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# Radio properties of steep-spectrum and flat-spectrum Seyfert nuclei

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**Abstract.** Radio observations of Seyfert nuclei with different spatial resolution have shown that the radio emission arising from the central parsec-scale structure is often much fainter than that derived from observations with lower resolution, even if the nucleus is unresolved. The comparison between pc- and kpc-scale properties has been improved by means of the study of the nearest and brightest Seyfert nuclei from the Southern Hemisphere. In VLA images the nuclei are usually unresolved, sometimes surrounded by diffuse emission from star-forming regions. When observed with the VLBI only a small fraction of the flux density could be recovered. Such a missing flux is not a common characteristic of all the Seyfert nuclei, but it is observed mainly in those with a steep spectrum. Its origin is likely related to low-surface brightness features of non-thermal emission, perhaps from a jet that gets disrupt by the dense environment of the spiral galaxy host.

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

## 1. Introduction

Seyfert galaxies are part of the radio-quiet AGN population, with faint radio luminosity $L_{1.4\,\mathrm{GHz}} < 10^{23}$ W/Hz. Despite of their weak radio emission, Seyfert nuclei are very near, allowing a detailed study of the radio properties of the central engine. Radio observations with arcsecond resolution of several Seyfert samples (Ulvestad & Wilson 1984; Morganti et al. 1999; Thean et al. 2000) showed that a large fraction of Seyfert nuclei have resolved structures, with hints of jets, and diffuse emission from star-forming regions. When observed with the high spatial resolution provided by VLBI techniques, the parsec-scale structure is usually resolved in several components resembling a core-jet morphology (e.g. NGC 7469, Lonsdale et al. 2003). Sometimes the pc-scale and the kpc-scale jets are misaligned, indicating either a possible interaction with the environment or a change in the jet ejection (Middelberg et al. 2004). An intriguing characteristic shown by Seyfert nuclei is that the flux density arising from their pc-scale structure is much fainter than what found in observations with lower resolutions, even if the nucleus is unresolved (e.g Sadler et al. 1995). However, the lack of a high percentage of flux density is mainly found in Seyfert nuclei with a steep spectrum, while in those with a flat spec-

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trum essentially all the emission on arcsecond scales is present on the parsec scale structure (Anderson et al. 2004). This indicates that in flat-spectrum Seyfert nuclei the radio emission is concentrated in the central region of the AGN, while a large fraction of the radio emission from steep-spectrum Seyfert nuclei arises from extended, low-surface brightness features.

## 2. Radio morphology

The radio structure of a sub-sample of 7 Seyfert nuclei from the Southern Hemisphere (Reunanen et al. 2010) has been studied by means of archival VLA and, when available, VLBA data. At VLA resolution almost all the Seyfert nuclei are unresolved, sometimes surrounded by diffuse emission of either thermal (e.g. NGC 1098 with its ring of star forming regions, Fig. 1) or non-thermal (NGC 5506, Fig. 2) origin. Only two sources, MCG-5-23-16 (Fig. 3) and NGC 7469 (Alberdi et al. 2006) have a resolved core-jet structure on kpc scales.

When observed with pc-scale resolution, 2 Seyfert nuclei, NGC 5506 and NGC 7469 show a core-jet morphology (Middelberg et al. 2004; Lonsdale et al. 2003), while Mkn 1239 is resolved in two components separated by ~30 pc (Orienti & Prieto 2010). The other source with available VLBA data, NGC 3783, is unresolved even at pc-scale resolution.

For all these Seyfert nuclei, the flux density arising from VLBI data represents only a smaller fraction (20% - 50%) of the flux density of the unresolved central component in VLA images, indicating that a large amount of radio emission comes from diffuse low-surface brightness features, undetected by VLBI observations.

## 3. Steep-spectrum vs flat-spectrum Seyfert nuclei

The fact that in Seyfert nuclei the pc-scale radio emission does not account for all the flux density measured at lower resolution was noted by Sadler et al. (1995). However, evidence of undetected emission on parsec scales is not a common characteristic of all Seyfert nuclei, but it depends on their spectrum. In flat-spectrum nuclei all the arcsec-scale flux density is recovered in VLBI images, indicating that the emission is concentrated in the central region. On the other hand, in Seyfert nuclei with a steep spectrum the pc-scale emission is significantly lower, suggesting the presence of a low-surface brightness component that is larger than about 0.1 arcsec, i.e. the larger structure detectable by the VLBI, and smaller than the VLA resolution. A clear example of diffuse emission undetected at pc-scale resolution is represented by NGC 5506. In this Seyfert nucleus a weak extended structure, detected by MERLIN, is not seen in VLBI observations (Middelberg et al. 2004). NGC 4151 is another noticeable example of a steep-spectrum nucleus in which the flux density almost disappears moving from arcsec- to mas-scale resolution, since the jet emission is completely undetected by the VLBI (Pedlar et al. 1993; Ulvestad et al. 1998). This indicates that the radio emission

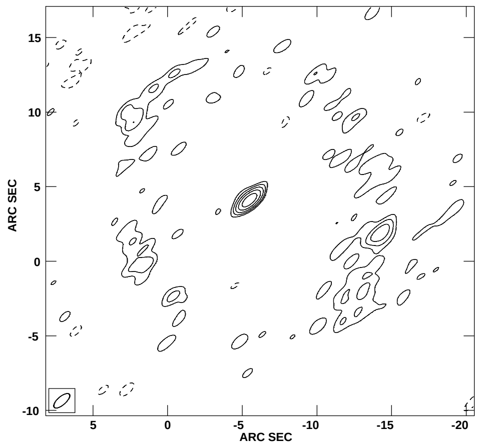


**Fig. 1.** VLA image at 8.4 GHz of the central region of NGC 1097. The peak flux density is 3.6 mJy/beam. The first contour intensity is 0.1 mJy/beam and it corresponds to three times the off-source noise level as measured on the image plane. Contour levels increase by a factor 2. Adapted from Orienti & Prieto (2010).

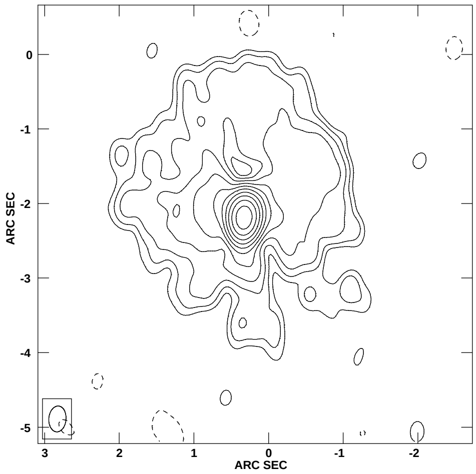


**Fig. 2.** VLA image at 8.4 GHz of the central region of NGC 5506. The peak flux density is 78.14 mJy/beam. The first contour intensity is 0.04 mJy/beam and it corresponds to three times the off-source noise level as measured on the image plane. Contour levels increase by a factor 2. Adapted from Orienti & Prieto (2010).

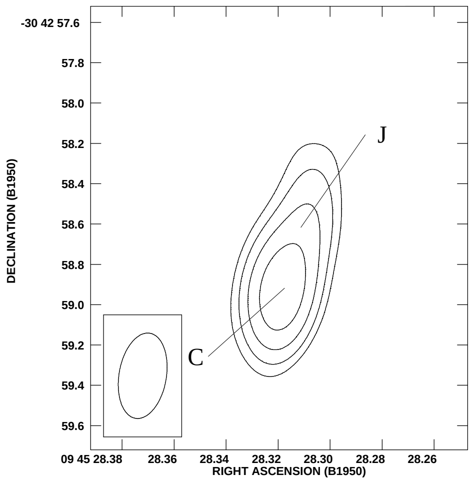


**Fig. 3.** VLA image at 8.4 GHz of the central region of MCG-5-23-16. The peak flux density is 2.1 mJy/beam. The first contour intensity is 0.1 mJy/beam and it corresponds to three times the off-source noise level as measured on the image plane. Contour levels increase by a factor 2. Adapted from Orienti & Prieto (2010).

in Seyfert nuclei with different spectral properties arises from different regions: the central core in flat-spectrum nuclei, whereas extended structures, like jets, in steep-spectrum nuclei.

### 3.1. Thermal or non-thermal origin?

The nature of the missing flux density may be either from thermal emission from ionized gas by the AGN and nuclear star-forming regions, or from non-thermal AGN-related radiation. To investigate a possible thermal free-free origin, we compute the electron density $n_{\rm e}$ that the ionized gas must have in order to produce such an emission, by means of

$$n_e^2 = 1.84 \times 10^{41} \left(\frac{T}{10^4 \mathrm{K}}\right)^{1/2} D_{\rm L}^2 S(\nu) V^{-1} g_{\rm ff}^{-1}$$

where $D_{\rm L}$ is the luminosity distance[1], $T$ the gas temperature in units of $10^4$ K, $V$ the source volume, $g_{\rm ff}$ the Gaunt factor, and $S$ the flux density. In the above equation we have assumed that electrons and protons have the same density and the temperature of the ionized gas is between $10^4$ and $10^6$ K. The missing flux is calculated as the difference between the VLA and VLBI flux densities. In the case of Seyfert nuclei considered here we find that the ionized gas must have $n_{\rm e} \sim 10^3 - 10^4$ cm$^{-3}$, over a spherical volume of 0.1 arcsec, corresponding to the larger angular size detectable by the considered VLBI observations (i.e. the VLBI is insensitive to structures larger than 0.1 arcsec), representing thus a lower limit to the source size (Orienti & Prieto 2010). Such a dense gas would completely absorb all the synchrotron

[1] We assume $H_0$ = 71 km s$^{-1}$ Mpc$^{-1}$, $\Omega_{\rm M}$ = 0.27 and $\Omega_\Lambda$ = 0.73, in a flat Universe.

emission from the AGN, indirectly supporting the non-thermal origin.

Another possibility may be that the ionized gas is not uniformly distributed around the AGN, or it arises from an $H_{II}$ region located in projection behind the AGN. In this way our line of sight reaches the central AGN without passing through the ionized gas, thus avoiding any absorption of the AGN radiation.

However, strong support to the non-thermal origin of the diffuse emission is provided by the comparison between the spectral index distribution in low- and high-resolution images. For instance in NGC 5506 the spectral index derived from VLA images is rather steep with a mean value of $\alpha = 0.8$[2]. On the other hand, at pc-scale resolution (Sadler et al. 1995) the spectrum is inverted up to 3.5 GHz. This indicates that a significant percentage of steep-spectrum diffuse emission is present in the central region, but it cannot be detected with high spatial resolution observations due to observational limitations. As in the case of NGC 4151 (Ulvestad et al. 1998), the steep-spectrum emission may be due to a jet that may be distorted or disrupted by the dense ambient medium. 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 makes the radio emission all concentrated in the central region.

## 4. Conclusions

From the analysis of archival VLA and VLBA observations of a sub-sample of the nearest and brightest Seyfert nuclei from the Southern Hemisphere we found that on arcsecond resolution the nuclei are usually unresolved, sometimes surrounded by diffuse emission from star-forming regions. A comparison between pc- and kpc-scale resolution revealed that a significant fraction of the radio flux density detected in VLA observations is not recovered in VLBA data, suggesting the presence of an extended low-surface brightness feature on scales of a few tens of parsecs, undetected with the VLBA. This difference between the flux density measured on arcsecond- and milliarcsecond-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 spilt off from a jet, which may easily become distorted and/or disrupted by the dense interstellar medium in the nucleus of spirals.

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[2] The spectral index is defined as $S(\nu) \propto \nu^{-\alpha}$