3C459: A highly asymmetric radio galaxy with a starburst

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ABSTRACT
Multifrequency radio observations of the radio galaxy 3C459 using MERLIN, VLA and the EVN, and an optical HST image using the F702W filter are presented. The galaxy has a very asymmetric radio structure, a high infrared luminosity and a young stellar population. The eastern component of the double-lobed structure is brighter, much closer to the nucleus and is significantly less polarized than the western one. This is consistent with the jet on the eastern side interacting with dense gas, which could be due to a merged companion or dense cloud of gas. The HST image of the galaxy presented here exhibits filamentary structures, and is compared with the MERLIN 5-GHz radio map. EVN observations of the prominent central component, which has a steep radio spectrum, show a strongly curved structure suggesting a bent or helical radio jet. The radio structure of 3C459 is compared with other highly asymmetric, Fanaroff-Riley II radio sources, which are also good candidates for studying jet-cloud interactions. Such sources are usually of small linear size and it is possible that the jets are interacting with clouds of infalling gas that fuel the radio source.

Key words: galaxies: active - galaxies: jets - galaxies: nuclei - galaxies: individual: 3C459 - radio continuum: galaxies

1 INTRODUCTION

Although the majority of high-luminosity extragalactic radio sources selected at a low frequency show symmetries in the brightness and location of the oppositely directed components, a small but significant fraction are highly asymmetric. The asymmetries of the oppositely directed lobes of emission are important because they could provide useful insights into the environments of sources and the interaction of jets with external clouds or galaxies. They also help in the understanding of the evolution of the individual components with time and provide tests of the orientation-based unified scheme for radio galaxies and quasars (Barthel 1989). Using the well-known 3CR sample, McCarthy, van Breugel \& Kapahi (1991) have shown that optical line-emitting gas tends to be brightest on the side on which the radio lobe is closer to the nucleus, demonstrating the importance of environmental effects in the structural asymmetries of powerful radio sources. Polarization studies of these lobes have shown that the nearer lobe also tends to depolarize more rapidly, possibly due to interaction of the radio plasma with the line-emitting gas (cf. Pedelty et al. 1989, Ishwara-Chandra et al. 1998). This suggests that the depolarization asymmetry of the lobes is determined by an asymmetric environment as well as the effects of orientation (Garrington et al. 1988; Laing 1988).

A class of sources that is of particular interest is the compact steep-spectrum sources (CSSs), defined to be less than \( \sim 20 \) kpc in size for a Universe with \( H_0 = 100 \) km \( s^{-1} \) Mpc\(^{-1} \) and \( q_0 = 0 \) (cf. O’Dea 1998 for a review). These sources, which are widely believed to be young radio sources, tend to be more asymmetric in both the brightness and location of the outer radio components compared with the larger sources (cf. Saikia et al. 2001). In a recent study of a sample of CSSs from the 3CR, S4, B2 and B3 samples it has been shown that the CSSs exhibit large brightness asymmetries with the flux density ratio for the opposing lobes being \( \sim 5 \) for \( \sim 25 \) per cent of the objects, compared with only \( \sim 5 \) per cent for the objects of larger size (Saikia et al. 2002). The authors estimate the sizes of the clouds responsible for these asymmetries to be \( \sim 3 \) to 7 kpc, similar to those of dwarf galaxies, and speculate that such clouds might be responsible for the inflow of gas which fuels the radio source. Amongst larger-sized objects, one of the most asymmetric sources is B0500+630, the structure of which appears to be inconsistent with the unified scheme and suggests that there is an intrinsic asymmetry in the oppositely-directed jets from the nucleus (Saikia et al. 1996). The most extreme form of asymmetry is when the source is completely one-sided with radio emission on only one side of the nucleus. Although most of these objects are core-dominated and their apparent asymmetry is likely to be due to bulk relativistic motion of the
extended lobes of emission, there do appear to be a number of weak-cored one-sided sources which are difficult to reconcile with the simple relativistic beaming scenario (Saikia et al. 1990).

As part of a study of highly asymmetric radio sources, the radio galaxy 3C459 has been observed extensively at radio and optical wavelengths. The results of these observations are presented in this paper. 3C459 is identified with a 17.55 V magnitude, N-galaxy at a redshift of 0.2199 (Spinrad et al. 1985; Eracleous & Halpern 1994), so that 1 arcsec corresponds to 2.39 kpc. Its optical/UV spectrum is dominated by the light of a young stellar population, with the Balmer break and higher Balmer absorption lines being detected (cf. Miller 1981; Tadhunter et al. 2002). Although Yee & Oke (1978) reported both Hα and Hβ to exhibit a broad, low profile, no clear evidence of broad permitted lines were found by Eracleous & Halpern (1994), and more recently by Tadhunter et al. (2002). Both of these sets of authors as well as Heckman et al. (1994) have classified 3C459 as a narrow-line radio galaxy. Its far-infrared luminosity at 60μm is unusually high, being about 10 times brighter than other radio sources from the 2-Jy sample at comparable redshifts (cf. Tadhunter et al. 2002). Tadhunter et al. also note a possible relationship between optical/UV starburst activity and far-infrared excess, and suggest that the high infrared luminosity is due to dust heating by the starburst. The source has been detected with ISO by Fanti et al. (2000); and HST F702W and WFPC2 V-band images have been presented by de Koff et al. (1996) and Farrah et al. (2001) respectively.

The radio galaxy has also been detected in HI absorption with the VLA as well as by the WSRT (Morganti et al. 2001). The FWHM of the absorption seems to be quite broad with a width of ~400 km s⁻¹. The integrated HI column density of ~2.7×10¹⁸ cm⁻² is similar to that found for other radio galaxies. It is interesting to note that the faint radio galaxy 3C236 also shows evidence of star formation, and HI absorption against a lobe of the inner radio source (Conway & Schilizzi 2000; Schilizzi et al. 2001; O’Dea et al. 2001).

The radio structure of this galaxy has been studied by Ulvestad (1985, hereinafter referred to as U85) using the VLA. His results have shown that the radio structure of the source comprises a core and two extended lobes, the eastern one being a factor of ~5 closer to the core than the western lobe and the whole source extending to approximately 8.2 arcsec. This corresponds to a linear size of 19.5 kpc, which is similar to other compact steep-spectrum objects. At the VLA resolution of ~0.4 arcsec at 16 cm, the eastern lobe, though significantly resolved, appears to have a smooth structure with no discernible small-scale features. The western lobe, extending half-way back to the core has a tail with two peaks of emission. The higher-resolution A2 cm image of U85 shows the source to have an edge-brightened, FRII structure, consistent with its radio luminosity of 2.1×10²⁵ W Hz⁻¹ sr⁻¹ at 1400 MHz. It is worth noting that the central component, which contributes ~30 per cent of the total flux density at 5 GHz, has a steep radio spectrum with a spectral index, α (Sν ~ ν^α), of ~0.78±0.15 between λ6 and 2 cm (U85). 3C459 also exhibits a high degree of polarization asymmetry between the two lobes (Davis, Stannard & Conway 1983; U85; Morganti et al. 1999). It has an integrated rotation measure of ~6±1 rad m⁻² with an intrinsic posi-

| Telescope | Obs. Freq. MHz | Antennas | Obs. Date |
|-----------|----------------|----------|----------|
| MERLIN 408 | 1420 C1,De,Kn,Lo,Ta,Wa | 1992 Oct 29 |
| MERLIN 1420 | C32,Kn,Lo,Mk2,Ta,Wa | 1993 Nov 07 |
| MERLIN 1658 | C32,Kn,Lo,Mk2,Ta,Wa | 1993 Nov 07 |
| MERLIN 4546 | C32,Kn,Mk2,Ta | 1995 Jul 02 |
| MERLIN 4866 | C32,Kn,Mk2,Ta | 1995 Jul 02 |
| MERLIN 4993 | C32,Kn,Mk2,Ta | 1995 Jul 19 |
| MERLIN 5186 | C32,Kn,Mk2,Ta | 1995 Jul 02 |
| EVN-VLBI 4987 | Eel,Me,Mk2,No,Wk | 1995 May 24 |

**Antennas:** C1 One antenna of the Cambridge one-mile telescope, C32 Cambridge 32m, Da Darnhall, De Delford, Ef Effelsberg, Kn Knockin, Lo Lovell, Me Medicina, Mk2 Jodrell Bank Mk2, No Noto, On Onsala, Ta Tabley, Wa Wardle, Wk Westerbork

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| MERLIN 4546 | C32,Kn,Mk2,Ta | 1995 Jul 02 |
| MERLIN 4866 | C32,Kn,Mk2,Ta | 1995 Jul 02 |
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**2 OBSERVATIONS AND ANALYSES**

The MERLIN observations presented in this paper have been made over a period of time from 1987 October to 1995 May. They cover a frequency range from 408 MHz to ~5 GHz, with resulting image resolutions ranging from 620 mas at 408 MHz to ~70 mas at 5 GHz. The size of 3C459 and its low declination (~4 degrees) make it a difficult source to map with MERLIN alone at 5 GHz. Thus, shorter spacing calibrated VLA A-array data, kindly provided by Ulvestad, have been combined with the MERLIN data to provide additional constraints in the ‘mapping’ process. Even so, it is still not possible to fully remove the north-south sidelobes associated with the strong core. An improved ‘VLA only’ 5 GHz image with a resolution comparable to that of the MERLIN 408 MHz image has also resulted from a reprocessing of the VLA data. Since 3C459 is known not to be variable, there is no difficulty in combining data or comparing the resulting images from the different frequencies or instruments over the period of the observations. 5 GHz VLBI observations have also been made with the EVN in May 1995, yielding an image of the core region of the source with a resolution of 6 mas. The dates of the MERLIN and VLBI observations and the antennas used are given in Table 1. The flux calibration sources are 3C48 and 3C286, their flux densities being calculated from the values given in the VLA calibrator source catalogue, which is based on the work of Baars et al. (1977). The point source baseline calibrator fluxes have been determined from a comparison of their MERLIN short spacing amplitudes with those of 3C48 or 3C286. 3C286 is assumed to have a position angle for its linear polarization of 32°. The baseline calibrators used were B1345+125 at 408 MHz and B0552+398 and OQ208 at the higher frequencies. The phase reference source used for all the MERLIN and
Figure 1. Upper panel: The MERLIN image of 3C459 at 408 MHz with an angular resolution of 0.62 arcsec. Peak brightness: 4436 mJy/beam; Contour levels: 3×(−1, 1, 2, 4, 8 ... ) mJy/beam. Middle panel: The VLA image at 4885 MHz with a resolution of 0.50 arcsec. Peak brightness: 382 mJy/beam; Contour levels: 0.25×(−1, 1, 2, 4, 8 ... ) mJy/beam. Polarization: 1 arcsec = 25 mJy/beam. Lower panel: The spectral index distribution between 408 and 4885 MHz made by convolving the VLA image to a resolution of 0.62
EVN observations except that at 408 MHz was B2318+049. Its position, obtained from the IERS93 list of VLBI calibrators, is J2000 $23^h 20^m 44.s85661 +053^\circ 49.749529$. An optical continuum WFPC2 image (Filter F702W) has been retrieved from the HST archive to provide a high resolution comparison between the radio and optical emission.

2.1 MERLIN 408 MHz Observation

The 408 MHz observation of 3C459 was made on 1987 October 29, i.e. during the period of upgrade of the original MERLIN (Thomasson 1986) when, with microwave links to Cambridge newly installed, it was possible to use one of the 18m `one-mile' synthesis telescopes at Cambridge with the original network and correlator prior to the completion of the new 32m antenna. As the original correlator could only be used to correlate data from 6 telescopes at that time because of a fault, the Lovell and Wardle telescopes, with their greater sensitivity at 408 MHz, were included in the network in preference to the somewhat similarly located Mk2 and Darnhall telescopes. The observing bandwidth was 5 MHz centred at 408 MHz and the polarization was limited to a single one (LL) by the frequency-modulated microwave link. Phase-referenced observations were not possible using the Cambridge 18m telescope and so 3C459 was simply followed approximately the period of time that it was above the horizon (~11 hrs.). In processing the data using the Jodrell Bank OLAF and NRAO AIPS packages, small corrections were made for the sky background temperatures using the 408 MHz all-sky survey of Haslam et al. (1982). The final 408 MHz image is shown in Figure 1. Since the observations were made without reference to a source of known position, the absolute position could not be determined from these observations. However, the positions shown in Figure 1 have been established from a comparison of the mean positions of the core and eastern lobes with that of the VLA image at 5 GHz at the same resolution.

2.2 MERLIN L-Band Observations

As indicated above, the uv coverage of MERLIN for a single frequency full-track observation of 3C459 is rather poor with quite large gaps. In an attempt to improve this at L-Band frequencies, 3C459 was observed with MERLIN at two L-Band frequencies, 1420 MHz and 1658 MHz. The observing frequency was switched between the two frequencies every 5.5 minutes with a total cycle time, including the time on the phase reference source, of 11 minutes. The source and its phase reference were observed for a total of ~10 hours in all four polarisations (LL, LR, RL and RR) with all the MERLIN telescopes included in the array. This resulted in a total of ~3 hours actual on-source time at each frequency. Lovell telescope drive restrictions and the very slow maximum speed of the Wardle telescope meant that these two telescopes were only moved to the phase reference source approximately every half hour. The changes in phase of the signals from these two telescopes during this half hour period were effectively tracked by comparison with the phase changes of the `nearby' Mk2 and Darnhall telescopes respectively. All the data were processed using the Jodrell Bank D-programmes (for the initial editing and calibration) and the MERLIN pipeline, which uses AIPS tasks, to produce initial images of 3C459 at the two frequencies. The 1420 MHz data amplitudes were then scaled to those of the 1658 MHz data with appropriate scaling factors based upon the relative amplitudes of the source at the same resolution at the two frequencies. Final total power and polarization images of 3C459 at a nominal frequency of 1658 MHz were produced (Figure 2) using the self-calibration and imaging routines in AIPS.

2.3 C-Band Observations

2.3.1 VLA A-array Observations

The calibrated VLA A-array data at 4885 MHz, kindly made available by Ulvestad, resulted from an observation on 1983 September 8. These data were further edited and a new 0.5 arcsecond resolution image produced using the self-calibration and IMAGR tasks in AIPS. Our final image, which shows rather more of the extended emission than that in the original map of Ulvestad, is shown in Figure 1.

2.3.2 MERLIN Observations

3C459 was observed with MERLIN at 4993 MHz on 1992 July 19 and, to improve the UV coverage, at 4546 MHz, 4866 MHz and 5186 MHz on 1995 July 2. The telescopes configured in the array are given in Table 1. A somewhat similar cycle to that at L-Band was used for switching round the three frequencies and between 3C459 and its phase reference source on July 2. This resulted in ~6 minutes on source integration at each frequency per half hour of elapsed time. For the full observation of ~11 hours, the integration time on 3C459 at each frequency was ~2.75 hours. The on-source integration time for the 4993 MHz observation was ~7.75 hours. As for the L-Band data processing, images of 3C459 were made at the same resolution at each of the four frequencies using the D-programmes for editing and calibration and the MERLIN pipeline and the AIPS self-calibration and IMAGR tasks for the imaging. The data at the four different frequencies were then combined together correcting for source spectral index with appropriate scaling factors based upon the relative amplitudes of the unresolved core of the source in the preliminary images. Finally, the VLA data were combined with the MERLIN data to yield the final maps at a resolution of 0.07 arcseconds shown in Figure 3.

2.3.3 EVN Observations

A MERLIN+EVN observation of 3C459 was made at 4988 MHz on 1995 May 24. The telescopes included in the EVN are given in Table 1. Only one polarisation was recorded, LL, and the bandwidth was 28 MHz. The Cambridge telescope was originally included in the system, but unfortunately this failed and thus left a significant gap between the MERLIN and EVN UV coverage. Consequently, only an EVN map of the core region has been produced. The data were correlated in Bonn and further processed using the standard AIPS VLBI calibration, fringe fitting and imaging routines. The calibration sources used were 0552+398 and 0Q208, though the flux scale was established from receiver noise measurements. After initial calibration, the phase reference
source, 2318+049, was imaged using the standard AIPS self-calibration and IMAGR routines. It was found to be only slightly resolved. The data for 3C459 were corrected for the telescope amplitude and phase variations determined from the phase-reference source and an image of the core region of 3C459 at a resolution of 6 mas was produced (de Vries et al. 1999). The image was further processed using standard routines in IRAF and a FITS file produced. This was read into AIPS and the image re-gridded to be the same as the MERLIN + VLBI C-Band image. The image is shown in Figure 5.

3 DISCUSSION

Some of the observational parameters and observed values from the radio observations are summarised in Table 2. This table is arranged as follows. Column 1: telescope used for the observations; column 2: observing frequency in MHz; column 3: the angular resolution in arcsec; column 4: the rms noise in the image in units of mJy/beam; column 5: component designation, with a superscript \( g \) indicating that the values in columns 6 to 9 have been estimated by a fitting a two-dimensional Gaussian; columns 6 and 7: the right ascension and declination of the peak of emission of the component in J2000 co-ordinates; columns 8 and 9: the peak and total flux density of the component in units of mJy/beam and mJy respectively; column 9: the degree of polarization of the component estimated by integrating the polarized- and total-intensity images over identical boxes around each component for the extended lobes. The values for the central compact components are at the pixels of maximum brightness.

3.1 The overall radio structure

The MERLIN image of 3C459 at 408 MHz with an angular resolution of 0.62 arcsec is more strongly polarized with the peak in the hotspot being 13.3% polarized. The tail of emission from the western hotspot is the most strongly polarized feature with typical values ranging from ~25 to 30%. The low rotation measure (U85), suggests that the magnetic field lines are along this feature, similar to those seen in the jets of FRII radio sources. There is no significant polarization detected from the central component, the percentage polarization, \( m \), at the total-intensity peak being <0.1%. The eastern lobe is weakly polarized with \( m <0.2\% \) at the total-intensity peak, but there are regions of emission which are up to ~5 and 2% polarized to the north and east respectively of the peak.

The spectral index of the western lobe is ~ −0.9 near the peak of emission and varies between approximately −0.8 and −0.9 along the ridge of emission extending eastwards. The central component has a spectral index of −0.6 near its peak, while the eastern lobe has the steepest spectrum with \( \alpha \sim −1.2 \) in the central region and steepening to ~ −1.6 in the northern and southern ends of the lobe. The marginally flatter regions with \( \alpha \sim −1.1 \) towards the north and south of the total-intensity peak in the eastern lobe are close to the regions of higher brightness seen in the higher-resolution images. However, the prominent hotspot seen in the higher-resolution image has \( \alpha \sim −1.2 \). U85 also find the eastern component to have a steeper spectrum than the western one, the average values of \( \alpha \) being −1.4 and −0.95 respectively. Our values are somewhat smaller, suggesting a steepening of the spectrum towards higher frequencies. However, there is no evidence of a spectral index as steep as −1.65 between the central component and the eastern lobe as noted by U85.

The MERLIN image at 1658 MHz which has an angular resolution of 0.225 arcsec (Figure 2) reveals greater details of the structure. A two-dimensional Gaussian fit to the central component shows it to be extended along a PA of 100°, while the extension towards the south-east is along a PA of ~110°. The western component contains a curved high-brightness region of emission at the outer edge with the field lines also appearing to follow the bend. In addition there are two peaks along the ridge of emission pointing towards the central component. The polarization vectors are consistent with the low integrated value of RM and also the low value of RM estimated for this lobe by U85.

One of the striking features of the image at 1658 MHz is the shell-like structure of the eastern component where the central region of the lobe is of lower surface brightness than the surrounding features. The 4866 MHz image with an angular resolution of 70 mas, which has been made by combining the MERLIN and VLA data (Figure 3), shows greater details of the eastern lobe with several distinct components surrounding the region of lower surface brightness. The peak of emission on the western side of the eastern lobe at RA 23° 16′ 45.25, Dec 04° 05′ 18.34 has a narrow-elongated ridge of emission which would meet Bridle & Perley’s (1984) criterion of being called a jet. This feature, which we identify as part of a radio jet, points directly at the eastern hot-spot which is the brightest component in the eastern lobe. This jet also appears to be present outside of the shell and to be connected to the core region. The two other peaks of emission in the lobe north and south of the hotspot and the jet are likely to be secondary hot-spots caused by outflow from the prominent one. The image of the western lobe at 4866 MHz shows the hotspot to have a C-shaped structure,
Table 2. Observational parameters and observed properties

| Telescope | Freq. MHz | Resn. | σ | Cmp | RA(J2000) h m s | Dec(J2000) ° ′ ″ | S_p mJy/beam | S_t mJy | % |
|-----------|-----------|-------|---|-----|-----------------|-----------------|------------|--------|---|
| MERLIN    | 408       | 0.620 | 1.05 | W   | 23 16 34.73     | 04 05 19.05     | 1019       | 2650   |   |
|           |           |       |     | C^g | 35.19           | 18.43           | 1564       | 2220   |   |
| VLA       | 4885      | 0.500 | 0.08 | W   | 23 16 34.73     | 04 05 18.97     | 96         | 265    | 17.8|
|           |           |       |     | C^g | 35.19           | 18.43           | 381        | 392    | <0.2|
| MERLIN    | 1658      | 0.225 | 0.22 | W   | 23 16 34.73     | 04 05 18.84     | 126        | 723    | 13.0|
|           |           |       |     | C^g | 35.20           | 18.31           | 775        | 873    | ~0.4 |
| MERLIN+   | 4866      | 0.070 | 0.07 | W   | 23 16 34.73     | 04 05 18.81     | 9.4        | 300    | 20.0|
| VLA       |           |       |     | C^g | 35.19           | 18.31           | 390        | 413    | ~0.3 |
| EVN-VLBI  | 4987      | 0.006 | 0.18 | C^g | 35.1942         | 04 05 18.446    | 25         | 55     |     |
|           |           |       |     | C1^g| 35.1944         | 18.438          | 75         | 127    |     |
|           |           |       |     | C1C^g| 35.1949       | 18.435          | 84         | 132    |     |
|           |           |       |     | C1D^g| 35.1960       | 18.437          | 10         | 23     |     |

Figure 2. The MERLIN images of 3C459 at 1658 MHz with an angular resolution of 225 mas. The upper panel shows the total-intensity image while the lower one shows the polarization E-vectors superimposed on the total intensity contours. Peak brightness = 769 mJy/beam; Contours = 0.66 × (−1, 1, 2, 4, 8 . . .) mJy/beam. Polarization: 1 arcsec = 11.1 mJy/beam.
Figure 3. The MERLIN images of 3C459 at 4866 MHz with an angular resolution of 70 mas. The total-intensity image is shown in the upper panel, while the lower panel shows the components with the polarization E-vectors superimposed on the total intensity contours. Peak brightness: 391 mJy/beam; Contours: $0.29 \times (-1, 1, 2, 4, 6, 8, 10 \ldots 36, 38, 40)$ mJy/beam. Polarization: 1 arcsec = 5 mJy/beam.

with the field lines following the curvature. The field lines are possibly sheared to follow the direction of fluid flows, suggesting that the hotspot structure is caused by outflows from the point of impact of the jet from the nucleus.

Hydrodynamic simulations of light, large-scale jets in a decreasing density profile, which have also been examined by Carvalho & O’Dea (2002), show that the jet bow shock undergoes two phases, firstly a nearly spherical one and secondly the well-known cigar-shaped one (Krause 2002; Krause & Camenzind 2002). The shell-like structure of the eastern lobe is suggestive of the first phase of the development of the bow-shock. In this scenario, the eastern jet has not yet entered the cigar phase and deposits its radio-emitting plasma in a bigger part of the bubble, almost filling the region within the bounds of the bow shock. On the other hand, the western jet appears to be in the cigar phase, and should therefore have a fairly regular backflow around it, which flows back into the central parts diffusing and mixing with the shocked external gas.

In the highest resolution image at 5 GHz, the peak in the hotspot in the western lobe is $\sim 18\%$ polarized, while the corresponding feature in the eastern lobe is $<2\%$ polarized. Besides the asymmetry in the location and brightness of the outer components, another striking feature of this source is the polarization asymmetry. Since the images with radio polarization information are of very different resolutions, it is not possible to derive reliable values of depolarization. However, it is clear that the western lobe is only slightly depolarized between 5 and 1.7 GHz, while the eastern lobe is strongly depolarized by $\sim 5$ GHz. 3C459 is consistent with the Liu-Pooley relationship (Liu & Pooley 1991), which shows that the radio lobe with a flatter radio spectrum is less depolarized. This relationship is significantly stronger for smaller sources, but is similar for both radio galaxies and quasars suggesting that in addition to Doppler effects there are intrinsic differences between the lobes on opposite sides (cf. Ishwara-Chandra et al. 2001). Assuming that the extension of the core towards the south-east and the jet-like feature within the lobe defines the jet direction to be towards the east, 3C459 is not consistent with the Laing-Garrington effect (Laing 1988; Garrington et al. 1988). This is not surprising if the external environment is very asymmetric with the eastern jet interacting with dense gas which slows down the jet and also depolarizes the radio emission.
It is also to be noted that in the 1658-MHz image there is a possible indication of a jet-like structure pointing towards the western lobe from the core.

3.2 The central component

The central component is clearly resolved into two distinct components with a separation of \( \sim200 \) mas along a PA of 110\(^\circ\). The dominant component (C1) is more compact with a deconvolved size of 23\(\times\)9 mas along a PA of 117\(^\circ\) compared with 130\(\times\)55 mas along a PA of 108\(^\circ\) for the weaker one (C2). The peak brightness of C1 is also higher than that of C2 by \( \sim5 \), and perhaps contains the true nucleus or radio core of this galaxy. As noted earlier, the overall spectrum of the central component is steep between 400 and 5000 MHz with a spectral index of \( \sim0.6 \). Since the stronger component, namely C1, dominates the flux density of the entire central component seen in the lower-resolution images, C1 must have a steep spectral index although multifrequency, high-resolution data are not available to determine the spectral indices of C1 and C2 separately.

The EVN image of the dominant central component, C1, (Figure 4) shows a rather complex structure with at least four components along a strongly curved ridge of emission. The components are within a factor of 5 in brightness, and it is not clear which, if any of these components, represents the true nucleus of the galaxy. If the jet is one-sided, as in most high-luminosity radio sources, then the northernmost component could be the true nucleus of the galaxy. Multifrequency data with similar resolution would be required to confirm this possibility. However, if this is the case, the jet swings from an initial PA of 165\(^\circ\) to \( \sim120\)^\(^\circ\), defined by the two prominent peaks, and later to \( \sim80\)^\(^\circ\). Considering that C2 is at PA of 110\(^\circ\) and then goes northwards, the jet appears to have a helical structure. No emission was detected in the VLBI image at the position of C2.

3.3 The HST image and comparison with the radio image

The HST image of 3C459 using the F702W filter is shown in Figure 5. Its position has been determined by aligning the dominant nucleus of this N-galaxy with the core component, C1, seen in the MERLIN+VLA image (Figure 3). In addition to the nucleus, there is a prominent secondary peak east of the nucleus at RA 23\(^h\)\ 16\(^m\) 35.233, Dec 04\(^h\) 05\(^m\) 18.22, and a filamentary structure extending from near this peak towards the east. A less prominent filamentary structure is also seen extending north at \( \sim RA \) 23\(^h\)\ 16\(^m\) 35.22, Dec 04\(^h\) 05\(^m\) 18.8, and there are also other weaker peaks of emission in the HST image. The secondary peak is separated from the nucleus by 575 mas along a PA of 90\(^\circ\). Although this lies well beyond the weaker radio component in the nucleus, C2, and does not correspond to any obvious feature in the radio image, it could affect the path of the jet (Figure 6). The eastern filament, skirts the lower end of the eastern radio lobe.

A ground-based V-band image of 3C459 with the CTIO 4m telescope shows filamentary or ‘fanlike protrusion’ extending \( \sim8^\prime \) to the east and a similar but more knotty feature towards the south (Heckman et al. 1986). Long-slit spectroscopic observations along and perpendicular to the radio source axis and passing through the east and south fans show the emission line gas to be fairly compact. This led Heckman et al. to suggest that the fans are continuum-emitting structures. There are no other galaxies nearby with which it could be interacting, suggesting that if these morphological peculiarities are indeed of tidal origin 3C459 could be a case of a merger which has nearly reached completion. The secondary peak of emission seen in the HST image could be the merging galaxy buried in the debris. The possibility that gravitational interactions between galaxies might trigger nuclear activity has had a long lineage (e.g. Baade & Minkowski 1954; Toomre & Toomre 1972; Quinn 1984; Hernquist & Mihos 1995), and 3C459 with its optical morphology, high infrared luminosity, young stellar population, a highly asymmetric double-lobed FRII radio structure is possibly an archetypal example to illustrate this process and to be used to investigate further the relationship between nuclear and starburst activity.

3.4 Comparison with other sources

3C459 is clearly one of the most asymmetric sources with the ratio of separations of the outer hotspots, \( r_D \) defined to be >1, being \( \sim5 \) and the corresponding flux density ratio, \( r_S \), of the oppositely-directed lobes being \( \sim0.45 \) and 0.3 at 5 and 1.7 GHz respectively. From the compilation of symmetry parameters of high-luminosity 3CR and S4 sources (Saikia et al. 2001), there are only two objects with a separation ratio >4, namely 3C254 and the compact steep-spectrum source B0428+205. 3C254 is associated with a quasar at a redshift of 0.734 with \( r_D=6.95 \) and \( r_S=0.77 \) (Owen & Puschell 1984; Thomasson et al., in preparation). Optical line and continuum imaging of this source shows an extended emission-line region with the lobe on the nearer side interacting with a cloud of gas (Bremer 1997; Crawford & Vanderreet 1997). Although the flux density of the nearer lobe is brighter, the ratio is modest, which could be a consequence of relativistic
beaming of the hotspot further from the nucleus. The CSS object B0428+205 which has a largest angular size of only 250 mas, is associated with a galaxy at a redshift of 0.219 with $r_D=4.69$ and $r_S=0.16$ (Dallacasa et al. 1995), consistent with a high dissipation of energy on the side where the jet interacts with a dense cloud. Another example of a source with such a high degree of positional asymmetry is the quasar 3C2 at a redshift of 1.037 for which $r_D=4.7$ and $r_S \sim 0.25$ (Saikia, Salter & Muxlow 1987). There is a sign of a radio jet extending from the core to the northern lobe. Depolarization gradients in both the lobes suggest interaction with the external medium, but the northern lobe seems to be more significantly affected.

In the compilation of McCarthy, van Breugel & Kapahi (1991), there are only four galaxies with $r_D > 4$, namely, 3C99, 3C208.1, 3C459 and 3C460. All these sources exhibit a large asymmetry in their flux density ratio, with the brighter lobe being closer to the nucleus. In the case of 3C460, where they detect significant extended emission line gas, the surface brightness of this gas is much higher on the side of the lobe closer to the nucleus. The radio galaxy 3C99 is similar to 3C459 in that it also has a steep-spectrum radio core which was resolved by the EVN and shows multiple components. Its value of $r_D=4.8$ while $r_S \sim 0.04$ and 0.03 at 5 and 1.7 GHz respectively, is consistent with the possibility that the jet on the side of the nearer lobe is interacting with denser gas. Optical spectroscopic observations along the axis of the source does indeed show that the gas on the side of the nearer component is blue-shifted while that on the opposite side is red-shifted relative to the galaxy. The blue-shifted gas is possibly approaching us, shifted outwards by interaction with the radio jet (Mantovani et al. 1990).

4 CONCLUDING REMARKS

The radio galaxy, 3C459, with its young stellar population and high infrared luminosity may have undergone a recent starburst, possibly triggered by the merging of a companion galaxy. The HST image presented here shows evidence of filamentary structures, which are possibly of tidal origin, and a prominent peak of emission close to that of the nucleus of this N-galaxy, which could be due to galaxy in the late stages of merging. The multifrequency radio observations using MERLIN, VLA and the EVN, clarify the small- and large-scale structure of the source, which is highly asymmetric. The eastern component, which is brighter, closer to the nucleus and more strongly depolarized is interacting with denser gas, possibly related to the merging process. This lobe has a shell-like structure with a prominent hotspot and two secondary peaks of emission. The MERLIN and EVN observations show the central component to consist of several sub-components whose orientations are suggestive of a helical or strongly bent jet. However, we have not been able to identify a flat-spectrum radio core from these observations. It may be possible to do this with multifrequency, mas-resolution observations. 3C459 is an archetypal example of a high-luminosity, compact steep-spectrum radio galaxy exhibiting evidence of a starburst. Identification of a larger sample of such objects could enhance our understanding of the relationship between these two forms of activity.

Figure 5. The HST image of 3C459 using the F702W filter. The contour levels are $2.799 \times 10^{-18} \times (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20, 40, 80, 160, 320, 640) \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$, while the peak value is $8.327 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$.

Figure 6. The MERLIN image of the central and eastern components at 4866 MHz with an angular resolution of 70 mas superimposed on the HST image show in grey scale. The contour levels for the radio image are the same as in Figure 3.
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