Radio structures of the nuclei of nearby Seyfert galaxies and the nature of the missing diffuse emission

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ABSTRACT

We present archival high-spatial-resolution VLA and VLBA data of the nuclei of seven of the nearest and brightest Seyfert galaxies in the Southern Hemisphere. At VLA resolution (∼0.1 arcsec), the nuclei of the Seyfert galaxies are unresolved, with the exception of MCG-5-23-16 and NGC 7469, which show a core–jet structure. Three Seyfert nuclei are surrounded by diffuse radio emission related to star-forming regions. VLBA observations with parsec-scale resolution demonstrate that in MRK 1239 the nucleus is clearly resolved into two components separated by ∼30 pc, whereas the nucleus of NGC 3783 is unresolved. Further comparison between VLA and VLBA data of these two sources shows that the flux density at parsec scales is only 20 per cent of that measured by the VLA. This suggests that the radio emission is not concentrated in a single central component, as in elliptical radio galaxies, and an additional low-surface-brightness component must be present. A comparison of Seyfert nuclei with different radio spectra shows that the ‘presence’ of undetected flux on a milliarcsecond scale is common in steep-spectrum objects, whereas in flat-spectrum objects essentially all the radio emission is recovered. In the steep-spectrum objects, this ‘missing’ flux probably results from non-thermal radiation related to active galactic nuclei, perhaps from a jet that is disrupted in Seyfert galaxies because of the denser environment of their spiral hosts.

Key words: galaxies: active – galaxies: Seyfert – radio continuum: general.

1 INTRODUCTION

Only a small fraction (∼10 per cent) of the population of active galactic nuclei (AGN) display a powerful radio emission ($L_{\text{1.4GHz}} > 10^{23}$ W Hz$^{-1}$), as found in radio galaxies/quasars and blazars. Seyfert galaxies are part of the ‘radio-quiet’ AGN population, with radio luminosity $L_{\text{1.4GHz}} \leq 10^{20–23}$ W Hz$^{-1}$. Despite their weak radio emission, Seyfert nuclei are very near, meaning that we can study the radio properties of their central engine in detail.

Radio observations with arcsecond resolution of several Seyfert samples (see e.g. Ulvestad & Wilson 1984; Morganti et al. 1999; Thean et al. 2000) have shown that a large fraction of Seyferts have resolved structures, with hints of jets and/or extended emission, the latter usually related to star-forming regions. Several objects, such as NGC 1052 (Wrobel 1984), NGC 1068 (Ulvestad, Neff & Wilson 1987), NGC 7674 (Momjian et al. 2003) and MRK 3 (Kukula et al. 1999), have been found to display a radio morphology, with a core, collimated jets and hot spots similar to those found in radio-loud galaxies. However, powerful radio sources have linear structures on scales of hundreds of kiloparsecs or even megaparsecs, whereas in Seyferts the radio emission is confined to scales of a few kiloparsecs or even subkiloparsec scales.

When observed with milliarcsecond resolution, the parsec-scale structure of Seyfert nuclei is usually resolved into several components (e.g. NGC 3079, Trotter et al. 1998), resembling a jet structure (e.g. NGC 4151, Ulvestad et al. 1998; Nagar, Wilson & Falcke 2001), and sometimes with the presence of extended emission (e.g. NGC 5793, Hagiwara et al. 2000). A comparison between arcsecond and milliarcsecond radio properties reveals a frequent misalignment between parsec- and kiloparsec-scale jets, suggesting either a change in jet ejection axis or a bending caused by pressure gradients in the ambient medium (Middelberg et al. 2004).

An intriguing characteristic of a large number of Seyfert nuclei is that the radio emission arising from their parsec-scale structure is often much fainter than that derived from observations with lower resolution, even if the nucleus is unresolved. This suggests that in Seyfert nuclei the radio emission is not concentrated in the central region, as found in powerful radio galaxies, but rather extends on scales of tens or hundreds of parsecs (see e.g. Sadler et al. 1995). However, not all Seyfert nuclei have missing flux on parsec scales, as in the case of MRK 530 (Lal, Shastri & Gabuzda 2004), indicating that the radio emission arises mainly from the central compact...
component, without evidence of extended, low-surface-brightness features.

In this paper, we present the results of multi-frequency archival VLA and/or VLBA data for a sample of some of the nearest and brightest Seyfert galaxies, taken from the infrared high-spatial-resolution studies conducted by Prieto et al. (2009) and Reunanen, Prieto & Siebenmorgen (2009). For these sources, no complete and/or unambiguous information on their radio properties could be found in the literature. A comparison between these data and those at parsec-scale resolution available from the literature allows a better determination of the physical conditions of the radio emission at kiloparsec and parsec scales.

Throughout this paper, we assume the following cosmology: \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.27 \) and \( \Omega_k = 0.73 \), in a flat universe. The spectral index is defined as \( S(\nu) \propto \nu^{-\alpha} \).

2 THE SAMPLE

The objects studied in this paper are from the sample of Seyfert nuclei obtained by Prieto et al. (2009) and Reunanen et al. (2009). They consist of the nearest and brightest Seyfert nuclei accessible from the Southern Hemisphere. The proximity of these objects allows us to study them at scales of a few tens of parsecs in the infrared with the VLT, which provides adaptive optics and interferometry that deliver spatial resolution comparable to that achieved in the optical with the HST, and in radio with the VLA and VLBI. In Fig. 1 we present VLT-VISIR images at 11.8 \( \mu \text{m} \) of the Seyferts studied in this paper. Details on VISIR observations and data reduction can be found in Reunanen et al. (2009). The dominant infrared (IR) emission comes from the central nucleus, which is unresolved with full width at half maximum (FWHM) \( < 0.35 \) arcsec, which corresponds to linear sizes between 30 and 190 pc, depending on the redshift.

High-spatial-resolution spectral energy distributions (SEDs) have been produced for these objects. For the majority of the Seyferts considered, multifrequency, high-resolution information in the radio band has not been fully exploited. For this reason, we collected and analysed archival radio data with subarcsecond resolution in order to supplement the information already available and to constrain the radio emission from these nuclei.

The list of the Seyfert nuclei studied in this paper is given in Table 1. We considered only data sets at frequencies and resolutions not available in the literature, or for which no unambiguous information could be found.

2.1 Radio properties of the selected sources

2.1.1 NGC 1097

NGC 1097 is a barred spiral galaxy hosting a Seyfert 1 nucleus (Storchi-Bergmann, Baldwin & Wilson 1993). The radio emission is dominated by a ring-like structure related to star-forming regions also detected in the optical. At the centre of the ring there is an unresolved (beam \( \sim 0.3 \) arcsec at 8.4 GHz) component (Thean et al. 2000) with an inverted non-thermal spectrum (Morganti et al. 1999). The radio core was observed by Sadler et al. (1995) with the Parkes–Tidbinbilla interferometer (PTI), which provides a resolution of \( < 0.1 \) arcsec. No radio emission was detected, implying that the core flux density is \( < 5 \) mJy at 2.3 GHz.

2.1.2 MCG-5-23-16

MCG-5-23-16 is an S0 galaxy hosting a Seyfert 2 nucleus. Its radio properties were studied by Ulvestad & Wilson (1984) with VLA observations at 1.4 and 4.8 GHz. The radio structure of the nucleus is slightly resolved (beam \( \sim 0.4 \) arcsec at 4.8 GHz) with a spectral index \( \alpha \sim 0.5 \). No evidence of extra-nuclear emission was detected. High-spatial-resolution (beam \( \sim 0.1 \) arcsec) observations with the PTI (Sadler et al. 1995) could set only an upper limit to the flux density of the core, namely \( S_{0.4 \text{GHz}} < 7 \) mJy.

2.1.3 MRK 1239

MRK 1239 is an early-type E/S0 galaxy hosting a Seyfert 1.5 nucleus. Its central radio structure was studied by Ulvestad, Antonucci & Goodrich (1995) and Rush, Malkan & Edelson (1996) with the VLA. The source appears unresolved at all frequencies (beam \( \sim 0.2 \) arcsec at 8.4 GHz) without evidence of extended emission surrounding the nucleus. Ulvestad et al. (1995) noted a strong steepness in the radio spectrum between 4.8 and 8.4 GHz (\( \alpha \sim 1.6 \)), which they interpreted as resulting from flux variability (observations were not carried out simultaneously).

2.1.4 NGC 3783

NGC 3783 is a barred spiral galaxy with a highly variable Seyfert 1 nucleus. Multi-frequency radio VLA observations by Ulvestad & Wilson (1984), Unger et al. (1986) and Schmitt et al. (2001) revealed the presence of an unresolved component (beam \( \sim 0.25 \) arcsec at 8.4 GHz) with a spectral index \( \alpha \sim 0.5 \). No extended extra-nuclear emission was found. High-spatial-resolution (beam \( < 0.1 \) arcsec) observations with the PTI (Sadler et al. 1995) could set only an upper limit to the flux density of the core, namely \( S_{1.6 \text{GHz}} < 6 \) mJy.

2.1.5 NGC 5506

NGC 5506 is a spiral galaxy with a Seyfert 2 nucleus. The central radio structure was studied by Ulvestad, Wilson & Sramek (1981) and Unger et al. (1986) with VLA and MERLIN observations. It shows a diffuse bubble-like feature extending to the north-west of the unresolved nucleus. At 5 GHz, Wehrle & Morris (1987) found a low-surface-brightness halo enshrouding the central structures.

Multifrequency observations of the nucleus with the PTI (Sadler et al. 1995) showed that it has a convex spectrum. Parsec-scale VLBI observations at 18, 6 and 3.6 cm (Middelberg et al. 2004) resolved the nucleus into three main components roughly aligned in the east–west direction and extending within an area of about 50 mas (~ 6 pc). The flattish spectrum displayed by the brightest component suggests that it is the true source core.

2.1.6 NGC 7469

NGC 7469 is a spiral galaxy with a Seyfert 1 nucleus embedded in a ring of starburst activity. At radio frequencies, its structure shows an unresolved central component surrounded by a ring of star-forming regions (Wilson et al. 1991). MERLIN observations with high spatial resolution (beam \( \sim 0.05 \) arcsec) showed that the nucleus is clearly resolved into two components, namely a core–jet structure elongated in the east–west direction. VLBI observations (beam \( \sim 10 \) mas) at 1.6 GHz (Lonsdale et al. 2003) resolved the...
Figure 1. VLT-VISIR images at 11.8 \( \mu \)m of the Seyfert nuclei studied in this paper. Images adapted from Reunanen et al. (2009). Contours are at 3, 5, 7, 11 and 19\( \sigma \) levels. The quadrant in NGC 7582 represents the ionization cone.

core–jet structure into five different components, lying in an east–west line, as found in the lower-resolution MERLIN image, and contained within an area of about 168 mas (~55 pc).

2.1.7 NGC 7582

NGC 7582 is a barred spiral galaxy hosting a Seyfert 2 nucleus surrounded by a star-forming ring. Its radio structure shows an unresolved central component embedded in a diffuse emission related to the star-forming region also detected in the optical (Ulvestad & Wilson 1984). The extended emission is elongated in the NW–SE direction, with a spectral index \( \alpha \sim 0.7 \) (Morganti et al. 1999). High-spatial-resolution (beam <0.1 arcsec) observations with the PTI (Sadler et al. 1995) could set only an upper limit to the flux density of the core, namely \( S_{8.4\,\text{GHz}} < 5 \) mJy.

3 NEW RADIO DATA

Archival VLA/VLBA radio data from the aforementioned sample were analysed in order to supplement the information available in the literature. To achieve an adequate spatial resolution to resolve the nuclear structure, we considered observations carried out when the VLA was in one of the extended configurations (array A or B) at frequencies ranging between 1.4 and 14.9 GHz, when available. We considered data sets either at frequencies lacking...
Table 1. The Seyfert sample. Column 1, source name; column 2, type; column 3, redshift; column 4, luminosity distance; column 5, scale.

| Source       | Type | z       | D_L  | kpc/arcsec |
|--------------|------|---------|------|------------|
| NGC 1097     | 1    | 0.00424 | 18.0 | 0.086      |
| MCG-5-23-16  | 2    | 0.008486| 36.1 | 0.172      |
| MRK 1239     | 1.5  | 0.02883 | 124.5| 0.570      |
| NGC 3783     | 1    | 0.009730| 41.4 | 0.197      |
| NGC 5506     | 2    | 0.006181| 26.2 | 0.126      |
| NGC 7469     | 1    | 0.016317| 69.8 | 0.328      |
| NGC 7582     | 2    | 0.005254| 22.3 | 0.107      |

information or for which data presented in the literature were found to be unsatisfactory.

The data reduction was carried out following the standard procedures for the VLA implemented in the NRAO AIPS package. Images were produced after a few phase-only calibration iterations. In order to obtain an accurate flux density at 1.4 GHz, it was necessary to image several confusing sources falling within the primary beam. Uncertainties in the determination of flux density are dominated by amplitude calibration errors, which are between 3 and 5 per cent, being worse at 14.9 GHz. The rms noise level (1σ) on the image plane is usually below 0.1 mJy, being irrelevant for our targets, with the exceptions of NGC 1097 and MCG-5-23-16 for which it is comparable to the amplitude calibration errors.

In the cases of NGC 1097, MRK 1239 and NGC 3783, for which no information on their parsec-scale structure could be found in the literature, we reduced archival VLBA data. No archival VLBA data were found for the sources MCG-5-23-16 and NGC 7582. The Seyfert nuclei considered in this paper are not bright enough to give detectable fringes. VLBI fringe-fitting was done on a bright source lying close to the target, and off-beam phase referencing was performed to calibrate the phases of the target source. In the case of NGC 1097, no signal of the source was detected. For MRK 1239 and NGC 3783, the structure was visible from the first image with a 4σ noise level. Phase self-calibration with a solution interval of 30 s was then performed using the CLEAN component model. After a few iterations we used natural weights to pick up possible extended emission. No amplitude calibration was performed owing to the weakness of the targets.

4 RESULTS

4.1 Radio images

Full-resolution VLA images of the sources discussed in this paper are presented in Figs 2 to 7. For NGC 7469 and NGC 7582, for which an extended diffuse emission is present around the central nucleus, an image without the shortest baselines was produced in order to describe better the compact components without contamination from the low-surface-brightness extended emission (Figs 6b and 7b). For MRK 1239 and NGC 3783, VLBA images at 1.6 GHz are presented in Figs 4(c) and 8 respectively.

Flux density and angular size were measured by means of the task IMFIT, which performs a Gaussian fit on the image plane. In the case of extended structures, the flux density was derived using TVSTAT, whereas the source size was measured from the lowest contour on the image plane. The nuclei of these Seyfert galaxies are unresolved or marginally resolved in VLA observations. We consider marginally resolved those nuclei whose largest angular size (LAS) is between 0.5 and 1 beam size at the best resolution, and we term unresolved those whose LAS is smaller than half of the beam.

Source parameters, together with information on the observations, are reported in Table 2. In Table 3, we present the observational parameters of the source components.

4.2 Notes on individual sources

In this section we describe the characteristics of the Seyfert nuclei arising from the new images presented in this paper.
Radio structures of the nuclei of nearby Seyfert galaxies

4.2.1 *NGC 1097*

The new images at 8.4 and 14.9 GHz are presented in Fig. 2, and have a resolution of $0.66 \times 0.25\text{arcsec}^2$ and $1.15 \times 0.45\text{arcsec}^2$, respectively. Fig. 2(a) shows for the first time the ring structure at 8.4 GHz. Four star-forming regions, labelled R1, R2, R3 and R4 in Fig. 2(a), are also present at 1.4 and 5 GHz (see e.g. Hummel, van der Hulst & Keel 1987). The central component appears unresolved in both the 8.4- and 14.9-GHz images, giving an upper limit to its linear size of <0.5 arcsec (<43 pc). The spectral index is found to be inverted between 1.4 and 14.9 GHz.

4.2.2 *MCG-5-23-16*

The VLA image at 8.4 GHz (Fig. 3), with a resolution of $0.43 \times 0.23\text{arcsec}^2$, is presented for the first time. The source is resolved in the north direction, suggesting the presence of a jet-like structure. The total radio spectrum shows a slight steepening at 8.4 GHz, with a spectral index $\alpha = 0.8 \pm 0.1$.

4.2.3 *MRK 1239*

New 14.9-GHz VLA and 1.6-GHz VLBA images are presented in Figs 4(b) and (c) with a resolution of $0.97 \times 0.42$ and $0.011 \times 0.004\text{arcsec}^2$, respectively. The central structure is unresolved in our VLA images at all frequencies, giving an upper limit to the linear size of <0.57 pc (Figs 4a and b). The spectral index we obtain is $\alpha \sim 0.9 \pm 0.1$, without any evidence of the steepening reported by Ulvestad et al. (1995) (see Section 2.1.3), and in better agreement with what was found by Rush et al. (1996). It is worth noting that...
Figure 5. VLA images at 4.8 GHz (top), 8.4 GHz (centre) and 14.9 GHz (bottom) of the central region of NGC 5506. For each image we provide the observing frequency; the restoring beam, plotted in the bottom left corner; the peak flux density in mJy beam$^{-1}$; and the first contour intensity (f.c. in mJy beam$^{-1}$), which is 3 times the off-source noise level. Contour levels increase by a factor of 2.

Figure 6. VLA images of the central region of NGC 7469 at 8.4 GHz (top), without the shortest baselines (centre), and at 14.9 GHz (bottom). For each image we provide the observing frequency; the restoring beam, plotted in the bottom left corner; the peak flux density in mJy beam$^{-1}$; and the first contour intensity (f.c. in mJy beam$^{-1}$), which is 3 times the off-source noise level. Contour levels increase by a factor of 2.
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data reported by Rush et al. (1996) refer to low-resolution observations carried out when the VLA was in the D configuration. The good agreement between these values and our measurements suggests that no extended emission on kiloparsec scales is present. When observed with parsec-scale resolution, the nucleus of MRK 1239 at 1.6 GHz is resolved into two components separated by \( \sim 50 \) mas (\( \sim 30 \) pc), with a position angle of 40\(^\circ\) (Fig. 4c). The lack of multifrequency observations with similar resolution prevents us from studying the spectral index of these components.

The flux density measured on the VLBA image at 1.6 GHz is 10.2 mJy, that is, only 20 per cent of the VLA flux density at 1.6 GHz, obtained by re-scaling the 1.4-GHz VLA flux density with the spectral index computed between 1.4 and 4.8 GHz (\( \alpha = 0.6 \)). This indicates that almost 80 per cent of the flux density measured with the VLA is missing in the VLBA image.

4.2.4 NGC 3783

The VLBA image at 1.6 GHz, with a resolution of 0.028 \( \times \) 0.008 arcsec\(^2\) (Fig. 8), is presented for the first time. In this image, the nucleus is unresolved, with a linear size <4 pc. The total flux density measured on the VLBA image is 4.6 mJy, which represents only 20 per cent of the flux density of the unresolved component in VLA observations (Unger et al. 1986). This indicates that the majority (\( \sim 80 \) per cent) of the flux measured with the VLA is missing in the VLBA image.

4.2.5 NGC 5506

New VLA images at 4.8 and 8.4 GHz, with resolutions of 0.48 \( \times \) 0.37 arcsec\(^2\) and 0.27 \( \times \) 0.20 arcsec\(^2\), respectively, are shown in Figs 5(a) and (b). The source displays an unresolved central component with a diffuse wing-like emission extending mainly to the north-west and east of the nucleus. The high dynamic range, namely the ratio between the peak flux density and the 1\( \sigma \) noise level, of our images allows detection also at 8.4 GHz of the extended low-surface-brightness halo (Figs 5a,b). The halo has a diameter of \( \sim 2.75 \) arcsec (\( \sim 350 \) pc), enshrouding the central features. The nucleus is unresolved in our VLA images, giving an upper limit of <0.08 arcsec (<10 pc). The nucleus accounts for the majority (75 per cent) of the radio emission. Its spectral index is \( \alpha = 0.8 \pm 0.1 \). The low-surface-brightness halo and the extended wing-like structures have a slightly steeper spectral index \( \alpha = 0.9 \pm 0.1 \).

A comparison between simultaneous MERLIN and EVN observations at 18 and 6 cm clearly indicates that almost 43 per cent of the flux density detected by MERLIN cannot be recovered in EVN images (Middelberg et al. 2004). In fact, a diffuse emission detected by MERLIN observations is not seen by the EVN, as the EVN is insensitive to structures larger than 35 and 11 mas at 18 and 6 cm, respectively.

4.2.6 NGC 7469

We produced a new VLA image at 8.4 GHz with a resolution of 0.2 \( \times \) 0.18 arcsec\(^2\) (Fig. 6b) that was obtained without the shortest (<35 k\( \lambda \)) baselines in order to pinpoint the compact central structure and to reduce the contamination from the surrounding ring. The radio emission is dominated by an unresolved central component surrounded by a ring of star-forming regions with a diameter of about 3.7 arcsec (\( \sim 1.2 \) kpc). In our new image at 14.9 GHz (Fig. 6c), the nucleus is elongated in the east–west direction. The spectral
Table 2. Radio observations and source parameters for the Seyfert galaxies. Column 1, source name; column 2, observing frequency; column 3, array configuration (Config.); column 4, beam size; column 5, observing date; column 6, flux density; column 7, luminosity (Log P); column 8, largest angular size (LAS); column 9, largest linear size (LLS); column 10, morphology of the nuclear component (Morph: Un, unresolved; MR, marginally resolved; double, two well-separated components); column 11, morphology of the extended structure, when present (Ext.).

| Source     | Frequency (GHz) | Config. | Beam (arcsec) | Obs. date  | Flux density (mJy) | Log P (W/Hz) | LAS (arcsec) | LLS (pc) | Morph. | Ext. |
|------------|-----------------|---------|---------------|------------|--------------------|--------------|--------------|----------|--------|------|
| NGC 1097   | 8.4             | A       | 0.66×0.25     | Oct 31 1992 | 30.0               | 21.04        | 18           | 1550     | Un     | Ring |
| NGC 1097   | 14.9            | B       | 1.15×0.45     | Feb 24 2001 | 5.0                | 20.30        | <0.5         | <48      | Un     | No   |
| MCG-5-23-16| 8.4             | A       | 0.43×0.23     | Aug 21 1999 | 2.6                | 20.60        | 1.2          | 206      | MR     | No   |
| MRK 1239   | 1.4             | A       | 1.54×1.25     | Jan 16 1993 | 60.0               | 23.04        | <0.3         | <171     | Un     | No   |
| MRK 1239   | 4.8             | A       | 0.46×0.40     | Jul 31 1987 | 27.0               | 22.60        | <0.1         | <57      | Un     | No   |
| MRK 1239   | 8.4             | A       | 0.33×0.26     | Jan 16 1993 | 15.0               | 22.44        | <0.1         | <57      | Un     | No   |
| MRK 1239   | 8.4             | A       | 0.26×0.22     | Jul 15 1995 | 14.5               | 22.44        | <0.1         | <57      | Un     | No   |
| MRK 1239   | 14.9            | B       | 0.97×0.42     | Dec 15 2003 | 9.0                | 22.22        | <0.2         | 114      | Un     | No   |
| MRK 1239   | 1.6             | VLBA    | 0.011×0.004   | May 09 2005 | 10.2               | 22.26        | 0.070        | 40       | Double | No   |
| NGC 3783   | 1.6             | VLBA    | 0.028×0.008   | Nov 30 1999 | 4.6                | 20.95        | 0.022        | 4.3      | Un     | No   |
| NGC 5506   | 1.4             | A       | 1.71×1.24     | Nov 06 2002 | 324.0              | 22.42        | 4.0          | 500      | Un     | Halo |
| NGC 5506   | 4.8             | A       | 0.48×0.37     | May 06 2002 | 181.6              | 22.11        | 4.2          | 530      | Un     | Halo |
| NGC 5506   | 8.4             | A       | 0.27×0.20     | Nov 14 2000 | 111.6              | 21.96        | 3.8          | 480      | Un     | Halo |
| NGC 5506   | 14.9            | B       | 0.72×0.43     | Dec 05 1991 | 65.0               | 21.72        | 3.3          | 415      | Un     | Halo |
| NGC 7469   | 8.4             | A       | 0.22×0.19     | Feb 05 2006 | 31.4               | 22.26        | 3.1          | 1200     | MR     | Ring |
| NGC 7469   | 14.9            | A       | 0.14×0.10     | Sep 08 1999 | 10.6               | 21.71        | 0.1          | 33       | MR     | No   |
| NGC 7582   | 4.8             | A       | 1.25×0.32     | Dec 12 2000 | 75.0               | 21.64        | 10           | 1070     | Un     | Ring |
| NGC 7582   | 8.4             | A       | 0.75×0.19     | Dec 12 2000 | 42.0               | 21.34        | 6           | 640      | Un     | Ring |

4.2.7 NGC 7582

We produced a new VLA image at 4.8 GHz with a resolution of 0.94 × 0.24 arcsec² (Fig. 7b), obtained without the shortest (<45 kλ) baselines in order to pinpoint the compact central structure and to reduce the contamination from the surrounding extended emission. The radio emission is dominated by an unresolved central component surrounded by diffuse emission related to star-forming regions (Fig. 7), also detected in the optical. The nucleus, with a spectral index α = 0.6 ± 0.1, is unresolved at all frequencies, giving an upper limit of about 0.4 arcsec (<40 pc) to its linear size. The extended emission has a maximum diameter of about 9 arcsec (~950 pc) and a spectral index α = 1.0 ± 0.1, which is steeper than the value (α = 0.7) found by Morganti et al. (1999). The discrepancy may arise from the different resolutions of the observations taken into account. Three compact regions, labelled R1, R2, R3 in Figs 7(a) and (b), are present in the diffuse emission at 4.8 GHz. For these clumps, near-infrared counterparts were found by Fernandez-Ontiveros (in preparation), which suggests that they are star-forming regions. Component R1 is visible also at 8.4 GHz, with a flux density of ~2.1 mJy and a spectral index of α = 0.9 ± 0.2, which is a little flatter than the spectral index of the whole extended emission.

5 DISCUSSION

5.1 The nuclear radio emission

In general, the nuclei of these Seyfert galaxies are unresolved at the resolution provided by the VLA in its larger configurations (A and B arrays), giving an upper limit to the linear size between about 20 and 120 pc. Only MCG-5-23-16 and NGC 7469 are marginally resolved at the highest resolution (FWHM ~ 0.2 arcsec). In both cases the central component is elongated, suggesting a core–jet morphology.

For all the sources we find that the spectral index of the nucleus ranges between 0.5 and 0.9, with the only exception being NGC 1097, for which the spectrum is inverted.

When observed with parsec-scale resolution, most sources display a resolved structure. This is the case for MRK 1239 (Fig. 4c), NGC 5506 (Middelberg et al. 2004) and NGC 7469 (Lonsdale et al. 2003). MRK 1239 shows a well-defined double morphology with a total linear size of 40 pc. The lack of multifrequency information prevents us from studying the spectral index distribution. NGC 5506 and NGC 7469 are characterized by several compact components resembling a core–jet structure. For NGC 5506, the availability of multifrequency observations singles out one of the components with a flat spectrum (Middelberg et al. 2004).

NGC 3783 is still unresolved at parsec-scale resolution (Fig. 8), and an upper limit to the linear size of 4 pc is estimated.

For the sources with VLBA information, MRK 1239, and NGC 3783, NGC 5506 and NGC 7469, estimates of the brightness temperature $T_B$, the equipartition magnetic field $H_{eq}$ and the minimum energy density $u_{min}$ are provided. We do not compute physical parameters for the sources unresolved in VLA images because no tight constraints on their values can be derived. To compute the physical parameters of MRK 1239 and NGC 3783 we make use of the values at 1.6 GHz reported in Table 3. For NGC 5506 and NGC 7469, we compute the physical parameters, making use of the values reported in Middelberg et al. (2004) and Lonsdale et al.
Table 3. Radio properties of the source components. Column 1, source name; column 2, source component—the name refers to the label as reported in Figs 2 to 8; column 3, observing frequency; column 4, flux density; columns 5 and 6, deconvolved major and minor axes.

| Source | Comp. | Freq. (GHz) | Flux (mJy) | \(\theta_{\text{max}}\) (arcsec) | \(\theta_{\text{min}}\) (arcsec) |
|--------|-------|-------------|------------|----------------------------------|---------------------------------|
| NGC 1097 | C | 8.4 | 4.0 | <0.5 | - |
| | C | 14.9 | 5.6 | <0.5 | - |
| | R1 | 8.4 | 1.8 | 0.9 | 0.7 |
| | R2 | 8.4 | 0.8 | 1.7 | 1.3 |
| | R3 | 8.4 | 0.6 | 1.6 | 0.8 |
| MCG-5-23-16 | A | 8.4 | 2.1 | <0.1 | - |
| | B | 8.4 | 0.5 | <0.1 | - |
| MRK 1239 | C | 1.4 | 60.0 | <0.3 | - |
| | C | 5.0 | 26.8 | <0.1 | - |
| | C | 8.4 | 15.5 | <0.1 | - |
| | C | 14.9 | 9.3 | <0.2 | - |
| | A\(^a\) | 1.6 | 6.0 | 0.013 | 0.006 |
| | B\(^a\) | 1.6 | 4.2 | 0.013 | 0.004 |
| NGC 3783 | C\(^a\) | 1.6 | 4.6 | 0.022 | 0.007 |
| NCG 5506 | C | 1.4 | 304.0 | <1.0 | - |
| | C | 4.8 | 136.0 | <0.1 | - |
| | C | 8.4 | 84.0 | <0.08 | - |
| | C | 14.9 | 58.0 | <0.2 | - |
| | Wing | 4.8 | 27 | 2.4 | 2.0 |
| | Wing | 8.4 | 16 | 2.2 | 1.7 |
| | Halo | 4.8 | 18 | 4.2 | 3.0 |
| | Halo | 8.4 | 3.8 | 3.2 | |
| NGC 7469 | C | 8.4 | 14.8 | <0.14 | - |
| | C | 14.9 | 10.6 | 0.1 | <0.05 |
| | R1 | 8.4 | 0.3 | 0.8 | 0.4 |
| | R2 | 8.4 | 0.6 | 0.9 | 0.7 |
| | R3 | 8.4 | 0.7 | 1.1 | 0.8 |
| NGC 7582 | C | 4.9 | 9.5 | 0.8 | <0.1 |
| | C | 8.4 | 6.9 | 0.4 | 0.2 |
| | R1 | 4.9 | 3.6 | 0.4 | 0.3 |
| | R2 | 8.4 | 2.1 | 0.3 | 0.3 |
| | R3 | 4.9 | 0.8 | 0.3 | <0.1 |
| | R3 | 4.9 | 1.1 | 0.5 | 0.3 |

\(^a\)Values derived on VLBA images.

(2003), respectively. The brightness temperature is computed from

\[
T_B = \frac{S(v)}{2k\theta_{\text{maj}}\theta_{\text{min}}} (\frac{C}{v})^2,
\]

where \(S(v)\) is the flux density at frequency \(v\), \(\theta_{\text{maj}}\) and \(\theta_{\text{min}}\) are the source major and minor axes, \(k\) is Boltzmann’s constant, and \(c\) is the speed of light. For the magnetic field and energy density we follow standard formulae (Pacholczyk 1970), assuming the equipartition condition between radiating particles and the magnetic field. The equipartition magnetic field is

\[
H_{\text{eq}} = \sqrt{\frac{124}{7\pi u_{\text{min}}} n_{\text{u}},}
\]

and the minimum energy density \(u_{\text{min}}\) is

\[
u_{\text{min}} = 1.04 \times 10^{-23} \left(\frac{L}{V}\right)^{4/7},
\]

where \(L\) is the synchrotron luminosity in watts, and \(V\) is the volume of the emitting region in pc\(^3\). We assume that the volume of the emitting region is a prolate spheroid:

\[
V = \frac{\pi}{6}d_{\text{maj}}d_{\text{min}}^2.
\]

where \(d_{\text{maj}}\) and \(d_{\text{min}}\) are the source linear sizes. We assume a filling factor of unity; that is, the source volume is fully and homogeneously filled by relativistic plasma. Furthermore, proton and electron energy densities are assumed to be equal. For the Seyfert nuclei with VLBI information, we obtain \(u_{\text{min}}\) of the order of \(10^{-6}\)–\(10^{-7}\) erg cm\(^{-3}\), \(H_{\text{eq}} \sim 1.5–10\) mG and \(T_B \sim 10^7–10^8\) K. These values are comparable to those derived in the nucleus of other Seyfert galaxies (e.g. Ulvestad & Wilson 1984; Kukula et al. 1999).

5.2 The off-nucleus radio emission

Of the seven Seyfert nuclei studied, four (NGC 1097, NCG 5506, NGC 7469, and NGC 7582) are surrounded by diffuse emission extending on kiloparsec scales. Regarding NGC 5506, Wöhrle & Morris (1987) suggested that its extended 0.35-kpc halo may be the result either of a radio plasma bubble expanding from the AGN, or of a magnetically dominated coronal arc. Another possibility is that it is produced by free–free emission from the ionized gas heated by the AGN. However, the steep spectral index, \(\alpha = 0.9\), makes this interpretation unlikely, as thermal emission would produce a flatter spectral index. Furthermore, the extended emission does not seem to be related to starburst activity, as no evidence for this is seen in high-spatial-resolution IR images up to 20 \(\mu\)m (Prieto et al. 2009; Reunanen et al. 2009).

In NGC 1097, NGC 7469 and NGC 7582, the extended emission is resolved into knots (Table 3), each having a counterpart star-forming region in high-spatial-resolution IR images (Reunanen et al. 2009). An analysis of the SED of the individual star-forming clumps in these galaxies, from radio to UV, shows that these regions are young super-massive stellar clusters, analogous to those seen in the starburst nucleus of NGC 253 (Fernandez-Ontiveros, Prieto & Acosta-Pulido 2009). In the radio, the spectral index is relatively steep, \(\sim 0.4–0.9\) in NGC 1097 (Hummel et al. 1987) and NGC 7469 (Alberdi et al. 2006), and \(\sim 0.9\) in region R1 of NGC 7582 (there is not enough information available for the other knots of NGC 7582 to derive the spectral index), suggesting a dominant non-thermal
origin, most probably from supernova events in these clusters. Not all the IR star-forming regions are detected in the radio, suggesting different evolution phases of the clusters within the same star-forming ring (Fernandez-Ontiveros, in preparation).

5.3 The missing flux density

5.3.1 Observational limitations

An interesting feature of the Seyfert nuclei with VLBI information, namely MRK 1239, NGC 3783, NGC 5506 and NGC 7469, is that their parsec-scale flux density is significantly lower than that measured on VLA images, even in the presence of unresolved structures. In MRK 1239 and NGC 3783, the flux density derived from VLBA data accounts for only 20 per cent of that measured on VLA images. This suggests that a significant fraction of the radio emission is not concentrated in a compact component at the centre, but rather spreads over a region that is slightly larger than 0.1 arcsec, which is the largest angular scale detectable by the VLBA at 1.6 GHz, and smaller than the resolution of VLA data at the same frequency, namely <0.3 arcsec for MRK 1239 (see Table 2) and <0.5 arcsec for NGC 3783 (Ulvestad & Wilson 1984). Strong support for this interpretation comes from observations with different resolutions of the nucleus of NGC 7469. In MERLIN observations at 1.6 GHz (Alberdi et al. 2006), the nucleus is slightly resolved in an east–west direction, giving an upper limit to its angular size of about 0.15 arcsec. The east–west elongation is confirmed by parsec-scale-resolution VLBI observations (Lonsdale et al. 2003), in which the nucleus is resolved into five components spread over an area of about 0.17 arcsec, which is comparable to that derived from MERLIN data. However, the flux density recovered from VLBI data accounts for only ~50 per cent of that measured on MERLIN images. A similar result was found for NGC 5506 by Middelberg et al. (2004), with EVN observations of the nucleus recovering only 43 per cent of the flux density measured by MERLIN. In this case, an extended, low-surface-brightness region, detected by MERLIN, is not seen by the EVN, as it is insensitive to structures larger than 35 mas at 18 cm, and than 11 mas at 6 cm.

From these results we can argue that, in the case of NGC 5506 and NGC 7469, the missing flux density on the VLBI image is probably the result of diffuse, steep-spectrum low-surface-brightness emission that is undetectable by VLBI observations either because of sensitivity limitations or because the structure is larger than the maximum scale detectable by the interferometer, or because of a combination of both. A similar result was found in the case of the Seyfert NGC 1068, for which Gallimore, Baum & O’Dea (2004) noted that deep VLBA observations could detect a flux density almost 50 per cent higher than that of the lower-sensitivity VLBA observations by Roy et al. (1998); however, the total flux density measured on images with lower spatial resolution could still not be recovered.

5.3.2 Steep-spectrum versus flat-spectrum Seyfert nuclei

The fact that in Seyfert nuclei the parsec-scale radio emission does not account for all the flux density measured at lower resolution, even in the presence of an unresolved component, was noted by Sadler et al. (1995), who studied a sample of 22 nearby Seyferts with the PTI. They suggested that in Seyfert galaxies the radio emission is more diffuse and less centrally concentrated than in elliptical radio galaxies. A similar behaviour was found by Lal et al. (2004), who compared simultaneous VLA and VLBI observations of a sample of Seyfert galaxies. They found that in ~60 per cent of the sources more than half of the VLA flux density of the unresolved component was missing in VLBI images.

However, evidence of undetected flux density on parsec scales is not a feature common to all Seyfert nuclei. For example, it has been found that in flat-spectrum Seyfert nuclei essentially all the emission on arcsecond scales is present on VLBI scales (Anderson, Ulvestad & Ho 2004; Anderson & Ulvestad 2005), indicating that all the radio emission is concentrated in the central component. On the other hand, in Seyfert nuclei characterized by a steep spectrum, the flux density recovered on milliarcsecond scales is usually significantly lower than that expected from arcsecond-scale images, suggesting that the radio emission is not centrally concentrated, but rather is diffuse over a larger region. A noticeable example of a steep-spectrum Seyfert nucleus in which the flux density almost disappears moving from arcsecond to milliarcsecond scales is represented by NGC 4151, for which only 8 per cent of the flux density from the central component could be recovered by VLBI observations (Pedlar et al. 1993; Ulvestad et al. 1998), and a large fraction of the jet emission is undetected. This suggests that in Seyfert nuclei unresolved on arcsecond scales but with different spectral index properties, the dominant radio emission may originate from different features: from the central core in flat-spectrum objects, and from extended features, such as jets, in steep-spectrum nuclei.

5.3.3 Thermal or non-thermal origin?

So far, the nature of the missing flux density has not been investigated in detail. This diffuse emission may result either from thermal emission from ionized gas heated by the AGN, or from nuclear star-forming regions, or from non-thermal radiation from the AGN itself.

To investigate a possible free–free origin of the missing flux we computed the electron density $n_e$ that the ionized gas must have in order to emit the ‘missing’ flux density:

$$n_e^2 = 1.84 \times 10^{41} \left( \frac{T}{10^4 \text{K}} \right)^{1/2} D_l L_e / (\nu)^{-2} g_{\text{ff}},$$

where $D_l$ is the luminosity distance, $T$ is the gas temperature in units of $10^4$ K, and $g_{\text{ff}}$ is the Gaunt factor. In equation (1) we have assumed that electrons and protons have the same density. At radio frequencies, $g_a \sim 17.7 + \ln (T^{1/2}/\nu)$ (e.g. Pacholczyk 1970). We assume that the gas temperature $T \sim 10^4$–$10^6$ K. The missing flux is calculated as the difference between the VLA and VLBI flux densities. In the case of MRK 1239 and NGC 3783, the missing flux at 1.6 GHz is ~50 and 18 mJy, respectively. If we consider these parameters in equation (1), we obtain an upper limit to the electron density of $n_e \sim 10^2$–$10^4$ cm$^{-3}$, over a spherical volume of 0.1 arcsec (i.e. 57 and 20 pc for MRK 1239 and NGC 3783, respectively) in diameter. This value is the largest angular size detectable from the VLBA (i.e. the VLBA at 1.6 GHz is insensitive to structures larger than 0.1 arcsec) and it represents, therefore, a lower limit to the source size. Such a dense gas would completely absorb the synchrotron emission arising from the embedded AGN:

$$S_{\text{obs}} (\nu) = S_0 (\nu) e^{-\mu(\nu)/\nu},$$

where $S_{\text{obs}}$ and $S_0 (\nu)$ are the observed and the intrinsic flux density at the frequency $\nu$, respectively, $l$ is the width of the ionized region, and $\mu(\nu)$ is the absorption coefficient at the frequency $\nu$ (Rybicki
The assumed geometry for the ionized gas heated by the AGN. The AGN is located in the centre of the ionized sphere with an angular diameter of 0.1 arcsec, which corresponds to the largest region detectable by the VLBA at 1.6 GHz.

\[ \mu(\nu) \sim 0.018 T^{-3/2} n_e^{-2/3} \text{GHz} \]

We consider that the parsec-scale structure found in the VLBA images (Figs 4c and 8) arises from the central AGN, and the observed flux density is 10 mJy and 5 mJy for MRK 1239 and NGC 3783, respectively. We assume that the AGN is located at the centre of the ionized region; that is, \( l \) is equal to the radius of the ionized sphere (Fig. 9) that accounts for 28.5 and 10 pc in the case of MRK 1239 and NGC 3783, respectively. With these parameters in equation (2) we obtain an intrinsic flux density arising from the central AGN that is much higher than a few thousands of Janskys. This suggests that the ‘missing’ flux is not free–free from gas ionized by the central AGN, and a non-thermal AGN-related origin is more plausible.

Another possibility may be that the ionized gas is related to an H II region located in projection behind the AGN, or that the gas around the AGN is not ionized uniformly. In this way, our line of sight to the central AGN does not pass through the ionized gas, thus avoiding any absorption of the AGN radiation.

However, strong support for the non-thermal synchrotron origin of the diffuse emission comes from a comparison, when possible, between the spectral index distributions in low- and high-spatial-resolution images. For example, in the case of NGC 5506, the unresolved nucleus in VLA data has a steep spectrum with a mean value of \( \alpha \sim 0.8 \), whereas at parsec-scale resolution (Sadler et al. 1995) the spectrum has a convex shape with the peak occurring around 3.5 GHz. This suggests that a significant fraction of steep-spectrum, low-surface-brightness emission is present in the nuclear region, but it cannot be detected in VLBI observations, probably because of observational limitations.

As in the case of NGC 4151 (Ulvestad et al. 1998), the steep emission may arise from a jet, which may be distorted and/or disrupted by the dense ambient medium. For example, on arcsecond scales, NGC 4151 displays a compact core and two collimated jets (Pedlar et al. 1993; Kukula et al. 1995). When observed with higher resolution, the compact core is resolved into several knots forming a jet that is not aligned with the arcsec-scale jet (Ulvestad et al. 1998). The misalignment often found between the radio jets on milliarcsecond scales and those on larger scales (Ulvestad et al. 1998) may be evidence of the interaction between the radio jet and the environment. In this scenario it is also possible that, for some reason, flat-spectrum Seyfert nuclei are not able to develop a radio jet, and this causes all their emission to be produced in the central compact component.

6 CONCLUSIONS

We have presented an analysis of multi-frequency archival VLA and VLBA data of seven close and bright Seyfert nuclei. The conclusions we can draw from this investigation are as follows.

(i) At VLA resolution, FWHM \( \sim 0.1 \) arcsec, the nucleus of the Seyfert galaxies is unresolved, with the exceptions of MGC-5-23-16 and NGC 7469, which show a core–jet structure. At VLBA resolution, equivalent to a few parsecs, the nucleus of MRK 1239 is resolved into two components, whereas in NGC 3783 it is still unresolved.

(ii) The Seyfert galaxies in this study with known circumnuclear star-forming regions in the IR, namely NGC 1097, NGC 7469 and NGC 7582 (Reunanen et al. 2009) present a radio counterpart for a few (\( \sim 10 \) per cent) of these regions. Most are not detected in the radio, indicating that those detected may be characterized by a higher supernova rate. Their steep radio spectral index is in line with this idea. In contrast, none of the other Seyfert nuclei present any circumnuclear radio emission. The only exception is NGC 5506, which shows a radio halo surrounding the nucleus.

(iii) A comparison between arcsecond and milliarsecond resolution in MRK 1239 and NGC 3783 revealed that almost 80 per cent of the radio flux density detected in VLA observations is not recovered at parsec-scale resolution. This suggests the presence of a diffuse component on scales of a few tens of parsecs, undetected with the VLBA. A similar situation is found in NGC 1068, NGC 4151, NGC 5506 and NGC 7469. The nature of this ‘missing’ flux component is probably a result of synchrotron AGN-related emission. This difference between the flux density measured on arcsecond- and milliarsecond-resolution images is not found in the case of elliptical radio galaxies, but it appears to be a common phenomenon in Seyfert galaxies with a steep spectrum, mostly hosted in spirals. If of synchrotron origin, this emission may be split off from a jet, which may easily become distorted and/or disrupted by the dense interstellar medium in the nucleus of spirals.

(iv) A comparison between Seyfert nuclei with different spectral properties reveals that in flat-spectrum nuclei almost all of the flux density is recovered on milliarcsecond scales. This indicates that in flat-spectrum objects the radio emission is essentially concentrated in the compact core, without evidence of a jet-like structure even on milliarcsecond scales, whereas in steep-spectrum objects a significant fraction of the radio emission arises from low-surface-brightness, extended features.

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