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# RADIO SOURCES IN LOW-LUMINOSITY ACTIVE GALACTIC NUCLEI. II. VERY LONG BASELINE INTERFEROMETRY DETECTIONS OF COMPACT RADIO CORES AND JETS IN A SAMPLE OF LINERS

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## ABSTRACT

We have used the VLBA[2] at 5 GHz to observe all galaxies with nuclear radio flux densities above 3.5 mJy found in a VLA survey at 15 GHz of a sample of nearby LINER galaxies. All galaxies were detected revealing high brightness temperature ($T_b \gtrsim 10^8$ K) radio sources. Free-free emission is unlikely since it greatly overpredicts the soft X-ray luminosities. We infer the presence of active galactic nucleus (AGN)–like, nonthermal radio emission most likely powered by underfed black holes. Together with our VLA sample we estimate from our observations that at least one-half of LINER galaxies host genuine AGNs. We find no evidence for highly inverted radio cores as predicted in the advection-dominated accretion flow model: the (nonsimultaneous) spectral indices are on average around $\alpha = 0.0$. In the two brightest sources we detect some extended emission, which appears to originate in jets in at least one of these galaxies. Together with the spectral indices this suggests that the nuclear emission at centimeter radio waves is largely dominated by emission from radio jets, very similar to the situation in more luminous AGNs. The energy released in these jets could be a significant fraction of the energy budget in the accretion flow.

*Subject headings:* galaxies: active — galaxies: jets — galaxies: nuclei — galaxies: Seyfert — galaxies: structure — radio continuum: galaxies

## 1. INTRODUCTION

The evidence for supermassive black holes in the nuclei of most galaxies has become much stronger recently. Some of the best cases are the Milky Way (Eckart & Genzel 1997), NGC 4258 (Miyoshi et al. 1995), and a number of other nearby galaxies (Richstone et al. 1998) where convincing dynamical evidence for black holes exists. In quasars and radio galaxies their existence is commonly inferred from the huge energy output of the active galactic nucleus (AGN), which is probably powered by accretion onto the black hole. However, despite the alleged presence of black holes in both cases, there is a huge span in luminosity between weakly active galaxies such as the Milky Way and AGNs. The question of how these central engines are related to each other and why they appear so different despite being powered by the same type of object is therefore of major interest. For many nearby galaxies with low-luminosity nuclear emission lines, it is not even clear whether they are powered by an AGN or by star formation. This is especially true for low-ionization nuclear emission-line region (LINER) galaxies (Heckman 1980), some of which can be explained in terms of aging starbursts (Alonso-Herrero et al. 2000).

One of the best ways to probe the very inner parts of these engines is to study the compact radio sources found in many AGNs. Indeed, despite their low optical luminosity, quite a few nearby galaxies have such radio sources in their nuclei (e.g., Jones, Terzian, & Sramek 1981), prominent cases in spiral galaxies being the Milky Way (Sgr A*) and M81 (see Bietenholz et al. 1996). In addition some relatively nearby elliptical galaxies such as M87 and NGC 1275 appear as low-power FR I radio galaxies and also contain well-known compact radio cores (Cohen et al. 1969; Schilizzi et al. 1975).

These radio sources resemble the cores of radio-loud quasars, showing a very high brightness temperature and a flat to inverted radio spectrum that extends up to submillimeter wavelengths. Models proposed for these low-luminosity radio nuclei are either a scaled AGN model, in which the core is the synchrotron self-absorbed base of a radio jet coupled to an underluminous accretion disk (Falcke, Mannheim, & Biermann 1993; Falcke 1996; Falcke & Biermann 1999), or an advection-dominated accretion flow (ADAF; Narayan et al. 1998; see also Melia 1992; Fabian & Rees 1995).

Earlier surveys have shown that E and S0 galaxies often have compact, flat-spectrum radio sources in their nuclei (Wrobel & Heeschen 1984, 1991; Sadler, Jenkins, & Kotanyi 1989; Slee et al. 1994). Some of the most prominent flat-spectrum nuclear radio sources in nearby galaxies are found in galaxies with LINER nuclear spectra (O'Connell & Dressel 1978), but so far there has been no comprehensive

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study of radio nuclei in a significant sample of LINER galaxies, which make up the majority of galaxies with low-level nuclear activity. We have, therefore, recently conducted a survey of LINER galaxies with the Very Large Array (VLA; Thompson et al. 1980) in its A configuration at 15 GHz (resolution $\sim 0''.15$) to search for compact radio emission (Nagar et al. 2000). The sources were drawn from the extensive and sensitive spectroscopic study of a complete, magnitude-limited sample of 486 nearby galaxies (Ho, Filippenko, & Sargent 1995), one-third of which showed LINER-like activity (Ho, Filippenko, & Sargent 1997). From those active galaxies with a LINER spectrum a subsample of 48 bright sources was drawn with no well-defined selection criterion other than that they had been observed with other telescopes as well, e.g., *ROSAT*, the *Hubble Space Telescope* (*HST*; UV imaging; Maoz et al. 1996; Barth et al. 1998), and the VLA at 15 GHz in A configuration (Nagar et al. 2000) and at 1.4 and 8.4 GHz in A and B configurations (van Dyk & Ho 1997). The sample also included so-called transition objects, which have spectra intermediate between LINER and H II region galaxies. While the project was being conducted a few sources in the original sample were reclassified as low-luminosity Seyfert galaxies. However, only one of the 10 sources discussed here has a " pure " Seyfert spectrum.

The 15 GHz VLA survey found a surprisingly large number (15 of 48) of galaxies with compact radio cores and flat spectral indices. Here we present Very Long Baseline Array (VLBA; Napier et al. 1994) observations of the 11 brightest of these galaxies to investigate the central region of LINER galaxies at the subparsec scale and clarify the nature of their radio cores.

## 2. SAMPLE SELECTION AND OBSERVATIONS

From our A configuration VLA survey (Nagar et al. 2000), we selected all 11 galaxies with both nuclear flux densities above 3.5 mJy at 15 GHz and flat spectra ($\alpha > -0.5, S_\nu \propto \nu^\alpha$). Only one source, NGC 2655, was above the flux-density limit and was excluded because of its steep spectrum. The flux-density limit was chosen so that we could detect all sources with the VLBA in snapshot mode in a single 12 hr observation if most of the 15 GHz emission were indeed compact on milliarcsecond (mas) scales.

The observations were performed on 1997 June 16 with all 10 antennas of the VLBA at 4.975 GHz. Because the sources are so faint, we had to use phase referencing. Observation of each program source was preceded by observation of a bright nearby phase calibrator. The observation sequence was cal-source-cal-source, which was repeated for three different hour angles to improve $(u, v)$ coverage. The integration times per scan were roughly 1–2 minutes for the calibrators and $\sim 8$ minutes for the program galaxies. The total integration time per galaxy was therefore about 45 minutes.

The data for the calibrators were fringe fitted, imaged, and self-calibrated in AIPS, and the solutions for antenna gains, phases, delays, and clock rates were transferred to the program sources. The data for the program sources were then imaged and cleaned. Since the initial coordinates were taken from our VLA observations, we had in most cases a position uncertainty of $\sim 0''.05$–$0''.1$, and hence we first imaged a wide field of view ($0''.4$). The map center was then shifted to the highest peak in this image, and the source was remapped and phase self-calibrated. A final amplitude and phase self-calibration was also performed for a long solution interval (25 minutes), and the sources were imaged.

The observations of NGC 3147 failed since the phase calibrator was not detected, thus reducing our sample to 10 sources. We note, however, that this source, together with NGC 2655 and NGC 4143, which is just barely under our flux-density limit, are included in further VLBA observations (N. M. Nagar et al. 2000, in preparation).

## 3. RESULTS

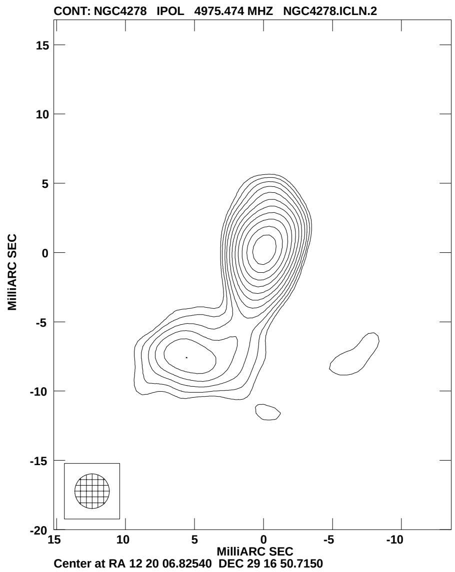
We detected all 10 sources with the VLBA. The results are shown in Table 1, where we list the galaxy names, distances (from Ho et al. 1997), Hubble galaxy type from RC3 (de Vaucouleurs et al. 1991), and spectroscopic classification from Ho et al. (1997) in columns (1)–(4). The sources are equally distributed between early- and late-type galaxies. We also give the positions of the radio sources (cols. [5] and [6]). The internal errors of the positions should be about

TABLE 1

PROPERTIES OF VLBA LINER SAMPLE

| Name (1) | $D$ (Mpc) (2) | $T$ (3) | Spec. (4) | R.A. (J2000) (5) | Decl. (J2000) (6) | $\Delta_{pos}$ (mas) (7) | $S_{5GHz}^{total}$ (mJy) (8) | $S_{5GHz}^{peak}$ (mJy) (9) | $T_b$ ($\times 10^8$K) (10) | P.A. (deg) (11) | $S_{15GHz}^{VLA}$ (mJy) (12) | $\alpha$ (13) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NGC 266 ....... | 62.4 | 2 | L1.9 | 00 49 47.8174 | +32 16 39.749 | 55 | 3.8 | 3.2 | 0.25 | ... | 4.1 | 0.07 |
| NGC 2787 ...... | 13.0 | −1 | L1.9 | 09 19 18.6095 | +69 12 11.690 | 10 | 11.5 | 11.2 | 0.87 | ... | 7.0 | −0.45 |
| NGC 3169 ...... | 19.7 | 1 | L2.0 | 10 14 15.0500 | +03 27 57.844 | 14 | 6.6 | 6.2 | 0.48 | ... | 6.8 | 0.03 |
| NGC 3226 ...... | 23.4 | −5 | L1.9 | 10 23 27.0113 | +19 53 54.496 | 150 | 4.8 | 3.5 | 0.27 | (64) | 5.0 | 0.04 |
| NGC 4203 ...... | 9.7 | −3 | L1.9 | 12 15 05.0519 | +33 11 50.359 | 55 | 8.9 | 8.9 | 0.69 | ... | 9.5 | 0.06 |
| NGC 4278 ...... | 9.7 | −5 | L1.9 | 12 20 06.8254 | +29 16 50.715 | 1 | 87.3 | 37.2 | 2.9 | 163 | 88.3 | 0.01 |
| NGC 4565 ...... | 9.7 | 3 | S1.9 | 12 36 20.7820 | +25 59 15.632 | 55 | 3.1 | 3.2 | 0.25 | ... | 3.7 | 0.16 |
| NGC 4579 ...... | 16.8 | 3 | L1.9 | 12 37 43.5222 | +11 49 05.488 | 1 | 21.3 | 21.3 | 1.7 | ... | 27.6 | 0.23 |
| NGC 5866 ...... | 15.3 | −1 | T2.0 | 15 06 29.4989 | +55 45 47.568 | 1 | 8.4 | 7.0 | 0.55 | (11) | 7.1 | −0.15 |
| NGC 6500 ...... | 39.7 | 2 | L2.0 | 17 55 59.7827 | +18 20 17.661 | 14 | 83.6 | 35.8 | 2.8 | 39 | 83.5 | 0.00 |

NOTE.—Col. (1): Galaxy name. Col. (2): Distance in megaparsecs. Col. (3): Host galaxy morphological type from RC3. Col. (4): Spectroscopical AGN classification: L = LINER, S = Seyfert, T = LINER–H II region transition galaxy. Cols. (5) and (6): VLBI J2000 coordinates. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Col. (7): Position uncertainty of phase referencing calibrator in milliarcseconds. Col. (8): Total flux density at 5 GHz (VLBA). Col. (9): Peak flux density at 5 GHz (VLBA); the statistical $1\sigma$ error is 0.2 mJy. Col. (10): Brightness temperature in $10^8$ K. Col. (11): Position angle, measured north through east, of 5 GHz radio core if extended; values in parentheses are very uncertain. Col. (12): Peak VLA flux density at 15 GHz; Nagar et al. 2000. Col. (13): Spectral index between peak 15 GHz (VLA) and total 5 GHz (VLBA) flux densities. Cols. (2)–(4) are from Ho et al. 1997.



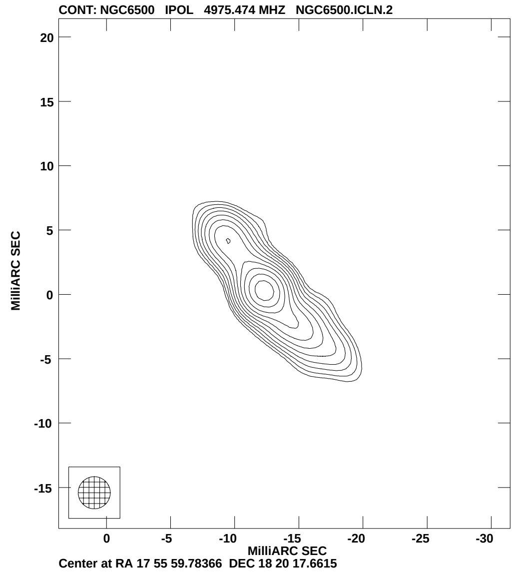




FIG. 1.—VLBA maps of (*left*) NGC 4278 and (*right*) NGC 6500. The beam is 2.5 mas, and contours are integer powers of $\sqrt{2}$, multiplied by the $\sim 5\ \sigma$ noise level of 0.9 mJy. The peak flux densities are 37.3 and 35.8 mJy, respectively.

the beam size (2.5 mas) or better for the stronger ones, but the absolute astrometric accuracy is limited by the uncertainty in the positions of the phase calibrators (listed in col. [7]). In addition, we list the total and peak flux densities in the VLBA maps and the brightness temperature (col. [10], defined below). Our 1 $\sigma$ rms noise is typically 0.2 mJy, and hence for the weakest source we obtain a dynamic range of 15:1. For extended sources we give the position angle (col. [11]) of an elliptical Gaussian component fitted to the core. For comparison we also list the peak VLA flux density at 15 GHz (col. [12]) from our previous survey and the (nonsimultaneous) spectral index $\alpha$ between the peak VLA 15 GHz and total VLBA 5 GHz flux densities (col. [13]).

The two brightest sources in our sample, NGC 4278 and NGC 6500, for which we have the largest dynamic range, show core plus jet structures (Fig. 1). While the compact emission in these two sources was known before (Jones et al. 1981), the new observations now show the extended emission with unprecedented quality. NGC 6500 has a core and a symmetric two-sided jet, while NGC 4278 has an extended core and an elongated source toward the southeast. The other sources are pointlike, with the possible exceptions of NGC 3226 and NGC 5866, although phase errors may be responsible for the extension in these faint sources. The spectral indices range from $\alpha = -0.5$ to $\alpha = 0.2$, with an average $\langle \alpha \rangle = 0.0 \pm 0.2$. We note that the VLBA does not provide spacings as short as those of the VLA. The VLBA measurements at 5 GHz may then underestimate the true flux density if the sources are extended below the 150 mas scale, so the actual spectrum might be less inverted (i.e., the spectral index smaller) than we measure here. The statistical error in our flux-density measurements produces a 1 $\sigma$ error of up to $\pm 0.1$ in the 5–15 GHz spectral index for the weakest sources.

From the flux densities and the sizes we have measured, we can calculate the brightness temperatures for a Gaussian flux-density distribution with the following equation:

$$T_b = 7.8 \times 10^6\ \mathrm{K} \left(\frac{S_\nu}{\mathrm{mJy}}\right)\left(\frac{\theta}{2.5\ \mathrm{mas}}\right)^{-2}\left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2}, \quad (1)$$

where $\theta$ is the FWHM of the Gaussian beam (e.g., Condon et al. 1982). Using our beam size of 2.5 mas and the peak 5 GHz flux densities in Table 1, we find brightness temperatures in the range $T = 0.25\text{–}2.9 \times 10^8$ K for our sample, with an average brightness temperature for all sources of $\langle T_b \rangle = 1.0 \times 10^8$ K. Since most of our sources are unresolved, these values are usually lower limits.

## 4. DISCUSSION

Our result has a number of interesting implications. The presence of high brightness temperature radio cores in our LINER sample confirms the presence of AGN-like activity in these galaxies. It is unlikely that the radio sources represent free-free emission, as has been claimed, for example, in NGC 1068 (Gallimore, Baum, & O'Dea 1997), since a much higher soft X-ray luminosity than is typically observed in low-luminosity AGNs would result. The emission coefficient for thermal bremsstrahlung from a gas at temperature $T$ is (e.g., Longair 1992, eq. [3.43])

$$\epsilon_\nu = 6.8 \times 10^{-51} Z^2 T^{-1/2} N_p N_e g(\nu, T) \times \exp(-h\nu/kT)\ \mathrm{W\ m^{-3}\ Hz^{-1}}, \quad (2)$$

where $g(\nu, T)$ is the Gaunt factor. If we consider a plasma at temperature $T \simeq 10^8$ K, then at 5 GHz, the exponential factor in equation (2) is 1, while the Gaunt factor is $\sim 12$. In the soft X-ray regime, taken as 0.4–2 keV, the Gaunt factor varies between 1.7 and 0.8, respectively, while the exponential factor in equation (2) varies between 0.95 and 0.8, respectively. Therefore, the luminosity per hertz at 0.4 and 2 keV is $\sim 0.25$ and $\sim 0.05$ times that at 5 GHz, respectively. The geometric mean monochromatic luminosities of the nuclei observed by us is $10^{27.5 \pm 0.6}$ ergs s$^{-1}$ Hz$^{-1}$ at 5 GHz. If this emission traces thermal bremsstrahlung, we would expect the total 0.4–2 keV luminosity of these nuclei to be $10^{43.9}$ ergs s$^{-1}$. However, the observed 0.4–2 keV luminosities for low-luminosity AGNs tend to be of the order of $10^{39-40}$ ergs s$^{-1}$ (e.g., Ptak et al. 1999)—many orders of magnitude lower and thus rendering a thermal origin of the radio emission very unlikely. Of course photoelectric absorption could attenuate some of the soft X-ray emission;

however, since seven of our galaxies show broad H$\alpha$ emission (spectral type 1.9), the absorption should be only moderate. To make this argument more watertight one will need to investigate multiwavelength data for our galaxies on a case-by-case basis.

On the other hand, the compact, flat-spectrum cores we have found are similar to those typically produced in many AGNs. Hence, we can take the presence of compact, nonthermal radio emission as good evidence for the presence of AGNs in our galaxies. The 100% detection rate with the VLBA, based on our selection of flat-spectrum cores found in a 15 GHz VLA survey, shows that for statistical purposes we could have relied on the VLA alone for identification of these compact, high-brightness radio sources. Hence, with 15 GHz VLA surveys of nearby galaxies one has an efficient tool for identifying low-luminosity AGNs. This complements other methods for identifying AGNs, such as searching for broad emission lines or hard X-rays, and has the advantage of not being affected by obscuration.

If we consider only galaxies with LINER spectra, we find at least 11 flat-spectrum radio cores at 15 GHz in a subsample of 24 LINERs observed by Nagar et al. (2000). Eight of these 11 LINERs are included in our sample here, yielding a lower limit to the AGN fraction for LINERs of at least 33% $\pm$ 12% (8/24). Based on our 100% detection rate of these flat-spectrum cores with the VLBA, we can, however, argue that all 11 flat-spectrum sources found in the VLA study are likely to be AGNs, raising the AGN fraction of LINERs to at least 46% $\pm$ 14% (11/24). These ratios do not change significantly if we include the galaxies classified as Seyfert galaxies. Since the selection of our parent sample is not very well defined, we could still be subject to an unquantifiable bias. This can be minimized by studying the radio emission of a distance-limited sample, which we plan in a future paper. First results (Falcke et al. 2000) seem to indicate that the bias is not large.

The two brightest radio sources in our sample show extended structure suggestive of jetlike outflows, and the other seven sources are unresolved or slightly resolved. Our very limited dynamic range is not good enough to prove or exclude the presence of jets for the latter. Moreover, VLBA observations of M81 (Bietenholz, Bartel, & Rupen 2000) have shown that jets in low-luminosity AGNs can be very compact and difficult to detect. The only clue we therefore have is the spectrum, which is flat or slightly inverted. Such a spectrum is obtained in jet models (Blandford & Königl 1979; Falcke 1996; Falcke & Biermann 1999), where the spectral index $\alpha$ ranges from 0.0 to 0.23 as a function of inclination angle to the line of sight. In no case do we find a spectral index as high as $\alpha = 0.4$ as predicted in the ADAF model (Yi & Boughn 1998). This does not necessarily exclude the ADAF model but argues for the parsec-scale radio emission at centimeter radio waves being dominated by another component, such as a radio jet or a wind. A combination of an underluminous disk or an ADAF and a radio jet is one possibility (e.g., Donea, Falcke, & Biermann 1999).

Assuming the cores are produced by randomly oriented, maximally efficient jets from supermassive black holes (of order $10^8\ M_\odot$), we can use equation (20) of Falcke & Biermann (1999) to calculate that for an average monochromatic luminosity of $10^{27.5}$ ergs s$^{-1}$ Hz$^{-1}$ at 5 GHz the jets would require a minimum *total* jet power of order $Q_{\rm jet} \gtrsim 10^{42.5}$ ergs s$^{-1}$. Compared with quasars this is a rather low value and supports the conclusion, based on their low UV and emission-line luminosities, that the cores are powered by underfed black holes. On the other hand, this jet power is well within the range of the bolometric luminosity of typical low-luminosity AGNs ($10^{41-43}$ ergs s$^{-1}$; Ho 1999) and, compared with radiation, jets could be a significant energy loss channel for the accretion flow.

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