A measure of the size of the magnetospheric accretion region in TW Hydrae

Stars form by accreting material from their surrounding disks. There is a consensus that matter flowing through the disk is channelled onto the stellar surface by the stellar magnetic field. This is thought to be strong enough to truncate the disk close to the corotation radius, at which the disk rotates at the same rate as the star. Spectro-interferometric studies in young stellar objects show that hydrogen emission (a well known tracer of accretion activity) mostly comes from a region a few milliarcseconds across, usually located within the dust sublimation radius. The origin of the hydrogen emission could be the stellar magnetosphere, a rotating wind or a disk. In the case of intermediate-mass Herbig AeBe stars, the fact that Brackett γ (Brγ) emission is spatially resolved rules out the possibility that most of the emission comes from the magnetosphere because the weak magnetic fields (some tenths of a gauss) detected in these sources result in very compact magnetospheres. In the case of T Tauri sources, their larger magnetospheres should make them easier to resolve. The small angular size of the magnetosphere (a few tenths of a milliarcsecond), however, along with the presence of winds make the interpretation of the observations challenging. Here we report optical long-baseline interferometric observations that spatially resolve the inner disk of the T Tauri star TW Hydrae. We find that the near-infrared hydrogen emission comes from a region approximately 3.5 stellar radii across. This region is within the continuum dusty disk emitting region (7 stellar radii across) and also within the corotation radius, which is twice as big. This indicates that the hydrogen emission originates in the accretion columns (funnel flows of matter accreting onto the star), as expected in magnetospheric accretion models, rather than in a wind emitted at much larger distance (more than one astronomical unit).

The T Tauri star TW Hydrae (TW Hya) belongs to an association of young stars around 8 million years old. Its proximity to Earth, as well as its favourable pole-on orientation, makes it an ideal candidate for protoplanetary disk studies. The disk structure of TW Hya includes a dust-depleted inner hole, as well as a series of bright rings, with the closest one located at about one astronomical unit (1 AU) from the star. The presence of the inner hole and the small near-infrared excess make TW Hya the prototypical ‘transitional disk’, in which planets and photoevaporation are expected to be the main mechanisms of disk dispersal. However, the measurement of non-negligible accretion rates (2.3 x 10⁻⁶ M☉ yr⁻¹; where M☉ is the solar mass) indicates that the inner-disk region of TW Hya is still rich in gas. Further evidence of accretion is given by the detection of a nearly pole-on cool photospheric spot (stable over several years), coincident with the location of the main magnetic pole (B = 2.5 kG), and a region of accretion-powered excess line emission. This suggests that accretion in TW Hya takes place mostly poleward, and that the stellar magnetic field is strong enough to magnetically truncate the inner disk at a few stellar radii from the star. This value is equivalent to a few tenths of a milliarcsecond, and so it is impossible to directly resolve the magnetospheric accretion region, even for such a nearby star, using conventional methods. This leaves spectro-interferometry as the only suitable technique.

With this aim, we conducted high-angular resolution observations of the hydrogen Brγ line in TW Hya using the Very Large Telescope Interferometer (VLTI) instrument GRAVITY with the four 8-m Unit Telescopes (Fig. 1). The Brγ line is a well known tracer of accretion in low-mass protostars through an empirical relationship that relates the line and accretion luminosities. Our interferometric measurements allowed us to probe the Brγ line and K-band emitting regions along six different baselines (projected baselines ranging from approximately 130 m to 45 m, resulting in nominal angular resolutions of around 4 mas to 10 mas) and at various position angles. By fitting a geometrical model (see Methods) to the continuum emission (star plus continuum circumstellar emission) and assuming a K-band to stellar flux ratio of 1.18 (refs. ), we derive a stellar radius of Rd = (1.29 ± 0.19)R☉ (consistent with theoretical expectations; where Rd is the solar radius and R☉ is the solar radius) and a radius for the K-band continuum excess/circumstellar emission of RK = (6.50 ± 0.16)R☉ (see Table 1 and Fig. 2). These values are in agreement with previous interferometric results and spectroscopic studies. Furthermore, the location of the K-band...
excess emission is consistent with the location of a disk rim, owing to silicate sublimation (see Methods).

By removing the continuum contribution to the line emission (see Methods), we find that the Brγ line emitting region is very compact, but nonetheless marginally resolved for the longest projected baselines (more than about 60 m). This allows us to measure a radius for the Brγ emitting region of \( R_{\text{Brγ}} = (3.49 \pm 0.20) R^* \) assuming a distance of about 60 pc from the Sun to TW Hya (see Table 1, Fig. 2 and Extended Data Fig. 1). This size is consistent with the small (less than about 1°; with total amplitude of less than 2°) photocentre shift of the line with respect to the continuum (the so-called differential phase) detected in our longest baselines (see Fig. 1). Such a differential phase roughly translates into a Brγ line displacement of less than about 5 \( R^* \) (see Methods for more details), in agreement with the value derived from the continuum-subtracted Brγ line visibilities.

The inferred size of the Brγ line emission is too compact to be emitted in a photoevaporative wind that in TW Hya is expected to be launched beyond the dust cavity (\( R > 0.5–1 \) au, that is, \( R > 80 R^*–160 R^* \)). It should be pointed out that in TW Hya there is no evidence of the presence of a disk wind, which is typically emitted within 0.5 au from the star (20, 21). It should be pointed out that in TW Hya there is no evidence of the presence of a disk wind, which is typically emitted within 0.5 au from the star.

Table 1 | Size estimates of TW Hya

| TW Hya | \( R \) (mas) | \( R \) (au) | \( R \) (\( R^* \)) |
|--------|--------------|-------------|-----------------|
| Star   | 0.10 ± 0.01  | 0.006 ± 0.001 | 1.29 ± 0.19     |
| Disk   | 0.65 ± 0.02  | 0.039 ± 0.001 | 8.39 ± 0.21     |
| Line   | 0.35 ± 0.02  | 0.021 ± 0.001 | 4.50 ± 0.26     |

Estimates are derived from the best fit of the continuum and continuum-compensated Brγ line data.
source, or a jet, which would be associated with bright fast blue-shifted emission in lines, such as Ha and [O I] 6,300 Å and [S II] 6,717 Å, that are not observed in this object13–15. Therefore, the results presented here indicate that the Brγ line is emitted in the magnetospheric accretion region. Classical magnetospheric accretion models assuming free-fall velocities along an axisymmetric, dipolar magnetosphere predict indeed that the Brγ line is formed along the accretion columns23–25. In these models, the Brγ line has a broad profile, comparable to the free-fall velocity, centred around zero velocity. This is the case for the Brγ line observed in TW Hya, which shows a full width at zero intensity of about 400 km s⁻¹, consistent with the expected velocity of gas around a solar-mass star falling at free-fall from about 3R☉–4R☉. Therefore, our measurements indicate that the Brγ line is emitted along the magnetospheric accretion columns that truncate the disk at around 3.5R☉.

Is this value consistent with the expected magnetospheric truncation radius of TW Hya as determined by its magnetic field? Zeeman–Doppler imaging has been used to reconstruct the magnetic field topology and strength of TW Hya26,29. Those measurements showed that the magnetic field of TW Hya is strong (about 1.5 kG) and mostly poloidal and axisymmetric with respect to the stellar rotation axis. The field can be separated into a complex octupole component of approximately 2.5 kG and a much fainter dipolar large-scale field of 400–700 G. Models for such complex magnetic field topologies show that the gas initially accretes following the dipolar field lines, although near the stellar surface the octupole component alters the flow of matter26,29. In accordance with this idea, and with the theoretical work of Bessolaz et al.26, we estimate a truncation radius of 3R☉–4R☉ assuming a stellar radius and mass of 1.22R☉ and 0.6M☉ (ref. 14), and a mass accretion rate of 2.3 × 10⁻⁷ M☉ yr⁻¹ (refs. 14,15) for TW Hya, and a strength of the dipolar magnetic field component of 400–700 G. Therefore, the size of the Brγ line emitting region derived from our interferometric measurements and the size of the truncation radius estimated from the magnetic field of TW Hya are strikingly similar. In addition, the measured size of the line-emitting region is inconsistent with a disk wind, since it is much smaller than the inferred truncation radius. There is a small possibility that dust-free disk gas extends inwards of the inferred sublimation radius, and could be responsible for at least part of the line emission. However, the previously measured magnetic field strength and geometry implies a disk truncation radius consistent with the size of the K-band continuum. Finally, the detection of spatially resolved line emission rules out the possibility that most of the Brγ emission originates at the accretion shock near the stellar surface. A schematic view of our findings is shown in Extended Data Fig. 2. Our results are thus in agreement with the topology and strength of the magnetic field and they validate the assumption that when the magnetic field of the central star is complex, the truncation radius is located closer to the central star than would be expected if the magnetic field has a dipolar morphology of similar average strength26,29.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-020-2613-1.

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Methods

Observations and data reduction
TW Hya was observed with the VLTI instrument GRAVITY\(^{10}\) on 21 January 2019 using the four 8-m Unit Telescopes of the European Southern Observatory (see Extended Data Table 1). The target was observed in single-field combined polarization mode (that is, fringes were stacked and averaged on the target itself), using the MACAO on axis adaptive optics system. The data on the fringe tracker detector were recorded at low spectral resolution (\(R\approx 23\)) with a detector integration time per interferogram of 0.85 ms, whereas the science detector was working at high spectral resolution (\(R\approx 4,000\)), that is, \(\Delta \nu = 70 \text{ km s}^{-1}\) and with a detector integration time per interferogram of 30 s.

The data were reduced using the GRAVITY pipeline version 1.3.0 (ref. 10). The atmospheric transfer function was calibrated using the calibrators HD 91937 and HD 95470 (see Extended Data Table 1). The spectrum of TW Hya was obtained by averaging the high-spectral-resolution spectra recorded in the four photometric channels. Standard telluric correction was also applied to the spectrum using HD 95470 (SpT K2/3 III) as a telluric standard star. Finally, the spectrum was flux-calibrated assuming a Two Micron All-Sky Survey (2MASS) K-band magnitude of 7.3 for TW Hya. The wavelength calibration of the spectra was refined using several telluric absorption lines present in the spectrum. An average shift of about 4 Å was applied to the data.

Interferometric observables
VLTI-GRAVITY observations of TW Hya provided us with the K-band spectrum of the source, six spectrally dispersed visibilities (which give a measure of the size of the object, with \(V=1\) indicating a point source and \(V=0\) indicating a fully resolved object) and differential phases (which measure the photocentre shift of the line with respect to the continuum) and four closure phases (which provide a measure of the asymmetry of the continuum and/or line emission) (see Fig. 1).

The spectrum of TW Hya shows bright Brγ 2.166 μm line emission, along with Na i 2.206 μm, and Na i 2.209 μm, and rovibrational CO in absorption. No interferometric signal is detected for any of these lines except the Brγ line. A small differential phase signature of 2° in the Brγ line is detected along the two longest baselines. No closure phases were detected within the errors.

The continuum visibilities point towards a very compact circumstellar environment around TW Hya with measured continuum visibilities above about 0.95 in all our baselines. Interestingly, the total visibilities within the line decreases with respect to the continuum visibilities, indicating that the sum of the Brγ emitting region plus the continuum contribution (including the stellar plus circumstellar environment) is more extended than the continuum alone. However, it should be noted that the total visibility is not just the sum of each visibility component but is weighted by the flux of each component. In other words, assuming that the level of the continuum within and outside the line is the same and that the differential phase is zero, then: \(V_{\text{tot}} = V_{\text{cont}} + V_{\text{line}}\), with \(V_{\text{cont}}\) and \(V_{\text{line}}\) being the total and continuum contributions, respectively; and \(F_{\text{tot}} = F_{\text{cont}} + F_{\text{line}}\). In these expressions, \(F_{\text{cont}}\) and \(F_{\text{line}}\) are the continuum and line fluxes and visibilities, respectively; and \(V_{\text{cont}}\) and \(V_{\text{line}}\) are the stellar and circumstellar continuum fluxes and visibilities. To further investigate the circumstellar and Brγ line emitting region the contribution from the star and the overall continuum emission must be removed from the measured visibilities.

Circumstellar continuum emitting region
As mentioned above, to estimate the size of the continuum circumstellar emitting region the line from the star must be removed. In doing so, a K-band to stellar flux ratio of 1.18 was assumed\(^{17}\). As we expected to be able to marginally resolve TW Hya owing to its close distance (that is, \(V_s < 1\) on our longest baselines), we took the conservative approach of fitting two Gaussian components to the continuum visibilities measured by GRAVITY, one corresponding to the central star plus an additional component due to the circumstellar disk (assumed to be inclined, that is, the inclination (i) and position angle (PA) were allowed to be free parameters). Using this approach, our best-fitting model corresponds to two Gaussians with full-width-at-half-maximum values of FWHM = 0.20 ± 0.03 mas and FWHM\(_{\text{cont}} = 1.30 ± 0.04\) mas, respectively. The i and PA values of the latter component are consistent with a nearly face-on structure as reported by ALMA\(^{15}\). However, owing to the lack of long baselines, along with the nearly face-on geometry, we cannot provide stringent constraints on the i and PA values of the system, and from now on we will assume ALMA measurements of \(i=8°\) and PA = 32° as our fiducial values. Coming back to the size of the emitting region, the derived FWHM values correspond to a stellar radius of \(R_s = (1.29\pm 0.19) R_\odot\) and \(R_{\text{circ}} = (8.39\pm 0.21) R_\odot\), assuming a distance of 60 pc (ref. 41). The retrieved stellar and circumstellar radii are in agreement with previous values found in the literature\(^{14,20,32,33}\). If a lower value of the observed K-band to stellar flux ratio of 1.10 is assumed\(^{14,37}\), it would provide a worse fit, with stellar and circumstellar radii with much larger errors, namely, \(R_s = 0.05\pm 0.11\) mas (that is, \((0.68\pm 1.42) R_\odot\)) and \(R_{\text{circ}} = 0.70\pm 0.13\) mas (that is, \((9.03\pm 1.68) R_\odot\)).

Continuum-subtracted Brγ line visibilities
The size of the Brγ line emitting region can be estimated by assuming that the total visibilities within the Brγ line are due to the contribution of the line emitting region plus the continuum component. In this way, the pure (or continuum compensated) Brγ line visibilities can be derived by subtracting the continuum contribution from the total line visibilities following:\(^{26}\)

\[
V_{\text{cont}} V_{\text{tot}} e^{i \phi} = V_{\text{cont}} \left( F_{\text{cont}} V_{\text{cont}} + V_{\text{line}} e^{i \phi} \right) + (1)
\]

where \(\phi\) is the differential phase in the line, and \(\Delta \phi\) is the difference of the Fourier phases of the continuum and line components, that is \(\Delta \phi (B/\lambda)_{\text{line}} - \Phi (B/\lambda)_{\text{cont}} - \Phi (B/\lambda)_{\text{line}}\). Thus the errors on the continuum compensated visibilities have been estimated taking into account the error on the continuum and total visibilities (assuming the root-mean-square value as a conservative error), and the differential phase errors.

Initially, the continuum-compensated Brγ line visibilities were computed at three velocity channels at radial velocities of approximately \(-33\) km s\(^{-1}\), \(4\) km s\(^{-1}\), and \(40\) km s\(^{-1}\), and with a line-to-continuum ratio higher than 10%. For all six baselines, the continuum-compensated Brγ line visibilities measured at each spectral channel are roughly the same within the errors. Therefore, the weighted mean of the three pure line visibilities for each baseline was computed and used to derive the size of the Brγ line emitting region. The average pure Brγ line visibilities are shown in Figs. 1, 2. The Brγ line emitting region is marginally resolved only for the longest projected baselines (more than about 60 m), meaning that the emitting region is very compact.

To derive the size of the Brγ line emitting region, we computed a geometric model of the Brγ line continuum-compensated visibilities using a Gaussian fit. As for the continuum, we fixed the i and PA to the values derived by ALMA and we fitted the line visibility with only the Gaussian FWHM as a free parameter. The best-fit result is shown in Table 1, and it corresponds to a radius of the Brγ line emitting region of \(R_{\text{line}} = 0.35\pm 0.02\) mas or \(R_{\text{line}} = (4.5\pm 0.26) R_\odot\), assuming a distance of about 60 pc to TW Hya (Fig. 2 and Extended Data Fig. 1).

To probe the effect of the assumed \(F_{\text{tot}}/F_{\text{cont}}\) flux ratio on our results, we have repeated the analysis, varying this ratio by 10%. The results \((R_{\text{line}}^{\text{10%}} = 0.37\pm 0.05\) mas; \(R_{\text{line}}^{\text{10%}} = 0.33\pm 0.02\) mas) are consistent with the previous one within the error bars.

Continuum-subtracted Brγ line differential phase
As for the case of the visibilities, the contribution of the continuum to the differential phase can be removed. This type of analysis is especially
useful when the measured photocentre shift of the line is weak. Following ref. 36, the displacement of the photocentre of the line at any given wavelength can be derived from:

\[
\sin(\Delta \phi) = \sin(\phi) \times \frac{V_{\text{rad}}}{|V_{\text{rad}}|}
\]

(2)

The displacement of the photocentre of the emission at any given wavelength \(\delta\) is then:

\[
\delta = -\Delta \phi \frac{\lambda}{2\pi B}
\]

(3)

where \(B\) is the length of the baseline. The upper limit of the differential phase is about 1°. This translates into a maximum value of \(\Delta \phi_{\text{max}} = -6.2^\circ\), equivalent to a maximum displacement of \(\delta_{\text{max}} = 3.8 R_\odot = 4.9 R_\odot\). This value is very similar to the one derived from the continuum-subtracted visibilities.

**Rim radius**

We can estimate the rim radius (or the distance from the star where silicates sublimes) using equation (11) of Dullemond et al. under the assumption that the pressure scale height is a small fraction of \(R_\odot\). For the temperature (4,000 K) and radius \((R = 1.2 R_\odot)\) assumed here for TW Hya, a rim radius of \(R_{\text{rim}} = 7.5 R_\odot\cdot\) is found for a sublimation temperature of 1,500 K.

**Corotation radius**

The corotation radius depends on the stellar mass, radius and rotation velocity. This latter is uncertain owing to the low inclination of TW Hya with respect to the line of sight. Estimates of the rotation velocity ranges from 80 ± 34 km s\(^{-1}\) (assuming \(v\sin i = 7 ± 3\) km s\(^{-1}\) (ref. 18)) and a disk inclination of 5°; ref. 35) to about 17.4 km s\(^{-1}\) (assuming a rotation period of 3.56 days; ref. 40). Taking these values, and a stellar mass and radius of 0.58\(M_\odot\) and 1.22\(R_\odot\) (ref. 18), we find a corotation radius of \(R_{\infty} = 6.5 R_\odot\). The corotation radius is noticeably larger than \(R_{\infty}\) supporting our hypothesis that the Brγ size measures the radius of the magnetosphere, probably tracing the width of the region containing accretion columns.

**Data availability**

This work is based on observations collected at the European Southern Observatory (ESO) under ESO programme 0102.C-0408(C). The raw data are publicly available in the ESO Science Archive Facility.
Extended Data Fig. 1 | Best-fit model to the continuum-subtracted Brγ line visibilities. Continuum subtracted visibilities are represented in colour in the $u$–$v$ plane. The symbol size indicate the error of each single data point. For comparison, the average visibility error is represented by the dark full circle at the bottom right of the figure. Contours represent the visibility values of the best two-dimensional Gaussian model.
Extended Data Fig. 2 | Sketch of the inner-disk region of TW Hya. The main features of the inner disk are represented: the dusty disk (brown), the dust sublimation radius located at about $7.5R_\ast$, the inner gaseous disk (blue), truncated by the stellar magnetosphere (red) at about $3.5R_\ast$, along with the Brγ line emitting region, which is probably tracing the width of the accretion columns.
## Extended Data Table 1: Observation log of the VLTI GRAVITY+UT high-resolution observations of TW Hya

| UT Date  | Tot. Int. | DIT* | NDIT† | Proj. baselines | PA‡ | Calibrators | UD diameter§ |
|----------|-----------|------|-------|-----------------|-----|-------------|--------------|
|          | [s]       | [s]  | [s]   | [m]             | [°] |             |              |
| 2019-01-21 | 3900     | 30   | 10    | 45, 54, 61, 69, 42, 28, 114, 86, 99, 126 | 84, 34, 63 | HD 91937, 0.279 ± 0.004, HD 95470 | 0.367 ± 0.005 |

**UT**, Unit Telescope; **Tot. Int.**, total integration; **Proj.,** projected.

*DIT*, detector integration time per interferogram.

†NDIT, number of interferograms.

‡PA, baseline position angle from the shortest to longest baseline.

§UD diameter, the calibrator uniform-disk diameter (K band) was taken from the SearchCal tool available at http://www.jmmc.fr/searchcal.