to appear in: Proceedings of the International Symposium on Astrophysics Research And Science Education at The Vatican Observatory, June 14-21 1998, Castel Gandolfo, Italy, Ed. C. Impey

VLA and VLBA observations of compact radio cores in LINER galaxies

Heino Falcke

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany (hfalcke@mpifr-bonn.mpg.de)

Luis C. Ho

Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101, USA (lho@ociw.edu)

James S. Ulvestad

NRAO, P.O. Box O, 1003 Lopezville Road, Socorro, NM 87801 (julvesta@aoc.nrao.edu)

Andrew S. Wilson & Neil M. Nagar

Dept. of Astronomy, University of Maryland, College Park, MD 20742-2421, USA (wilson,neil@astro.umd.edu)

Abstract. A VLA survey of nearby LINER galaxies at 15 GHz has revealed the presence of a compact radio core in many sources. The cores seem to be correlated with the optical activity. Follow-up VLBA observations of the ten brightest sources confirm that these cores have brightness temperatures $> 10^8$ Kelvin, thus confirming their AGN nature. The two brightest radio sources show extended jet-like structures and the flat spectral indices of all cores also suggest a jet nature rather than emission from an ADAF.

1. Introduction

Quite a few nearby galaxies seem to have compact radio cores in their nuclei, the most prominent case being the Milky Way (Sgr A*). These radio cores resemble the cores of radio-loud quasars, showing a very high brightness temperature and a flat to inverted radio spectrum that extends up to submm wavelengths. The size of Sgr A* is only a few Schwarzschild radii of the central black hole (see Falcke 1996a for a review). Several models have been developed to explain those cores in the context of black hole accretion: spherical accretion models (Melia 1992), advection dominated accretion flows (ADAFs, Narayan et al. 1998), or scaled-down AGN jet models (Falcke, Mannheim, & Biermann 1993; Falcke & Biermann 1996). Recent observations have shown that the radio core in M81—in analogy to Sgr A* labelled as M81*—is very similar to Sgr A* and also well explained by a jet model (Falcke 1996b). This suggests that similar ultra-compact sources can be detected in other galaxies as well.

We have therefore conducted a high-frequency survey to search for compact, flat-spectrum radio cores in nearby galaxies and to obtain a statistically significant sample which can help to understand the energetic phenomena in low-luminosity active galactic nuclei (LLAGN) and the nature of radio cores similar to Sgr A* or M81*. Here we report first results from VLA and VLBA surveys aiming to detect such cores.

2. VLA survey of LINERS

It has been known for quite a while that early-type (E and S0) galaxies often do indeed have compact radio cores in their nuclei (Wrobel & Heeschen 1984; Slee et al. 1994) and that the probability of detecting a radio core is much higher for galaxies with nuclear optical emission-lines (O'Connell & Dressel 1978).

Recently Ho, Filippenko & Sargent (1995) have presented an extensive and sensitive spectroscopical study of a magnitude-limited and statistically well defined sample of 486 nearby elliptical and spiral galaxies (Palomar sample). One third of the galaxies surveyed show evidence for LINER-like activity and 13% turned out to be Seyferts (Ho et al. 1997). A subsample of 48 of the LINERS was recently observed with the VLA at 5 and 8 GHz in A and B configuration (van Dyk & Ho 1997). Surprisingly, almost all galaxies showed compact nuclei at a level of at least 0.5–2 mJy; but it is not clear whether this activity is due to a compact starburst or is AGN related. This sample is ideally suited to search for flat-spectrum, Sgr A*-like radio cores at high frequencies. First results of such a VLA survey were presented in (Falcke et al. 1997). Almost half of the galaxies were indeed detected above a $\sim 5\sigma$ detection level of 1 mJy at 15 GHz and at least a quarter of all LINERS had flat-spectrum cores. In contrast to the steep spectrum 5 GHz emission of these galaxies (van Dyk & Ho 1997), the flat-spectrum 15 GHz emission is well correlated with the Hα flux, supporting the AGN interpretation for LINERs (see Figure 1). Moreover, the detected radio cores fall exactly on the Hα vs. radio luminosity correlation predicted by the scaled down AGN jet model (Falcke & Biermann 1996; Falcke et al. 1997).

3. VLBA observation of brightest LINER cores

In order to further test our hypothesis that the radio cores in LINERs are indeed related to AGN activity, we have selected the eleven brightest cores from our sample which have a flat spectrum and flux densities larger than 3mJy. The sample was observed with the VLBA at 5 GHz in phase-referencing and snapshot mode, i.e. the telescopes switched every few minutes from the program source to a nearby phase calibrator source. This enabled us to detect compact (i.e. milli-arcsecond) structure at the level of a few mJy and at spatial scales of less than 0.1 pc. Observations of one source were lost because of problems with the phase-calibrator; however, all the remaining ten sources selected from our VLA sample were indeed detected at the flux density levels expected from extrapolating the 15 GHz VLA flux densities to 5 GHz with a flat spectrum. The two brightest sources showed jet-like extended structure (Fig. 2), while the remaining eight sources were basically point-like. This result has a number of important

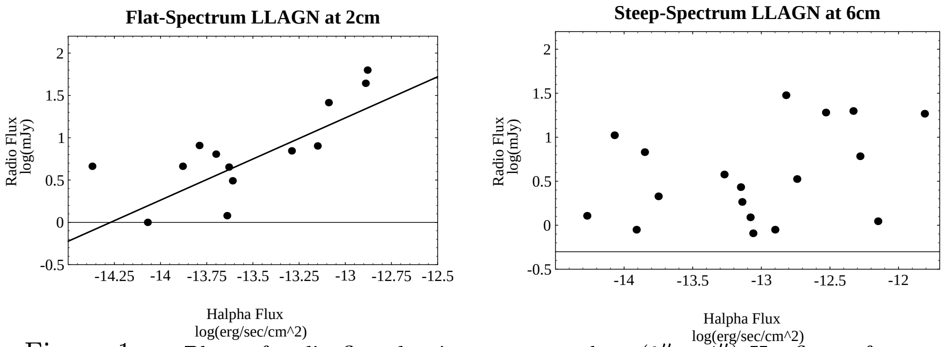

Figure 1. Plots of radio flux density versus nuclear ($2'' \times 4''$) Hα fluxes for a sample of nearby LINER galaxies. Left: 15 GHz (2cm) flux density of LINERS in the sample which were selected to have compact, flat spectrum emission at 15 GHz; Right: 5 GHz (6cm) emission of LINERS in the sample which were selected to have steep radio spectra. The former are supposed to be dominated by core emission while the latter are probably dominated by extended emission. The horizontal lines indicate the detection limits of the surveys, the inclined solid line in the left panel is a linear fit to the data.

consequences. First of all it demonstrates how effective our selection criterion was, giving us a 100% detection rate despite a technically challenging project. It seems that basically all the flux detected with the VLA is concentrated at the milli-arcsecond scales which validates our approach to use the VLA at 15 GHz to preferentially detect compact radio cores. Second, the brightness temperature of a radio source of size 1 milli-arcsec and flux density 5 mJy at 5 GHz is $T_b \sim 3 \times 10^8$K, and indeed all our sources have lower limits for $T_{\rm b}$ around $10^8 K$. Hence, we can probably exclude a thermal origin of the emission and argue that the radio emission is most likely due to an AGN. The fact that we get similar flux densities at 15 GHz and 5 GHz also suggests a relatively flat to inverted radio spectrum—the average 15/5 GHz spectral index of our non-simultaneous VLBA/VLA data is $\alpha = +0.1$. This is predicted in AGN jet models but is in stark contrast to the expectations for ADAF models, even though we cannot exclude an ADAF component at even higher frequencies. The idea, that these compact cores are jets is also strengthened by the extended structures seen in the two brightest sources.

4. Conclusion

Our observations have shown that galaxies with LINER-type nuclear spectra frequently contain very compact (< 0.1 pc) radio cores—most likely from low power radio jets similar to those seen in Seyferts or radio galaxies. The monochromatic luminosities at 5 GHz of the cores are in the range 10^{36-38} erg/sec and hence are comparable to M81* but are at least four orders of magnitude more luminous than Sgr A*. The VLBA observations have clearly demonstrated that at least some LINER galaxies are powered by an AGN-like engine and suggests a continuity of AGN activity from the most luminous quasars down to weakly active galaxies in our neighbourhood.

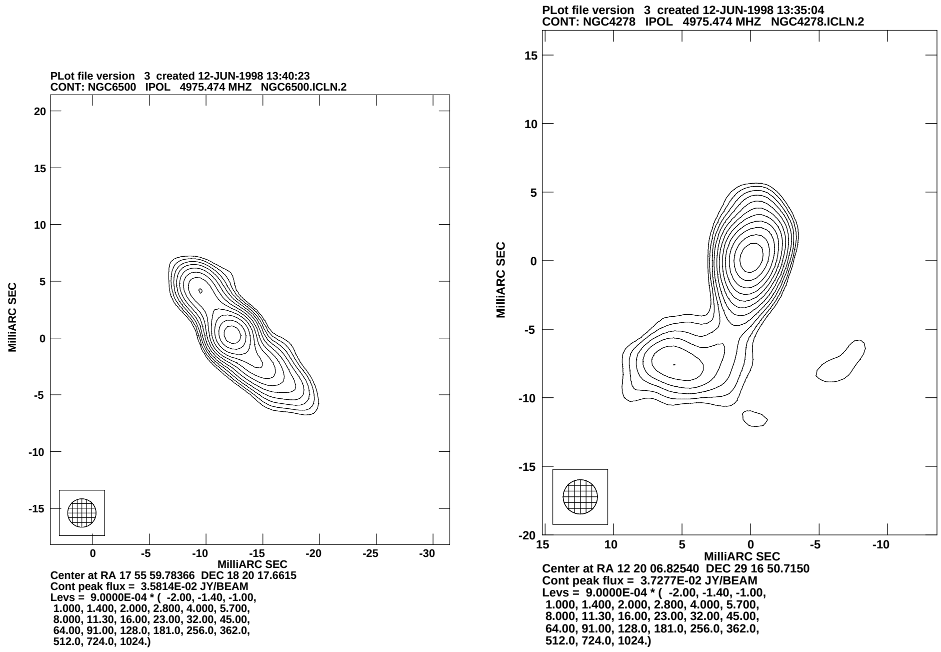

Figure 2. VLBA phase-referenced and self-calibrated maps of NGC 6500 (left) and NGC 4278 (right) at 5 GHz.

References

Falcke, H. 1996a, in "Unsolved Problems of the Milky Way", IAU Symp. 169, L. Blitz & Teuben P.J. (eds.), Kluwer, Dordrecht, p. 163

Falcke, H. 1996b, ApJ, 464, L67

Falcke, H., & Biermann, P.L. 1996, A&A 308, 321

Falcke, H., Mannheim, K., & Biermann, P. L. 1993, A&A, 278, L1

Falcke, H.,Wilson, A.S., Ho, L.C. 1997, in: "Relativistic Jets in AGN", Eds. M. Ostrowski, M. Sikora, G. Madjeski, & M. Begelman, Cracow, p. 13

Ho, L.C., Filippenko, A.V., & Sargent, W.L.W. 1995, ApJS, 98, 477

Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997, ApJ, 487, 568

Melia, F. 1992, ApJ, 387, L25

Narayan, R., Mahadevan, R., Grindlay, J. E., Popham, R.G., & Gammie, C. 1998, ApJ 492, 554

O'Connell, R.W., Dressel, L.L. 1978, Nature, 276, 374

Slee, O.B., Sadler, E.M., Reynolds, J.E., Ekers, R.D. 1994, MNRAS, 269, 928

van Dyk, S., Ho, L.C. 1997, IAU Coll. 164, A. Zensus, G. Taylor, J. Wrobel (eds.), ASP Conf. Ser. Vol. 144, p. 205

Wrobel, J.M., Heeschen, D.S. 1984, ApJ, 287, 41