Threads, Ribbons, and Rings in the Radio Galaxy IC 4296

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Abstract

The nearby elliptical galaxy IC 4296 has produced a large (510 kpc) low-luminosity radio source with typical FR I core/jet/lobe morphology. The unprecedented combination of brightness sensitivity, dynamic range, and angular resolution of a new 1.28 GHz MeerKAT continuum image reveals striking new morphological features, which we call threads, ribbons, and rings. The threads are faint narrow emission features originating where helical Kelvin–Helmholtz instabilities disrupt the main radio jets. The ribbons are smooth regions between the jets and the lobes, and they appear to be relics of jets powered by earlier activity that have since come into pressure equilibrium. Vortex rings in the outer portions of the lobes and their backflows indicate that the straight outer jets and ribbons are inclined by $i = 60^\circ \pm 5^\circ$ from the line of sight, in agreement with photometric, geometric, and gas-dynamical estimates of inclination angles near the nucleus.

Unified Astronomy Thesaurus concepts: Elliptical galaxies (456); Interstellar magnetic fields (845); Radio galaxies (1343); Radio jets (1347)

1. Introduction

IC 4296 is the brightest of 18 galaxies comprising the Nearby Optical Galaxy Group 722 in the cluster A3565 (Giuricin et al. 2000). It is a purely elliptical galaxy with a Sérsic brightness profile and no detectable exponential disk related to star formation (Donzelli et al. 2011). Its infrared color

$$\log \left( \frac{L_{24 \mu m}}{\text{erg s}^{-1}} \right) - \log \left( \frac{L_K}{L_{K_{\odot}}} \right) = 30.16 \quad (1)$$

between $\lambda = 24 \mu m$ and $\lambda = 2.2 \mu m$ is typical of “red and dead” gas-free galaxies with no evidence of recent star formation, and most of its $24 \mu m$ luminosity is likely circumstellar dust emission from old giant stars (Temi et al. 2009). Even if all of its far-infrared flux density $S_{\nu, \mu m} = 118 \pm 12$ mJy (Temi et al. 2009) were attributed to star formation consistent with the far-infrared/radio correlation, the 1.4 GHz flux density produced by star formation in IC 4296 would be a negligible $S < 1$ mJy.

IC 4296 is at heliocentric redshift $z = 0.01247 \pm 0.00003$ (Smith et al. 2000). However, its J2000 position $\alpha = 13^h 36^m 39.045$, $\delta = -33^\circ 57' 56".91$ (Skrutskie et al. 2006) is near the anticenter of the supergalactic plane (SGL = 151°8, SGB = −0°4), where the redshift distance may differ significantly from the actual distance. Velocity-independent angular-size estimates have been constructed from surface-brightness fluctuations of IC 4296 by Lauer et al. (1998) ($D_A = 49.4$ Mpc) and by Mei et al. (2000) ($D_A = 49$ Mpc). For simplicity we adopt the comoving distance $D_C = D_A (1 + z) = 50$ Mpc so $1'' = 240$ pc and $1' = 14.4$ kpc.

Mills et al. (1960) first identified IC 4296 with an extended (largest angular size $\text{LAS} > 50''$) radio source. The radio emission powered by IC 4296 is actually so extended (LAS $\sim 36'$) that it comprises three sources in the Parkes 2.7 GHz catalog (Wright & Otrupcek 1990): B1332−336 (northwest lobe), B1333−336 (core and inner jets), and B1334−338 (southeast lobe). Multifrequency radio images with various angular resolutions show that the radio source consists of an unresolved core on the nucleus of IC 4296, symmetric curved jets, and slightly edge-brightened lobes (Killeen et al. 1986; Grossová et al. 2019).

Our new MeerKAT 1.28 GHz continuum images are the first having the combination of high surface-brightness sensitivity and angular resolution needed to display striking morphological features that we call threads, ribbons, and rings. This paper describes the MeerKAT observations and data reduction (Section 2), presents the new total-intensity, spectral index, and polarization images (Section 3), and analyzes the new morphological features (Section 4). Section 5 summarizes these results and discusses their wider significance for radio astronomy and future radio telescopes.

Absolute quantities were calculated for a ΛCDM universe with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.3$ from equations in Condon & Matthews (2018). We use the spectral-index sign convention $\alpha \equiv +d \log (S)/d \log (\nu)$.

2. Observations and Data Analysis

The 64 antenna MeerKAT array (Jonas & MeerKAT Team 2016; Camilo et al. 2018; Mauch et al. 2020) observed IC 4296 during two sessions: from 2020 March 16 18:47 UTC to 2020 March 17 04:50 UTC (60 antennas) and from 2020 May 13 15:32 UTC to 2020 May 14 13:30 UTC (61 antennas), for a total of 14.9 hr on target. The sources PKS 0408−65 = J0408−6545 and PKS B1394−638 were used as the flux density, bandpass, and delay calibrators; 3C 138 and 3C 286 were the polarization calibrators; and PKS 1320−446 = J1323−4452 was the astrometric calibrator. The observing sequence cycled between J1323−4452 (1 minute) and IC 4296 (15 minutes) plus a flux/bandpass calibrator (10 minutes) every 2 hr. Our flux-density scale is based...
on the Reynolds (1994) spectrum of PKS B1934–638:
\[
\log(S) = -30.7667 + 26.4908(\log\nu) - 7.0977(\log\nu)^2 \\
+ 0.605334(\log\nu)^3,
\]
(2)
where \( S \) is the flux density in Jy and \( \nu \) is the frequency in MHz. We used 8 s integration times divided into 4096 spectral channels between 856 and 1712 MHz to minimize time and bandwidth smearing. The useful frequency range limited by radio-frequency response and filters is \( \approx 880–1670 \) MHz. Data flagging and calibration were performed as described in Cotton et al. (2020) and Mauch et al. (2020), with each session calibrated independently.

2.1. Imaging

The wide-band, wide-field imager MFlmage in the Obit package\(^5\) (Cotton 2008) was used as described in Mauch et al. (2020) and Cotton et al. (2020) except as noted below. MFlmage (Cotton et al. 2018) divides the imaged region into small facets to approximate the noncoplanarity (Perley 1999) of the sky, and multiple frequency bins are imaged independently and CLEANed jointly to accommodate smooth variations of the sky and the antenna pattern with frequency.

MeerKAT’s shortest baselines (\( \geq 29 \) m) double in wavelengths between 856 and 1712 MHz, potentially leading to a variable fraction of the total intensity from the very large radio source being recovered as a function of frequency, a frequency-dependent negative “bowl” in the radio image, and an artificially steepened source spectrum. To minimize these effects, we applied a Gaussian taper with a rms width \( \sigma = 500 \) wavelengths to the projected baselines at each frequency.

2.2. Deconvolution of Stokes Q and U

Independently imaging Stokes Q and U is operationally simpler than a joint deconvolution but loses some of the information available to a combined deconvolution. Averaging Q or U in a source with significant Faraday rotation reduces the wide-band average polarization. When applied to IC 4296, independent deconvolution of Stokes Q and U also destabilized the solution and produced large-scale artifacts. Consequently we derived the polarized intensity
\[
P = \sqrt{Q^2 + U^2}
\]
(3)
in each frequency bin from a combination of the Q and U images and used it to drive the deconvolution. The polarized intensity should vary smoothly with frequency and is relatively insensitive to Faraday rotation if the data and imaging processes have adequate spectral resolution. The rms-weighted frequency average of \( P \) can be used to drive deconvolution by CLEAN. The process used for each CLEAN major cycle is:

1. Form dirty/residual images. Dirty/residual images are formed in each of the Q and U images, in each frequency bin, and in each facet imaged.
2. Form polarized intensity. In each frequency bin and facet imaged, the Q and U images are combined into a polarized intensity plane.

3. Average polarized intensity. In each facet being imaged, a weighted average of the polarized intensity planes is made and used to drive CLEAN in both Q and U. The weighting is proportional to 1/rms in the Q and U frequency bin images.

4. Select CLEAN components. Clean components are selected by a Clark (1980) inner CLEAN from the polarized intensity plane. Selected pixels are collected into lists with a limited portion of the dirty beam for each facet, frequency bin, and polarization. At cells picked, the pixel values in the frequency-bin images for the Q and U residuals are recorded and the loop gain times the dirty beam is subtracted. This is repeated until a stopping criterion is satisfied.

5. Subtract from the \((u, v)\) data. The collected sets of CLEAN components in Q and U are Fourier transformed and subtracted from the Q and U residual data sets.

The polarization images were restored with elliptical Gaussian beams having FWHM diameter 7\(^\prime\)16 \( \times \) 7\(^\prime\)01 and major-axis PA = 89\(^\circ\)41 measured counterclockwise from north.

3. Imaging Results

The \((u, v)\) data were re-weighted in proportion to 1/rms in the observed visibilities in 10 minute intervals, and the data from the two observing sessions were combined. The total-intensity data were imaged over a circle of radius 1\(^\prime\)2 plus outlier facets up to 1\(^\prime\)5 from the pointing center to cover sources with attenuated flux densities \( S > 3 \) mJy from the Sydney University Molonglo Sky Survey (SUMSS) 843 MHz source catalog (Mauch et al. 2003). The total bandpass was divided into 14 subbands with 5% fractional bandwidths. CLEANing with loop gain 0.03 was stopped after 6.8 \( \times \) 10\(^6\) CLEAN components, leaving a maximum residual \( S_p = 71 \) \( \mu \)Jy beam\(^{-1}\). The total CLEANed flux density at the 1.28 GHz band center is 15.1 Jy. The 1.28 GHz total-intensity image was restored with an elliptical Gaussian beam having FWHM size 6\(^\prime\)96 \( \times \) 6\(^\prime\)67 and major-axis position angle PA = -88\(^\circ\)25.

Rayleigh–Jeans brightness temperatures in this clean image are related to peak flux densities via \( T_b(K) \approx 16.1 S_p(\text{mJy beam}^{-1}) \). The rms fluctuation in source-free areas near the center of the CLEAN image is \( \sigma = 5.4 \) \( \mu \)Jy beam\(^{-1}\) = 87 mK. The rms noise measured near the first zero of the primary beam is only \( \sigma_0 = 2.0 \) \( \mu \)Jy beam\(^{-1}\). The “rms” confusion \( \sigma_c \) can be defined as half the range of peak flux densities containing 68% of the pixels in a noiseless image. It is \( \sigma_c = 1.8 \pm 0.1 \) \( \mu \)Jy beam\(^{-1}\) at \( \nu = 1.266 \) GHz in a 7\(^\prime\)6 FWHM circular Gaussian beam (Matthews et al. 2021). For small changes in beam size it scales as beam solid angle, so we expect \( \sigma_c \approx 1.5 \) \( \mu \)Jy beam\(^{-1}\) in our 6\(^\prime\)96 \( \times \) 6\(^\prime\)67 beam. Thus the sensitivity of our total-intensity image is limited by dynamic range.

3.1. Astrometry

Source positions in the MeerKAT image were compared with the Gaia catalog available from the NASA/IPAC Infrared Science Archive (IRSA). There are 43 radio sources <1\(^\prime\)0 from the pointing center with attenuated flux densities >200 \( \mu \)Jy and Gaia matches offset by <1\(^\prime\)5. The rms scatter of the MeerKAT minus Gaia offsets is only 0\(^\prime\)0.13 in both R.A. and decl., but the mean offsets are \( \Delta \alpha = +0\(^\prime\).46 \pm 0\(^\prime\)0.02, \Delta \delta = -0\(^\prime\).09 \pm 0\(^\prime\)0.02.

\(^5\) https://www.cv.nrao.edu/~bcotton/Obit.html
These unexpectedly large offsets may reflect errors in the MeerKAT on-line coordinate calculations. All MeerKAT positions quoted in this paper have been corrected to the Gaia frame.

### 3.2. The Total-intensity On-sky Image

The image was divided by the primary-beam attenuation pattern (Mauch et al. 2020) to give on-sky total intensities. The depth of the negative bowl remaining after incomplete CLEANing was measured to be $-2 \pm 1 \mu$Jy beam$^{-1}$ by averaging over pixels near, but not in, extended emission from IC 4296. The bowl was removed by adding $+2 \mu$Jy beam$^{-1}$ to all pixels to create the final total-intensity image shown in Figure 1. The bright unresolved core and the inner jets are saturated in Figure 1, so they have been replotted with a wider linear stretch in the left panel of Figure 2. The faint “threads” leading from both the jets are emphasized by a logarithmic stretch in the right panel of Figure 2.

The outer edge of the northwest lobe is $15'3 \approx 220$ kpc from the core, and the southeast lobe reaches $20'3 \approx 290$ kpc from the core. The total LAS $= 35'5$ corresponds to a $510$ kpc length projected onto the sky.

We estimated the integrated 1.28 GHz flux density of IC 4296 by summing brightnesses over the whole source using the AIPS verb TVSTAT; it is $S = 14.8 \pm 0.5$ Jy over 19660 beam solid angles. A systematic zero-level error of $1 \mu$Jy beam$^{-1}$ would produce only a $0.02$ Jy error in $S$, and the random noise error is negligible. We quadratically added a 3% intensity-proportional error to yield the total flux-density uncertainty $\sigma_S \approx 0.5$ Jy.

### 3.3. Spectrum

The radio emission from IC 4296 is so extended that many of its published flux densities are too low. Even the selected flux densities listed in Table 1 and plotted in Figure 3 may be in error by more than their quoted uncertainties. The overall spectral index $\alpha = -0.70 \pm 0.08$ of IC 4296 is typical for an extended radio galaxy.

The MeerKAT L-band spectral-index distribution within IC 4296 is displayed as a false-color image in Figure 4. The spectrum steepens going from the jets to the ribbons, lobes, and the backflow regions behind the lobes. The gradient in brightness is high and the spectrum flattens in the brighter compression regions just inside the outer edges of the lobes. The very steep ($\alpha < -1$) spectra of the backflow regions is expected from old electrons experiencing synchrotron and inverse-Compton (IC) radiation losses.

### 3.4. Polarization

A rotation-measure (RM) fit was performed in each pixel by doing a direct search over RM. The test Faraday rotation that gives the highest averaged, unwrapped polarized intensity was taken to be the Faraday rotation at that pixel, the unwrapped polarization angle extrapolated to zero wavelength was taken to be the intrinsic polarization angle, and the maximum polarized intensity taken to be the polarized intensity in that pixel. This is essentially using the peak of the Faraday synthesis (Brentjens & de Bruyn 2005). The RMs across IC 4296 are shown in the false-color Figure 5. The RMs in the bulk of the jets and lobes range between $-25$ and $-45$ rad m$^{-2}$, with the northern portions of the lobes around...
The thread RMs range from $-30$ to $+8$ rad m$^{-2}$. The mean Galactic foreground obtained from the Taylor et al. (2009) RM catalog of NRAO VLA Sky Survey (NVSS; Condon et al. 1998) sources is $\langle RM \rangle = -35 \pm 4$ rad m$^{-2}$ within $2^\circ$ of IC 4296 at $l = 313.5^\circ$, $b = +28^\circ$, so it appears to account for most of the observed RM.

The polarized intensity image was corrected for positive noise bias (Appendix Wardle & Kronberg 1974) and then divided by the total intensity to yield fractional polarizations. Stokes I false-color intensities and fractional-polarization $B$ vectors rotated to zero wavelength tracing the direction of the magnetic field are shown in Figures 6–8. The vectors are plotted as white or black lines for contrast only and do not have different meanings. The magnetic fields in the inner parts of the jets are perpendicular to the jets, and velocity shear at the boundary layer with static ambient gas appears to turn the $B$ field parallel to the jet boundaries. Compression wraps $B$ around the outer edges of the lobes. The fractional polarization in the jets ranges from 10 to 30%; in the brightest parts of the northwest lobe it is typically $\gtrsim 10\%$ and 10% to 50% in the southeast lobe. The magnetic fields run along the threads. The narrow threads are 30% to 70% polarized, implying highly organized magnetic fields. Their $B$ fields are parallel to the threads, as expected from velocity shear at the interface between the threads and the ambient gas. The ribbons between

![Figure 2](image1.png)

**Figure 2.** The left panel shows the total-intensity image of the IC 4296 core and jets with an expanded linear stretch between $-0.08$ and $+80$ mJy beam$^{-1}$. The right panel brings out the faint threads with a logarithmic stretch between $-0.06$ and $+12$ mJy beam$^{-1}$. The dark lines radiating from the nucleus are faint ($\sim 40 \mu$Jy beam$^{-1}$ imaging artifacts caused by residual phase errors. The red circle with diameter $70^\prime$ and centered on $\alpha = 13^h 36^m 36^s$, $\delta = -33^\circ 58^\prime 45^\prime$ bounds the bright X-ray emission shown by the red circle in Figure 4 of Grossová et al. (2019).

![Table 1](image2.png)

**Table 1**

| $\nu$ (GHz) | $S$ (Jy) | Reference |
|-------------|---------|-----------|
| 0.076       | 65.4 ± 5.2 | (White et al. 2020) G4Jy 1080 |
| 0.084       | 63.6 ± 5.1 |          |
| 0.092       | 58.6 ± 4.7 |          |
| 0.099       | 60.1 ± 4.8 |          |
| 0.107       | 62.3 ± 5.0 |          |
| 0.115       | 61.5 ± 4.9 |          |
| 0.122       | 53.3 ± 4.3 |          |
| 0.130       | 50.8 ± 4.1 |          |
| 0.143       | 47.9 ± 3.8 |          |
| 0.151       | 45.6 ± 3.6 |          |
| 0.158       | 44.5 ± 3.6 |          |
| 0.166       | 42.1 ± 3.4 |          |
| 0.174       | 43.0 ± 3.4 |          |
| 0.181       | 40.9 ± 3.3 |          |
| 0.189       | 38.4 ± 3.1 |          |
| 0.197       | 40.1 ± 3.2 |          |
| 0.204       | 39.8 ± 3.2 |          |
| 0.212       | 39.6 ± 3.2 |          |
| 0.220       | 36.6 ± 2.9 |          |
| 0.227       | 38.2 ± 3.1 |          |
| 0.408       | 34.0 ± 3.4 | (Wright & Otrupcek 1990) |
| 0.843       | 26.5 ± 1.3 | (Allison et al. 2014) |
| 1.28        | 14.8 ± 0.5 | (this paper) |
| 2.7         | 7.76 ± 0.78 | (Wright & Otrupcek 1990) |
| 5.0         | 4.83 ± 0.48 | (Wright & Otrupcek 1990) |
| 23          | 2.0 ± 0.05 | (Grossová et al. 2019) |
| 33          | 1.5 ± 0.07 | (Grossová et al. 2019) |
| 41          | 1.2 ± 0.08 | (Grossová et al. 2019) |

The radio spectrum of IC 4296 based on the flux densities listed in Table 1. Abscissa: frequency (GHz). Ordinate: flux density (Jy).

![Figure 3](image3.png)
the jets and the lobes have lower polarization and less-organized magnetic fields.

4. Radio Source Analysis

The 1.28 GHz spectral luminosity of IC 4296 is

\[ L_{1.28 \text{ GHz}} = \frac{4\pi D_L^2 S_{1.28 \text{ GHz}}}{(1 + z)^{0.1}} \approx 4.5 \times 10^{24} \text{ W Hz}^{-1}. \] (4)

For \( \alpha = -0.7 \), the 1.4 GHz spectral luminosity is \( L_{1.4 \text{ GHz}} \approx 4.3 \times 10^{24} \text{ W Hz}^{-1} \). The spectral luminosity boundary separating FR I (center brightened) from FR II (edge brightened) radio sources (Fanaroff & Riley 1974) depends on the absolute \( R \) magnitude of the host galaxy, which is \( R_{25}(\text{Cousins}) = -23.3 \) (Lauberts & Valentijn 1989) for IC 4296. The 1.4 GHz luminosity of IC 4296 is 10\( \times \) below the Ledlow & Owen (1996) boundary, placing it well inside the FR I region. IC 4296 has always been classified as an FR I source in the literature. Our image in Figure 1 shows prominent FR I jets bright near the nucleus, but the extended lobes are slightly edge-brightened. The projected magnetic field is predominantly transverse (i.e., toroidal) in the inner jets, a characteristic of FR I radio sources (Brindle & Perley 1984).

4.1. The Core and Inner Jets

The brightest point in our 1.28 GHz MeerKAT image of IC 4296 is its unresolved (deconvolved LAS < 3\( \)\( '' \) FWHM) core whose peak flux density is \( S_p = 188 \pm 7 \text{ mJy beam}^{-1} \). Its J2000 position \( \alpha = 13^h 36^m 39.0025 \pm 0.0011, \delta = -33^\circ 57' 57.01\pm 0.013 \) matches both the International Celestial Reference Frame (ICRF) position \( \alpha = 13^h 36^m 39.03275, \delta = -33^\circ 57' 57.00783 \) (Fey et al. 2015) and the 2MASX infrared position. The core flux density at 10 GHz is 282 \( \pm \) 11 mJy (Ruffa et al. 2020), and the core spectral index \( \alpha(1.28 \text{ GHz}, 10 \text{ GHz}) = 0.20 \) implies significant synchrotron self-absorption. For typical kinetic temperatures \( \sim 10^4 \text{ K} \) of synchrotron electrons with critical frequencies near \( \nu = 1.28 \text{ GHz} \), self-absorption implies a core brightness temperature approaching \( T = 10^5 \text{ K} \). Thus the solid angle covered by the flat-spectrum core of IC 4296 is not much more than \( \Omega = 2 \times 10^{-6} \text{ arcsec}^2 \) and is \( \lesssim 1 \text{ pc} \) in extent. Also, any emission resolved by our MeerKAT image must be very nearly transparent (optical depth \( \tau \ll 1 \)) to synchrotron self-absorption.

Pellegrini et al. (2003) imaged the innermost jets of IC 4296 with 5 mas \( \times \) 2 mas resolution at 8.4 GHz and detected the bases of both jets with a brightness ratio \( R \sim 8 \), the northeast jet in PA \( \approx -40^\circ \) being the brighter of the two. For intrinsically similar jets and counterjets with bulk speeds \( \beta = v/c \) and inclination angle \( i \approx 90^\circ \) between the line of sight and the approaching jet, Doppler boosting alone produces a jet/counterjet brightness ratio (Blandford & Königl 1979)

\[ R = \left( \frac{1 + \beta \cos i}{1 - \beta \cos i} \right)^{2-\alpha}. \] (5)
Figure 5. False-color RM image of IC 4296 with the scale bar in rad m$^{-2}$ shown at the top. One white total-intensity contour is plotted at $S_0 = 100 \, \mu$Jy beam$^{-1}$. Most of this Faraday rotation is probably produced by the Galactic foreground, and not by any magnetized medium surrounding IC 4296.

Figure 6. Fractional polarization $B$ vectors superposed on false-color total intensities for the core, jets, and threads. A vector length of $1^\circ$ corresponds to 8% fractional polarization, and total intensities in mJy beam$^{-1}$ are indicated by the scale bar at the top. The FWHM restoring beam is shown by the white ellipse in the lower left corner.

Figure 7. Fractional polarization $B$ vectors superposed on false-color total intensities for the northwest jet, lobe, and ribbon. A vector length of $1^\circ$ corresponds to 2% fractional polarization, and total intensities in mJy beam$^{-1}$ are indicated by the scale bar at the top. The FWHM restoring beam is shown by the white ellipse in the lower left corner.
For a jet spectral index $\alpha \geq -0.7$ (Figure 4) and $\beta < 1$, the observed $R = 8$ suggests the parsec-scale approaching jet is inclined by $i < 69^\circ$. Alternatively, we can drop the assumption that the jets are intrinsically similar and use the flux-density ratio $R = 5.64 \text{ Jy}/3.73 \text{ Jy} = 1.51$ of the northwest/southeast lobes, which are presumably not Doppler boosted, to estimate the intrinsic jet luminosities. Inserting $R = 8/1.51 = 5.3$ into Equation (5) yields a more conservative kinematic inclination limit $i < 73^\circ$. In any case, the unique value of these photometric estimates of relativistic jet orientation is to determine that the northwest jet is approaching.

On a slightly larger angular scale, Dalla Bontà et al. (2009) used the HST to image the broad-line H$\alpha$ emission from IC 4296 = A3565-BCG and found it to be spatially extended with FWHM = 0\arcsec13 $\approx$ 30 pc. Their dynamical model matching the velocity field of the broad-line gas yields the inclination angle $i = 66^{\circ}0.0^{\circ}33^{\circ}38^{\circ}$ of the gas rotation axis. Dalla Bontà et al. (2009) also imaged the warped dust disk whose radius is $r \approx 174^{\circ} \approx 340$ pc and whose axial ratio indicates a morphological inclination angle $i \approx 71^\circ$. Ruffa et al. (2020) imaged the 230 GHz CO(2–1) emission line in the central $r \approx 100$ pc of the dust disk with ALMA, and they found the CO disk rotation axis is inclined by $i = 68^{\circ}0.0^{\circ}1^{\circ}2.5^{\circ}$.

If the inner jets are parallel to the rotation axes of the broad-line gas and the dust disk, the sidedness ratio $R = 5.3$ yields estimates of the jet velocity $\beta$ on mas scales ranging from $\beta = 0.6$ when $i = 60^\circ$ to $\beta = 0.9$ when $i = 71^\circ$.

Both radio jets brighten $\sim 4' \sim 1$ kpc from the nucleus (Ruffa et al. 2019), where their brightness ratio has fallen to $R = 1.8 \pm 0.1$ (Ruffa et al. 2020). At this distance, most FR1 jets have already decelerated significantly (Laing & Bridle 2014). If the jet inclination angle is still $i \approx 68^\circ$ and $\alpha = -0.7$, then $R \lesssim 1.8$ suggests $\beta \lesssim 0.04$. Ruffa et al. (2020) assumed the values $\alpha = -0.6$ and $\beta = 0.75$ (typical of the innermost FR1 jets) to estimate the IC 4296 jet inclination angle $i = 81^{\circ}4.0^{\circ}20^{\circ}$ on kiloparsec scales. However, such a large inclination angle would imply that jet bending projected along the line of sight is much greater than bending projected onto the plane of the sky. We consider that to be unlikely for jets that are so straight projected onto the sky. The JVLA 4.87 GHz image in Ruffa et al. (2019, Figure 1) shows that the jet and counterjet are antiparallel to within $2^\circ$ up to $\approx 5''$ from the nucleus. At $r \sim 1$ kpc the position angle of the approaching jet is $PA = -50^{\circ}5^{\circ} \pm 1^{\circ}0^{\circ}$ measured east from north.

### 4.2. The Jets on 10 kpc Scales

To highlight structures within the jets resolved by our MeerKAT image, we resampled the total-intensity image with small (0\arcsec24) pixels and used the AIPS task NINER to apply a 3 pixel $\times$ 3 pixel Sobel filter whose output (Figure 9) is proportional to the logarithm of the norm of the local intensity gradient. Not all narrow radio features originating near the core are jets, and Bridle & Perley (1984) “ask that they contain a “spine” of bright emission ... before we call them jets.” In Figure 9 the required spines appear as narrow dark ridge lines in the center of the jets. Out to $40'' \approx 10$ kpc from the core, the spines of both jets remain straight and parallel to $PA = -49^{\circ}5^{\circ} \pm 0^{\circ}5$. Their brightness ratios $R \lesssim 1.3$ indicate little or no Doppler boosting.

### 4.3. Threads

Both jets begin to bend and then wiggle visibly $100'' \approx 24$ kpc from the core (Figures 1, 2, and 9). Wiggles with wavelengths several times the jet radius are probably...
caused by the helical (α = 1) normal mode of the Kelvin–Helmholtz (KH) instability driven by velocity shear against the ambient medium (Hardee 2011) and appear sinusoidal in projection onto the sky. Brighter “knots” at the turning points (e.g., at α = 13h 36m 25s, δ = −33° 56′ in the northwest jet) about 2.5′ from the core may correspond to turning points where the helices are closer to the line of sight and hence have a larger optical depth. Long-wavelength KH jet oscillations promote mixing of the external medium with the jet fluid and can catastrophically disrupt the jet flow (Hardee 2011, 2013). Relativistic electrons escaping from the jets may be the origin of the three faint narrow “threads” (Figure 2, right panel) appearing to originate from the KH knots in the northwest jet and the single thread emerging from the southeast jet.

The threads must follow the ambient galaxy magnetic lines of force because the gyroradius of the synchrotron electrons (<1 pc) is much smaller than the ∼1 kpc thread radii and the magnetic fields are frozen into the ambient ionized medium. The threads originate around the half-light “effective” radius re = 37 kpc (Donzelli et al. 2011) of IC 4296, where the rms density of T = 107 K (kT = 1 keV) ambient electrons is ne = 10−3 cm−3 (Grossová et al. 2019). The ambient pressure from such keV protons and electrons is P = 2nkekT = 3 × 10−12 dyne cm−2. The 0.5–5 keV X-ray brightness is highest inside the red circle in the right panel of Figure 2 (matching the red circle in Grossová et al. 2019, Figure 4). The higher thermal pressure inside the circle may explain why the threads have avoided it.

The individual threads are marginally resolved with ∼2 kpc widths and have peak brightnesses ∼100 μJy beam−1. Where the three nearly transparent threads from the northwest jet merge (at least in projection), their total brightness adds up to ∼300 μJy beam−1. There may also be a very faint and marginally detected northern thread barely visible in the right panel of Figure 2 emerging at α = 13h 36m 48s, δ = −33° 59′.

As shown in Figures 4 and 6, the threads have (α) ≈ −1.2 indicating radiation losses and are highly polarized with longitudinal magnetic fields. The fractional polarizations are in excess of 50% over the bulk of the threads, indicating very ordered magnetic fields. Clearly these are coherent magnetic structures illuminated by an evolved population of relativistic electrons. The projected lengths of the threads are 30–50 kpc.

The minimum-energy magnetic field strength Bmin of a synchrotron source can be estimated from its brightness temperature Tb, line-of-sight thickness d, and proton/electron energy ratio κ in the approximation that the relativistic electrons emit at their critical frequencies from 107 to 1010 Hz (Pacholczyk 1970):

$$\left(\frac{B_{\text{min}}}{\mu G}\right) \approx 0.57 \left(\frac{T_b}{\text{K}}\right)\left(\frac{\nu(1+z)}{10^{10}\text{GHz}}\right)^{2-\alpha} \left(\frac{\text{kpc}}{d}\right)^{1+\kappa/2}. \quad (6)$$

The largest likely value of κ is the proton/electron mass ratio, so κ ≤ 2000. In marginally resolved threads with d ∼ 2 kpc, $S_p = 0.1$ mJy beam−1, and α = −1.2, $T_b \approx 2$ K and $B_{\text{min}} \lesssim 6$ μG. The corresponding particle pressure is 4/3 times the $B^2/(8\pi)$ magnetic pressure, making the maximum total relativistic pressure $P = 7B^2/(24\pi) \lesssim 3 \times 10^{-12}$ dyne cm−2 comparable with the ambient thermal pressure. Thus the narrow threads are likely confined and directed by the hot atmosphere of IC 4296.

![Figure 10](image-url) This grayscale image shows the southeast “ribbon” with a linear stretch from 400″ to 100 kpc from the core (Figure 1). What we call ribbons differ from jets in that they are not center-brightened and have no spines; instead they have nearly uniform brightness within straight and narrow boundaries. The southeast ribbon extends to at least 700″ ≈ 180 kpc from the core, where it becomes less distinct because it is seen in projection against the southeast lobe. It is less polarized than the jet, and the magnetic field direction is not perpendicular to the ribbon (Figure 8). Figure 4 shows that the ribbon has a much steeper spectrum ($\alpha = -0.9$) than the jet ($\alpha = -0.5$). The northwest jet also transitions to a ribbon, but the northwest ribbon is badly confused by emission from the northeast lobe.

4.4. Ribbons

The IC 4296 jets transition to “ribbons” approximately 400″ = 100 kpc from the core (Figure 1). What we call ribbons differ from jets in that they are not center-brightened and have no spines; instead they have nearly uniform brightness within straight and narrow boundaries. The southeast ribbon extends to at least 700″ ≈ 180 kpc from the core, where it becomes less distinct because it is seen in projection against the southeast lobe. It is less polarized than the jet, and the magnetic field direction is not perpendicular to the ribbon (Figure 8). Figure 4 shows that the ribbon has a much steeper spectrum ($\alpha = -0.9$) than the jet ($\alpha = -0.5$). The northwest jet also transitions to a ribbon, but the northwest ribbon is badly confused by emission from the northeast lobe.

These properties of the southeast ribbon (Figure 10) are reminiscent of those of the radio cocoon surrounding the X-shaped radio galaxy PKS 2014–55 (Cotton et al. 2020). They may be jet relics from an earlier time when the active galactic nucleus was more active. If the pressure in the external medium is less than the internal pressure of the ribbon, the ribbon will expand radially. The expansion speeds are typically supersonic in the external medium but subsonic in the ribbons, giving the ribbons time to reach internal pressure equilibrium (Begelman et al. 1984) and become nearly circular tubes with nearly uniform volume emissivity. Their synchrotron optical depths are very low, so the transverse brightness distribution of a circular tube with uniform volume emissivity is $\cos(\rho)$, $-\pi/2 < \rho < +\pi/2$, where $\rho$ is the angular offset from the center line of a tube with radius $\rho = \pi/2$.

We extracted the brightness profiles from four uniformly spaced slices (diagonal lines in Figure 10) through the southeast ribbon. Figure 11 shows the observed profiles tend...
to be more flat-topped and edge-brightened than the cosine profile, giving the appearance of thin, flat ribbons rather than circular tubes. The higher volume emissivity near the tube walls suggests electron reacceleration by shocks at those walls.

Along the center line, $T_e \approx 8$ K and the thickness of the circular tube is $d \approx 25$ kpc. For $\kappa < 2000$, Equation (6) indicates a minimum-energy magnetic field $B_{\text{min}} \lesssim 4 \mu$G. The corresponding synchrotron radiative lifetime $\tau_{\text{syn}} \sim c_2 B^{-3/2}$ (Pacholczyk 1970) is $\gtrsim 2 \times 10^8$ yr, and the radiative lifetime for IC scattering off the $2.73(1+z)\text{K}$ cosmic microwave background is about twice that. Only synchrotron and IC-scattering radiation losses steepen the radio spectra of the ribbons, so the large spectral-index difference between the jets ($\alpha = -0.5$) and the ribbons ($\alpha = -0.9$) is evidence that the ribbons are relics of jets that ceased activity $>10^8$ yr ago.

4.5. Rings

The southeast lobe and its backflow contains several elliptical structures roughly centered on and perpendicular to the southeast jet and ribbon as shown in Figure 1 and in the NINER Figure 12. The major axis of the brightest ellipse extends from $\alpha = 13^h \, 37^m \, 31^s$, $\delta = -34^\circ \, 09'$ to $\alpha = 13^h \, 37^m \, 51^s$, $\delta = -34^\circ \, 05'$. If that ellipse is a circular vortex ring seen in projection, its $2:1$ axis ratio indicates an inclination $i \approx \arccos(0.5) = 60^\circ \pm 5^\circ$ or $120^\circ \pm 5^\circ$ from the line of sight consistent with the expectation that the southeast ribbon is a nearly straight extension of the southeast jet and lies $\approx 30^\circ$ behind the plane of the sky. The ring brightens the outer edge of the southeast lobe and is further evidence that the IC 4296 radio source was more luminous and had an FR II morphology in the distant past.

5. Summary

The unprecedented combination of angular resolution ($\theta \approx 7''$ FWHM), surface-brightness sensitivity ($\sigma \approx 5 \mu$Jy beam$^{-1}$), and high dynamic range in the new MeerKAT image of IC 4296 revealed three new features: threads, ribbons, and rings. The threads are long ($\approx 50$ kpc), narrow (width $\approx 2$ kpc), and faint ($\approx 0.1$ mJy beam$^{-1}$) synchrotron sources powered by relativistic electrons escaping from helical Kelvin–Helmholtz instabilities in the main radio jets. The threads are highly polarized with parallel magnetic fields, and they are likely confined and directed by the higher-pressure ambient ionized gas and magnetic fields of the host galaxy. The ribbons begin where the main radio jets end $\approx 100$ kpc from the radio core. Unlike center-brightened FR I radio jets with well-organized transverse magnetic fields, the ribbons have a nearly uniform brightness distribution bounded by straight, sharp edges and less-organized magnetic fields. The IC 4296 ribbons are fainter ($\approx 0.5$ mJy beam$^{-1}$) than the jets, have steeper spectra ($\alpha \approx -0.9$ versus $\alpha \approx -0.5$), and appear to be relics of jet activity that diminished $>10^8$ yr ago. Near the leading edge of the southeast radio lobe and roughly centered on the end of the southeast ribbon is a thin vortex ring of emission observed projected onto the sky as an ellipse with a $2:1$ axis ratio. This axis ratio is an orientation indicator showing that the jet/ribbon axis of IC 4296 remains inclined by $\approx 60^\circ$ from the line of sight all the way into the lobes.

Such morphological features are rare but may become common as images with high angular resolution, brightness sensitivity, and dynamic range are produced by the Square Kilometre Array (SKA) precursor arrays MeerKAT and the Australian SKA Pathfinder (ASKAP). Recent examples include:

1. The collimated synchrotron threads linking the radio lobes of ESO 137-006 discovered in a MeerKAT image by Ramatsoku et al. (2020) are long and narrow like the IC 4296 threads, but their brightness can be much higher ($T_e \sim 100$ K), their polarization has not been measured, and their origin is unknown.
2. Faint ($T_e \approx 0.5$ K) cocoons surrounding the X-shaped radio galaxy PKS 2014−55 (Cotton et al. 2020) are backflow relics sharing many properties of the IC 4296 ribbons. These include smooth brightness distributions suggesting pressure equilibrium has been reached, and steep spectra indicating radiative aging of the synchrotron electrons.

3. Several odd radio circles (ORCs; Norris et al. 2021) have been discovered in ASKAP’s Evolutionary Map of the Universe pilot survey, although none are clearly vortex rings in radio lobes.

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Facilities: Gaia, IRSA, MeerKAT.

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