

The Filamentary Radio Lobes of the Seyfert–Starburst Composite Galaxy NGC 3079

Biny Sebastian¹, P. Kharb¹, C. P. O'Dea^{2,3}, E. J. M. Colbert^{4,5}, and S. A. Baum^{3,6}

¹ National Centre for Radio Astrophysics (NCRA)—Tata Institute of Fundamental Research (TIFR), S.P. Pune University Campus, Post Bag 3, Ganeshkhind, Pune

411007, India; biny@ncra.tifr.res.in

² School of Physics and Astronomy, Rochester Institute of Technology, Rochester, NY 14623, USA

³ Physics and Astronomy, University of Manitoba, Winnipeg, Manitoba, Canada

⁴ Hume Center for National Security and Technology, 900 N. Glebe Road, Arlington, VA 22203, USA

⁵ U.S. Army Research Laboratory, Adelphi, MD, USA

⁶ Carlson Center of Imaging Science, Rochester Institute of Technology, Rochester, NY 14623, USA

Received 2019 April 26; revised 2019 July 18; accepted 2019 July 24; published 2019 October 3

Abstract

We present results from multifrequency polarization-sensitive Very Large Array observations of the Seyfertstarburst composite galaxy NGC 3079. Our sensitive radio observations reveal a plethora of radio "filaments" comprising the radio lobes in this galaxy. We analyze the origin of these radio filaments in the context of existing *Chandra* X-ray and *HST* emission-line data. We do not find a one-to-one correlation of the radio filaments with the emission-line filaments. The northeastern lobe is highly polarized with polarization fractions $\sim 33\%$ at 5 GHz. The magnetic fields are aligned with the linear extents of the optically thin filaments, as observed in our, as well as other, observations in the literature. Our rotation measure images show evidence for rotation measure inversion in the northeastern lobe. Our data best fit a model where the cosmic rays follow the magnetic field lines generated as a result of the dynamo mechanism. There could be additional effects like shock acceleration that might also be playing a role. We speculate that the peculiar radio lobe morphology is a result of an interplay between both the superwinds and the active galactic nucleus jet that are present in the galaxy. The jet, in fact, might be playing a major role in providing the relativistic electron population that is present in the radio lobes.

Key words: galaxies: active – galaxies: individual (NGC 3079) – galaxies: jets – galaxies: Seyfert – radio continuum: galaxies

1. Introduction

Radio observations reveal that most Seyfert galaxies have sub-parsec-scale radio emission in spite of their "radio-quiet" active galactic nucleus (AGN) status (de Bruyn & Wilson 1976; Ulvestad & Wilson 1984a, 1984b; Roy et al. 1994; Thean et al. 2000; Lal et al. 2004; Kharb et al. 2010; Kharb et al. 2014). Many of these galaxies with small-scale radio emission show elongated kiloparsec-scale radio structures (KSRs), similar to the radio jets seen in powerful radio galaxies. The kiloparsecscale radio structures, however, are not always found to be aligned with the small-scale jets (Baum et al. 1993; Colbert et al. 1996; Gallimore et al. 2006). Furthermore, Seyfert radio jets were found to be randomly aligned with respect to the host galaxy major axes (Kinney et al. 2000; Schmitt et al. 2001; Schmitt & Kinney 2002). Abrupt changes of jet axes were also inferred in several Seyfert galaxies, e.g., NGC 4151 (Ulvestad et al. 1998), NGC 1068 (Gallimore et al. 1996), and Mrk 6 (Kharb et al. 2006). It appears that the radio structures in Seyfert galaxies are more complex than in radio galaxies. In particular, it is unclear if KSRs are purely AGN driven (either via a jet or an accretion-disk wind) or starburst superwind driven. It is essential to disentangle these contributions before the truly relevant questions of how radio outflows are produced in low-luminosity AGN (LLAGN) in general, and Seyfert galaxies in particular, can be answered. Also, the role played by LLAGN outflows in AGN feedback needs to be examined (Croton et al. 2006; Müller-Sánchez et al. 2011; Riffel et al. 2013).

NGC 3079 is a well-known nearby (z = 0.003723) Seyfert 2/LINER galaxy with a nuclear starburst, which is a member of an interacting galaxy pair. It is an edge-on spiral galaxy with

several regions of star formation along the disk. Its eightshaped radio structure with a ring-like feature (ring hereafter) inside its northeast lobe (Duric & Seaquist 1988; Irwin & Saikia 2003; Wiegert et al. 2015; Irwin et al. 2019), its slowmoving $(v \sim 0.1c)$ parsec-scale radio jet (Irwin & Seaquist 1988; Baan & Irwin 1995; Middelberg et al. 2005), and copious amount of hot X-ray gas and emission-line filaments (Cecil et al. 2001, 2002) have been well documented. NGC 3079 is a Compton-thick AGN (Iyomoto et al. 2001) having a disk-like pseudo-bulge. The origin of the doublelobed morphology observed in NGC 3079 is not yet completely understood. Duric & Seaguist (1988) argue that the lobe material is moving at supersonic velocities, though they dismiss the possibility that these are jets that may be precessing based on the difficulty in reproducing the closed-loop morphology using these models. They suggest that these are probably winds originating from a nuclear starburst or accretion activity. X-ray emission and emission-line imaging shows that NGC 3079 hosts a superwind (Veilleux et al. 1994; Cecil et al. 2001, 2002). Superwinds are believed to be generated when the kinetic energy from supernovae and massive stellar winds are transformed into thermal energy. The heated gas then expands into the lower pressure ambient medium. The direction of the steepest pressure gradient is along the minor axis. The hot gas is easily traced by the X-ray emission, which is a more direct tracer compared to the emission-line gas, which is generated at shock fronts as a result of the interaction with the ambient medium. The emission-line ratios seen in superwinds are typical of shock-ionized gas as also seen in the case of NGC 3079 (Veilleux et al. 1994). Although these authors favored a starburst-wind origin for the radio lobes, they were not able to rule out AGN-driven winds.

 Table 1

 Observation Log and Observed Parameters

Frequency (GHz)	Bandwidth (MHz)	VLA Array Configuration	Observation Date	Beam, PA (arcsec ² , °)	Total Flux Density (mJy)	rms (μ Jy beam ⁻¹)
4.86	50	А	1995 Jul 21	$0.45 \times 0.31, 81.1$	99.4	27
4.86	50	В	1995 Nov 2	$0.58 \times 0.43, 85.8$	161.0	16
1.42	50	А	1995 Jul 3	$1.45 \times 1.19, -80.2$	509.0	53
1.42	50	С	1996 Feb 17	$14.82 \times 13.03, 62.2$	838.0	80
5.50	2048	BnA	2018 Feb 16	$1.10 \times 0.47, -87.08$	260.3	8.6

Several authors favored the jet origin of the lobes (Irwin & Seaquist 1988; Irwin & Saikia 2003). Irwin et al. (2017) find that NGC 3079 is one of the few edge-on galaxies in the CHANG-ES sample (Irwin et al. 2012) that shows radio lobes that stand out in polarized intensity compared to the galactic disk emission that is not as highly polarized.

Sofue et al. (2001), Miyamoto et al. (2015), and Lin et al. (2016) have studied the molecular constitution and kinematics of NGC 3079 using various molecular lines in both emission and absorption. Many of these studies present evidence for blueshifted features or blue wings that was readily associated with outflowing molecular gas. Shafi et al. (2015) present evidence for outflowing HI gas. These authors propose that large amounts of cold gas, both molecular and atomic, are being blown out along with the ionized gas. They find that both the AGN and starburst scenarios are powerful enough to drive such outflows. They also point out that such multiphase gas outflows are being discovered in several AGN-driven outflows. The presence of a nuclear starburst in NGC 3079 was contested by Hawarden et al. (1995). They suggest that the molecular gas outflows are driven by the AGN rather than a starburst.

Despite the abundance of literature on NGC 3079, a consensus has not yet been reached regarding the origin of the kiloparsec-sized radio emission. In this paper, we present a polarization-sensitive radio study of NGC 3079 with the historical and expanded VLA, at multiple radio frequencies and array configurations. We attempt to disentangle the contribution of the starburst, AGN winds, and the jet in the formation of a double-lobed structure in NGC 3079. Throughout this paper, we assume $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$, and $\Omega_{\text{vac}} = 0.73$. At the distance of NGC 3079, 1" corresponds to 0.084 kpc. Spectral index α is defined such that flux density at frequency ν is $S_{\nu} \propto \nu^{\alpha}$.

2. Observations and Data Analysis

2.1. VLA Data from 1995

We observed NGC 3079 with the VLA at 1.5 and 4.9 GHz with the A-, B-, and C-array configurations in 1995–1996 (Project ID: AB740). 3C 286 and 3C 48 were used as the primary flux density as well as the polarization calibrators, while 1035+564 was used as the phase calibrator for the whole experiment. The data were processed with AIPS using standard imaging and self-calibration procedures. Table 1 lists the observing frequency, the corresponding bandwidth, the VLA configuration, the observation date, the FWHMs of the synthesized beams, the total flux densities of the source at the corresponding resolution, and the *rms* noise of the final images. AIPS task PCAL was used to solve for the antenna "leakage" terms (D terms) as well as polarization of the calibrators 3C 286 and 3C 48. The leakages were typically a few percent. Polarization calibration of the 4.9 GHz A-array

data was unsuccessful. This was a consequence of not having acquired enough scans of the polarization calibrator for adequate parallactic angle coverage; there were only two scans of 3C 286.

The polarization intensity (PPOL) and polarization angle (PANG) images were created by first running the task IMAGR for Stokes "Q" and "U" and then combining these images using the task COMB. Pixels with intensity values below 3σ and angle errors $>10^{\circ}$ were blanked before making PPOL and PANG images, respectively. Fractional polarization images were created using the PPOL and total intensity images where pixels with >10% errors were blanked. We created twofrequency spectral index images using the AIPS task COMB after convolving images at both frequencies with the same circular beam (=1."45 \times 1."45). Pixels with a total intensity value below 3σ were blanked before making the spectral index image. Rotation measure images were created using three frequencies using AIPS tasks MCUBE, TRANS, and RM. For this, we split the two IF data at the L band (IF1 = 1.465 GHz, IF2 = 1.385 GHz) and used the C-band (frequency = 4.860) GHz) data as such. Images were made after first convolving all images with the same circular beam (=1."45 \times 1."45). Pixels with errors $>13^{\circ}$ were blanked while making the polarization angle images (PANG). We created depolarization (DP) images by dividing the fractional polarization images at 1.42 and 4.86 GHz using the task COMB. We blanked pixels with fractional errors $>20^{\circ}$ before making the DP image.

2.2. EVLA Data from 2018

New polarization-sensitive Expanded Very Large Array (EVLA) data at 5 GHz were acquired in 2018 (project ID: 17B_074; see Table 1) using the BnA array configuration. 3C286 and 1035+564 were observed as the primary flux + polarization calibrator and phase calibrator, respectively. OQ208, which is a strong unpolarized source, was observed to calibrate the polarization leakages. Data were reduced using CASA version 5.1.2-4. Basic calibration and editing of the data were carried out using the CASA pipeline for EVLA data reduction. Polarization calibration was performed on the precalibrated data. The model of 3C 286 was defined using the model parameters that were fed manually to the task "setjy." The model parameters required for completely defining the source model included the Stokes I flux density at the reference frequency, the spectral index, and the coefficients of the Taylor expansion of both the degree of linear polarization as a function of the frequency about the reference frequency and the reference frequency itself. The polarization angle of 3C 286 appears to be a constant across frequencies, whereas the degree of polarization varies across frequencies. Therefore, we estimated the coefficients by fitting a first-order polynomial using the data from Perley & Butler (2013). The cross-hand



Figure 1. Grayscale images of total intensity showing the filamentary radio structures observed in NGC 3079 with the (left) VLA A-array at 1.4 GHz with a beam size $1.4^{\prime\prime}$ 45 × $1.1^{\prime\prime}$ 19 and PA -80° 2 and (right) VLA B-array at 5 GHz with a beam size $0.1^{\prime\prime}$ 58 × $0.1^{\prime\prime}$ 43 and PA 85°8.

delays between both the polarizations were corrected. The leakage terms per channel were solved using the CASA task "polcal" with the unpolarized source OQ208. The polarization angle was calibrated using the known polarization angle of 3C286.

The target NGC 3079 was then SPLIT out before imaging. We made use of the MT-MFS algorithm in CASA while cleaning to take care of the wideband effects. Imaging and phase-only self-calibration were performed iteratively for three times before a final round of A&P self-calibration and imaging was performed. The Stokes "Q" and "U" images were made using the final calibrated UV-data file. The EVLA data had 16 spectral windows spanning a bandwidth of 2 GHz. The data set was then divided into four chunks each consisting of four spectral windows. The "QU" Stokes image cubes of these data sets were then created using task "tclean" in CASA. We have corrected the polarized emission for Ricean bias using the AIPS task COMB. Finally, the task "rmfit" was used to make an inband rotation measure image from these cube images. The RM image obtained is shown in Figure 6. The pixels where the errors are greater than 200 rad m⁻² were blanked.

3. Radio Morphology: Lobes, Ring, Galaxy

The total intensity and linearly polarized emission images for NGC 3079 are presented in Figures 3, 1, 2. The 1.4 GHz image in Figure 1 (right panel) shows the northeastern lobe with an extent of 27'' (=2.3 kpc) and the southwestern lobe with an

extent of 20'' (=1.7 kpc) in exquisite detail, especially the extremely filamentary nature of the lobes. The northeastern lobes show three distinct filaments annotated as A, B, and C; two of them forming the "edges" of the radio bubble/lobe. The filament at the southern edge (A) extends up to the top edge of the lobe. This filament shows increased brightness toward the top edge of the lobe. The northern filament (C) can also be traced until the lower end of the ring-like structure after which the trajectory is not clear. This filament also appears brighter, farther away from the core. It is probable that the ring is a 3D-shell-like structure seen in projection. The ring-like feature at the top of the northeastern lobe appears to be comprised of additional radio filaments. They are the brightest filaments and do not appear to be connected to the center of the galaxy.

The southwestern lobe, on the contrary, is not comprised of as many filamentary structures. Yet, the edges of the lobe, especially at the base, appear brighter compared to the emission from the inner parts. Further away, toward the southernmost tip, there is an increase in brightness where two filaments, namely, E and D, undergo bending and point toward the nuclear core. Unlike the northeastern lobes, there are no standalone filamentary structures apparently disconnected from the core.

3.1. Host Galaxy Emission

Figure 4 shows a higher-resolution image (VLA A-array 5 GHz) and a lower-resolution image (VLA C-array 1.4 GHz).



Figure 2. (Left) 1.4 GHz VLA A-array image with contour levels $0.850 \times (-0.170, 0.170, 0.350, 0.700, 1.400, 2.800, 5.600, 11.25, 22.50, 45, 90)$ mJy beam⁻¹ and (right) 5 GHz VLA B-array image with contour levels $0.800 \times (-0.085, 0.085, 0.170, 0.350, 0.700, 1.400, 2.800, 5.600, 11.25, 22.50, 45, 90)$ mJy beam⁻¹ of NGC 3079 with magnetic field vectors whose length is proportional to the fractional polarization superimposed in red.



Figure 3. New EVLA 5 GHz image of NGC 3079 with total intensity in contours and polarized intensity in color. The magnetic field vectors are shown in red. Contour levels represent $25.5 \times (2, 4, 6, 8, 16, 64, 256, 512, 1024) \mu$ Jy beam⁻¹. The beam shown in the bottom left corner as a filled magenta ellipse is of size 1.10×0.147 and PA is -87° .

The lower-resolution image reveals the large extent of host galaxy radio emission. The lobes are seen embedded slightly above the disk in the low-resolution view. Apart from the lobes, there are several features that protrude out of the disk. A prominent spur-like feature is seen rising up to \sim 8 kpc above the disk at nearly 4 kpc in the northeast direction along the disk from the center. It is also interesting to note that most of these protrusions are highly polarized. Such spurs were previously seen in other starburst systems hosting a radio halo like NGC 253 (Carilli et al. 1992). They suggest that the material from the disk gets convected up and is driven by both cosmic-ray pressure as well as thermal pressure. The protrusion can also be explained as galactic fountains (Shapiro & Field 1976; Bregman 1980).

The 615 MHz GMRT image by Irwin & Saikia (2003) shows an entire loop-like structure coming out of the disk plane of the galaxy. The "spur" appears spatially coincident with the eastern-most edge of the loop. At the lower frequency, the halo comprises much more extended structures than seen in our own images, whereas the ring is seen clearly even in our higher-frequency maps. The higher-resolution image does not show any lobe emission, whereas the emission from the disk that is aligned very well with the outer disk is very prominent.

3.2. Spectral and Polarization Properties

The 1.4–5 GHz spectral index image of NGC 3079 is shown in Figure 5. The spectrum is mostly steep (mean $\alpha \sim -1.2 \pm 0.13$) except at the core. The spectral index



Figure 4. (Left) 1.4 GHz VLA C-array image of NGC 3079 with contour levels = $3.0 \times (-0.085, 0.085, 0.170, 0.350, 0.700, 1.400, 2.800, 5.600, 11.25, 22.50, 45, 90)$ mJy beam⁻¹ and (right) 5 GHz VLA A-array image with contour levels = $0.61 \times (-0.085, 0.085, 0.170, 0.350, 0.700, 1.400, 2.800, 5.600, 11.25, 22.50, 45, 90)$ mJy beam⁻¹. The magnetic field vectors with length proportional to fractional polarization are superimposed in red.

image shows that the inner parts of the disk have a flatter spectrum compared to the rest of the source. The core possesses a flat spectrum ($\alpha \sim -0.3 \pm 0.002$) pointing toward current AGN activity as is substantiated by the presence of a relativistically moving very long baseline interferometry (VLBI) jet (Irwin & Seaquist 1988; Trotter et al. 1998; Sawada-Satoh et al. 2000; Middelberg et al. 2007). The spectral index image also reveals regions of flat spectrum along the edges of the ring. The spectral index becomes as flat as -0.5 in certain locations along the edges.

The fractional polarization (FP = P/I) images reveal the ring to have FP = $16 \pm 5\%$ at the *L* band and FP = $33 \pm 9\%$ at the *C* band. For the central part of the galaxy showing polarization, we find FP = $4 \pm 1\%$ at the *L* band and FP = $16 \pm 3\%$ at the *C* band. For the *L*-band C-array image with a resolution of ~14'' where the KSR is not clearly resolved (Figure 4), we find that the average fractional polarization is FP = $19 \pm 3\%$. Interestingly, the "spur"-like feature to the northeast of the host galaxy disk is very highly polarized: FP = $40 \pm 7\%$. Images made with fractional polarization pixels blanked for errors greater than 20% suggest that at the *L* band, the ring and the galaxy have FP = $14 \pm 4\%$ and FP = $4 \pm 1\%$, respectively, and at the *C* band, the ring and the galaxy have FP = $40 \pm 12\%$ and FP = $24 \pm 7\%$, respectively.

The new EVLA image at 5 GHz mostly detects the ring-like feature (Figure 3); the fractional polarization is $37 \pm 8\%$ in the ring and $6 \pm 2\%$ in the galaxy. The filaments comprising the ring are more clearly delineated in the new image in polarized

light. Our in-band RM image indicates that the average RM values are in the range of $\pm 50-100$ rad m⁻², similar to what was previously observed in the ring by Cecil et al. (2001).

The three-frequency RM image (see Figure 6, left panel) reveals an RM = $+150 \text{ rad m}^{-2}$ with an error of 30 rad m⁻², for the southern part of the host galaxy emission. For the western jet region, RM = -210 rad m^{-2} with an error of 15 rad m⁻². We have also estimated the depolarization parameter, DP, as DP = m_l/m_h , where m_l and m_h are the fractional polarization at low and high frequencies, respectively. The DP image is shown in Figure 7. A higher value of DP implies lower depolarization. We find that the average DP = 0.3 in the ring and 0.4 in the galaxy; the average DP approaches 0.8 in the central regions of the galaxy. The higher depolarization around the ring could be suggestive of greater confinement.

4. Energetics of Radio Lobes

NGC 3079 has a flared and clumpy accretion disk (Hu 2008) with detections of water maser emission on milliarcsecond scales (Kondratko et al. 2000). Kondratko et al. (2000) have estimated a black hole mass of $2 \times 10^6 M_{\odot}$ in NGC 3079 using a Very Long Baseline Array (VLBA) study of water masers within a radius of 0.4 pc. Iyomoto et al. (2001) find that X-ray emission is heavily obscured and the luminosity after correction for absorption turns out to be $10^{42}-10^{43} \text{ erg s}^{-1}$. This luminosity would imply that the source is accreting at a rate of 0.01–0.1 times its Eddington luminosity. The accretion



Figure 5. 1.4–5 GHz VLA spectral index image of NGC 3079 in color superimposed by the 1.4 GHz radio contours. The circular beam shown in the bottom left corner is of size $1.4^{\prime\prime}$ 45 × $1.4^{\prime\prime}$ 45.

rates are consistent with that seen in Seyfert galaxies (Ho 2008).

The parameters derived from our radio observations of NGC 3079 are listed in Table 2. The parameters derived were total radio luminosity (L_{rad}), magnetic field at minimum pressure (B_{min}), minimum energy (E_{min}), minimum pressure (P_{min}), total energy (E_{tot}), energy per unit volume for a given filling factor or energy density (E_{den}), and electron lifetime from synchrotron and inverse Compton (over cosmic microwave background; CMB) radiative losses (t_{life}). The minimum pressure parameters were estimated for the northeast lobes, southwest lobes, and the galactic disk separately using Equations (1)–(5) from O'Dea & Owen (1987). The lifetimes were estimated using the relation given in Pérez-Torres & Alberdi (2007).

The B-array image at 5 GHz and the A-array image at 1.4 GHz were used while estimating the flux densities as these images had matched baseline coverages. These images were

then convolved with the same beam size. Rectangular regions were used for estimating the flux densities. The radio spectrum was assumed to extend from 10 MHz to 10 GHz. The protonto-electron energy ratio was assumed to be unity. However, Beck & Krause (2005) have noted that protons are more dominant than electrons according to currently proposed mechanisms for the origin of cosmic rays. In this scenario, our magnetic field values will be underestimated by a factor of $(K_0 + 1)^{\frac{1}{\alpha+3}}$, where K_0 is the ratio of proton-to-electron number densities. Hence, for typical values of spectral indices seen in the lobes of NGC 3079 ($\alpha \sim -1$) and assuming $K_0 = 100$, the magnetic fields are underestimated by a factor of 3. However, in the lobes of radio galaxies, the classical equipartition magnetic fields often match with those measured from X-rays (Brunetti et al. 1997), justifying our choice of K_0 . Table 2 lists the parameters corresponding to volume filling factor (ϕ) values of 1, 0.5, and 10^{-4} (Blustin & Fabian 2009).

To further investigate the underlying mechanism we derive the equipartition magnetic fields for every pixel in a similar manner. A spatially resolved image of the spectral index was made instead of assuming an average spectral index value. A volume filling factor equal to unity was used. A cylindrical volume with a height equal to the width of the lobe (0.8 kpc) was assumed. The radius of the cylinder was chosen to be the same as that of the synthesized beam of the image. The pixels with flux density less than 3σ were blanked. The spectral index image and the magnetic field image of the source are shown in Figure 8. The EVLA polarized intensity image at 5 GHz is shown overlaid in contours. The spectral index image shows flatter spectral indices along the ring.

The spectral index and the magnetic field structure are quite complex. Several regions along the ring, like those marked X and Z in Figure 8, shows a flat spectrum, whereas region Y shows a steep spectrum. Region Y forms the inner part of the ring as seen at 1.4 GHz. The width of the ring is not as large at 5 GHz, where most of the emission is confined to the outer edges where the spectral indices are flatter as well. Region Y also shows high magnetic field values, though polarized emission is not detected at 5 GHz probably because of the steep spectrum that reduces the total intensity and thereby polarized flux density, or because of the absence of ordered magnetic fields, or both.

5. The Origin of the Ring and Filamentary Morphology

In this section, we try to understand the origin of the peculiar morphology of the radio lobes in NGC 3079 using our radio observations in conjugation with the existing results from the X-ray and emission-line data from the literature.

Cecil et al. (2002) find evidence for a large-scale diffuse X-ray halo surrounding the radio superbubble that is delineated by H α filaments at wide angles. These H α filaments were explained as the contact discontinuity between the shocked wind and the galaxy halo gas. The inner four filaments of H α emission form the walls of the superbubble (Cecil et al. 2001). Cecil et al. (2001) infer that the radial velocities in these filaments increase with distance from the disk. They also find that the four filaments get disrupted at some height that was explained as a result of Rayleigh–Taylor instabilities that may develop in the case of wind-driven superbubbles.

The three prominent radio filaments (A, B, and C) mentioned in Section 3, at first glance, appear to be aligned with the

Sebastian et al.



Figure 6. (Left) Three-frequency VLA rotation measure image in color superimposed by the 1.4 GHz radio contours and (right) the color in-band EVLA rotation measure image of the northeastern lobe. The circular beam shown in the bottom left corner of the left panel is of size $1.4^{\prime\prime}$ 45.



Figure 7. VLA depolarization image of NGC 3079 in color made using the 1.4 and 5 GHz image, superimposed by the 1.4 GHz radio contours. The circular beam shown in the bottom left corner is of size $1.4^{\prime\prime}$ 45 × $1.4^{\prime\prime}$ 45.

ionized filaments seen in the [N II] $\lambda 6583 + H\alpha$ line emission image (Cecil et al. 2001).

Figure 9 shows the overlay of the *Hubble Space Telescope* WFPC2 $H\alpha + [N II]$ emission-line contours and *Chandra* ACIS-S X-ray emission contours over the radio continuum VLA A-array image at 1.4 GHz. There is no one-to-one correspondence between the radio and the thermal emission filaments (see Figure 9).

The [N II] $\lambda 6583 + H\alpha$ line emission image shows no counterpart for the southwestern lobes due to extinction, although there is soft-X-ray emission (Cecil et al. 2002). Among the three radio filaments that seemingly arise from the radio core, the filament marked C is aligned with the H α

filaments. Such a correlation was previously seen in M82 by Adebahr et al. (2013). They suggested that this could be a proof for magnetic fields that are frozen into the ionized medium and get transported along with the superwind.

However, there are several other observational signatures in NGC 3079 that cannot be explained using a simple frozen-in magnetic field. Although partially aligned, it has to be noted that the weakest radio filament (A) corresponds to the brightest $H\alpha$ filament, which is also aligned almost along the same direction as that of the parsec-scale VLBA jet. This trend goes against the frozen-in magnetic field picture, where one would expect a correlation in the brightness of the radio and $H\alpha$ filaments. The brightest radio filament being offset from the direction of the VLBI jet also poses a problem for these filaments being powered by jets, unless the jet is changing its direction or undergoing precession. Moreover, the middle radio filament annotated B in Figure 9 does not appear to be associated with the central H α filament. Cecil et al. (2002) have shown that X-ray and H α filaments were spatially well correlated using their high-resolution images from Chandra and HST, respectively. However, radio emission that is also mostly filamentary in nature does not seem to be well correlated with the thermal filaments. In the northern lobe, the closed-loop-like structure appears displaced northward compared to the emission-line filaments. The dearth of emission lines and X-ray emission at the topmost loop is intriguing. The radio emission also extends farther beyond the point where the emission-line gas reaches a blowout phase as a result of the growth of Rayleigh-Taylor instabilities (Cecil et al. 2001).

The radio plasma and thermal emission are not completely intermixed, which would imply different sources of origin. Such a lack of intermixing despite the disruption of the jet at early stages is also witnessed in X-ray cavities in clusters of galaxies, where the ambient hot gas is simply pushed aside by the expanding radio source (Bîrzan et al. 2004). Similar to NGC 3079, NGC 253, a starburst galaxy hosting superwinds, possesses magnetic fields that are aligned along the filaments. Heesen et al. (2011) model the walls of the outflow cones of the galaxy to be threaded by helical magnetic fields as indicated by

 Table 2

 Source Parameters Estimated from the "Minimum Energy" Condition

Component	$L_{\rm rad}$ (erg s ⁻¹)	B _{min} (Gauss)	E_{\min} (erg)	$P_{\rm min}$ (dynes cm ⁻²)	E _{tot} (erg)	$E_{\rm den}$ (erg cm ⁻³)	t _{life} (Myr)
Filling factor = 1.0							
NE lobes SW lobes Disk Filling factor = 0.5	$\begin{array}{c} 3.0 \times 10^{38} \\ 5.0 \times 10^{38} \\ 5.0 \times 10^{38} \end{array}$	$\begin{array}{c} 3.88 \times 10^{-5} \\ 4.75 \times 10^{-5} \\ 3.59 \times 10^{-5} \end{array}$	$\begin{array}{c} 1.49 \times 10^{55} \\ 1.63 \times 10^{55} \\ 2.52 \times 10^{55} \end{array}$	$\begin{array}{c} 1.40 \times 10^{-10} \\ 2.10 \times 10^{-10} \\ 1.2 \times 10^{-10} \end{array}$	$\begin{array}{c} 1.86 \times 10^{55} \\ 2.03 \times 10^{55} \\ 3.15 \times 10^{55} \end{array}$	$\begin{array}{l} 3.0 \times 10^{-10} \\ 4.5 \times 10^{-10} \\ 2.6 \times 10^{-10} \end{array}$	2.74 2.03 3.07
0 NE lobes SW lobes Disk	$\begin{array}{c} 3.0 \times 10^{38} \\ 5.0 \times 10^{38} \\ 5.0 \times 10^{38} \end{array}$	$\begin{array}{c} 4.73 \times 10^{-5} \\ 5.79 \times 10^{-5} \\ 4.38 \times 10^{-5} \end{array}$	$\begin{array}{c} 1.10 \times 10^{55} \\ 1.21 \times 10^{55} \\ 1.87 \times 10^{55} \end{array}$	$\begin{array}{c} 2.08 \times 10^{-10} \\ 3.11 \times 10^{-10} \\ 1.78 \times 10^{-10} \end{array}$	$\begin{array}{c} 1.38 \times 10^{55} \\ 1.51 \times 10^{55} \\ 2.34 \times 10^{55} \end{array}$	$\begin{array}{c} 4.5 \times 10^{-10} \\ 6.7 \times 10^{-10} \\ 3.8 \times 10^{-10} \end{array}$	2.04 1.51 2.29
Filling factor = 1.0×10^{-4}							
NE lobes SW lobes Disk	$\begin{array}{c} 3.0 \times 10^{38} \\ 5.0 \times 10^{38} \\ 5.0 \times 10^{38} \end{array}$	0.00054 0.00066 0.0005	$\begin{array}{c} 3.00 \times 10^{53} \\ 3.00 \times 10^{53} \\ 5.00 \times 10^{53} \end{array}$	$\begin{array}{c} 2.70 \times 10^{-8} \\ 4.05 \times 10^{-8} \\ 2.30 \times 10^{-8} \end{array}$	$\begin{array}{l} 4.00 \times 10^{53} \\ 4.00 \times 10^{53} \\ 6.00 \times 10^{53} \end{array}$	$\begin{array}{c} 5.8 \times 10^{-8} \\ 8.7 \times 10^{-8} \\ 5.0 \times 10^{-8} \end{array}$	0.05 0.04 0.06

Note. Column 1: radio source components including the northeast (NE), southwest (SW) lobes and the galactic "disk" minus the AGN. Column 2: total radio luminosity. Columns 3–5: "minimum energy" magnetic field strength, energy, and pressure, respectively. Column 6: total energy. Column 7: total energy density. Column 8: electron radiative lifetimes via synchrotron and inverse Compton (over CMB) losses. See Section 4.



Figure 8. (Left) Spectral index image and (right) equipartition magnetic field image in color, of the northeastern lobe made using the 1.4 and 5 GHz VLA images. The pink contours denote the EVLA polarized intensity at 5 GHz. The bottom left corner of the left panel shows the 1.4 and 5 GHz VLA circular beams enclosing the elliptical EVLA beam at 5 GHz.

RM inversion. They appear as filaments in projection. But unlike NGC 3079, there are only two filaments each at the edge of the outflow cone. If the inner H α or radio filaments actually trace the wall of a superbubble in the case of NGC 3079, the expectations would be to see edge-brightened structures in projection or a completely filled volume rather than discrete filaments at intermediate angles.

The presence of separate filaments in between the edge filaments in NGC 3079 casts doubts over the simple picture of these being the edge of the walls seen in projection. Cecil et al. (2001) have studied the rotation measure of the northern ring of NGC 3079. They have found that the RM changes its sign from the +50 rad m⁻² on the inside of the ring to -50 rad m⁻² on the outside. We note that our EVLA in-band RM image exhibits average RM values in the same range and also shows the RM inversion. In our RM image of the northern lobe (see Figure 6) we see the RM inversion in individual filaments on

the right-hand side, although the polarized emission with positive RM has not yet been recovered.

Below we consider plausible physical mechanisms that might be a playing a role in the formation of the ring in NGC 3079.

5.1. Shock Compression at the Boundaries of an Expanding Superbubble

Duric & Seaquist (1988) propose that shocks at the interface between ambient medium and the outflow would be a natural consequence of the supersonic velocities derived for the winds present in NGC 3079. Several features seen in the ring of NGC 3079 are suggestive of the presence of a shock. With our better resolution images, it can be seen that the ring-like structure also comprises several filaments. The entire structure is reminiscent of a supernova remnant shell. Shocks can



Figure 9. (Left) Overlay of the contours representing the HST WFPC2 H α + [N II] line emission in blue and (right) Chandra ACIS-S X-ray emission in pink, over the total intensity image in color of NGC 3079 with the VLA A-array at 1.4 GHz.

produce synchrotron emission via diffusive shock acceleration (DSA) or Fermi first-order acceleration (Blandford & Eichler 1987). The power-law index of the energy distribution of the particles is determined by the strength of the shock, which can be described using the Mach number.

The flattening in the spectral index along the ridges of the ring at various locations might point toward the reacceleration of charged particles (see Section 3.2). The spectral index image shows that the spectrum is as flat as -0.5 at several locations that match with the mean spectral index values typically seen in galactic supernova remnants (Klein et al. 2018).

By using the spectral age of ~2.8 Myr (see Table 2) and an outflow length of 2.3 kpc, we obtain a wind velocity of 800 km s^{-1} . Since the velocity of the wind increases with the distance from the disk (Cecil et al. 2001), our wind velocity represents an average value of the projected wind velocities at various distances above the disk. The thermal gas traced by emission lines exhibits a radial velocity that increases with distance from the disk to attain velocities as high as 1000 km s^{-1} (Veilleux & Osterbrock 1987; Cecil et al. 2001). Since most of the radio emission is from above the emission-line complex and assuming that the radio emission is coexisting with the superwind we can assume a radial velocity of 1000 km s^{-1} for the radio outflow as well. Hence, the total velocity of the radio outflow is $v \sim 1250 \text{ km s}^{-1}$.

The sound speed in the hot wind regions present in typical starbursts is about 100 km s⁻¹ (Romero et al. 2018). Hence, the sonic Mach number turns out to be ~12. The spectral index, α , depends on the Mach number of the shock (Blandford & Eichler 1987; van Weeren et al. 2016) as follows:

$$\alpha = \frac{1}{2} - \frac{M^2 + 1}{M^2 - 1}.$$
 (1)

For a sonic Mach number of 12, we obtain $\alpha \sim -0.5$. Hence, the shock present in NGC 3079 is strong enough to produce the spectral index values as flat as those seen in NGC 3079 from an underlying thermal distribution of electrons.

It is also possible that an already existing relativistic population of electrons gets reaccelerated at the shock front. Detailed DSA simulations would be required to understand the contribution of the reacceleration of an already existing relativistic electron population.

Shock compression often leads to the ordering of the tangled or turbulent magnetic fields that permeate the ambient medium. The magnetic fields parallel to the shock front get amplified leading to high degrees of polarized emission aligned perpendicular to the shock fronts (Laing 1980; Ensslin et al. 1998). The northern ring shows high fractional polarization compared to the rest of the galaxy. The polarization vectors are also aligned perpendicular to the individual filaments as expected in the case of shock amplification. The ring also shows higher depolarization (see Section 3.2), which might be due to a higher Faraday depth within or in front of it (Cioffi & Jones 1980). So either the magnetic field or electron density (or both) is higher here. It might be that the expansion of the shell (that we see projected as a ring) is sweeping up gas, so there is a denser shell of gas along the shell. It could also be that the magnetic fields are being compressed along the edges, although compressing magnetic fields can lead to higher absolute polarization (Laing 1980).

Although the conditions in NGC 3079 are favorable for the presence of shocks powerful enough to reproduce the observed spectrum, all the observed properties of NGC 3079 cannot be explained using shock acceleration. The lack of correlation between the thermal and nonthermal emission suggests different mechanisms. More importantly, the RM inversion in filaments cannot be explained solely using shock acceleration and requires organized magnetic fields. In the next section, we consider if the draping of magnetic fields at the leading edge of the outflow can address these shortcomings.

5.2. Magnetic Draping

Bernikov & Semenov (1979) and Lyutikov (2006) have pointed out that as an object moves through a weakly magnetized medium with a velocity greater than its Alfvén speed, it necessarily drags up a layer of magnetic field lines along with it. For magnetic draping to be playing a role it is required that the velocity of the wind is higher than the Alfvén velocity. Adebahr et al. (2019) show that the radio lobes of B2 0258+35 are probably being affected by magnetic draping using their polarization and HI study. We test this idea to explain the polarization structures observed in the lobes of NGC 3079.

We estimate the Alfvén velocity of the wind using the following equation:

$$v_a = 2.18 n_e^{-\frac{1}{2}} B \text{ km s}^{-1}, \tag{2}$$

where *B* is the magnetic field in μ G and n_e is the electron number density in cm⁻³. For the northern lobes we have estimated an equipartition magnetic field of 40 μ G (see Table 2). Our RM images show an average RM value of 50 rad m⁻². If we assume a Faraday screen path length of 100 pc, which is equal to the widths of the filaments as seen in our EVLA images, the electron number density turns out to be 0.015 cm⁻³ by using the relation RM = 812 $n_e B_{||} \ell$ rad m⁻². We obtain an Alfvén velocity of ~700 km s⁻¹. Therefore, the wind is super Alfvénic with an Alfvénic Mach number, M_A of 1.8. Pfrommer & Jonathan Dursi (2010) suggest that the following criteria have to be met for magnetic draping to occur:

$$\frac{\lambda_B}{R} \gtrsim \frac{1}{M_A},$$
 (3)

where λ_B is the magnetic coherence length. The thickness of the polarized filaments in our image, which is about 100 pc, can be regarded as a lower limit of the magnetic coherence length. Assuming a radius of curvature, $R \sim 0.4$ kpc, we obtain a value for the ratio of $\frac{R}{M_A}$ that is greater than the magnetic coherence length. Therefore, magnetic draping might not be a viable mechanism in the case of NGC 3079.

Guidetti et al. (2011) have suggested that RM inversion could be produced by magnetic field draping. However, it is not clear how any supersonic outflow that forms a draped magnetic field layer at its edge can lead to a dome-like structure as observed in the northern lobe of NGC 3079, rather than a conical structure. Hence, we suggest that magnetic field draping does not play a significant role in the formation of the lobes in NGC 3079.

5.3. Filaments as Magnetic Flux Tubes

Cecil et al. (2001) put forth three explanations for the observed RM inversion. In their first model, they consider that the wind entrains material from the cold disk with a frozen-in magnetic field that is transported upstream and gives rise to the positive RM values. Once the disk material cools down the material starts falling back resulting in the reverse fields.

Second, they consider a globally ordered magnetic field of the halo, which surrounds the wind. The negative RM results from the compressed halo gas, whereas the outflowing wind contributes to the positive RM. In both these models, the outer shells lead to a positive RM while material inside leads to negative RM. However, as they had pointed out in Section 3.5 of their paper, Faraday rotation closely follows a λ^2 dependence that rules out a Faraday rotating medium within the synchrotron source. Therefore it is unlikely that the outflowing wind enclosed within either the host galaxy halo or the wind material that is falling back to the disk is giving rise to the positive RM.

They propose a third scenario that is similar to the solar prominence. Here, we consider the possibility of these being actual standalone filaments, in which case the RM inversion seen in the individual filaments can be easily explained using a helical magnetic field structure. The Faraday rotation is probably introduced by a sheath around the filaments with increased particle density and width of about 10% of the filament size itself. The sheath that is threaded by a helical magnetic field can introduce such an inversion. A helical magnetic field morphology is often invoked to explain the RM inversion seen in VLBI-scale jets (Kharb et al. 2009; Clausen-Brown et al. 2011; Pudritz et al. 2012).

Henriksen (2019) suggested that galaxies possess force-free magnetic fields that are generated by the α^2 dynamo action; cosmic rays are transported in a direction parallel to the magnetic field lines under force-free conditions. Dome-like structures, as seen in NGC 3079, and the active regions in the Sun, can be reproduced by some of the solutions.

The morphology of radio filaments that are anchored to the core is especially reminiscent of the nonthermal radio filaments found in the Galactic center (Morris et al. 2014). The Galactic center filaments also possess organized magnetic fields often aligned along the filament, similar to that seen in NGC 3079. It is in principle possible that these filaments are magnetic flux tubes through which the relativistic material is transported from the core to the top.

Interestingly, it can also be inferred from Figure 1 that the middle filament, B, is steeper compared to the edge filaments. The edge filaments might be tracing the shocked walls, whereas the filament B might have a different source of origin and is completely unrelated to the other two filaments. This seems unlikely given the similarity in morphology. It is, however, possible that all the filaments are directed by the same dynamo mechanisms, whereas the edge filaments are also being acted upon by shocks leading to a flatter spectrum. Hence, we conclude that this model successfully explains the structures and the RM inversion observed in NGC 3079.

6. Role of the Jet in Inflating the Radio Bubble

Irwin & Seaquist (1988) argue that the large-scale radio lobes and the VLBI-scale jet are unusual in spiral galaxies and are therefore probably related. In this section, we investigate the role of the jet in actually inflating the radio bubbles.

Radio halos were discovered in several starburst galaxies (Ekers & Sancisi 1977; Allen et al. 1978; Carilli et al. 1992; Duric et al. 1998). These were believed to be composed of the material that was convected up from the central starburst regions, where it was created by supernovae (Lerche & Schlickeiser 1980). However, these radio halos that are purely powered by starbursts have a very different morphology compared to NGC 3079 (Colbert et al. 1996). These radio halos are more spherical and diffuse, whereas NGC 3079 shows two distinctly directional lobes. The low-resolution images of NGC 3079 show more extended and diffuse structures at lower frequencies (see Section 3.1), indicating a steep spectrum in the halo compared to the central ring. Hence, the nuclear lobes are distinct from the rest of the halo emission arising from the star formation activity in NGC 3079.

Star formation rates (SFRs) from the radio flux density of northeast lobes, southwest lobes, and the disk are 2.58, 2.14, and 17.87 M_{\odot} yr⁻¹, respectively (using the relations in Condon et al. 2002), for stars more massive than >0.1 M_{\odot} . Yamagishi et al. (2010) have estimated the SFR using *AKARI* far-infrared data. They find that the SFR is 5.6 M_{\odot} yr⁻¹ in total and 2.6 M_{\odot} yr⁻¹ in the central 4 kpc region. The SFR estimated in

the east and west lobes together exceeds that estimated from IR emission in the central regions by about a factor of 2. Therefore, it is unlikely that the lobes are composed of plasma that is accelerated solely by supernovae and stellar winds. A certain contribution from the jet is inevitable unless the radio emission is generated as a result of in situ particle acceleration in the lobes due to shocks (see Section 5.1).

Energy and pressure requirements of the radio lobe can provide constraints on the origin of the bubble. Duric & Seaquist (1988) invoke accretion along with a nuclear starburst due to the very high rates of star formation required to meet the energy budget. Although the AGN at the core is weak, the radio jet on VLBI scales, as was pointed out by Irwin & Seaquist (1988), is capable of powering the superbubble.

Irwin & Seaquist (1988) compare the momentum flux that is required to feed the kiloparsec-scale radio lobes to the parsecscale jets. They find that the momentum flux of the parsec-scale iets is $3 \times 10^{31} h^{\frac{-10}{7}} \,\mathrm{g \, cm \, s^{-2}}$ while that of the northeastern radio lobe is $1 \times 10^{32} h^{\frac{-10}{7}}$ g cm s⁻². However, these values are three orders of magnitude lower compared to the wind model parameters of Duric & Seaquist (1988). Following Irwin & Seaquist (1988) we assume a slab volume with size 1.1 kpc. We find a momentum flux value of $1 \times 10^{33} h^{\frac{-10}{7}}$ g cm s⁻² for the northeastern lobe for a filling factor value of 1.0. Irwin & Seaquist (1988) pointed out that the momentum flux of the lobes derived is a lower limit owing to the underlying minimum energy assumption. When we use a filling factor value of 1×10^{-4} (Blustin & Fabian 2009) we find a momentum flux value of $3.5 \times 10^{35} h^{\frac{-10}{7}}$ g cm s⁻², which is comparable to the momentum flux derived from wind model parameters (Duric & Seaguist 1988). Interestingly, for the volume filling factor of 1×10^{-4} , the radio lobes are overpressured with respect to the surrounding hot gas (e.g., see Heckman et al. 1990).

Shafi et al. (2015) estimate the jet power of NGC 3079 using various relations that connect radio luminosities to jet power. Their estimated value of $10^{41} \text{ erg s}^{-1}$ is two orders of magnitude lower than that required by the wind model in Duric & Seaquist (1988). However, the uncertainties in the relations used for conversion is often high enough that this difference is consistent with the wind model within error bars.

The radio continuum emission in NGC 3079 is very different from the typical jet lobe morphology seen in powerful radio galaxies. Several VLBI studies had revealed that the jet in NGC 3079 is expanding with mildly relativistic speeds in the range 0.1c to 0.18c (Trotter et al. 1998; Sawada-Satoh et al. 2000; Kondratko et al. 2005). It is also known that Seyfert galaxies often host very low power jets that often get disrupted or show S-shaped or twisted morphology (Ulvestad et al. 1981; Booler et al. 1982; Wilson & Ulvestad 1982, 1983; Wehrle & Morris 1988; Kharb et al. 2006). A precession jet model can connect the VLBI jet to the large-scale lobes with a jet precession period of $\sim 10^5$ yr using the precession model of Hjellming & Johnston (1981). For instance, fixing the jet speed to be the one observed on VLBI scales ($v \sim 0.2c$) yields a precession period of 9.5×10^4 yr for a precessing cone half opening angle of 10° and jet inclination of 20° , for the northeastern lobe. However, one episode of precession is insufficient to explain the entire complex morphology of the jet lobe structure.

Henriksen et al. (1981) and Fiedler & Henriksen (1984) have invoked galactic pressure gradients and buoyancy to explain jet bending that produce S-shaped jets for certain viewing angles. Smith & Norman (1981) and Wilson & Ulvestad (1982) have suggested that ram pressure bending due to a rotating ISM can produce S-shaped jets. However, this idea is difficult to test in the edge-on disk of NGC 3079, where the galaxy spiral arms are not clearly seen, making it difficult to ascertain the sense of the galactic ISM rotation. It is possible that the jet in NGC 3079 got disrupted due to its interaction with the ambient medium or an accretion-disk wind.

This disrupted jet material probably gets transported out along with the superwind or along the force-free magnetic field lines generated via the dynamo mechanism, or both. As discussed in Section 5, the lack of correlation of radio plasma with the superwind also suggests that the jet might be playing an important role. We conclude that the jet, the active nuclei, and the superwind together give rise to the peculiar lobe morphology in NGC 3079, which is neither similar to a typical AGN jet or a starburst radio halo.

7. Summary and Conclusions

We have carried out a multifrequency, multiscale radio study of NGC 3079, a Seyfert 2 galaxy that also hosts a nuclear starburst. The origin of the radio continuum emission in this galaxy is widely debated. With our high-resolution and highsensitivity data, we favor a scenario that involves an interplay of various processes and outflows. Our findings can be summarized as follows.

- 1. There is no one-to-one correlation between the thermal emission (traced by X-ray and emission line) and nonthermal emission (traced by radio), which is inconsistent with magnetic fields frozen-in within the super-wind hot material and being transported out.
- 2. We propose that the filamentary structures are not merely edges of the superbubble seen in projection, but actual individual filaments (see Section 5.3). The RM inversion observed in the individual filaments can also be easily explained using such a scenario. Each filament is like a jet segment threaded by helical magnetic fields. Structures similar to those seen in NGC 3079 have been reproduced using dynamo models in the literature.
- 3. We find that the conditions in NGC 3079 are favorable for shock acceleration to occur. However, it is insufficient to explain all the observed signatures, like RM inversion. Detailed simulations would be required to disentangle the role played by shock acceleration in the resulting morphology.
- 4. The SFR estimated from the lobes suggest that supernovae and stellar outflows cannot feed the lobe material entirely and a contribution from the AGN jet is required. As discussed in Section 5.1, shock acceleration of the thermal pool of electrons in the wind has not been ruled out. It is not entirely clear if all the emission can be accounted for by this mechanism. An observational test would be to check whether such a radio excess is seen in other starburst galaxies hosting superwinds in which an AGN core is absent.

We conclude that the AGN jet contributes to the relativistic plasma that is observed in the lobes of NGC 3079. We, therefore, propose that the radio lobes in NGC 3079 are AGN jet related. However, the presence of starburst superwind is also indicated, and it is hard to discriminate the effects of each mechanism. THE ASTROPHYSICAL JOURNAL, 883:189 (12pp), 2019 October 1

We thank the anonymous referee for the insightful suggestions, which led to the improvement of the manuscript. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. S.A.B. and C.P.O. are grateful to the Natural Sciences and Engineering Research Council of Canada (NSERC) for support.

ORCID iDs

Biny Sebastian [®] https://orcid.org/0000-0001-8428-6525 P. Kharb [®] https://orcid.org/0000-0003-3203-1613 C. P. O'Dea [®] https://orcid.org/0000-0001-6421-054X

References

- Adebahr, B., Brienza, M., & Morganti, R. 2019, A&A, 622, A209
- Adebahr, B., Krause, M., Klein, U., et al. 2013, A&A, 555, A23
- Allen, R. J., Baldwin, J. E., & Sancisi, R. 1978, A&A, 62, 397
- Baan, W. A., & Irwin, J. A. 1995, ApJ, 446, 602
- Baum, S. A., O'Dea, C. P., Dallacassa, D., de Bruyn, A. G., & Pedlar, A. 1993, ApJ, 419, 553
- Beck, R., & Krause, M. 2005, AN, 326, 414
- Bernikov, L. V., & Semenov, V. S. 1979, Ge&Ae, 19, 671
- Bîrzan, L., Rafferty, D. A., McNamara, B. R., Wise, M. W., & Nulsen, P. E. J. 2004, ApJ, 607, 800
- Blandford, R., & Eichler, D. 1987, PhR, 154, 1
- Blustin, A. J., & Fabian, A. C. 2009, MNRAS, 396, 1732
- Booler, R. V., Pedlar, A., & Davies, R. D. 1982, MNRAS, 199, 229
- Bregman, J. N. 1980, ApJ, 236, 577
- Brunetti, G., Setti, G., & Comastri, A. 1997, A&A, 325, 898
- Carilli, C. L., Holdaway, M. A., Ho, P. T. P., & de Pree, C. G. 1992, ApJL, 399, L59
- Cecil, G., Bland-Hawthorn, J., & Veilleux, S. 2002, ApJ, 576, 745
- Cecil, G., Bland-Hawthorn, J., Veilleux, S., & Filippenko, A. V. 2001, ApJ, 555, 338
- Cioffi, D. F., & Jones, T. W. 1980, AJ, 85, 368
- Clausen-Brown, E., Lyutikov, M., & Kharb, P. 2011, MNRAS, 415, 2081
- Colbert, E. J. M., Baum, S. A., Gallimore, J. F., O'Dea, C. P., & Christensen, J. A. 1996, ApJ, 467, 551
- Condon, J. J., Cotton, W. D., & Broderick, J. J. 2002, AJ, 124, 675
- Croton, D. J., Springel, V., White, S. D. M., et al. 2006, MNRAS, 365, 11
- de Bruyn, A. G., & Wilson, A. S. 1976, A&A, 53, 93
- Duric, N., Irwin, J., & Bloemen, H. 1998, A&A, 331, 428
- Duric, N., & Seaquist, E. R. 1988, ApJ, 326, 574
- Ekers, R. D., & Sancisi, R. 1977, A&A, 54, 973
- Ensslin, T. A., Biermann, P. L., Klein, U., & Kohle, S. 1998, A&A, 332, 395
- Fiedler, R., & Henriksen, R. N. 1984, ApJ, 281, 554
- Gallimore, J. F., Axon, D. J., O'Dea, C. P., Baum, S. A., & Pedlar, A. 2006, AJ, 132, 546
- Gallimore, J. F., Baum, S. A., O'Dea, C. P., & Pedlar, A. 1996, ApJ, 458, 136
- Guidetti, D., Laing, R. A., Bridle, A. H., Parma, P., & Gregorini, L. 2011, MNRAS, 413, 2525
- Hawarden, T. G., Israel, F. P., Geballe, T. R., & Wade, R. 1995, MNRAS, 276, 1197
- Heckman, T. M., Armus, L., & Miley, G. K. 1990, ApJS, 74, 833
- Heesen, V., Beck, R., Krause, M., & Dettmar, R.-J. 2011, A&A, 535, A79
- Henriksen, R. 2019, Galax, 7, 53
- Henriksen, R. N., Vallee, J. P., & Bridle, A. H. 1981, ApJ, 249, 40

- Hjellming, R. M., & Johnston, K. J. 1981, ApJL, 246, L141
- Ho, L. C. 2008, ARA&A, 46, 475
- Hu, J. 2008, MNRAS, 386, 2242
- Irwin, J., Beck, R., Benjamin, R. A., et al. 2012, AJ, 144, 43
- Irwin, J., Wiegert, T., Merritt, A., et al. 2019, AJ, 158, 21
- Irwin, J. A., & Saikia, D. J. 2003, MNRAS, 346, 977
- Irwin, J. A., Schmidt, P., Damas-Segovia, A., et al. 2017, MNRAS, 464, 1333 Irwin, J. A., & Seaquist, E. R. 1988, ApJ, 335, 658
- Iyomoto, N., Fukazawa, Y., Nakai, N., & Ishihara, Y. 2001, ApJL, 561, L69
- Kharb, P., Gabuzda, D. C., O'Dea, C. P., Shastri, P., & Baum, S. A. 2009, ApJ, 694, 1485
- Kharb, P., Hota, A., Croston, J. H., et al. 2010, ApJ, 723, 580
- Kharb, P., O'Dea, C. P., Baum, S. A., et al. 2014, MNRAS, 440, 2976
- Kharb, P., O'Dea, C. P., Baum, S. A., Colbert, E. J. M., & Xu, C. 2006, ApJ, 652, 177
- Kinney, A. L., Schmitt, H. R., Clarke, C. J., et al. 2000, ApJ, 537, 152
- Klein, U., Lisenfeld, U., & Verley, S. 2018, A&A, 611, A55
- Kondratko, P. K., Greenhill, L. J., & Moran, J. M. 2000, BAAS, 32, 1586
- Kondratko, P. T., Greenhill, L. J., & Moran, J. M. 2005, ApJ, 618, 618
- Laing, R. A. 1980, MNRAS, 193, 439 Lal, D. V., Shastri, P., & Gabuzda, D. C. 2004, A&A, 425, 99
- Lerche, I., & Schlickeiser, R. 1980, ApJ, 239, 1089
- Leiche, I., & Schnekeiser, K. 1960, ApJ, 259, 1069
- Lin, M.-Y., Davies, R. I., Burtscher, L., et al. 2016, MNRAS, 458, 1375
- Lyutikov, M. 2006, MNRAS, 373, 73
- Middelberg, E., Agudo, I., Roy, A. L., & Krichbaum, T. P. 2007, MNRAS, 377, 731
- Middelberg, E., Krichbaum, T. P., Roy, A. L., Witzel, A., & Zensus, J. A. 2005, in ASP Conf. Ser. 340, Future Directions in High Resolution Astronomy, ed. J. Romney & M. Reid (San Francisco, CA: ASP), 140
- Miyamoto, Y., Nakai, N., Seta, M., et al. 2015, PASJ, 67, 5
- Morris, M. R., Zhao, J. H., & Goss, W. M. 2014, in IAU Symp. 303, The Galactic Center: Feeding and Feedback in a Normal Galactic Nucleus (Cambridge: Cambridge Univ. Press), 369
- Müller-Sánchez, F., Prieto, M. A., Hicks, E. K. S., et al. 2011, ApJ, 739, 69
- O'Dea, C. P., & Owen, F. N. 1987, ApJ, 316, 95
- Pérez-Torres, M. A., & Alberdi, A. 2007, MNRAS, 379, 275
- Perley, R. A., & Butler, B. J. 2013, ApJS, 206, 16
- Pfrommer, C., & Jonathan Dursi, L. 2010, NatPh, 6, 520
- Pudritz, R. E., Hardcastle, M. J., & Gabuzda, D. C. 2012, SSRv, 169, 27
- Riffel, R. A., Storchi-Bergmann, T., & Winge, C. 2013, MNRAS, 430, 2249
- Romero, G. E., Müller, A. L., & Roth, M. 2018, A&A, 616, A57
- Roy, A. L., Norris, R. P., Kesteven, M. J., Troup, E. R., & Reynolds, J. E. 1994, ApJ, 432, 496
- Sawada-Satoh, S., Inoue, M., Shibata, K. M., et al. 2000, PASJ, 52, 421
- Schmitt, H. R., Antonucci, R. R. J., Ulvestad, J. S., et al. 2001, ApJ, 555, 663
- Schmitt, H. R., & Kinney, A. L. 2002, NewAR, 46, 231
- Shafi, N., Oosterloo, T. A., Morganti, R., Colafrancesco, S., & Booth, R. 2015, MNRAS, 454, 1404
- Shapiro, P. R., & Field, G. B. 1976, ApJ, 205, 762
- Smith, M. D., & Norman, C. A. 1981, MNRAS, 194, 771
- Sofue, Y., Koda, J., Kohno, K., et al. 2001, ApJL, 547, L115
- Thean, A., Pedlar, A., Kukula, M. J., Baum, S. A., & O'Dea, C. P. 2000, MNRAS, 314, 573
- Trotter, A. S., Greenhill, L. J., Moran, J. M., et al. 1998, ApJ, 495, 740
- Ulvestad, J. S., Roy, A. L., Colbert, E. J. M., & Wilson, A. S. 1998, ApJ, 496, 196
- Ulvestad, J. S., & Wilson, A. S. 1984a, ApJ, 278, 544
- Ulvestad, J. S., & Wilson, A. S. 1984b, ApJ, 285, 439
- Ulvestad, J. S., Wilson, A. S., & Sramek, R. A. 1981, ApJ, 247, 419
- van Weeren, R. J., Brunetti, G., Brüggen, M., et al. 2016, ApJ, 818, 204
- Veilleux, S., Cecil, G., Bland-Hawthorn, J., et al. 1994, ApJ, 433, 48
- Veilleux, S., & Osterbrock, D. E. 1987, ApJS, 63, 295
- Wehrle, A. E., & Morris, M. 1988, AJ, 95, 1689
- Wiegert, T., Irwin, J., Miskolczi, A., et al. 2015, AJ, 150, 81
- Wilson, A. S., & Ulvestad, J. S. 1982, ApJ, 263, 576
- Wilson, A. S., & Ulvestad, J. S. 1983, ApJ, 275, 8
- Yamagishi, M., Kaneda, H., Ishihara, D., et al. 2010, PASJ, 62, 1085