No Sun–like dynamo on the active star \( \zeta \) Andromedae from starspot asymmetry

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Sunspots are cool areas caused by strong surface magnetic fields that inhibit convection1–2. Moreover, strong magnetic fields can alter the average atmospheric structure3, degrading our ability to measure stellar masses and ages. Stars that are more active than the Sun have more and stronger dark spots than does the Sun, including on the rotational pole4. Doppler imaging, which has so far produced the most detailed images of surface structures on other stars, cannot always distinguish the hemisphere in which the starspots are located, especially in the equatorial region and if the data quality is not optimal5. This leads to problems in investigating the north–south distribution of starspot active latitudes (those latitudes with more starspot activity); this distribution is a crucial constraint of dynamo theory. Polar spots, whose existence is inferred from Doppler tomography, could plausibly be observational artefacts6. Here we report imaging of the old, magnetically active star \( \zeta \) Andromedae using long-baseline infrared interferometry. In our data, a dark polar spot is seen in each of two observation epochs, whereas lower-latitude spot structures in both hemispheres do not persist between observations, revealing global starspot asymmetries. The north–south symmetry of active latitudes observed on the Sun is absent on \( \zeta \) And, which hosts global spot patterns that cannot be produced by solar–type dynamos5.

\( \zeta \) And is a nearby active star that is both spatially large and spotted, making it one of a small number of promising targets for imaging with current interferometric capabilities. \( \zeta \) And is a tidally locked close binary (RS CVn) system consisting of a K-type cool giant star and an unseen lower-mass companion star7. Tidal interactions have spun-up the cool primary component, causing unusually strong starspots and magnetic activity4,10.

We observed \( \zeta \) And during two observing campaigns of eleven nights spanning Universal Time (UT) 9–22 July 2011 and fourteen nights spanning UT 12–30 September 2013 (see Extended Data Table 1) with the Michigan InfraRed Combiner (MIRC)11 using all six telescopes at Georgia State University’s Center for High Angular Resolution Astronomy (CHARA) Array12 on Mount Wilson, California, USA.

The 2011 and 2013 data sets were separately imaged onto a prolate ellipsoid using the imaging software SURFING (SURFace ImaGING), an aperture synthesis imaging technique (J.D.M., manuscript in preparation). This approach replicates the fundamental ideas behind Doppler imaging in that the whole data set is mapped onto the rotating surface at once instead of night–by–night snapshots. Treating each data set as an ensemble also allows SURFING to fit stellar and orbital parameters (see Table 1) along with the surface temperature maps (see Figs 1 and 2).

The surface temperature maps for \( \zeta \) And show peaks of 4,530 K and 4,550 K and minimum values of 3,540 K and 3,660 K in 2011 and 2013, respectively. The \( \sim 900 \)-K range of temperatures we see across the surface is slightly larger than the \( \sim 700 \)-K range found from recent Doppler imaging work (from the Fe i \( \lambda = 6,430 \) Å line). A strong dark polar spot is present in both of our imaging epochs, also consistent with recent Doppler imaging studies7,13,14. In contrast to this persistent feature, many other large dark regions change completely between 2011 and 2013 with no apparent overall symmetry or pattern. These features and their locations can only unambiguously be imaged by interferometry, since Doppler and light-curve inversion imaging techniques experience latitude degeneracies (see Methods section for more details). We now discuss the starspot implications on the dynamical large-scale magnetic field of \( \zeta \) And.

The extended network of cool regions stretching across the star suggest that strong magnetic fields can suppress convection on global scales, rather than just local concentrations forming spot structures. The extent to which starspots can cover the surface of a star is at present unknown and of interest in understanding how activity saturates on rapidly rotating, convective stars15. The observations in hand lend support to studies that have suggested magnetic activity can be so widespread as to alter the apparent fundamental parameters of a star16,17. For example, a larger region of suppressed convection gives a lower observed temperature, leading to inaccurate estimates for stellar mass and age1. The changes in global magnetic features will produce long-term photometric variations that are often attributed only to changes in a growing or shrinking polar starspot. We note that a polar starspot for \( \zeta \) And does not affect the flux of the star as much as other large-scale magnetic structures do, owing to the effects.

Table 1 | Parameters of \( \zeta \) And

| Measured parameter | Value |
|--------------------|-------|
| Angular polar diameter, \( R_p \) (mas) | 2.502 ± 0.008 |
| Polar radius (\( R_\odot \)) | 15.0 ± 0.8 |
| Oblateness (major to polar axis) | 1.060 ± 0.011 |
| Inclination, \( i^\circ \) | 70.0 ± 2.8 |
| Pole position angle (\( \ell^\circ, E \) of N) | 126.0 ± 1.9 |

Values from the literature:

Distance, \( d \) (pc) | 19.78 ± 0.83 (ref. 29) |
Effective temperature, \( T_{\text{eff}} \) (K) | 4600 ± 100 (ref. 9) |
Luminosity, \( \log L/\ell_\odot \) | 1.98 ± 0.04 (ref. 9) |
Primary mass (\( M_\odot \)) | 2.6 ± 0.4 (ref. 9) |
Secondary mass (\( M_\odot \)) | 0.75 ± 0.09 (ref. 9) |
Iron metallicity (Fe/H)/[Fe/H] | −0.30 ± 0.05 (ref. 9) |

\( \zeta \) Andromedae from starspot asymmetry

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of limb darkening and foreshortening on this highly inclined system ($i \approx 70.0^\circ$).

The interferometric images of ζ And provide a clear confirmation of the existence of polar spots. Polar spots have been seen in Doppler images of ζ And (refs 9, 13 and 14) and of many other active stars. Polar spots produce spectral line-profile changes only in the line core itself (no Doppler shift), and the spectral signature of a symmetric polar spot is the same at each rotational phase of the star. This signature means that polar spots can very easily be produced as artefacts in the Doppler imaging process; if the depth of the spectral line profile is not correctly modelled, then the image will exhibit a polar spot. Strong chromospheric activity has also been postulated to fill in at least some of the photospheric lines used in Doppler imaging, potentially producing a polar spot. These facts made the existence of polar spots a matter of debate in the early days of Doppler imaging. And this is now independent confirmation of their existence, settling the debate.

The interferometric images of ζ And presented here reveal the exact hemispheres of the spots and show strong asymmetries between the hemispheres, with the 2011 map showing dominant spots on the northern and the 2013 map showing them on the southern hemisphere. On the Sun the spots are typically seen on both hemispheres in certain active mid-latitude regions, with some breaking of the symmetry in the spot numbers on the two hemispheres but not as large an asymmetry as seen on ζ And. Such asymmetries require a departure from the solar-type αΩ-dynamo to a more complicated dynamo for ζ And, such as one with mixed parity modes.

Although our results strictly apply only for giant stars in RS CVn binaries, we note strong parallels between the physical conditions and magnetic behaviour of these and pre-main-sequence stars. To reach these conditions, the giant primary stars in RS CVn binaries rotate rapidly owing to tidal spin-up and pre-main-sequence stars rotate rapidly owing to contraction and angular momentum transfer caused by accretion of material from a circumstellar disk. These similar physical conditions hint at shared field-generation mechanisms that are observationally indistinguishable and manifest as starspots. In young associations, it has been noted that derived ages are probably strongly affected by global suppression of convection. These commonalities and the known consequences argue that strong stellar magnetism must be accounted for in models for both pre-main-sequence stars and for the stages of evolution in the most active giant stars.

Results from imaging studies using light-curve inversion and Doppler imaging techniques, as well as new interferometric spot studies, all re-enforce the picture that global magnetic structures cover the faces of the most active stars. Our interferometric imaging has found unambiguous signposts of these structures and clearly points to a perspective beyond the typical isolated spots observed on the Sun. The large-scale suppression of convection by these global magnetic fields will have structural effects on the stellar atmosphere, including puffing up the star and decreasing the effective temperature and luminosity, dramatic alterations that must be accounted for by modern stellar structure calculations especially for young, low-mass stars that universally show strong magnetic activity.

To understand these structural effects, we must image more targets with as much detail as possible. The procedures used here can provide similar $H$-band images for a handful of bright, spatially large, spotted stars (such as α Geminorum and λ Andromedae). Impending
advances in visible interferometry will allow for similar resolution on more stars (down to $\theta \approx 1.1$ mas). For stars that cannot be resolved in detail, combining interferometrically observed photocentre shifts due to rotation of starspots in and out of view with Doppler imaging would resolve the degeneracies inherent in the Doppler images, allowing for more accurate surface maps. By acquiring a number of these maps on several stars or a few observation epochs of the same targets, we could investigate how the changing magnetic field affects our determinations of stellar parameters (including mass and age)\textsuperscript{26,27}. In addition, the development of new dynamo models would shed light on the impact of stellar parameters (including mass and age)\textsuperscript{26,27}.

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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Figure 2 | Surface images of $\zeta$ And from September 2013 with fourteen nights of data using SURFING. a and b are presented as in Fig. 1, except that the 200-K contours of the Aitoff projection (a) range from 3,600 K to 4,600 K. The polar spot is observed to have evolved between the two sets of observations. The lower-latitude spots present in the 2011 data set are not present in the 2013 data set, with the new spots located mostly below the equator, emphasizing the spot-latitude asymmetry observed.

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Author Contributions

R.M.R., J.D.M., F.B., X.C., S.K. and M.Z. obtained the observations of ζ And. R.M.R., J.D.M., F.B., X.C., S.K., G.H.S. and M.Z. obtained the observations of 37 And. R.M.R. performed the data reduction and calibration. R.M.R. and G.T. determined the orbital parameters of 37 And. J.D.M. and R.M.R. created the images of ζ And, which were interpreted by R.M.R., J.D.M., H.K., Zs.K., R.O.H. and A.N.A. T.A.t.B., G.H.S., J.S. and L.S. provided observational setup and technical support.

Author Information

Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to R.M.R. (rmroett@umich.edu).
METHODS

Starspot imaging methods. Large spots covering a substantial fraction of the stellar surface have been indirectly imaged using light-curve inversion and Doppler imaging techniques31,32. Light-curve inversion reproduces spotted stellar surfaces based on time-series data and can only reproduce structures observed as rotational modulations—structures such as static polar spots are practically invisible to light-curve inversion imaging. Light-curve inversion typically reveals only weak relative latitude information for the spots, although this can be improved with the combination of concurrent observations in multiple filters33. A more detailed surface map, both in latitude and longitude, can be obtained with Doppler imaging, which creates surface temperature maps from tracking small changes in absorption lines as starspots rotate in and out of view32. Nevertheless, this method cannot always distinguish the hemisphere in which the structures are located. To confirm important findings from these methods and to understand the global characteristics of activity that can alter stellar radii and effective temperature, a more direct imaging method is required that is immune to these ambiguities.

The nearest magnetically active stars are too small to be resolved by even our largest telescopes. However, long-baseline interferometry has the potential to image sub-milliarcsecond features on the surfaces of nearby stars. To date, interferometric imaging has been used successfully to confirm the oblateness and gravity darkening of rapidly rotating stars34 and even to image a spotted stellar surface35. To improve the resolution and imaging quality for rotating stars that show strong magnetic activity, we present here an ‘imagining-on-a-sphere’ technique that uses interferometric observations from multiple nights to constrain a surface temperature map. This naturally takes advantage of the multiple views we have of starspot structures as they rotate across the disk of the star. Interferometric imaging produces unique images that resolve the degeneracies in latitude. Doppler imaging observed over many cycles of rotation provides the first independent confirmation of the existence of polar starspots.

Interferometric data. Our interferometric observations were obtained using the Michigan InfraRed Combiner (MIRC) at the Center for High Angular Resolution Astronomy (CHARA) Array. The CHARA Array consists of six 1-m telescopes in a Y-shaped configuration with baselines ranging from 34 m to 331 m (ref. 12). For the ζ And data, MIRC35 combined light from all six CHARA Array telescopes in the H-band (eight channels across 1.5–1.8 μm for λ/Δλ ≈ 40), resulting in an angular resolution of λ/2Δλ ≈ 0.5 milliarcseconds, where B is the longest baseline used by the interferometer, that is, the distance between the two farthest apart telescopes of the interferometer.

The data were reduced and calibrated with the standard MIRC pipeline35. We searched without success for evidence of the faint companion in our interferometric data using our proven grid search method36, and could secure only a 1σ lower limit of 300:1 on the H-band flux ratio between primary and companion.

The data products obtained from reducing the CHARA/MIRC data with the standard pipelines consist of visibilities, closure phases and triple amplitudes. Representative samples of the visibilities and closure phases are presented in Extended Data Figs 1 and 2 for a single night (17 September 2013) of six-telescope CHARA/MIRC observations of ζ And. The reduced data are available in OI-FITS format37 upon request.

Calibration stars. The twenty-five nights of interferometric data span 9–22 July 2011 and 12–30 September 2013. For these nights of observation we use four calibration stars (37 Andromedae, γ Pegasi, γ Trianguli and 58 Ophiuchi) inter-spersed with observations of the target star ζ And. γ Peg, γ Tri, and 58 Oph are modelled as spherical, uniform disk stars38 with their parameters as in Extended Data Table 2.

The calibrator 37 And is a recently discovered binary system39 with a primary-to-secondary H-band flux ratio of 80 ± 20. Ordinarily, binary stars make poor calibration objects because of the complicated system of seven binary components. However, 37 And is a single object that is much easier to model. This is especially useful when the system changes gradually over time, changing the apparent separation of the components.

SURFING imaging code. The image reconstruction code SURFING (SURFace imagingNG) was specially written for this project: to image surfaces of rotating stars. We create a global model of the star, including geometrical parameters (polar radius, oblateness, inclination, pole position angle, limb darkening coefficient, rotational period, epoch) as well as the surface temperature map. We cover the surface with tiles of equal area using the HEALPix methodology40, using 768 tiles to match the spatial resolution of CHARA. Each tile has an area of 0.025 mas2. We represent the shape of the stellar photosphere as a prolate spheroid to approximate a slightly filled Roche potential. The deviation from spherical appears as gravity darkening and accounts for a temperature difference of only ~60 K, which is much smaller than the temperature variations of the starspots.

We sampled the large range of geometrical models using an affine invariant ensemble Markov chain Monte Carlo approach41, with a nested loop to iteratively optimize the surface temperature map within each walker of the outer loop (this was needed because the 768 free parameters needed to characterize the temperature map would be intractable using a Markov chain approach). Extensive testing was carried out using blind simulated data to optimize the speed of convergence. In addition to minimizing the χ2 statistic, we also incorporated priors on each parameter and could experiment with a variety of imaging regularizers, such as total variation or the L2norm of wavelet coefficients.

In addition to testing the code on simulated data, we were also able to check results using soon-to-be-published data on the spotted star ζ And (ref. 24), finding comparable results and confirming the inclination and position angle of the pole. We also checked that the imaging-derived orientation of another RS CVn (ζ Gem, R.M.R., J.D.M., H.K., R.O.H., F.B., X.C., G. W. Henry, G.H.S., M. Weber & K. G. Strassmeier, manuscript in preparation) matched the orbital plane of the close companion. The results of these tests and additional details about the implementation of our method will be described in a future paper (J.D.M., manuscript in preparation).

ζ And parameters from SURFING. Another test of the robustness of our fitting methodology is to determine the stellar orientation for independent data sets and compare the results. While the magnetic field structures will vary from year to year, the inclination of the pole and its position angle on the sky will not. Extended Data Fig. 5 shows a χ2 surface for three separate years: a 2008 pilot set of observations using the MIRC four-telescope system, the 2011 data set, and the 2013 data set. This figure shows two large regions of reduced χ2 around inclination i = 90° and position angle (PA) = −60° or 120°. These regions reflect the oblateness of the star and the basic orientation on the sky. The region near inclination i = 70°, PA = 120° has the lowest χ2 in all years, and especially in 2013. This tells us that the spots move from the southwest towards the northeast and not the other way around, and the consistent picture from year to year both shows the efficacy of the code and gives confidence that we are measuring the true astrophysical signal and not over-fitting noise or systematic errors.

The results from these grid studies have been used to robustly estimate the geometrical parameters for ζ And, and these parameters are found in Table 1. The error bars associated with the parameters were determined by combining the results of data sets from 2011 and 2013, with the additional data from 2008. The 2008 data were obtained with only four CHARA telescopes, so they are not of high enough quality for imaging.

To convert H-band regions ins' isites from the reconstructed images into photospheric temperatures, we used Kurucz atmospheric models43 for iron metallicity [Fe/H] = −0.25 and appropriate surface gravity (logg). Note that the overall temperature scale in our maps is uncertain (overall multiplicative scaling) owing to lack of coeval photometry at H band; here we adopted a mean H-band magnitude of H = 1.64, based on archival infrared photometry.

ζ And imaging tests. The previous section laid out our robust method for determining the geometrical parameters of ζ And by using three independent observing data from different years. The next issue is to determine the reliability of the surface temperature maps. We split the extensive CHARA/MIRC data from ζ And into two partial data sets reproducing the main features observed by the full data set shown in the main text. This proves that the features seen in the maps are real and are not the result of an over-fitting to poor-quality data or peculiarities of the nightly baseline coverage.

The unprecedented phase coverage in the 2011 and (especially) the 2013 observing runs have allowed for textbook imaging fidelity tests for ζ And. We show that the large-scale dark regions that cover ζ And are highly robust, probably deriving from magnetically suppressed convection.

Code availability. At present, we have opted not to make the SURFING code available because of a publication in preparation, which will detail the use and the applicability of the resource.
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Extended Data Figure 1 | Visibility curve of \( \zeta \) And with CHARA/MIRC. The observed visibilities (unitless) are plotted in black with 1\( \sigma \) error bars and the SURFING model visibilities are overlaid in red.
Extended Data Figure 2 | Closure phases of UT 15 September 2013 observations of ζ And with CHARA/MIRC. Each block represents a temporal block of closure phase (CP) observations with data plotted in black (with 1σ errors) and SURFING model in red. Each row represents the CP from a unique set of three telescopes, labelled in the standard CHARA format.
Extended Data Figure 3 | Orbit of 37 And. The grey plus signs represent measurements of the companion (1σ errors on detections are smaller than the symbols). The observed resolved disk of 37 And is plotted as the black dot at the origin. The thin solid black line is the best-fit orbit from combining the interferometric detections and the ELODIE radial velocities. Note that the axis units are milliarcseconds (mas) with north up and east to the left.
Extended Data Figure 4 | Radial velocity curve of the primary star of 37 And. The data points are based upon archival ELODIE spectra (with 1σ error bars). The orbital solution used the velocity measurements and the interferometric measurements simultaneously. The solid line is the best-fit orbit and the grey lines are fifty Monte Carlo realizations of the orbit.
Extended Data Figure 5 | Reduced, normalized $\chi^2$ surface plot of the SURFING model fitted for position angle and inclination of $\zeta$ And. The peak is found at $\text{PA} = 126.0^\circ \pm 1.9$ and $i = 70.0^\circ \pm 2.8$. The epoch of each data set is located in the upper left of each panel. The different colours represent varying normalized $\chi^2$ values with the black contours labelled with specific values.
Extended Data Figure 6 | Comparison of the 2013 CHARA/MIRC data set divided into two sets of seven nights of data. These projections are plotted in the same way as the Aitoff projection in Fig. 2.
Extended Data Table 1 | Observations and calibrators of ζ And

| UT Date   | Modified Julian Date (MJD) | Calibrators Used |
|-----------|-----------------------------|-------------------|
| 2011 Jul 9| 55751.536                   | 37 And            |
| 2011 Jul 10| 55752.531                  | γ Peg             |
| 2011 Jul 11| 55753.480                  | 37 And            |
| 2011 Jul 12| 55754.469                  | γ Peg             |
| 2011 Jul 14| 55756.478                  | γ Peg             |
| 2011 Jul 16| 55758.505                  | 58 Oph            |
| 2011 Jul 17| 55759.481                  | γ Peg             |
| 2011 Jul 19| 55761.475                  | 37 And, γ Peg     |
| 2011 Jul 20| 55762.517                  | γ Peg             |
| 2011 Jul 21| 55763.478                  | γ Peg, γ Tri      |
| 2011 Jul 22| 55764.480                  | γ Peg, γ Tri      |
| 2013 Sep 12| 56547.449                  | 37 And, γ Tri     |
| 2013 Sep 13| 56548.426                  | 37 And, γ Tri     |
| 2013 Sep 15| 56550.392                  | 37 And, γ Peg, γ Tri |
| 2013 Sep 16| 56551.365                  | 37 And, γ Peg, γ Tri |
| 2013 Sep 17| 56552.345                  | 37 And, γ Tri     |
| 2013 Sep 18| 56553.359                  | 37 And, γ Peg, γ Tri |
| 2013 Sep 19| 56554.407                  | 37 And, γ Peg, γ Tri |
| 2013 Sep 20| 56555.365                  | 37 And, γ Peg, γ Tri |
| 2013 Sep 21| 56556.403                  | 37 And, γ Tri     |
| 2013 Sep 23| 56558.403                  | 37 And, γ Tri     |
| 2013 Sep 24| 56559.343                  | 37 And, γ Peg, γ Tri |
| 2013 Sep 28| 56563.367                  | 37 And, γ Tri     |
| 2013 Sep 29| 56564.357                  | 37 And, γ Tri     |
| 2013 Sep 30| 56565.334                  | 37 And, γ Tri     |
Extended Data Table 2 | Uniform disk sizes (H-band) of calibrators

| Star Name (HD number) | $\theta_{UD}$ (mas) |
|-----------------------|---------------------|
| $\gamma$ Peg (HD 886) | $0.41 \pm 0.03$     |
| $\gamma$ Tri (HD 14055) | $0.51 \pm 0.03$     |
| 58 Oph (HD 160915)    | $0.68 \pm 0.05$     |

The uniform disk diameters $\theta_{UD}$ were obtained with SearchCal$^{38}$. 

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Extended Data Table 3 | Binary separation and position angle measurements of 37 And

| UT Date     | Modified Julian Date (MJD) | Separation (mas) | Position Angle (°, E of N) | Error Ellipse Major Axis (mas) | Error Ellipse Minor Axis (mas) | Error Ellipse Position Angle (°) |
|-------------|-----------------------------|-------------------|-----------------------------|--------------------------------|--------------------------------|---------------------------------|
| 2011 Jul 9  | 55751.492                   | 11.46             | 217.0                       | 0.13                           | 0.11                           | 300                             |
| 2011 Jul 12 | 55754.499                   | 9.09              | 230.6                       | 20.10                          | 0.08                           | 270                             |
| 2011 Jul 19 | 55761.465                   | 6.38              | 295.4                       | 0.06                           | 0.05                           | 330                             |
| 2011 Nov 29 | 55894.159                   | 63.57             | 143.9                       | 0.82                           | 0.16                           | 340                             |
| 2013 Sep 12 | 56547.470                   | 82.28             | 152.6                       | 0.58                           | 0.15                           | 330                             |
| 2013 Sep 13 | 56548.399                   | 82.51             | 152.7                       | 0.02                           | 0.10                           | 30                              |
| 2013 Sep 15 | 56550.340                   | 82.47             | 152.8                       | 0.81                           | 0.26                           | 350                             |
| 2013 Sep 16 | 56551.344                   | 82.73             | 152.9                       | 1.23                           | 0.27                           | 340                             |
| 2013 Sep 17 | 56552.329                   | 82.63             | 152.9                       | 0.48                           | 0.17                           | 330                             |
| 2013 Sep 18 | 56553.250                   | 82.88             | 153.0                       | 0.95                           | 0.21                           | 340                             |
| 2013 Sep 19 | 56554.292                   | 83.06             | 153.1                       | 0.72                           | 0.27                           | 350                             |
| 2013 Sep 20 | 56555.301                   | 83.02             | 153.2                       | 0.79                           | 0.14                           | 330                             |
| 2013 Sep 23 | 56558.416                   | 83.08             | 153.4                       | 1.01                           | 0.22                           | 340                             |
| 2013 Sep 24 | 56559.239                   | 83.29             | 153.5                       | 0.58                           | 0.23                           | 340                             |
| 2013 Sep 28 | 56563.303                   | 83.62             | 153.7                       | 1.08                           | 0.21                           | 340                             |
| 2013 Sep 30 | 56565.276                   | 83.65             | 153.8                       | 0.83                           | 0.20                           | 340                             |
| 2014 Aug 19 | 56888.422                   | 14.45             | 98.2                        | 0.32                           | 0.18                           | 280                             |
| 2014 Aug 20 | 56889.446                   | 15.58             | 100.8                       | 0.24                           | 0.17                           | 10                              |
| 2014 Sep 1  | 56901.412                   | 22.82             | 116.9                       | 0.11                           | 0.07                           | 300                             |
Extended Data Table 4 | Orbital parameters of 37 And

| Parameter                              | Value             |
|----------------------------------------|-------------------|
| Semimajor axis, $a$ (mas)              | 46.66 ± 0.06      |
| Eccentricity, $e$                      | 0.8405 ± 0.0009   |
| Inclination, $i$ (°)                   | 52.5 ± 0.3        |
| Argument of periastron, $\omega$ (°)   | 168.9 ± 0.3       |
| Ascending node, $\Omega$ (°)           | -17.6 ± 0.2       |
| Orbital period, $P_{\text{orb}}$ (days) | 550.7 ± 0.2       |
| Time of periastron passage, $T_0$ (MJD)| 55765.45 ± 0.04   |
| Velocity semi-amplitude, $K_\Lambda$ (km/s) | 11.1 ± 0.5     |
| System velocity, $\gamma$ (km/s)       | 5.33 ± 0.07       |

The orbital parameters were obtained by combining the ELODIE radial velocity curve with the CHARA/MIRC detections.