A planet within the debris disk around the pre-main-sequence star AU Microscopii

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AU Microscopii (AU Mic) is the second closest pre-main-sequence star, at a distance of 9.79 parsecs and with an age of 22 million years. AU Mic possesses a relatively rare and spatially resolved edge-on debris disk extending from about 35 to 210 astronomical units from the star, and with clumps exhibiting non-Keplerian motion. Detection of newly formed planets around such a star is challenged by the presence of spots, plage, flares and other manifestations of magnetic ‘activity’ on the star. Here we report observations of a planet transiting AU Mic. The transiting planet, AU Mic b, has an orbital period of 8.46 days, an orbital distance of 0.07 astronomical units, a radius of 0.4 Jupiter radii, and a mass of less than 0.18 Jupiter masses at 3σ confidence. Our observations of a planet co-existing with a debris disk offer the opportunity to test the predictions of current models of planet formation and evolution.

Fig. 1 | TESS light curve for AU Mic. Black dots, normalized flux as a function of time, obtained from the MAST archive. Transit ephemerides of AU Mic b are indicated as ‘b’ in red. The double-humped sinusoidal-like pattern is due to the rotational modulation of starspots, with the 4.863-day rotation period readily apparent. The large, brief vertical streaks of data points deviating upwards from this slower modulation are due to flares. Data with non-zero quality flags indicating the presence of spacecraft-related artefacts, such as momentum dumps (see Fig. 2 legend), are removed. The gap at about 1,339 days corresponds to a gap in the data downlink with Earth during the spacecraft’s perigee. A third transit of AU Mic b was missed during this data downlink data gap, and thus the orbital period of AU Mic b is one-half of the period inferred from the two TESS transit events seen. AU Mic exhibited flaring activity with energies ranging from 10^{31.6} to 10^{33.7} erg in the TESS bandpass over the 27-day light curve (±~60%), with a mean flare amplitude of 0.01 relative flux units. 1σ measurement uncertainties are smaller than the symbols shown (<1 parts per thousand, p.p.t.).
transit is observed in the TESS light curve, which suggests the possible and a radius of 0.4 Jupiter radii. An additional, shallower candidate AU Mic b. Our analyses show that this transiting planet has an orbital observations with the Spitzer Space Telescope11 confirm the transits of sits of AU Mic b appear in the TESS photometric light curve. Follow-up during the first 27 days of its survey of most of the sky (Fig. 1). Two tran-

NASA’s Transiting Exoplanet Survey Satellite (TESS) mission10 was launched on 18 April 2018, and monitored the brightness of AU Mic during the first 27 days of its survey of most of the sky (Fig. 1). Two trans-

high-resolution adaptive optics imaging rules out other planets in this system more massive than Jupiter interior to about 20 au. The 3σ upper limit to the velocity reflex motion semi-amplitude for AU Mic b is \( K < 28 \text{ m s}^{-1} \) (see Methods), corresponding to an upper limit for the mass of AU Mic b of \(<0.18 \text{ Jupiter masses (}\text{M}_{\text{Jupiter}})\) or \(<3.4 \text{ Neptune masses (}\text{M}_{\text{Neptune}}\)). Hence, uncertainty shown are 1σ for detections, and 3σ for mass upper limits.
an important test of migration models since we expect any obliquity in this young system to be unaffected by stellar tides and thus primordial.

AU Mic is a member of the β Pictoris Moving Group; the group’s archetype β Pic is a much more massive (about 3.5×), luminous (about 100×) and hotter (approximately 2×) A-type star, also possessing a debris disk. β Pic has a more massive Jovian planet β Pic b observed by direct imaging at a semi-major axis of about 9 au, with a mass of approximately (11±2)M_Jup determined with astrometry. AU Mic and β Pic are of the same stellar age, but are very different exoplanet host stars. While AU Mic b possibly formed at a distance similar to β Pic b and then migrated inwards to its present location, β Pic b has not substantially migrated inward. These two coeval systems provide an excellent differential comparison for planet formation.

Finally, the combined effect of stellar winds and interior planets have been invoked to explain the high-speed ejection of dust clumps from the system. The observed clumps are dynamically decoupled from AU Mic b; the ratio of the semi-major axes (0.06 AU versus >35 AU) is >100, but the clumps could have originated much closer to the star. Dust produced in the debris ring at about 35 au may spiral inwards primarily as a result of stellar wind drag, which, for AU Mic and a mass loss rate about 1,000 times that of the solar wind, is estimated to be 3,700 times stronger than Poynting–Robertson drag. To compare the timescales between collisions of dusty debris and the stellar wind drag force, we assume a birth ring fractional width of 10% (3.5 au), and given AU Mic’s infrared flux excess, find that the stellar wind drag and dust collision timescales are roughly equal. Thus, some fraction of the dust grains generated in the birth ring at about 35 au may spiral inward to the host star under the action of stellar wind drag, instead of being ground down further by dust collisions until blown out of the system by radiation pressure. For 1-μm-sized solid grains of dusty debris, the in-spiral time would be approximately 7,500 years, much shorter than the age of the star. Such dust may have been observed by ALMA at <3 au, interior to the birth ring at 35 au. Dust reaching the orbit of an interior planet could be dynamically ejected, depending on the Safronov number: we estimate that of AU Mic b to be 0.07 and thus inefficient at ejecting dust.

There is no other known system that possesses all of these crucial pieces—an M-dwarf star that is young, nearby, still surrounded by a debris disk within which are moving clumps, and orbited by a planet with a direct radius measurement. As such, AU Mic provides a unique laboratory to study and model planet and planetary atmosphere formation and evolution processes in detail.

### Online content

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pipeline planet detection algorithms, ExoFAST v1.0 and v2.0, and to identify and model the transits present, including the TESS mission interferometric stellar radius determination rules out bound stellar colour terms) is 76 arcsec or 3 TESS pixels from AU Mic. Finally, the eclipsing binary (with G-band contrast = 5.7 mag, ignoring TESS-G-band nearest Gaia DR2 source that is capable of producing a false positive if an orbit is present in or rule out one-half of the orbit period for AU Mic b as seen in the TESS light curve. One candidate partial transit event ingress was observed (Barycentric Modified Julian Date (BMJD) = 58,524.53, to make sure we weren’t biasing the transit depth. The systems-corrected light curve is used in our light-curve modelling in the main text.

**Ground-based light-curve analysis**

Ref. 34 conducted a dedicated ground-based search for planets transiting AU Mic. One candidate partial transit event ingress was observed (Barycentric Julian Date (BJD) = 2,453,590.885), with a depth (flux dimming of the star) of -3%. By itself, this could be attributed to a number of phenomena associated with the star’s youth, debris disk, or systematic effects. The photometric precision of this light curve is not sufficient to identify additional transits of AU Mic b or the candidate transit signal from the TESS light curve.

The SuperWASP team monitored AU Mic for seven seasons as part of a larger all-sky survey for planets transiting AU Mic. One candidate partial transit event ingress was observed (Barycentric Julian Date (JD) = 2,453,590.885, with a depth (flux dimming of the star) of -3%. By itself, this could be attributed to a number of phenomena associated with the star’s youth, debris disk, or systematic effects. The photometric precision of this light curve is not sufficient to identify additional transits of AU Mic b or the candidate transit signal from the TESS light curve.

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**Joint TESS and Spitzer photometric analysis**

We carry out a custom analysis that simultaneously accounts for the rotational modulation of starspots, the flares and the transit events for both the TESS and Spitzer light curves to evaluate the impact our detrending of the spot rotational modulation and flares has on our analysis of the transit events: this is the analysis we adopt in the main text (Extended Data Fig. 1). We use the TESS pre-search data conditioned light curve created by the TESS pipeline, to perform this analysis.

To remove flares, we create a smoothed version of the light curve by applying a third-order Savitzky–Golay filter with a window of 301 data points, subtracting the smooth light curve, and clipping out data points more deviant than 1.5× the r.m.s. We performed 10 iterations of this clipping, removing the majority of stellar flares. We then used the exoplanet package (https://github.com/dfm/exoplanet) to simultaneously model the stellar variability and transits. Exoplanet uses several other software packages: Starry for the transit model (https://github.com/rodluger/starry) and celerite (https://github.com/dfm/celerite) for the GP, which we use to model stellar variability. Our GP model consists of two terms: a term to capture long-term trends, and a term to capture the periodic modulation of the star’s light curve that is caused by spots on the stellar surface. The latter is a mixture of two stochastically-driven, damped harmonic oscillatory terms that can be used to model stellar rotation. It has two modes in Fourier space: one at the rotation period of the star and one at half the rotation period. The transit model is parameterized by two stellar limb-darkening parameters, the log of the orbital period, the log of the stellar density, the time of first transit, the log of the planet-to-star radius ratio, the impact parameter of the transit, orbital eccentricity of the planet, and the periapsis angle.

We next run a Markov Chain Monte Carlo (MCMC) to fit the 9 PLD coefficients (the cs), a slope + quadratic ramp to represent the rotational modulation of the stellar activity still visible for AU Mic in the Spitzer light curve at 4.5 μm, as well as a transit model including two limb-darkening coefficients for a quadratic limb-darkening law (Extended Data Fig. 2). We leave the photometric uncertainty as a free parameter, which we fit for during the MCMC. Prior to the MCMC, we cut out the dip that occurs during the transit, potentially due to a large spot crossing, from Barycentric Modified Julian Date (BMJD) = 58,524.5 to 58,524.53, to make sure we weren’t biasing the transit depth. The systematics-corrected light curve is used in our light-curve modelling in the main text.
The ground-based photometric monitoring\textsuperscript{21,22} of AU Mic establishes the long spot lifetimes, which persist for longer than a single observing season as evidenced by the lack of changes in the light curve over many stellar rotations, a defining characteristic of BY Draconis variables. By comparing the TESS, SuperWASP and ref.\textsuperscript{21} light curves, it is clear there is spot evolution on a timescale of a few years, as the shape of the phased light curve does differ between the datasets.

**Radial-velocity analysis**
Seven RV datasets of AU Mic have been obtained by our team or from the literature and archival data, and a detailed analysis to search for additional planets in the AU Mic system is a subject for future work. In this section, we present the utilization of the higher precision radial velocities from iSHELL, HARPS and HIRES (see below) to rule out higher mass companions, correlations with stellar activity, and confirm the planetary nature of AU Mic b by placing an upper limit on its mass.

AU Mic b is a near-infrared echelle spectrometer with a resolution of $R = 70,000$ and a simultaneous grasp of a wavelength range of 300 nm at the 3.0-m NASA Infrared Telescope Facility (IRTF); it is equipped with the custom-built methane isotope polpologue absorption gas cell for wavelength calibration and instrument characterization\textsuperscript{33}. The iSHELL data reduction and RV extraction follows the prescription in ref.\textsuperscript{33}. We combine our data with archival observations from the visible wavelength HARPS at the ESO La Silla 3.6-m telescope\textsuperscript{32}, and the visible wavelength HIRES on the 10-m Keck telescope\textsuperscript{31} obtained for the California Planet Survey. All HARPS spectra were extracted and calibrated with the standard ESO Data Reduction Software, and RVs were measured using a least-squares template matching technique (Extended Data Figs. 4–6).

AU Mic is very active relative to a main-sequence dwarf, and we find RV peak-to-peak variations in excess of 400 m s$^{-1}$ in the visible range due to the rotational modulation of stellar activity (r.m.s. $= 175$ m s$^{-1}$ for HIRES and 115 m s$^{-1}$ for HARPS). With iSHELL, the RVs exhibit stellar activity with a smaller but still substantial peak-to-peak amplitude of ~150 m s$^{-1}$ (r.m.s. $= 59$ m s$^{-1}$). Consequently, no individual RV dataset possesses a statistically significant periodogram signal at the period of planet b. This renders the mass detection of a planet with a velocity semi-amplitude smaller than the activity amplitude challenging\textsuperscript{33–38}.

We perform an MCMC simulation to model the stellar activity with a Gaussian Process (GP) simultaneously with a circular orbit model for AU Mic b using the regression tool RAVEL\textsuperscript{30} (Extended Data Fig. 7). Offsets for the velocity zero point of each RV instrument are modelled. We fix the orbital period and time of transit conjunction (orbital phase) for AU Mic b to the best-fit values constrained by the TESS observations. We assume a velocity semi-amplitude prior with a width of 50\% of the best-fit value and positive-definite. Owing to the stochastic activity and relatively sparse cadence sampling leading to GP model overfitting, no statistically significant constraints on orbital eccentricity are possible; the eccentricity posterior distributions are unconstrained and the range of eccentricities allowed. Thus, for the sake of brevity we present here only scenarios with fixed circular orbits, although eccentric orbits are considered. Constraining the eccentricity (and periastron angle) of AU Mic b will require a more intensive RV cadence and/or new modelling and mitigation of stellar activity beyond a GP model.

The stellar activity is modelled as a GP with a four ‘hyper-parameter’ auto-correlation function that accounts for the activity amplitude, the rotation period of the star modulating the starspots, and spot lifetimes treated as an autocorrelation decay\textsuperscript{32–34}. From photometric time-series, the spot lifetime for AU Mic is observed to be longer than an observing season. Combined with its known rotation period, this enables us to generate priors on the GP hyper-parameters. We use a Jeffreys’ prior on the GP hyper-parameter activity amplitudes bounded between 1 and 400 m s$^{-1}$ for the visible, and 1 and 200 m s$^{-1}$ for the near-infrared, a spot decay lifetime prior that is a Gaussian centred on 110 days with a width of 25 days, a stellar rotation period prior of a Gaussian centred on 4.863 days with a width of 0.005 days, and a Gaussian prior centred on 0.388 with a width of 5\% for the fourth hyper-parameter. We assess the dependence of our model comparison on the priors and prior widths used for the planet and GP parameters, which yield qualitatively similar results.

We use the MCMC simulations (Extended Data Fig. 8) to compare statistically favoured models obtained from evaluating the model log-likelihoods, AICc (corrected Akaike information criterion) and BIC (Bayesian Information Criterion) statistics (Extended Data Table 1), and to provide robust characterization of model parameter uncertainties (for example, posterior probability distributions). We derive an upper limit to the velocity reflex motion from AU Mic b of $K < 28.9$ m s$^{-1}$ at 3σ confidence, corresponding to a mass upper limit of $M_{\text{b}} < 0.18 M_{\text{Jupiter}}$ or $< 3.4 M_{\text{Neptune}}$. We restrict our analysis to estimating an upper limit to the mass of AU Mic b for a number of reasons. First, while our statistical analysis favours the detection of AU Mic b, we do not rule out a non-detection at high statistical confidence. Second, our analysis relies on the assumption that a GP model is an adequate model for stellar activity. Studies of other starspot-dominated convective M dwarfs\textsuperscript{38} suggest this is adequate, but additional future observations and modeling efforts are needed, particularly for stars as active as AU Mic. From Kepler photometric time series of main-sequence stars, we demonstrated\textsuperscript{40} that stellar activity should not introduce substantial power in densely sampled (approximately nightly) RV time series at orbital periods longer than the stellar rotation period, as is the case for AU Mic b. However, for more sparsely sampled RV cadences such as ours, stellar activity can introduce apparent periodicities at timescales longer than the stellar rotation period that can persist for several seasons\textsuperscript{41}. The long-term magnetic activity evolution of AU Mic on timescales $>$100 days is also neither constrained nor modelled.

**Wavelength dependence of stellar activity**
At near-infrared wavelengths, the expected stellar activity amplitude depends on the effective temperature contrast of the starspots to the photosphere and the effects of Zeeman broadening\textsuperscript{42,43}. If the spot temperature contrast is small (for example, a few hundred kelvin), then the RV (and photometric) amplitude due to the rotational modulation of starspots should scale as $1/\text{A}$ to first order. This is the case for the Sun\textsuperscript{44}. From the HARPS RV r.m.s., one would expect an RV r.m.s. at 2.3 μm of ~50 m s$^{-1}$ if the HARPS RV r.m.s. is entirely ascribable to stellar activity from cool starspots or plages. However, if the spot temperature contrast is large (for example, >1,000 K), one would expect only a marginal (~10\%) reduction in RV stellar activity amplitude in the near-infrared. AU Mic lies close to but slightly above the theoretical expectation for cool starspots with small rather than large spot temperature contrast—showing an RV r.m.s. of 59 m s$^{-1}$, a reduction of about two-thirds overall in r.m.s. The modelled GP hyper-parameters for the GP amplitudes show a reduction of about one-half from the visible to the near-infrared.

Ref.\textsuperscript{21} obtained multi-band photometry of AU Mic over the course of several rotation periods in their search for transiting exoplanets. Ref.\textsuperscript{21} demonstrates that AU Mic exhibits a decreased amplitude of photometric variability as a function of wavelength, again consistent with cool starspots with a relatively small temperature contrast (Extended Data Fig. 9). This is also consistent with multi-band photometry of young pre-main-sequence stars and the Sun\textsuperscript{44,45}.

**Host star parameters**
We compare the mass derived from transit photometry plus Center for High Angular Resolution Astronomy (CHARA) array radius to pre-main-sequence solar-metallicity isochrones of Baraffe et al.\textsuperscript{19}. We logistically interpolate onto a finer grid, and fit to the absolute J, H and K, magnitudes (from 2MASS photometry and the Gaia parallax), the radius derived from CHARA\textsuperscript{22} and the Gaia parallax, and the effective temperature. The best-fit ($\chi^2 = 20.7, \nu = 3$) age and mass are 19 Myr.
of 0.58, the uncertainties in age and mass are highly correlated, with a 95.4% confidence interval that spans 9–25 Myr, and (0.38–0.63)M☉.

Future work

Additional RVs are necessary to increase the statistical confidence in the determination and recovery of the orbital parameters for AU Mic b and to search for additional planets. In particular, red-sensitive and near-infrared RVs with a nightly monitoring campaign for at least one season are necessary given the relatively large amplitude and timescale of stellar activity, and if possible to search for additional Neptune-mass and smaller planets. Near-simultaneous chromatic RVs, taken at multiple wavelengths across the visible and near-infrared, and/or polarimetric observations may enable a future analysis that more robustly models the stellar activity than can be accomplished with GP and the non-simultaneous multi-wavelength RVs presented here. Simultaneous multi-wavelength RVs could isolate the chromatic stellar activity signal from the achromatic planet signals. Additionally, AU Mic has a v sin i value of 8.7 km s⁻¹, and Zeeman Doppler imaging may enable a mapping of the spot configuration on the stellar surface of AU Mic to monitor long-term activity changes.

Future ground- and space-based photometric monitoring, particularly at red and infrared wavelengths, are needed to further constrain the transit parameters. Observing transit timing variations (TTVs) may be possible for this system to search for additional planets, but the analysis will be complicated by the rotational modulation of the starspots and flares. Flares occur frequently during transit, and since AU Mic b potentially crosses active features on the stellar surface, this renders precise transit depth and duration measurements challenging. Here again, simultaneous multi-wavelength photometry could assist in distinguishing the transit signal from stellar activity. In particular, the Spitzer light curve presented here and planned future observations will provide insights into the spot structure of the surface of AU Mic from spot-crossings by AU Mic b for cross-comparison with the Zeeman Doppler imaging maps.

AU Mic b is also an interesting target to search for signatures of its atmosphere, and for extended hydrogen or helium exospheres, with multiple existing and planned near-term instrumentation on the ground and in space. Given its potentially low density, AU Mic b is one of the most favourable targets to search for planetary atmospheres, even taking into account the upper-limit mass measurement. In particular, since the host star AU Mic is a young active star, it may promote the helium mass loss already detected in other Neptune-size bodies. Thus, high-dispersion transmission spectroscopy with visible and near-infrared spectrographs, around the 1,083 nm He i and the Hα line, will measure or constrain atmospheric mass loss rate from this young warm planet.

Since the AU Mic system is young, nearby, possesses a debris disk and is a planet that can be observed in transit, it provides an interesting laboratory to explore several theoretical issues. First, simulations should be carried out of the present and past interactions between the inner planet, the possible inner debris disk at <3 au (ref. 249), and the outer debris disk including its clumpy structures. These interactions depend on the masses of both the outer disk and the inner planet, so that this analysis could provide constraints on their properties; moreover, given the 22 Myr age of the star, these integrations can be carried out over the entire possible age of the stellar system. Second, sensitive searches for trace gas could be carried out for this system. Until a few years ago, the classical definition of a debris disk was the secondary generation of dust. Recently, an increasing number of debris disks have shown gas (today up to 17 sources), including the debris disk orbiting β Pic5, which is rich in carbon, oxygen and nitrogen, perhaps originating from icy grains rich in CO.

Last, it would be useful to compare the properties of AU Mic b with predictions from planet formation/evolution models. If the mass of AU Mic b is close to our upper limit, the observed radius is close to its expected value for a several Gyr-old planet, whereas the predicted contraction timescale of Neptune-size, gas-rich planets is longer than the age of the system.23 These can be reconciled if the planet is substantially less massive than our upper limit. A better mass limit or determination could place interesting constraints on the entropy of planet formation and early thermal evolution.

Data availability

In addition to the figure data available, all raw spectroscopic data are available either in the associated observatory archive or upon request from the corresponding author. The TESS light curve is available at the MAST archive, and the SuperWASP light curve is available at the NASA Exoplanet Archive. Source data are provided with this paper.

Code availability

All code that is not readily available on GitHub is available upon request.

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Extended Data Fig. 1 | TESS and Spitzer light curves for AU Mic centred on four transit events. a, b, Two TESS transits (respectively 1 and 2) for AU Mic b, with the model components plotted as indicated in the key. A flare is present during the egress of the first transit of AU Mic b, and a flare is present just after the ingress during the second transit of AU Mic b. Although this is unfortunate timing, flares of this amplitude are pervasive throughout the TESS light curve for AU Mic, and complicate the recovery of these events from automated transit search algorithms. c, The Spitzer transit observation of AU Mic b. The deviations in transit are not instrumental and will be the subject of a future paper, and are likely to be related to the planet crossing large active regions on the stellar surface (key from a and b applies here). d, The ~1 p.p.t. candidate single transit event seen in the TESS light curve. For all panels, 1σ measurement uncertainties are suppressed for visual clarity and are <1 p.p.t. 1σ model uncertainties in transit are shown as shaded regions.
Extended Data Fig. 2 | MCMC corner plot for custom combined Spitzer and TESS light-curve analysis for AU Mic. The full set of model parameters are shown, with the posterior probability distributions along the diagonal, the others are the two-dimensional parameter covariance plots.
Extended Data Fig. 3 | One season (July to October 2007) of SuperWASP light curves for AU Mic from the NASA Exoplanet Archive, phase-folded to the rotation period of the star. Measurements with large photometric uncertainties (>5%) have been excluded from the plot. 1σ measurement uncertainties are suppressed for visual clarity and are typically <1% but occasionally up to 5% at phases where there is more apparent vertical scatter in the measurement values themselves.
Extended Data Fig. 4 | Correlation plots of the standard HARPS stellar activity indicators with the RVs. The bisector values for the cross-correlation function (‘CCF bisector’), but not the activity indicators (Hα, Na D, Ca II H and K), show a correlation with the RVs, with substantial remaining scatter. Formal uncertainties are smaller than the plotted symbols.
Extended Data Fig. 5 | Correlation plots of the HARPS activity indicators with each other. The activity indicators Ca II H and K, Hα, and Na D are strongly correlated with one another, but not with the RVs or with the CCF bisector.
Extended Data Fig. 6 | The HARPS RVs and standard activity indicators, phase folded to the rotation period of the star. Blue circles, HARPS RVs; black circles, standard activity indicators. None of the activity indicators show a statistically significant trend with the period of AU Mic b. The Ca and Na activity indicators appear to show (by eye) some cyclic variation with the rotation period of the star. Formal uncertainties are smaller than the plotted symbols.
Extended Data Fig. 7 | RV time-series of AU Mic, with fitting residuals, and phased to the orbital period of AU Mic b. Shown are data from three spectrometers: iSHELL (yellow circles), HIRES (black circles) and HARPS (red squares). Uncertainties shown are 1σ for HARPS and iSHELL. For HIRES, a 5 m s⁻¹ minimum 1σ uncertainty is adopted, although the formal 1σ uncertainties are smaller for all but one epoch at 5.43 m s⁻¹. The maximum-likelihood best fit model is overlaid in blue, with shaded regions indicating the 1σ model confidence interval, with a separate GP for each dataset indicated with different coloured shaded regions. b, Model-subtracted residuals, with the same colours as in a. Because our RVs are undersampled with respect to the stellar rotation period⁹, the GP best-fit model overfits the AU Mic RV time-series. c, RV measurements are phased to the orbital period of AU Mic b, and binned in phase (red circles). The blue curve is a maximum-likelihood best-fit circular orbit model, after subtracting the best fit GP model of stellar activity and the modelled instrument offsets. The plot is labelled with the best-fit orbital period $P_b$, velocity semi-amplitude $K_b$, and the assumed circular orbit ($e_b = 0$).
Extended Data Fig. 8 | RADVEL MCMC corner plot for the model parameters for the iSHELL, HARPS and HIRES RV datasets. Along the diagonal are the one-dimensional posterior probability distributions for a given model parameter; the others are the two-dimensional parameter covariance plots.
Extended Data Fig. 9 | Photometric variability amplitudes obtained contemporaneously in four different bandpasses. The amplitudes (black squares) are from ref. 21. The horizontal error bars correspond to the effective bandpass widths, and the 1σ vertical error bars are set to 1 mmag. A 1/λ trend is shown in red, as would be expected for cool starspots with relatively small temperature contrast35.
## Extended Data Table 1 | Model comparison results

| AU Mic Model (all include GP & data set offsets) | RV datasets | Free Parameters | Number of RV epochs | Best-fit model rms | log-likelihood | BIC | AICc | Δ AICc between favoured model | AICc qualitative comparison |
|-------------------------------------------------|-------------|-----------------|---------------------|--------------------|-----------------|-----|-----|----------------------------|------------------------------|
| b                                               | iSHELL, HARPS, HIRES | 9               | 91                  | 2.68               | -505.14         | 1050.88 | 1030.50 | 0                          | Favoured Model               |
| Gaussian Process only                           | iSHELL, HARPS, HIRES | 8               | 91                  | 3.02               | -509.05         | 1054.18 | 1035.85 | 5.35                       | Strongly disfavoured         |