of the brown dwarf, the Doppler-broadened absorption line profiles exhibit deviations at the projected radial velocities of the darker areas. Features near the equator cause changes across the entire line profile and move across the full span of velocities; features at higher latitudes move more slowly, experience smaller Doppler shifts, and affect a narrower range of velocities.

Our modelling framework is based on that described in ref. 20. We break the brown dwarf’s surface into a 10 × 20 grid, giving an effective equatorial cell size of roughly 20,000 km. The recovered maps do not change significantly if we use finer resolution. We verify our analysis by constructing a number of Doppler images using simulated data. These simulations demonstrate that we can robustly detect large, isolated features with strong brightness temperature contrasts (Extended Data Fig. 5) but that we are not sensitive to axially symmetric features such as zonal banding (Extended Data Fig. 6).

**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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1. Kumar, S. S. The structure of stars of very low mass. **Astrophys. J.** 137, 1121–1125 (1963).

2. Becklin, E. E. & Zuckerman, B. A low-temperature companion to a white dwarf star. **Nature** 336, 656–658 (1988).

3. Lubineau, J. L., Hubbard, W. B. & Marley, M. S. Evolution and infrared spectra of brown dwarfs. **Astrophys. J.** 310, 238–260 (1986).

4. Kirkpatrick, J. D. et al. Dwarfs cooler than "M": the definition of spectral type "L" using discoveries from the 2 Micron All-Sky Survey (2MASS). **Astrophys. J.** 519, 802–833 (1999).

5. Stephens, D. C. et al. The 0.8–14.5 \(\mu\)m spectra of mid-L to mid-T dwarfs: diagnostics of effective temperature, grain sedimentation, gas transport, and surface gravity. **Astrophys. J.** 702, 154–170 (2009).

6. Burgasser, A. J. et al. Evidence of cloud disruption in the L/T dwarf transition. **Astrophys. J.** 571, L111–L114 (2002).

7. Tsuji, T., Nakajima, T. & Yanagisawa, K. Dust in the photospheric environment. II. Effect on the near-infrared spectra of L and T dwarfs. **Astrophys. J.** 607, 511–529 (2004).

8. Ackerman, A. S. & Marley, M. S. Precipitating condensation clouds in substellar atmospheres. **Astrophys. J.** 556, 872–884 (2001).

9. Fletcher, L. N. et al. Retrievals of atmospheric variables on the gas giants from ground-based mid-infrared imaging. **Icarus** 200, 154–175 (2009).

10. Buenzli, E. et al. Vertical atmospheric structure in a variable brown dwarf: pressure-dependent phase shifts in simultaneous Hubble Space Telescope-Spitzer light curves. **Astrophys. J.** 760, L31–L36 (2012).
11. Apai, D. et al. HST spectral mapping of L/T transition brown dwarfs reveals cloud thickness variations. Astrophys. J. 768, 121–136 (2013).
12. Luhman, K. L. Discovery of a binary brown dwarf at 2 pc from the Sun. Astrophys. J. 767, L1–L6 (2013).
13. Knaiae, A. Y. et al. Characterization of the nearby L/T binary brown dwarf WISE J104915.57–531906.1 at 2 pc from the Sun. Astrophys. J. 770, 124–128 (2013).
14. Burgasser, A. J., Sheppard, S. S., & Luhman, K. L. Resolved near-infrared spectroscopy of WISE J104915.57–531906.1AB: a flux-reversal binary at the L dwarf/T dwarf transition. Astrophys. J. 772, 129–135 (2013).
15. Gillon, M. et al. Fast-evolving weather for the coolest of our two new substellar neighbours. Astron. Astrophys. 555, L5–L8 (2013).
16. Käufl, H.-U. et al. CRiRES: a high-resolution infrared spectrograph for ESO’s VLT. Proc. SPIE 5492, 1218–1227 (2004).
17. Burrows, A., Heng, K. & Nampaisarn, T. The dependence of brown dwarf radii on atmospheric metallicity and clouds: theory and comparison with observations. Astrophys. J. 736, 47–60 (2011).
18. Biller, B. A. et al. Weather on the nearest brown dwarfs: resolved simultaneous multi-wavelength variability monitoring of WISE J104915.57–531906.1AB. Astrophys. J. 778, L10–L16 (2013).
19. Wheelwright, H. E., Vink, J. S., Oudmaijer, R. D. & Drew, J. E. On the alignment between the circumstellar disks and orbital planes of Herbig Ae/Be binary systems. Astron. Astrophys. 532, A28 (2011).
20. Vogt, S. S., Penrod, G. D. & Hatzes, A. P. Doppler images of rotating stars using maximum entropy image reconstruction. Astrophys. J. 321, 496–515 (1987).
21. Rice, J. B., Weihau, W. H. & Khokhlova, V. L. Mapping stellar surfaces by Doppler imaging—technique and application. Astron. Astrophys. 208, 179–188 (1989).
22. Agúndez, M. et al. The impact of atmospheric circulation on the chemistry of the hot Jupiter HD 209458b. Astron. Astrophys. 548, A73 (2012).
23. Cho, J. Y.-K., Menou, K., Hansen, B. M. S. & Steeghs, S. The changing face of the extrasolar giant planet HD 209458b. Astrophys. J. 587, L117–L120 (2003).
24. Showman, A. P. & Kaspi, Y. Atmospheric dynamics of brown dwarfs and directly imaged giant planets. Astrophys. J. 776, 85–103 (2013).
25. Vasavada, A. R. & Showman, A. P. Jovian atmospheric dynamics: an update after Galileo and Cassini. Rep. Prog. Phys. 68, 1935–1996 (2005).
26. Freytag, B., Allard, F., Ludwig, H.-G., Homeier, D. & Steffen, M. Radiation-hydrodynamics simulations of cool stellar and substellar atmospheres. ASP Conf. Ser. 448, 855–862 (2011).
27. Collier Cameron, A. & Unruh, Y. C. Doppler Images of AB Doradus. Mon. Not. R. Astron. Soc. 269, 814–836 (1995).
28. Artigau, É., Donati, J.-F. & Delfosse, X. Planet detection, magnetic field of protostars and brown dwarfs meteorology with SPIRou. ASP Conf. Ser. 448, 771–778 (2011).
29. Majeau, C., Agol, E. & Cowan, N. B. A two-dimensional infrared map of the extrasolar planet HD 189733b. Astrophys. J. 747, L20–L24 (2012).
30. de Wit, J., Gillon, M., Demory, B.-O. & Seager, S. Towards consistent mapping of distant worlds: secondary-eclipse scanning of the exoplanet HD 189733b. Astron. Astrophys. 548, A128 (2012).

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METHODS

Observation and data reduction. We observed the Luhman 16AB system for five hours with the Very Large Telescope/CRIRES on 5 May 2013 Universal Time. Our spectra span wavelengths from 2.288–2.345 μm to cover the CO (3,1) and CO (2,0) bandheads. During our observations the spectrograph slit was aligned to the binary position angle, so that both brown dwarfs were observed contemporaneously. The telescope was nodded along the binary axis to subtract the emission from the infrared-bright sky using standard techniques. A small, random offset was applied to each nod position to mitigate bad detector pixels. Observing conditions were good: seeing was roughly 0.5″. Humidity was <10%, air mass ranged from 1.2 to 1.6, and the Moon was down during our observations. We spatially resolved the two brown dwarfs and over five hours obtained 56 spectra with exposures of 300 s each. We calibrate the raw CRIRES data frames using the standard CRIRES esorex data reduction routines, combining spectra in sets of four to boost the signal to noise ratio. We extracted one-dimensional spectra from both brown dwarfs in each combined frame using the standard astronomical IRAF data analysis package.

We used these extracted, raw spectral data to measure precisely the physical parameters of both brown dwarfs. We followed past work using high-precision infrared spectroscopy and used a forward-modelling approach13–15 to calibrate our data. This analysis method transforms high-resolution spectra of the telluric transmission32 and of modelled brown dwarf atmospheres33 into a simulated CRIRES spectrum using an appropriate set of instrumental and astrophysical parameters. We used a model whose free parameters are the radial velocity of the model brown dwarf, rotational broadening (vsini) and linear limb-darkening coefficients34, two multiplicative scaling factors for the telluric and brown dwarf models, polynomial coefficients that convert pixel number into wavelength, and coefficients for a low-order polynomial with which to normalize the continuum. As weights in the fits we used the uncertainties reported by IRAF after scaling these so that the weighted sum of the residuals equals the number of data points. The effect of all this is to place all observations on a common wavelength scale, to remove the effects of variable telluric absorption and spectrograph slit losses (from slight guiding errors or changes in airmass) and to estimate the astrophysical parameters listed above. Extended Data Fig. 1 shows examples of the raw and modelled data in this approach, and all calibrated spectra are shown in Extended Data Fig. 2. For each brown dwarf, we took as uncertainties the standard deviation on the mean of the measurements from each of the 14 spectra.

We applied the above modelling approach using a wide range of model brown dwarf spectra from the BT-Settl library36, a set of models computed with the PHOENIX code that spans effective temperatures (Teff) of 1,000–1,600 K and surface gravities (log(gg)) of 4.0–5.5. We performed a separate fit to data from each of the four CRIRES detectors and found that the same model does not always give the best fit to the data from all four detectors. Judging from the residuals to the fits (see Extended Data Fig. 1), this effect resulted from inaccuracies in both the adopted telluric spectrum and in the brown dwarf atmospheric models. Considering all these ambiguities, we concluded that the models with log(gg) = 5.0 and Teff = 1,500 and 1,450 K (for components A and B, respectively) gave the best fits to data from all four detectors. There is some degeneracy between temperature and surface gravity, with greater Teff allowing somewhat higher log(gg). Brown dwarf atmospheres have never before been tested at this level of precision and so we did not interpolate between models to improve marginally the quality of the fit. The effective temperatures estimated from our analysis moderately exceeded the values reported by previous studies33,34, and we attribute this difference to the well-known phenomenon that the effective temperature estimated from fitting model spectra to the CO bandheads typically exceeds the temperature derived from integrating the broad-band spectral energy distribution35–37. Comparison of future models to these data should be highly instructive in refining substellar atmospheric models. In the analyses that follow, we use the BT-Settl models with the parameters given above; using slightly different model parameters does not change our conclusions.

To conduct a Doppler imaging analysis properly we had to account for the radial velocity shift of the brown dwarfs. We measure radial velocities for the A and B components of 20.1 ± 0.5 km s−1 and 17.4 ± 0.5 km s−1, respectively, relative to the Solar System barycentre; the uncertainties in these absolute measurements are dominated by systematic uncertainties in our instrument model. Although the radial velocities of Luhman 16A exhibited little internal scatter during our observations, we saw an anomalous deviation (lasting from 1.5 h to 3 h after the start of observations) of roughly 1 km s−1 in the radial velocity measurements of Luhman 16B. Assuming that the systematic effects in measuring radial velocities are common to our observations of both brown dwarfs and examining a short time window around the time of anomalous radial velocities, we obtained a relative radial velocity between the components of 2.800 ± 0.200 m s−1. This measurement is consistent with the orbital velocity expected between two old brown dwarfs in an orbit of a few decades4, and indicates that it will eventually be possible to test brown dwarf evolutionary models5 by measuring the individual component masses via a full three-dimensional orbital solution using the system’s radial velocities and astrometry26–28.

To enhance our sensitivity, we used the technique of least squares deconvolution (LSD) to transform each spectrum into a single mean absorption line, with high signal-to-noise ratio. Deviations in the resulting mean line profiles are difficult to see with the unaided eye, but after subtraction of the night’s mean profile, variations were apparent. Extended Data Fig. 3 shows the resulting temporal evolution in the deviations from the global mean line profile: the rotational signature of Luhman 16B’s inhomogeneous surface is clearly visible, dominated by the rotation of a darker region into and then out of view. Hints of brighter regions are visible at other times. We found that the total absorption depth of the mean line profile decreased by about 4% during this period. No such coherent signatures are observable beyond Luhman 16B’s projected rotational velocity of ±26.1 km s−1, and we do not see any such time-variable phenomena in our simultaneously acquired spectra of Luhman 16A.

Spot modelling. To interpret our LSD line profiles, we first implemented a simple spot model similar to that used to interpret photometry of variable brown dwarfs5. This initial toy model assumes that Luhman 16B’s surface is dominated by a single spot. We divided the surface into a grid, regularly spaced in latitude and longitude. A 10 × 20 grid (18 degrees across each cell) is sufficient for the analysis to converge. The spot was assumed to be circular and the remainder of the photosphere was assumed to have uniform surface brightness with a linear limb-darkening law. The free parameters are the brightness of the spot relative to the photosphere and the spot’s radius, latitude and longitude. For a given set of parameters we generated a surface map with the specified surface brightness distribution. For each grid cell we then used the projected visible area and apparent flux, and the cell’s rotational Doppler shift, to generate a set of rotationally broadened line profiles corresponding to the time of each observation. Each line profile was continuum-normalized, and the set of displaced line profiles was compared to the observed LSD line profiles.

To estimate the uncertainty on the spot parameters we used the emcee tool38, which implements an affine-invariant Markov chain Monte Carlo approach. We initialized 150 chains near a set of reasonable guess parameters (final results are insensitive to this guess) and run all chains for 1,500 steps. After this initial ‘burn-in’ phase the Markov chains were randomized and had lost any memory of their initial starting conditions; we discarded the initial steps and ran the chains for an additional 1,500 steps, afterwards verifying that they were well mixed both by examination of the autocorrelation of the individual chains and by visual inspection of the likelihood and parameter values of the chains. Extended Data Fig. 4 shows the resulting posterior distributions of the spot’s latitude, radius and surface brightness assuming i = 30 degrees; the results do not change significantly for smaller values of i. In this model the dark spot lies ≤31 degrees from the equator, has a radius of ≥3 ± 7 degrees, and is 88 ± 3% as bright as the surrounding photosphere. This result implies a photometric variation of about 3%, consistent with the wide range of variability seen from this system1,19. However, such parametrized models typically exhibit strong degeneracies and tend not to lead to unique maps of the surface brightness distributions of brown dwarfs21.

Doppler imaging. We constructed our Doppler imaging model as described by ref. 20 using the 10 × 20 grid and line profile simulation techniques described above. Our results did not change significantly if we increased the model’s spatial resolution. Instead of an arbitrarily parameterized spot, in the Doppler imaging model there are 200 free parameters: the contributions to the line profile from each grid cell. Because there are approximately 35 pixels across each of 14 mean line profiles, we nominally had 490 constraints; thus the problem appears well posed and simple matrix techniques (for example, singular value decomposition) would seem to be sufficient. However, it has long been recognized that such an approach yields extremely noisy maps20,21,42, often with nonphysical values (for example, negative surface brightness in some cells). Regularization was needed, so we used a maximum entropy approach38 in which the merit function is Q = ∑κi |gi|2 (where Q is the loss function, gi is the difference of Luhman 16B’s grid cells, and κ is a hyperparameter that determines the balance between goodness of fit and entropy). We minimized Q using a standard multivariate optimizer, and we sped up convergence by calculating the analytical gradients of Q relative to the brightnesses of the map cells.

Our data is noisier, and the spectroscopic variations weaker, than in typical Doppler imaging analyses of stars, so we tuned a to minimize the appearance of spurious features while maintaining the fidelity of the resulting map. We did this by generating a number of synthetic surface maps, simulating their line profiles and adding Gaussian noise of the same amplitude as we found in our observed LSD profiles. When we tuned a to minimize line profile recovery and is shown in Extended Data Fig. 5, using the same value of a as in the analysis leading to Fig. 2. This analysis demonstrates that the prominent mid-latitude and polar artifacts are probably real, whereas the lower-contrast equatorial features may be more affected by noise. The longitudinal elongation of equatorial
features is a known feature of Doppler imaging maps\textsuperscript{44}, so features near the equator may be narrower than they appear. The main features in our recovered map do not change for small variations in the Doppler imaging modelling parameters. Finally, we find that although we cannot yet directly measure $i$ with the current data\textsuperscript{44}, our maps do not change much for expected values of $i$ (0–30 degrees).

**Zonal banding and brown dwarf line profiles.** The detection of axisymmetric features (such as zonal banding) via Doppler Imaging is more challenging than the detection of features lacking such symmetry; the latter are easily seen via their time-variable effects on the line profiles, but the former can only be distinguished by discerning deviations of the mean line shape from the modelled profile. We ran a number of simulated Doppler imaging analyses on brown dwarfs with various levels of banding. Extended Data Fig. 6 shows one such example, which is typical insofar as it demonstrates our inability to recover even strong, large-scale zonal bands. Even if the band contrast were 100%, our simulations show that recovery of such features would be tentative only, given the current precision of our data. Future observations at higher precision should have greater sensitivity to such features, and these efforts will therefore become more susceptible to the spurious axisymmetric bands that can result from Doppler imaging analyses performed with inappropriate line profile shapes\textsuperscript{21,27,46}. We therefore consider below possible sources of uncertainty in modelling the detailed line shapes probed by our analysis.

In the PHOENIX synthetic atmosphere and spectral model employed in our analysis, the strongest molecular lines are modelled as regular, symmetric Voigt profiles extending out to a maximum half width of 20 cm\textsuperscript{s–1}. Beyond this detuning, effects of asymmetry and mixing of neighbouring lines no longer allow an adequate representation of the wings by a simple Lorentzian. A generic half width at half maximum (HWHM) of 0.08 cm\textsuperscript{s–1} at 296 K and a temperature exponent of 0.4 has been assumed for the Lorentz (pressure broadening) part of all molecular lines\textsuperscript{21}, and Doppler broadening was calculated for the thermal velocity plus an isotropic microturbulence of 0.8 km s\textsuperscript{–1}. The part of the spectrum covered by our observations formed mainly at pressure levels of 1–2 bar (ref. 18). Specifically, the wings of the strongest CO lines would form as deep as 4 bar, whereas the most central portion of the line cores formed as high as the 10 mbar level. The corresponding atmospheric temperatures in these layers (1,000–1,500 K) yielded a total Doppler broadening of the order of 1.1–1.25 km s\textsuperscript{–1}, whereas the half width of the collisional profile ranges from a few hundred metres per second in the cores up to nearly 10 km s\textsuperscript{–1} in the outer wings.

The true line profiles might deviate in several respects from the assumptions used in the PHOENIX model. Microturbulence, which in stellar atmosphere modelling simply denotes a random Gaussian velocity distribution on scales small compared to the photon mean free path, has not been constrained very tightly for brown dwarfs yet. A badly estimated microturbulence, particularly in the case of an anisotropic distribution with a stronger horizontal component, may affect the retrieval of surface features\textsuperscript{21,27,46}.

Radiation hydrodynamic simulations do allow us some insight into the dynamic structure of brown dwarf atmospheres, predicting horizontal root-mean-square velocities of the order of 0.3 km s\textsuperscript{–1} for our case, compared to values 3–5 times smaller for the vertical component\textsuperscript{45}. However, unlike for typical stars mapped by Doppler imaging, in our case the total broadening is always dominated by the thermal velocity, so given the constant microturbulent velocity of 0.8 km s\textsuperscript{–1} of the PHOENIX models, any realistic changes are unlikely to have a noticeable impact on the line shapes. Pressure broadening of molecular lines, in contrast, has been poorly studied for stellar and substellar atmosphere conditions, that is, for temperatures of 1,000 K and higher and with molecular hydrogen (H\textsubscript{2}) and helium (He) as main perturbers. Measurements of the broadening of CO lines in the fundamental band at 4.6 μm by noble gases and various other perturbers have yielded a HWHM of approximately 0.07 cm\textsuperscript{s–1} at 296 K for H\textsubscript{2} (ref. 48). A study of the overtone band at 2.3 μm perturbed by various noble gases showed very similar widths to those in the fundamental\textsuperscript{49}, so it may be safe to assume that the H\textsubscript{2} broadening in this band is also comparable, and only about 12% smaller than our model value. The temperature dependence, however, could be stronger, with a possible temperature exponent of 0.5–0.75 (refs 50, 51). With all these effects combined, we may expect the actual damping widths to be up to a factor of two smaller than assumed in our model. On the other hand, the actual atmospheric conditions also remain poorly constrained, without a detailed spectral analysis or tighter limits on age and mass of the system. For an older and more massive brown dwarf, a surface gravity up to three times higher with correspondingly larger atmospheric pressures is possible, which would affect the collisional damping part of the line wings, but not the Doppler cores. Finally, collisional perturbations are also known to shift molecular lines. This effect, and in particular its temperature dependence, is even less well studied for perturbers other than H\textsubscript{2} and He\textsuperscript{32,33}, but the shifts should be around an order of magnitude smaller than the HWHM and thus have little effect on the position of the line cores.

In conclusion, it seems feasible that future observations at higher precision could determine whether Luhman 16B exhibits zonal banding. At present, our current data are not sufficiently sensitive to address this issue.

31. Blake, C. H., Charbonneau, D., White, R. J., Marley, M. S. & Saumon, D. Multipole radial velocity observations of L dwarfs. Astrophys. J. 666, 1198–1204 (2007).
32. Bean, J. L. et al. The CRIRES search for planets around the lowest-mass stars. I. High-precision near-infrared radial velocities with an ammonia gas cell. Astrophys. J. 713, 410–422 (2010).
33. Hinkle, K. H., Wallace, L. & Livingston, W. Atmospheric transmission above Kitt Peak. 0.5 to 5.5 microns. Bull. Am. Astron. Soc. 35, 1260 (2003).
34. Allard, F., Horner, D., Freytag, B., Schaaffberger, W. & Rajpurohit, A. S. Progress in modeling very low mass stars, brown dwarfs, and planetary mass objects. Mem. Soc. Astron. Ital. 24, Suppl., 128–139 (2013).
35. Grey, D. F. The Observation and Analysis of Stellar Photospheres 3rd edn, Ch. 18 (Cambridge Univ. Press, 2006).
36. Jones, H. R. A. et al. Carbon monoxide in low-mass dwarf stars. Mon. Not. R. Astron. Soc. 358, 105–112 (2005).
37. Schweitzer, A. et al. Effective temperatures of late L dwarfs and the onset of methane signatures. Astrophys. J. 666, 433–441 (2002).
38. Konopacky, Q. M. et al. High-precision dynamical masses of very low mass binaries. Astrophys. J. 711, 1087–1122 (2010).
39. Dupuy, T. J. & Liu, M. C. On the distribution of orbital eccentricities for very low-mass binaries. Astrophys. J. 733, 122–135 (2011).
40. Donati, J.-F., Semel, M., Carter, B. D., Rees, D. E. & Collier Cameron, A. Spectropolarimetric observations of active stars. Mon. Not. R. Astron. Soc. 291, 658–682 (1997).
41. Foreman-Mackey, D., Hogg, D. W., Lang, D. & Goodman, J. emcee: The MCMC hammer. Publ. Astron. Soc. Pacif. 125, 306–312 (2013).
42. Vogt, S. S. Doppler images of spotted late-type stars. In The Impact of Very High S/N Spectroscopy on Stellar Physics 253–272 (Proc. 132nd Symp. Int. Astron. Union, 1988).
43. Narayan, R. & Nityananda, R. Maximum entropy image restoration in astronomy. Annu. Rev. Astron. Astrophys. 24, 127–170 (1986).
44. Rice, J. B. Doppler imaging of stellar surfaces—techniques and issues. Astron. Nachr. 323, 220–235 (2002).
45. Rice, J. B. & Strassmeier, K. G. Doppler imaging from artificial data. Testing the temperature inversion from spectral-line profiles. Astron. Astrophys. 147, Suppl., 151–168 (2000).
46. Unruh, Y. C. & Collier Cameron, A. The sensitivity of Doppler imaging to line profile models. Mon. Not. R. Astron. Soc. 273, 1–16 (1995).
47. Freytag, B., Allard, F., Ludwig, H.-G., Horner, D. & Steffen, M. The role of convection, overshoot, and gravity waves for the transport of dust in M dwarf and brown dwarf atmospheres. Astron. Astrophys. 513, A19 (2010).
48. Draeger, D. A. & Williams, D. Collisional broadening of CO absorption lines by foreign gases. J. Opt. Soc. Am. 58, 1399–1403 (1968).
49. Bouanich, J. Détermination expérimentale des largesses et des déplacements des raies de la bande 0 → 2 de CO perturbées par les gaz rares (He, Ne, Ar, Kr, Xe). J. Quant. Spec. Radiat. Transf. 12, 1609–1615 (1972).
50. Malathy Devi, V. et al. Spectral line parameters including temperature dependences of self- and air-broadening in the 2 → 0 band of CO at 2.3 micron. J. Quant. Spec. Radiat. Transf. 113, 1013–1033 (2012).
51. Faure, A., Wiesenfeld, L., Drouin, B. J. & Tennyson, J. Pressure broadening of water and carbon monoxide transitions by molecular hydrogen at high temperatures. J. Quant. Spec. Radiat. Transf. 116, 79–86 (2013).
52. Prezioso-Cross, A., Bouanich, J. P., Benner, D. C., May, A. D. & Drummond, J. R. Broadening, shifting, and line asymmetries in the 2 → 0 band of CO and CO–N\textsubscript{2}: experimental results and theoretical calculations. J. Chem. Phys. 113, 158–168 (2000).

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Extended Data Figure 1 | Spectral calibration for Luhman 16A (a and b) and Luhman 16B (c and d). The red curves (a and c) show the modelled spectra, which mostly overlap the observed spectra (plotted in black). The gaps in the spectra correspond to physical spaces between the four infrared array detectors. The residuals to the fits (b and d) are generally a few per cent, with larger deviations apparent near CO bandheads (for example, at 2.294 μm and 2.323 μm) and strong telluric absorption lines (for example, at 2.290 μm and 2.340 μm).
Extended Data Figure 2 | Calibrated spectra of the brown dwarfs, showing the individual calibrated spectra of Luhman 16A (a) and Luhman 16B (b). The time of each observation is indicated.
Extended Data Figure 3 | Luhman 16B shows strong rotationally induced variability (b) whereas Luhman 16A does not (a). The colour scale indicates the deviations from a uniform line profile as measured relative to the line continuum. Luhman 16B’s variations are dominated by a dark region (diagonal streak, corresponding to a decrease of roughly 4% in equivalent width) that comes into view at 1.5 h heading towards the observer, rotates across the brown dwarf to the receding side, and is again hidden behind the limb at 3 h. Brighter regions are visible at earlier and later times, but are less prominent. No significant spectroscopic variability is apparent for Luhman 16A, and no coherent features are seen beyond Luhman 16B’s projected rotational velocity (enclosed between the vertical dashed lines). All these points indicate that we are detecting intrinsic spectroscopic variability from Luhman 16B.
Extended Data Figure 4 | Posterior parameter distributions from our single-spot toy model, showing a large mid-latitude spot. The inner and outer curves in panels a-c indicate the 68.3% and 95.4% confidence regions. The plot shown assumes $i = 30$ degrees; smaller inclinations result in a slightly more equatorial spot, but the best-fit values remain within the inner 68.3% confidence regions.
Extended Data Figure 5 | Simulated brown dwarf with spots, and the map recovered from Doppler imaging. a, Simulated variable brown dwarf seen at an inclination of $i = 30$ degrees. The dark and light mid-latitude spots are, respectively, 40% darker and 10% brighter than the photosphere; the dark streak is 10% darker and the polar spot is 20% brighter. b, Surface map recovered from Doppler imaging, assuming noise levels similar to that seen in our observed data, after tuning the hyperparameter $a$ to minimize spurious features. High-contrast features are recovered: the dark spot is in the correct location and the polar spot is only moderately distorted. The equatorial bright spot is visible in the recovered map, but it cannot be reliably distinguished from image artefacts that preferentially cluster near the equator. The dark stripe is not recovered. Thus our analysis can accurately recover strong features, but data quality precludes us from discerning smaller or fainter features.
Extended Data Figure 6 | Simulated brown dwarf with spots and bands, and the map recovered from Doppler imaging.  

a, Simulated variable brown dwarf with the same surface features as in Extended Data Fig. 5, but now also exhibiting zonal bands with an amplitude of $\pm 20\%$ of the mean photospheric brightness level.  

b, Surface map recovered from Doppler imaging under the same assumptions as in Extended Data Fig. 5. High-contrast, non-axisymmetric features are recovered as before, but we cannot recover even prominent global bands with the current precision of our data.