The magnetic field across the molecular warped disk of Centaurus A

Enrique Lopez-Rodriguez

Magnetic fields are amplified as a consequence of galaxy formation and turbulence-driven dynamos. Galaxy mergers can potentially amplify the magnetic fields from their progenitors, making the magnetic fields dynamically important. However, the effect of mergers on magnetic fields is still poorly understood. We use thermal polarized emission observations to trace the magnetic fields in the molecular disk of the nearest radio active galaxy, Centaurus A, which is thought to be the remnant of a merger. Here, we detect that the magnetic field orientations in the plane of the sky tightly follow the ~3.0 kpc-scale molecular warped disk. Our simple regular large-scale axisymmetric spiral magnetic field model can explain, to some extent, the averaged magnetic field orientations across the disk projected on the sky. Our observations also suggest the presence of small-scale turbulent fields, whose relative strengths increase with velocity dispersion and column density. These results have strong implications for understanding the generation and role of magnetic fields in the formation of galaxies across cosmic time.

Nearby galaxies are known to have regular large-scale magnetic fields (B-fields) with a spiral-like pattern at kiloparsec scales, but they also appear to have an important small-scale (or turbulent, or random) component. These regular large-scale B-fields are thought to be generated by a mean-field galactic dynamo, which relies on differential rotation of the galactic disk to amplify and order a 'seed' B-field. This B-field is driven by supernova explosions at turbulent scales of \( l \approx 50-100 \text{ pc} \) (refs. 1-3). The turbulent or random B-fields are thought to be generated by small-scale dynamos, which rely on turbulent gas motions at scales smaller than the energy-carrying eddies. The correlation length of the turbulent or random B-fields is comparable to or smaller than the turbulent scale, \( l \). Once the B-fields are amplified and in close equipartition with thermal and turbulent forces, magnetic fields can influence galaxy evolution. Galaxies at redshifts of up to \( z \approx 2 \), which are thought to be the progenitors of present-day galaxies, have been observed to host magnetic fields (refs. 1,11). Magnetohydrodynamical simulations suggest that during the violent feedback-dominated phase in the galaxy formation history, weak seed B-fields can be first amplified by a small-scale dynamo. In the subsequent quiescent galaxy evolution phase, the turbulent or random B-fields can weaken or be maintained via large-scale dynamo action. These observations and simulations invite the question of the origin and evolution of the B-fields in galaxy evolution.

Centaurus A (distance 3.42 Mpc, 1'' = 16 pc; see Methods) is thought to be the remnant of a merger about \((1.6-3.2) \times 10^8 \text{ yr} \) ago (refs. 14,15). The chaotic dust lane and shells within it form a warped disk \( \approx 12 \text{ kpc} \) in length along the east–west direction, with a median position angle of \( 122 \pm 4^\circ \) (refs. 6,14) and inclination of \( \approx 90 \pm 30^\circ \) (ref. 14). The observed parallelogram-shape structure in the mid-infrared (mid-IR) is caused by folds in a thin, dusty warped disk rich in molecular gas, which has the most active star formation present in the galaxy. The warped disk has a rapidly rotating gas of radius \( \approx 3 \text{ kpc} \), based on measures of the velocity field of several tracers (refs. 16,21,23-25). A warped disk model was adequate to describe the mid-IR morphology and kinematics of the galaxy disk (refs. 16,21,23-25). This model suggests that tidal forces during the merger modified the original gas motions of the spiral galaxy, forming rings around the central elliptical galaxy. In this scenario, the merger may enhance and amplify the B-fields by small-scale dynamo action when the B-fields are coupled to the gas component of the galaxy.

Pioneering work (refs. 26) using optical polarimetric observations with 24–69-inch telescopes detected the polarization signature of dichroic absorption in the dust lane of Centaurus A. Those authors concluded that the most likely reason for this detection is that the B-fields have been confined in the general orientation of motion of the gas in the galaxy disk. Although major efforts have been undertaken using optical and infrared polarimetric studies, only small regions around the central active nucleus and across the dust lane have been measured in the infrared (refs. 27-29). In general, the position angle (PA) of polarization is measured to be in the range of \( 110-117^\circ \), which is parallel to the dust lane and shows small angle fluctuations of \( \approx 9^\circ \) (ref. 30). The degree of polarization (P) decreases from \( \approx 6\% \) in the optical to \( \approx 2\% \) in the infrared, which is entirely consistent with polarization arising from dichroic absorption. These results indicate that the galaxy disk may have an ordered B-field, although the B-fields of the whole galaxy disk have not yet been traced using infrared polarimetric techniques. Therefore, a whole picture of the B-fields and how they relate to the gas dynamics in the molecular warped disk of Centaurus A is still missing.

The data

We observe Centaurus A using the High-resolution Airborne Wideband Camera-plus (HAWC+) on the 2.7-m Stratospheric Observatory For Infrared Astronomy (SOFIA) telescope, with a beam size (full-width at half-maximum) of \( 7.80'' \) at 89 \( \mu \text{m} \). We performed observations using the on-the-fly-map polarimetric mode (the Methods and Extended Data Fig. 1). The polarization map of Centaurus A at 89 \( \mu \text{m} \) observed with HAWC+, overlaid on a composite image, as well as with the total and polarized intensities at 89 \( \mu \text{m} \), is shown in Fig. 1. The total flux image is consistent with the \( 70-160\mu\text{m} \) Herschel observations (ref. 31). The near-constant PA of polarization from optical to far-IR wavelengths indicates a single dominant polarization mechanism. We estimate that our 89 \( \mu\text{m} \)
polarization measurements arise from dichroic emission of magnetically aligned dust grains in the molecular disk (the Methods).

The most prominent polarization signature of Centaurus A is the measured B-fields with orientations tightly following the $\sim$3.0 kpc-scale molecular warped disk. The measurements of the B-field orientations and warped disk morphology are those projected on the plane of the sky. We measure that the B-field orientations have a dispersion of $8.6^{+15.5}_{-15.5}^\circ$ across the observed $\sim 181''$ ($\sim 3.0$ kpc) molecular warped disk (the Methods). However, the B-fields closely follow the warped disk without evidence of systematic dispersion. The polarized flux morphology is spatially coincident with the low surface brightness regions at the top and bottom of the edges of the parallelogram structure observed at $8''$ with Spitzer and $70-160\mu m$ with Herschel. These regions are the closest to our line of sight (LOS) with low column density in the molecular disk, where the dust is optically thin at far-IR wavelengths.

We report the measurement of a polarized radio-loud active nucleus with a $P$ of $1.5\pm 0.2\%$ and a PA of $151\pm 4^\circ$ (B-field) within an $8''$ (128 pc) diameter region at 89$\mu m$ (Extended Data Fig. 4). We estimated that the polarization arises from magnetically aligned dust grains, where the B-field orientation is found to be almost perpendicular to the radio jet axis, PA $\approx 51^\circ$ (ref. 36).

There are striking morphological similarities with the B-fields in the disks of highly inclined galaxies observed using radio polarimetric techniques. However, radio polarimetric observations of the host galaxy of Centaurus A have not been performed. We note that Faraday rotation is not a factor at far-IR wavelengths. The total gas column density is traced more effectively by our far-IR observations than by the relativistic electrons producing the synchrotron emission at radio wavelengths. Near-infrared polarization is subject to scattering effects from the disk, and dichroic absorption is only sensitive to the outer layers of the dust lane. Our far-IR observations trace deeper regions of the molecular disk than those in the
near-infrared. In addition, far-IR emissive polarization observations reveal the orientation of the ordered B-field, but not its direction. Hence, we cannot distinguish between regular large-scale fields and anisotropic random fields with frequent reversals.

The large-scale regular magnetic field
Spiral arms have been reported in the central ~3 kpc of Centaurus A using $^{12}$CO(2−1) observations$^{38}$, and no bar has been found using the H I 21 cm line$^{15}$. We produce a three-dimensional model of the regular large-scale B-field morphology using an axisymmetric spiral B-field configuration$^{39,40}$, which is a mode of a galactic dynamo with a symmetric spiral pattern in the galactic midplane and a helical component (see the Methods for a full mathematical description of the B-field model). This model is used to investigate trends that result from regular large-scale B-fields and is not intended to truly represent the B-fields of a warped disk or to account for turbulent small-scale B-fields.

Our B-field morphological model (Fig. 2) obtains an edge-on (inclination $i = 89.5^{+0.7}_{-0.8}$) galaxy with a tilt angle of $\theta = 119.3^{+0.5}_{-0.4}$ east from north in the counterclockwise direction. The axisymmetric spiral B-field on the plane of the galaxy has a pitch angle of $\psi_0 = -54.9^{+0.5}_{-0.5}$, where the helical component has a radial pitch angle of $\chi_0 = 74.8^{+10.5}_{-16.3}$ and vertical scale of $z_0 = 1.7^{+0.2}_{-0.2}$ kpc. The term $x_0$ is defined as the pitch angle at a radius $r_0$ along the vertical axis of the galaxy (see the Methods and Extended Data Figs. 5 and 6 for details of the fitting routine). Our model produces a spiral B-field structure with a large pitch angle in the plane of the galaxy, potentially due to the tidal effects of the galaxy interaction. However, the molecular disk of Centaurus A is likely to be warped, where the inclination angle, $i$, and tilt angle, $\theta$, have been measured$^{17}$ to be in the range of [60, 120], and [92, 169]$^\circ$, respectively, from 2 pc to 6,500 pc. Specifically, the mean inclination and tilt angles are estimated to be $83 \pm 6^\circ$ and $114 \pm 14^\circ$ in the range of [0.5, 3] kpc (ref. 17), respectively, in agreement with our inferred results. The complex dynamics along the disk may change the pitch angle, $\psi_0$, as a function of the radius from the core.

Both our model and observations agree within 10$^\circ$ along the mid-plane of the dust lane (Fig. 3). We estimate the median difference between the PA of the B-fields of HAWC+, PA$_{HI}$, and our model, PA$_M$ to be $\Delta$PA = (PA$_{HI}$ − PA$_M$) = 3.6 $\pm$ 22.7$^\circ$. We find that the angular dispersions from our model and those from magnetically aligned dust grains at scales of 124.8 pc resolution are greater than can be accounted for by errors from our observations ($\sigma_{PA} \leq 9.6^\circ$) within the molecular disk (Fig. 3). Therefore, another B-field component (that is, small-scale B-fields) is required to explain the angular dispersion between the regular axisymmetric B-field model and the measured B-field.

Our model also shows a vertical and twisted pattern in the central region of Centaurus A at PA $\approx 30^\circ$, which is in close agreement with the radio jet at PA $\approx 51^\circ$ (east of north) at the core of the radio-loud active nucleus. The central ~100 pc of Centaurus A shows very complex structures$^{41}$ that are expected to generate some level of misalignment.
between the radio jet axis and the kiloparsec-scale structures. It is also worth noting the change of the observed B-field orientation at \((X, Y) = (-0.6 \text{kpc}, +0.2 \text{kpc})\) in Fig. 3, which may be explained by the change from the mid-plane spiral pattern to the helical pattern. However, on the other edge, at \((X, Y) = (0.0 \text{kpc}, +0.3 \text{kpc})\), the helical pattern seems to have a lower effect. We point out that we have excluded the central \(0.8 \times 0.8 \text{kpc}^2\) in our modelling because the polarization is affected by energetic processes associated with the active galactic nucleus (AGN). The exclusion zone is determined by the low polarized regions from our observations and the physical inner bubble\(^{42}\), which indicate that different mechanisms of polarization are present in the central \(0.8 \times 0.8 \text{kpc}^2\). Therefore, the...
The thermal polarization and the multi-phase interstellar medium

The B-field of the interstellar medium (ISM) in galaxies is turbulent, and random fluctuations of the B-field are not necessarily isotropic (that is, they are anisotropic, random B-fields). Note the different nomenclature in the literature: anisotropic random fields, tangled fields, striated, ordered random, and our choice, which is to follow the nomenclature of ref. 1. The B-fields in the ISM are typically described using a combination of ordered and random components, where the relationship between the fractional polarization and intensity (I) provides a proxy to characterize the effect of the turbulent component. In general, the fractional polarization in the ISM has been found to decrease with increasing column density \(N_{H_2}\), which can be attributed to (1) variations in the alignment efficiency of dust grains with column density \(N_{H_1+H_2}\), (2) tangled B-fields along the LOS, and/or (3) turbulent fields. Note that the anisotropic random fields also contribute to the observed polarized dust emission. As dynamos convert kinetic energy into magnetic energy, we use the measurements of the velocity dispersion as a proxy for the turbulence in the gas, where depolarization effects are expected if turbulence increases with increasing column density.

The warped disk of Centaurus A is rich in molecular gas, and the molecular gas emission generally originates in high-density regions of the ISM close to the spiral arms. We use the \(^12\text{CO}(1-0)\) emission line to characterize the dynamics in the molecular disk of Centaurus A. The measurements of the velocity dispersion of the \(^12\text{CO}(1-0)\) emission line (\(\sigma_{v,^{12}\text{CO}(1-0)}\), Extended Data Fig. 7) observed by the Atacama Large Millimeter/submillimeter Array (ALMA) are used as a proxy of the turbulence in the molecular gas. We use the polarized intensity versus total intensity (PI–I) plot to identify several physical regions in the galaxy disk of Centaurus A (Fig. 4 and Extended Data Fig. 8). We find three distinct regions: outer disk, molecular disk, and low polarized regions (see the Methods for specific criteria). To quantify the effect of turbulent B-fields in these regions, we use the correlations between \(P\), \(I\), PI, temperature (T), \(N_{H_1+H_2}\), and \(\sigma_{v,^{12}\text{CO}(1-0)}\) (Fig. 5). See the Methods for details of how these maps have been computed. We show the median values of these parameters for each region in Table 1.

For the three regions, we find that each region has unique physical conditions (the Methods, Fig. 5 and Extended Data Fig. 9). The outer disk of the galaxy, \(6\) kpc in diameter, is characterized by low \(N_{H_1+H_2}\), high turbulence fields, and/or (3) competing mechanisms of polarization (i.e. magnetic field, B, and/or radiation direction, K, radiative torque alignment). At the location of the active nucleus, an ordered B-field in a dusty circumnuclear disk around the active nucleus may be the dominant physical structure that produces the measured far-IR polarization.
The origin of the magnetic field in Centaurus A

Our B-field model at a radius >500 pc reproduces the ordered B-fields parallel to the dust lane of the galaxy from optical absorptive polarization observations. Our model also reproduces, to some extent, the orientations of the observed B-fields along the central ~3 kpc of the galaxy from our far-IR observations. We find that the morphology given by the thermal emission of the warped disk deviates from our regular large-scale B-field model. The inferred B-field orientations from our observations have a higher spatial correspondence with the structure of the warped disk than with the regular large-scale B-field model. It is difficult to combine the regular large-scale B-field model with warped ring models to explain the warped disk. Our interpretation is that the outer layers of the dust lane may have a less turbulent B-field than at deeper regions of the galaxy, where the large velocity dispersion in the molecular gas may be enhancing the turbulent B-field in the molecular warped disk. Furthermore, other physical mechanisms, such as small-scale turbulent fields, may play an important role in the B-fields of the warped disk of Centaurus A.

We show that our measured angular dispersions are larger than those that arise solely from the observational uncertainties. In addition, we find that the polarized emission is less affected by $T$, $N_{\text{H}+\text{H}_2}$ and $\sigma_{v,12\text{CO}(1-0)}$ than is the unpolarized emission. Our interpretation is that the isotropic turbulent field, which is traced by the unpolarized thermal emission, is more affected by these quantities than the ordered field, which consists of the regular large-scale and
is regenerated by the merger of an elliptical and spiral galaxy. This work serves as a valuable reminder of the potential importance of B-fields, which are usually completely overlooked, in the formation and evolution of galaxies.

**Methods**

**Centaurus A.** Another alternative name for this galaxy is NGC 5128. The galaxy disk divides the elliptical galaxy and obscures the nucleus and most of the structures at optical wavelengths within the central ~50 pc (ref. 61). Estimations exist for the velocity fields of the tracers H i (ref. 1), Hα (ref. 1), 12CO(1–0) (ref. 1) and 12CO(2–1) (ref. 1). The merger is estimated to have occurred about (1.6–3.2)×10^9 yr ago (ref. 1) to the current galaxy pair. The last merger estimate was obtained using two independent methods: the Mira period-luminosity relation and the rotation curve. The rotation curve, and the range of distances is estimated to be 3.2–4.2 Mpc, based on the review by ref. 2. We estimate that any potential uncertainties (~18.4 pc) due to the estimation of the distance to Centaurus A are smaller than a single detector pixel scale (~70 pc) of our observations.

**Observations and data reduction.** Centaurus A was observed (PI: E. Lopez-Rodriguez, ID:07_0032) at 89 μm using HAWC+ polariometric observations simultaneously performed during SOFIA Cycle 7 observations as part of engineering time to optimize the polariometric observations of HAWC+. Here, we focus on the scientific results of Centaurus A and describe the high-level steps of these observations.

We performed OTFMAP polarimetric observations in a sequence of four Lissajous scans, in which each scan has a different halfwave plate PA in the following sequence: 5°, 50°, 27.5° and 72.5°. This sequence is called a ‘set’ hereafter. In this new HAWC+-observing mode, the telescope is driven to follow a parametric curve with a non-repeating period whose shape is characterized by the relative phases and frequency of the scan. An example of the OTFMAP for total intensity observations of NGC 1068 using HAWC+ on board SOFIA is shown by ref. 55. Each scan is characterized by the scan amplitude, scan rate, scan phase and scan duration. A summary of the observations is shown in Extended Data Fig. 1. The scan amplitude is defined by the length of the scan parallel (EL) and perpendicular (XEL) to the direction of the telescope elevation. We performed rectangular scans to cover the central molecular warped disk (the ‘parallelogram’), which is ~3.8 kpc (~240°) in diameter, along the diagonal of the scan.

We reduced the data using the Comprehensive Reduction Utility for SHARP II v.2.42-1 (CRUSH, refs. 60,62) and the HAWC_DRP_V2.3.2 pipeline developed by the data reduction pipeline group at the SOFIA Science Center. Each scan was reduced by CRUSH, which estimates and removes the correlated atmospheric and instrumental signals, solves for the relative detector gains, and determines the noise weighting of the time streams in an iterated pipeline scheme. Each reduced scan produces two images associated with each array. Both images are orthogonal components of linear polarization at a given halfwave plate PA. We estimated the Stokes IQU parameters using the double difference method in the same manner as the standard chop–nod observations carried by HAWC+, described in Section 3.2 in ref. 2. The degree (P) and PA of polarization were corrected by instrumental polarization (IP) estimated using OTFMAP polarization observations of planets. We estimated an IP of Q/I = −2.1% and I/U = 0.8% at 89 μm, with an estimated uncertainty of ~0.8%. The IP values found using OTFMAP observations are in agreement within their uncertainties with the estimated IP using the chop–nod technique. The Stokes QU parameters were corrected by instrumental polarization (IP) estimated using OTFMAP polarization observations of planets. We estimated an IP of Q/I = −1.6% and I/U = 0.8%. To ensure the correction of the PA of polarization of the instrument with respect to the sky, we took each set with a fixed LOS of the telescope. For each set, we rotated the Stokes QU from the instrument to the sky coordinates. The polarization fraction was debiased and corrected by polarization efficiency. The final Stokes IQU (P, PA, polarization intensity (IP) and their associated errors were calculated and re-sampled to one-quarter of the beam size, 1.95° at 89 μm.

Several advantages and limitations are found with the OTFMAP polarization mode. The advantages are the reduction of overheads and radiative offsets when compared with the chop–nod technique. The overheads are improved by a factor of two in comparison with the chop–nod technique. This improvement is owing to the fact that the OTFMAP is constantly integrating with the source on the field of view while covering off-source regions to estimate the background levels. For the

### Table 1 | Median values of the physical parameters of each region identified in Fig. 4

| Parameter | Outer disk | Molecular disk | Low polarized region |
|-----------|------------|----------------|---------------------|
| T (K)     | 27.8 ± 0.7 | 28.8 ± 0.8     | 31.4 ± 0.9          |
| σ_{12CO} (1–0) (km s^{-1}) | 6.4 ± 6.0 | 18.4 ± 9.2     | 34 ± 4              |
| P (%)     | 9.5 ± 3.3  | 3.9 ± 2.4      | 1.2 ± 0.6           |
| I (M Jy sr^{-1}) | 55 ± 13   | 63 ± 18        | 71 ± 26             |
| λ (M Jy sr^{-1}) | 627 ± 264 | 1,761 ± 554    | 6,500 ± 1,876       |

### Articles

**Nature Astronomy**

610 | Nature Astronomy | Vol 5 | June 2021 | 604–614 | www.nature.com/natureastronomy

---

anisotropic small-scale components. A possible explanation is that the small-scale turbulent field is relatively more important at higher velocity dispersions and column densities of the molecular gas than the large-scale axisymmetric field. Our results can be interpreted as a decreasing ratio of the large-to-small B-fields. Therefore, a substantial amount of the observed B-field at far-IR wavelengths may arise from anisotropic small-scale turbulent (ordered) fields that also contribute to the polarized emission or tangled fields at scales below or beyond the 124.8 pc scale of our observations.

The most likely scenario is that the observed B-fields have been generated by a dominant small-scale dynamo across the fast rotating and turbulent gas and dust molecular warped disk. For the outer disk, the turbulence may be driven by disk gravitational instabilities mixed with density-wave or merger-driven streaming motions. In addition to the turbulent B-fields from the dense and cold ISM of galaxies, especially when radio polarimetric observations are

---

**Table 1**

| Parameter | Outer disk | Molecular disk | Low polarized region |
|-----------|------------|----------------|---------------------|
| T (K)     | 27.8 ± 0.7 | 28.8 ± 0.8     | 31.4 ± 0.9          |
| σ_{12CO} (1–0) (km s^{-1}) | 6.4 ± 6.0 | 18.4 ± 9.2     | 34 ± 4              |
| P (%)     | 9.5 ± 3.3  | 3.9 ± 2.4      | 1.2 ± 0.6           |
| I (M Jy sr^{-1}) | 55 ± 13   | 63 ± 18        | 71 ± 26             |
| λ (M Jy sr^{-1}) | 627 ± 264 | 1,761 ± 554    | 6,500 ± 1,876       |
The telescope is always on-axis, without chopping the secondary mirror, as it does in the chop–nod technique. Therefore, the radiative offset is not present, and the sensitivity of the observations was estimated to improve by a factor of 1.6. The limitation of this technique is the recovering of large-scale diffuse and faint emission from the astrophysical objects. This is a result of the finite size of the array, variable atmosphere conditions, variable detector temperature, and the applied filters in the reduction steps to recover extended emission. In general, the noise increases as a function of the length, L, of the extended emission as L^-1. Although we can adjust CRUSH parameters to recover the extended emission in total intensity, the polarization is highly affected by the filter selection of the data reduction software. We applied several filters using CRUSH to recover large-scale emission structures of Centaurus A without compromising the intrinsic polarization pattern of the astrophysical object. We performed chop–nod and OTTMAP observations of well-known objects, 30 Doradus and OMC-1, to test several filter options. We conclude that A combination of the extended filter with 12 iterations using CRUSH can recover large-scale emission structures up to 200” from our observations of Centaurus A at 89 μm. Using Herschel images at 70 μm and 160 μm (ref. 6), we estimate that the fluxes at the regions in which we are not able to recover large-scale emission from our observations are ≤0.01 Jy arcsec^-2 at 89 μm. For the total on-source time of 3.200 s (Extended Data Fig. 1) and assuming an expected degree of polarization of ~5% from our observations at 89 μm, the signal-to-noise ratio of the polarization is estimated to be ≤1.5 for the uncovered regions (sensitivities can be estimated using the SOFIA Instrument Time Estimator (SITE) at https://dcs.arc.nasa.gov/proposalDevelopment/SITE/index.jsp). Although we are missing some of the large-scale structures, our observations would have not been sensitive enough to provide statistically significant polarization measurements of this region. As the molecular disk of Centaurus A has a diameter of ~140° at 89 μm, we are able to achieve our scientific goals using our observations.

Physical regions as a function of the B-field orientation and its dispersion. We computed histograms of the degree of polarization and B-field orientations for all polarization measurements with πPAM ≥ 3.0. We identify three regions in the galaxy disk based on the overall orientation and dispersion of the magnetic field: (1) the west side with a PA range of [90, 120]°, (2) the east side with a PA range of [120, 175]° and (3) the low polarized region with large angle dispersion at PA > 175°. For each region, we compute the mean of the degree of polarization and B-field orientation and their dispersions (Extended Data Fig. 2). A colour code polarization map of the three regions is shown in Extended Data Fig. 3.

The west and east regions of the warped disk. We estimate a median PA of the B-field orientation of 105° in the west side of the galactic disk and 147° in the east side. Previous optical to near-infrared polarimetric studies have measured a polarization PA of 110–117° from dichroic absorption, which is roughly parallel to the dust lane (ref. 21). These measurements were based on observations of several patches across the dust lane and/or the central ~1 kpc.

The central kiloparsec. The third region is mostly spatially coincident with low polarized areas within the central ~0.8 kpc diameter around the AGN and at the edge of the northwest regions of the galaxy disk. This region has the largest PA dispersion of 28.9°. Extended Data Fig. 4 shows a zoom-in of the central 50×50” (0.8×0.8 kpc), where the twist of the polarized PA from the dust lane to the nucleus can be seen. The central 0.8 kpc region lacks molecular gas and dust due to energetic processes near the AGN that have disturbed the inner regions of the warped disk (ref. 21). We conclude that the large PA dispersion, low polarization and change of polarization PA are due to the combination of the intrinsic polarization in the dust lane and the nucleus, both of which have a different PA of polarization and arise from different physical structures.

Magnetic field model. In this section, we describe the mathematical description of the magnetic field model. The three components of the vectorial magnetic field in cylindrical coordinates (r, ρ, z) centred at the galactic centre are described as

\[ B_r = B_0 \sin \varphi_0 \cos \chi_r \]  
\[ B_\rho = B_0 \cos \varphi_0 \cos \chi_\rho \]  
\[ B_z = B_0 \sin \chi_z \]

where \( B_0 \) is the amplitude of the regular magnetic field strength, \( \varphi_0 \) is the pitch angle of the spiral pattern, and \( \chi_r \) is the pitch angle of the field vector given by

\[ \chi_r = \varphi_r \tan \left( \frac{z}{R_z} \right) \]

where \( \varphi_r \) is interpreted as a helical angle with a radial pitch angle \( \varphi_r \), purely longitudinal with a given vertical scale at \( z_c \) (ref. 21).

The magnetic field is projected on the plane of the sky, which adds two free parameters, the inclination \( \iota \) and tilt angle \( \theta \). For a face-on view, \( \iota = 0° \), and for an edge-on view, \( \iota = 90° \). The tilt angle, also described as the position angle of the major axis of the projected galaxy plane, has a reference \( \theta = 0° \) along the north–south direction and positively increases east from north. We use Euler rotations around the x-axis \( R_x(\theta) \) and the z-axis \( R_z(\theta) \), to compute the final magnetic field \( B_{PA} = R_z(\theta)R_x(\theta)B_z \), where \( B_z = (B_r, B_\rho, B_z) \) in Cartesian coordinates.

Model constraints. Thermal emissive polarization that arises from magnetically aligned dust grains is not directly sensitive to the magnetic field strength, but rather to variations in dust grain alignment, and gradients in temperature and column density. Although we can include a variation of the magnetic field strength as a function of the radius in our model, this information is negligible for the interpretation of the thermal emissive polarization. Radio polarimetric observations are sensitive to the magnetic field strength, but these observations have not been acquired for the warped disk of Centaurus A. Therefore, we do not have any information about the radial variation of the magnetic field strength in Centaurus A, where \( B_0 \) is an unknown variable with no constraints. If we still include a variable magnetic field strength as a function of the radius, such as \( R_z = r^{-n} \), where \( n \) is the index of the radial magnetic field strength profile, and assume an isotropic strength variation on the XYZ axes, given that the projected PA of polarization on the plane of the sky from our model is \( PAM = \arctan(B_\rho/B_z) \), \( B_0 \) does not depend on the value of \( B_z \). A model using an isotropic variation of the magnetic field strength produces the same B-field orientation as our current model. If we consider the radial dependence of the B-field to be different for each of the XYZ axes, then \( PAM \) changes as a function of the radius. This model provides a different B-field orientation when compared to our model. As we do not have any information about the radial dependency of the magnetic field strength in Centaurus A, and we are only interested in the orientation of the magnetic field, we assume a constant magnetic field strength, \( B_0 = \text{const} \).

The polarization in the central 0.8×0.8 kpc² is affected by energetic processes associated with the AGN. Therefore, we have excluded this region in this analysis. The central 0.2 kpc zone is determined by the low polarized region of ~120° for the central kiloparsec. We conclude that the large PA dispersion, low polarization and change of polarization PA are due to the combination of the intrinsic polarization in the dust lane and the nucleus, both of which have a different PA of polarization and arise from different physical structures.
Alternative magnetic field models. In this section, we describe the alternative B-field models. We compare our magnetic field model with alternative configurations. Bi-symmetric magnetic field configurations can also be used to describe the morphologies of magnetic field in galaxies. However, this morphology has only been argued for M81, which may be affected by Faraday depolarization. We study this magnetic field configuration described as (ref. 4). We compare our magnetic field model with alternative B-field models. We performed the same fitting methodology as described in ‘Computation of the magnetic field model’ above, but with the extra free parameter, \( r_\alpha \). We found that for all models in which \( r_\alpha < 1.5 \) kpc, the bi-symmetric spiral model does not provide any magnetic field configuration compatible with our observations. For \( r_\alpha > 1.5 \) kpc, the bi-symmetric spiral model converges to an axisymmetric spiral configuration within the central 3 kpc, and both bi-symmetric and bi-symmetric models are not distinguished. Because the bi-symmetric and axisymmetric spiral field models provide similar solutions for the magnetic field morphology within the central 3 kpc of Centaurus A, and the axisymmetric spiral field model has fewer free parameters, we use the axisymmetric spiral model results for our analysis.

The thermal emission of the molecular disk of Centaurus A has been modelled using warped disk configurations\(^{(18,21,23,24)}\). This model consists of tilted concentric rings of material that predict the structure of the warm and cold dust, as well as the velocity fields of the gas in the galaxy disk. Although warped disk models provide compatible solutions for total intensity and spectroscopic observations of several tracers, the concentric and tilted rings do not provide a physical model for magnetic field configurations. Therefore, magnetic field configurations based on purely thermal emission or spectroscopic analysis are not considered.

Expected emissive polarization from the ISM. In the following section, we show that our observations trace the magnetic field morphology by means of thermal emission by magnetically aligned dust grains. We can estimate the expected emissive polarization based on previous measurements of the absorptive polarization. At 2.2 \( \mu \)m, the typical degree of polarization in the galaxy disk is \( P \sim 2\% \) with a visual extinction of \( A_V = 7 \) mag (K-band optical depth \( \tau_0 = 0.14 \pm 0.07 \text{ ref.}^{(10)} \)). Using the typical extinction curve \( E(B-V) = 3.1 \text{ (ref.}^{(47)} \) and \( \beta = 1.5 \pm 0.7 \text{, ref.}^{(44,45)} \), for which isotropic random variations of the B-fields do not give rise to polarization. However, observations have found that the slope can be steeper than \(-0.5\); for example, in molecular clouds such as OMC-1 (ref. 70) and in external galaxies such as NGC 1068 (ref. 71). Hydromagnetic simulations have determined that variations of dust grain alignment with distance and turbulence, as well as the magnetic field morphology in the galaxy disk, may explain some of these trends in molecular clouds, with a lower limit of \( P \propto r^{-1} \).

We have plotted (Extended Data Fig. 8) the de-biased polarized flux against the total intensity at 89 \( \mu \)m because \( P - I \) contains selection effects owing to the chosen quality cuts of the degree of polarization and intensity. As the polarized flux is defined as \( P = P \times \tau \), the equivalence is such that a slope \( \alpha \) in \( P \times \tau \) becomes \( \alpha = \alpha + 1 \) in \( P \). The \( P - I \) plot (Fig. 4 and Extended Data Fig. 8) shows a complex structure. In the direction of increasing column density (also \( I \)), \( P \) increases up to \( \log [N_{\rm HI} (\text{cm}^{-2})] \approx 2.14 \) (\( I \approx 750 \text{ mJy mm}^{-1} \)), and then decreases with an inflection point at \( \log [N_{\rm HI} (\text{cm}^{-2})] \approx 2.19 \) (\( I \approx 1,000 \text{ mJy mm}^{-1} \)). After, \( P \) increases again up to \( \log [N_{\rm HI} (\text{cm}^{-2})] \approx 2.17 \) (\( I \approx 2,050 \text{ mJy mm}^{-1} \)), and then sharply decreases with an inflection point at \( \log [N_{\rm HI} (\text{cm}^{-2})] \approx 2.16 \) (\( I \approx 2,700 \text{ mJy mm}^{-1} \)). The final trend of \( P \) is an increase with increasing column density up to \( \log [N_{\rm HI} (\text{cm}^{-2})] \approx 2.26 \) (\( I \approx 9,150 \text{ mJy mm}^{-1} \)).

Molecular disk. Using the range of column densities \( 2.14 \leq \log [N_{\rm HI} (\text{cm}^{-2})] \leq 2.17 \), we identify this region as the outer disk of the galaxy (Fig. 4) with a diameter of \(-6\) kpc. From the \( P - I \) plot, the bulk of values show a trend of \( P \propto r \). If only the outer layers of the disk have perfectly aligned dust grains, then the polarized emission will be diluted by additional unpolarized flux, and \( P \propto r \) is expected. If high velocity dispersion may be present, then the \( P - I \) plot may show a steep decrease, as in the molecular disk.

Core and low polarized regions. This region contains several different physical structures. As we are focused on studying the magnetic fields in the galaxy disk, we only spatially identify the polarized structures in this region. The values with high \( I \), \( P \), and \( N_{\rm HI} \) are identified as the core of Centaurus A, with the location of the AGN. The values with intermediate \( P \) and high \( I \) and \( N_{\rm HI} \) are identified as star-forming regions in the molecular disk. The values with low \( P \) and high \( I \) and \( N_{\rm HI} \) are identified as low polarized regions that are mostly located in the central 500 pc around the AGN.

Thermal polarization versus \( ^{12}\text{CO}(1–0) \) velocity dispersion. In this section, we describe the data analysis that uses the \( ^{12}\text{CO}(1–0) \) observations. We use the \( ^{12}\text{CO}(1–0) \) emission line presented by ref. 72 to estimate the velocity dispersions of the galaxy disk of Centaurus A. These observations provide an angular resolution of 2.86 arcsec\( \times\)1.67 arcsec (46.1 arcsec\( \times\)26.9 pc), which allows us to estimate the kinematics at the turbulence scales of the galaxy disk. Observations were acquired from the ALMA Archive using the Program ID 2013.1.0833.5 (\( ^{12}\text{CO}(1–0) \) ALMA data can be found at http://telbib.eso.org/tbibcode=2019ApJ...887...88E; PI: D. Espada). We compute the moments using the IMMOMENTS task in the Common Astronomy Software Applications package with a 1 arcsec clip, where \( \sigma = 88.5 \text{ mJy beam}^{-1} \). Moments were smoothed to the beam size, 7.8 arcsec, of the HAWC+ observations. The integrated \( ^{12}\text{CO}(1–0) \) velocity (moment 0) and velocity dispersion (moment 2) are shown in Extended Data Fig. 7. Using the several physical components distinguished in Fig. 4, we measure the median velocity dispersion (Extended Data Fig. 9) across the molecular disk (parallellogram) to be \( \sigma_{\text{disp}} = 18.4 \pm 2.9 \text{ km s}^{-1} \) and across the outer disk to be \( \sigma_{\text{disp}} = 6.4 \pm 6.0 \text{ km s}^{-1} \) (Extended Data Fig. 10). Reference 72 estimated a velocity dispersion of \(-15 \text{ km s}^{-1} \) and \(-3 \text{ km s}^{-1} \) in the molecular disk and outer disk, respectively. These two populations of velocity dispersion may be biased because the mean \( \sigma_{\text{disp}} = 18.4 \pm 2.9 \text{ km s}^{-1} \) to larger values than those typically found, \( -8 \text{ km s}^{-1} \) (ref. 73), in nearby galaxies.

Power-law fits. We fit a power law, \( \nu \propto \nu^{\alpha} \), for each of the plots and physical regions shown in Fig. 5. Extended Data Fig. 9 shows the power-law indexes, \( \alpha \), of the fits for each physical region.

Alternative scenario. Another possible explanation for the observed B-field is that it could arise from field compression and amplification due to density shocks, in which
density shocks are discontinuities in the flow owing to a change in gas properties (density, temperature, velocity, etc.). These density-wave shocks bend the B-fields along the shocks, reducing the angular dispersion, which would make the general B-field morphology indistinguishable from regular large-scale fields. Therefore, small-scale anisotropic B-fields that arise from compression and amplification due to density shocks are inconsistent with our measured angular dispersions.

Data availability

The data that support the plots within this paper and other findings of this study are available from http://galmagfields.com or from the corresponding author upon reasonable request. Source data are provided with this paper.

Code availability

The code that supports the algorithms within this paper and other findings of this study are available from https://github.com/galmagfields or from the corresponding author upon reasonable request.

Received: 20 March 2020; Accepted: 10 February 2021; Published online: 1 April 2021

References

1. Beck, R., Chamandy, L., Elson, E. & Blackman, E. G. Synthesizing observations and theory to understand galactic magnetic fields: progress and challenges. Galaxies 8, 4 (2020).
2. Beck, R. & Wielebinski, R. in Planets, Stars and Stellar Systems. Volume 5: Galactic Structure and Stellar Populations (eds Oswalt, T. D. & Gilmore, G.) 641–723 (Springer, 2013).
3. Ruzmaikin, A., Sokolov, D. & Shukurov, A. Magnetism of spiral galaxies. Nature 336, 341–347 (1988).
4. Brandenburg, A. & Subramanian, K. Astrophysical magnetic fields and nonlinear dynamo theory. Phys. Rep. 417, 1–209 (2005).
5. Havercorn, M., Brown, J. C., Gaensler, B. M. & McClure-Griffiths, N. M. The outer scale of turbulence in the magnetized galactic interstellar medium. Astrophys. J. 680, 362–370 (2008).
6. Pakmor, R. & Springel, V. Simulations of magnetic fields in isolated disc galaxies. Mon. Not. R. Astron. Soc. 432, 176–193 (2013).
7. Pakmor, R., Marinacci, F. & Springel, V. Magnetic fields in cosmological simulations of disk galaxies. Astrophys. J. Lett. 783, L20 (2014).
8. Marinacci, F. et al. First results from the IllustrisTNG simulations: radio haloes and magnetic fields. Mon. Not. R. Astron. Soc. 480, 5113–5139 (2018).
9. Su, K.-Y. et al. Stellar feedback strongly alters the amplification and morphology of galactic magnetic fields. Mon. Not. R. Astron. Soc. 473, 111–115 (2018).
10. Ntormousi, E. Magnetic fields in massive spirals: the role of feedback and initial conditions. Astron. Astrophys. 619, L5 (2018).
11. Bernet, M. L., Minniti, F., Lilly, S. J., Kronberg, P. P. & Dessauges-Zavadsky, M. Strong magnetic fields in normal galaxies at high redshift. Nature 454, 302–304 (2008).
12. Mao, S. A. et al. Detection of microquasar coherent magnetic fields in a galaxy five billion years ago. Nat. Astron. 1, 621–626 (2017).
13. Li, L., Krichbaum, T. C., Matthews, H. E., Robson, E. I. & Eckart, A. A high-dispersion molecular gas component in nearby galaxies. Mon. Not. R. Astron. Soc. 457, 1722–1738 (2016).
14. Graham, J. A. The structure and evolution of NGC 5128. Astrophys. J. 232, 66–70 (1979).
15. Struve, C., Oosterloo, T. A., Morganti, R. & Saripalli, L. Centaurus A: morphology and kinematics of the atomic hydrogen. Astron. Astrophys. 515, A67 (2010).
16. Baade, W. & Minkowski, R. On the identification of radio sources. Astrophys. J. 119, 215–231 (1954).
17. Quillen, A. C., Neumayer, N., Oosterloo, T. & Espada, D. The warped disk of Centaurus A from a radius of 2 to 6500 pc. Publ. Astron. Soc. Aust. 27, 396–401 (2010).
18. Quillen, A. C., de Zeeuw, P. T., Phinney, E. S. & Phillips, T. G. The kinematics of the molecular gas in Centaurus A. Astrophys. J. 391, 121–136 (1992).
19. Mirabel, I. F. et al. A barred spiral at the centre of the giant elliptical radio galaxy Centaurus A. Astron. Astrophys. 341, 667–674 (1999).
20. Leeuw, L. L., Hawarden, T. C., Matthews, H. E., Robson, E. I. & Eckart, A. A deep submillimeter imaging of dust structures in Centaurus A. Astrophys. J. 565, 131–139 (2002).
21. Quillen, A. C. et al. Spitzer observations of the dusty warped disk of Centaurus A. Astrophys. J. 645, 1092–1101 (2006).
22. van Gorkom, J. H., van der Hulst, J. M., Haschick, A. D. & Tübs, A. D. VLA H1 observations of the radio galaxy Centaurus A. Astron. J. 99, 1781–1788 (1990).
23. Nicholson, R. A., Bland-Hawthorn, J. & Taylor, K. The structure and dynamics of the gaseous and stellar components in Centaurus A. Astrophys. J. 387, 503–521 (1992).
59. Dowell, C. D. et al. HAWCPol: a first-generation far-infrared polarimeter for SOFIA. *Proc. SPIE* **7735**, 77356H (2010).

60. Harper, D. A. et al. HAWC+, the far-infrared camera and polarimeter for SOFIA. *J. Astron. Instrum.* **7**, 1840008 (2018).

61. Lopez-Rodriguez, E. et al. The emission and distribution of dust of the torus of NGC 1068. *Astrophys. J.* **859**, 99 (2018).

62. Kovács, A. SHARC-2 350 Micron Observations of Distant Submillimeter-selected Galaxies and Techniques for the Optimal Analysis and Observing of Weak Signals. PhD thesis, California Institute of Technology (2006); [https://doi.org/10.7907/RZM9-6671](https://doi.org/10.7907/RZM9-6671).

63. Laing, R. A. Magnetic fields in extragalactic radio sources. *Astrophys. J.* **248**, 87–104 (1981).

64. Salvatier, J., Wiecki, T. V. & Fonnesbeck, C. Probabilistic programming in Python using PyMC3. *PeerJ Comput. Sci.* **2**, e55 (2016).

65. Ramachandran, P. & Varoquaux, G. Mayavi: 3D visualization of scientific data. *Comput. Sci. Eng.* **13**, 40–51 (2011).

66. Fujimoto, M. & Tosa, M. Spiral condensation of gas in disk galaxies by bisymmetric twisted magnetic fields – two-dimensional case. *Publ. Astron. Soc. Jpn* **32**, 567–580 (1980).

67. Weingartner, J. C. & Draine, B. T. Dust grain-size distributions and extinction in the Milky Way, Large Magellanic Cloud, and Small Magellanic Cloud. *Astrophys. J.* **548**, 296–309 (2001).

68. Aitken, D. K., Hough, J. H., Roche, P. F., Smith, C. H. & Wright, C. M. Mid-infrared polarimetry and magnetic fields: an observing strategy. *Mon. Not. R. Astron. Soc.* **348**, 279–284 (2004).

69. Hildebrand, R. H. The determination of cloud masses and dust characteristics from submillimetre thermal emission. *Q. J. R. Astron. Soc.* **24**, 267–282 (1983).

70. Chuss, D. T. et al. HAWC+/SOFIA multiwavelength polarimetric observations of OMC-1. *Astrophys. J.* **872**, 187–208 (2019).

71. King, P. K., Chen, C.-Y., Fissel, L. M. & Li, Z.-Y. Effects of grain alignment efficiency on synthetic dust polarization observations of molecular clouds. *Mon. Not. R. Astron. Soc.* **490**, 2760–2778 (2019).

72. Espada, D. et al. Star formation efficiencies at giant molecular cloud scales in the molecular disk of the elliptical galaxy NGC 5128 (Centaurus A). *Astrophys. J.* **887**, 88 (2019).

73. Dobbs, C. L. & Price, D. J. Magnetic fields and the dynamics of spiral galaxies. *Mon. Not. R. Astron. Soc.* **383**, 497–512 (2008).

**Acknowledgements**

I thank K. Subramanian, K. Tassis, R. Davies, B.-G. Andersson and T. Osterloo for many useful discussions on theoretical approaches, hydromagnetic simulation, gas dynamics and dust grain alignment theories. This work is based on observations made with the NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA) under the Program 07_0032. SOFIA is jointly operated by the Universities Space Research Association, Inc. (USRA), under NASA contract NASA-97001, and the Deutsches SOFIA Institut (DSI) under DLR contract 50 OK 0901 to the University of Stuttgart.

**Author contributions**

E.L.-R. led the project, carried out observations, developed the analysis methods and data reductions, interpreted results and wrote the text.

**Competing interests**

The author declares no competing interests.

**Additional information**

Extended data is available for this paper at [https://doi.org/10.1038/s41550-021-01329-9](https://doi.org/10.1038/s41550-021-01329-9).

**Supplementary information**

The online version contains supplementary material available at [https://doi.org/10.1038/s41550-021-01329-9](https://doi.org/10.1038/s41550-021-01329-9).

**Correspondence and requests for materials**

Correspondence and requests for materials should be addressed to E.L.-R.

**Peer review information**

Nature Astronomy thanks Dmitry Sokoloff and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

**Reprints and permissions information**

Reprints and permissions information is available at [www.nature.com/reprints](https://www.nature.com/reprints).

**Publisher’s note**

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s), under exclusive licence to Springer Nature Limited 2021.
Extended Data Fig. 1 | Summary of OTFMAP polarimetric observations. Columns, from left to right: filter central wavelength, filter bandwidth, angular resolution of the observations, scan rate, scan phase, scan amplitude, scan duration, number of observation sets obtained, and total observation time on-source. Source data.

| Wavelength (μm) | Bandwidth (μm) | Beam Size (") | Scan Rate ("/s) | Scan Phase (°) | Scan Amplitude (EL × XEL; ") | Scan Duration (s) | #Sets | t_{on-source} (s) |
|-----------------|---------------|-------------|----------------|----------------|-----------------------------|----------------|-------|-----------------|
| 89              | 17.0          | 7.80        | 100            | 0              | 180 × 120                   | 100            | 8     | 3200            |
Extended Data Fig. 2 | Polarization measurements of the several regions of the galactic disk. Columns, from left to right: region of the galaxy, median magnetic field orientation, uncertainty of the magnetic field orientation, median polarization degree, uncertainty of the polarization degree. Source data
Extended Data Fig. 3 | Physical regions based on B-field orientation and degree of polarization. Histograms of P (a) and PA (b) of polarization for measurements with P/σP > 3. Three distinct regions are found for the PA of polarization, which are identified with the west (orange), east (red) and low polarized (black) regions. The boundaries of each region are shown with vertical black dashed lines. (c), The spatial correspondence of the three regions identified using the PA distributions are shown with the same colors as the plots at b. The total intensity contours are shown as in Fig. 1. A legend polarization of 10% (black) and beam size of 7.8″ (red circle) are shown.
Extended Data Fig. 4 | Magnetic field of the central 50" x 50" (0.8 x 0.8 kpc$^2$) of Centaurus A. **a**, Total flux (colorscale) with overlaid B-field orientations (white lines). **b**, Polarized flux (colorscale) with overlaid B-field orientation (white lines). A legend polarization of 5% (black) and beam size of 7.8" (red circle) are shown.
### Extended Data Fig. 5 | Parameters of the magnetic field morphological model

Columns, from left to right: Free parameters used in the magnetic field model, symbols associated with the free parameter, boundaries of the flat prior distribution, median value of the posterior distribution with 1σ uncertainty values. Source data.

| Parameter              | Symbol | Priors       | Median Posterior |
|------------------------|--------|--------------|-----------------|
| Pitch angle (°)        | $\Psi_0$ | $[-90, 0]$  | $-54.9^{+0.5}_{-0.5}$ |
| Radial pitch angle (°) | $\chi_0$ | $[0, 90]$    | $74.4^{+10.5}_{-16.5}$ |
| Vertical scale (kpc)   | $z_0$   | $[0, 10]$    | $1.7^{+0.3}_{-0.4}$   |
| Inclination (°)        | $i$     | $[0, 90]$    | $89.5^{+0.7}_{-0.8}$   |
| Tilt angle (°)         | $\theta$ | $[0, 180]$  | $119.3^{+0.5}_{-0.4}$ |
Extended Data Fig. 6 | Posterior distributions of the magnetic field morphological model. A reference of the parameter definitions, used priors, and median values is shown in Extended Data Fig. 5.
Extended Data Fig. 7 | Polarization map vs physical parameters. Temperature (a) and column density (b) maps of Centaurus A with overlaid B-field orientation (while lines) with $P/\sigma_P > 2.5$ and $\Pi/\sigma_{\Pi} > 2$. Temperature contours start at 20 K increasing in steps of 0.5 K, and column density contours start at $\log(N_{\text{H}_2} \, \text{[cm}^{-2}\text{]} ) = 20.6$ increasing in steps of 0.1. $^{12}\text{CO}(1-0)$ integrated line emission (c) and velocity dispersion (d) of the warped disk of Centaurus A with overlaid B-field orientation (white lines) with $P/\sigma_P > 2.5$ and $\Pi/\sigma_{\Pi} > 2$. 
Extended Data Fig. 8 | Polarized flux vs. total intensity plots. P-I and PI-I plots at 89 μm vs temperature (a,b) and column density (c,d). The trend of the bulk of the P-I plot, $P \propto \tau^{-1}$, is shown as a black solid line in panels (a) and (c). The uncertainties of the debiased polarized intensity in plots (b) and (d) are shown. The blue dotted vertical lines at $I = 1000$ and 2700 MJy sr$^{-1}$ show the limits of the three physical regions found in this analysis. The black dotted lines in panels (b) and (d) show the maximum expected polarization, $P \propto I^0 = 15, 6.5, \text{ and } 1.5\%$ for each of these physical regions, respectively.
Extended Data Fig. 9 | Power-law index of plots from Fig. 5. Columns, from left to right: Parameters of the y-axis used in each fit, regions of the galaxy used for the fit, power-law indexes for the parameters used in the x-axis $T$, $N_{H}$, and $\sigma_{v, ^{12}CO(1-0)}$. Source data.
Extended Data Fig. 10 | Velocity dispersion of the outer and molecular disk. $^{12}$CO(1-0) velocity dispersion histograms of the outer disk (red) and molecular disk (blue) as identified in Fig. 4. The median (solid line) and 1σ (dashed line) are shown for each physical structure. These values correspond to $\sigma_{v, ^{12}\text{CO}(1-0)} = 18.4 \pm 9.2$ (km s$^{-1}$), and $\sigma_{v, ^{12}\text{CO}(1-0)} = 6.4 \pm 6.0$ (km s$^{-1}$) for the molecular disk and outer disk, respectively.