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‘Radio-loud’ low luminosity AGN

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Abstract

Our VLBA survey of nearby bright LLAGN has found high brightness temperature ($>10^8$ K) radio cores in 16 of 17 objects observed, with four of them even hosting parsec scale jets, strongly suggesting that at least 20% of LLAGN are accretion powered. Few LLAGN show the steep radio spectra expected in an advection dominated accretion flow (ADAF). However, the X-ray to radio, and $M_{\rm bh}$ to radio relationships, are consistent with the predictions of ADAF’s. The compact cores and flat to inverted spectral indices in some LLAGN are consistent with the predictions of the scaled jet model of Falcke and collaborators. Plotted on a log $P_{\rm 2\ cm}$ vs. log $L_{\rm emission\text{-}line}$ diagram, all LLAGN in elliptical hosts, and most other LINERs and Transition objects which host compact radio cores, appear more closely related to radio galaxies than to ‘classical’ Seyferts. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Low luminosity AGN (LLAGN), operationally defined as AGN with nuclear Hα luminosity, $L_{\rm H\alpha}$, $<10^{40}$ erg s^{-1} (Ho et al., 1997a), make up almost 50% of all nearby bright galaxies (Ho et al., 1997a). They can be spectroscopically sub-classified into Low Ionization Nuclear Emission Region nuclei (LINERs), low luminosity (LL-) Seyferts, and ‘Transition objects’, whose spectra are intermediate between LINER and HII region spectra. The low nuclear emission-line luminosity of LLAGN does not demand the presence of a super massive black hole, and can be explained by, e.g., models invoking hot stars (Filippenko and Terlevich, 1992; Binette et al., 1994). However, there is increasing evidence that a large fraction of LLAGN are related to higher luminosity AGN, e.g., the presence of compact radio cores (Heckman, 1980), broad Hα emission (Ho et al., 1997b) and broader Hα lines in polarized light than in total flux (Barth et al., 1999). If LLAGN are mini-AGN, viable accretion mechanisms include advection dominated accretion flows (ADAF’s; e.g. Narayan et al., 1996), spherical accretion (Melia, 1992) and a scaled AGN jet model fed by a matter-starved accretion disk (e.g. Falcke et al., 1993).

To determine the incidence of mini-AGN among LLAGN, and to constrain their accretion mechanism, we have embarked on a radio survey of a large sample of LLAGN with the Very Large Array (VLA; Thompson et al., 1980) at 2 cm, and the Very Long Baseline Array (VLBA; Napier et al., 1994) at 6 cm. For our sample, we selected the 96 nearest (D$<$17 Mpc) LLAGN from the Palomar spectroscopic survey (Ho et al., 1997a) of 486 nearby bright galaxies,

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and an additional ~20 interesting LLAGN with D> 17 Mpc.

2. Initial results

2.1. Compact radio cores

We detected 33% of the 96 nearest LLAGN with the VLA at 2 cm; all detected sources were unresolved at ~0.15″ (3.5–15 pc) resolution (Falcke et al., 1998, 2000). Non-simultaneous VLA observations of many of these detected objects show that they have flat to inverted radio spectra (Fig. 1; Nagar et al., 2000). Our follow up VLBA 6 cm observations of the 17 LLAGN with $S_{2\ \mathrm{cm}}^{\mathrm{VLA}} > 3$ mJy detected 16 objects, implying core brightness temperatures of $T_B \geq 10^8$ K (Falcke et al., 2000; Nagar et al., 2000). Four of these-NGC 4278 and NGC 6500 (see Falcke et al., 1998) and NGC 4374 and NGC 4552 (Fig. 2) even host parsec scale jets. The one galaxy not detected in the VLBA experiment (NGC 2655) has a

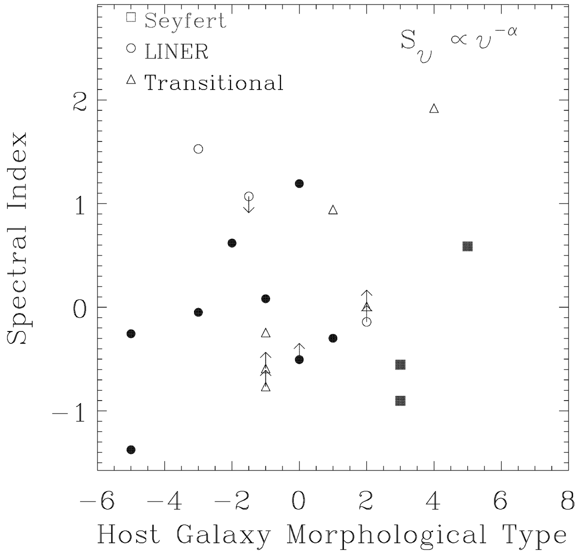

Fig. 1. Spectral index as derived from VLA 2, 3.6 or 6 cm data, as a function of host galaxy morphological type T. Filled symbols represent type 1 objects, open symbols represent type 2 objects. Note the presence of flat-spectrum LL-Seyferts.

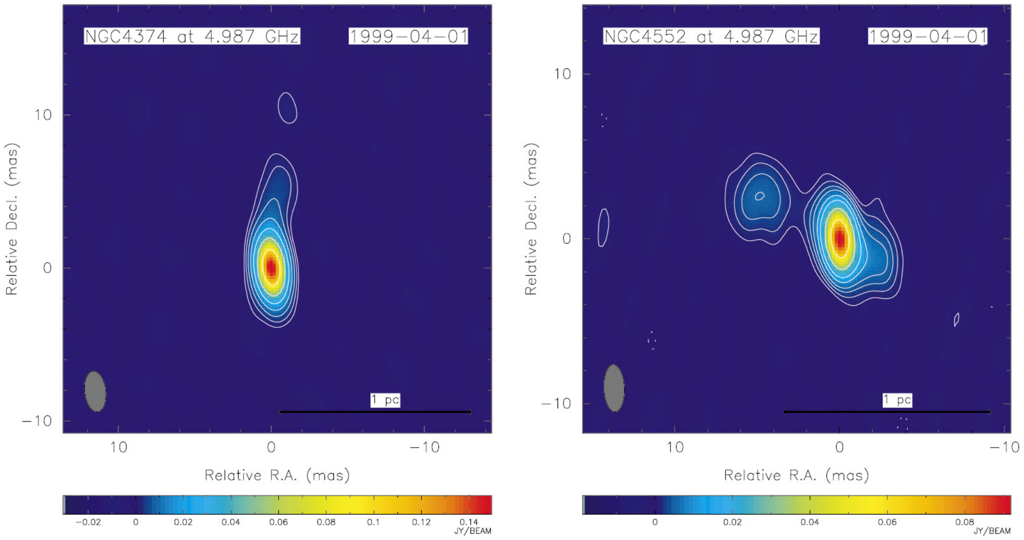

Fig. 2. VLBA phase-referenced and self-calibrated maps of NGC 4374 (left) and 4552 (right) at 5 GHz.

steep spectrum radio core, so its non detection is not surprising. The high incidence of compact, high brightness temperature cores, and flat to inverted radio spectra suggest that at least 20% of LLAGN are accretion powered.

Interestingly these compact, flat spectrum radio cores are preferentially found in type 1 LLAGN (i.e. LLAGN with broad Hα emission). This implies either of:

- only type 1 LLAGN are accretion powered. This is supported by the finding that $L_{X(2-10\ \mathrm{KeV})}/L_{\mathrm{H}\alpha}$ is high enough to power emission-lines in type 1 LLAGN but not type 2 LLAGN (Terashima, 1999);
- a duty-cycle scenario in which type 1's are in an outburst phase, which results in broad Hα emission and a compact, high brightness radio core.
- within the unified scheme (Antonucci, 1993), either: (a) type 1 LLAGN are beamed. Weakly relativistic jets ($\gamma \sim 2$) will give boost factors of ~5; or (b) type 2 LLAGN are free–free absorbed i.e. $\tau_{15\ \mathrm{GHz}} \geq 1$. X-ray absorption columns of 10^{20}–10^{24} are seen in LINERs, but columns in type 2 LLAGN are not systematically higher than those in type 1 LLAGN (Terashima, 1999). Invoking absorption also requires that *all* radio emission originate within the 'torus', which may be as small as 10 pc (e.g. Gallimore et al., 1999).

2.2. Accretion mechanism

Only 4 of 30 LLAGN have radio spectral indices which are consistent with the highly inverted spectrum expected in a pure ADAF ($S_\nu \propto \nu^{0.4}$; e.g. Narayan et al., 1996), though some of the radio emission may originate in an outflow wind from the ADAF (Blandford and Begelman, 1999). About 7 are consistent with the expectations of the scaled jet model (Falcke et al., 1993; $\alpha \sim 0$ to -0.2, $S_\nu \propto \nu^{-\alpha}$). If all of the 2 cm flux originates from an ADAF (see Yi and Boughn, 1999 for a scaling from radio power to black hole mass), then 33% of the 96 nearest LLAGN must host black holes of mass $> 10^7\ \mathrm{M}_\odot$. Seven of the nine objects in our sample with estimated black hole masses (Richstone et al., 1998; Magorrian et al., 1998), are consistent with the ADAF prediction $L_{\mathrm{radio}} \propto \dot{m}^{6/5} M_{\mathrm{bh}}^{8/5}$ (as developed in Yi and Boughn, 1999). For consistency with this relation, the black hole masses in NGC 4168 and NGC 4472 must be ~0.3 times and ~0.1 times, respectively, that derived for them in Magorrian et al. (1998). Alternatively, these two objects may have lower than usual accretion rates. Further, for the objects in our sample with published 2–10 keV luminosities (Ptak et al., 1998), the radio X-ray relationship is as expected in ADAF models with $M_{\mathrm{bh}} = 10^7$–$10^9\ \mathrm{M}_\odot$ and $\dot{m} \sim 10^{-2}$ (Yi and Boughn, 1999).

2.3. Integrating LLAGN with AGN

The ellipticals in our sample have higher radio luminosities than galaxies of morphological type S0 and later (99% confidence). However, as emphasized by Sadler et al. (1989), it is important to consider the bulge luminosity when making these comparisons. The following comparisons were made using the 2 cm luminosity for the 96 nearest LLAGN. The conclusions do not change significantly if all other LLAGN are included. The best fit to LINERs of morphological type S0 and later (solid line in Fig. 3) is closest to the low-luminosity extrapolation of the relationship for FR I radio galaxies i.e. $L_{\mathrm{line}} \propto L_{\mathrm{B}}^{0.7}$(bulge) (Zirbel and Baum, 1995). For a given bulge magnitude, the ellipticals appear underluminous in emission-lines as compared to later types. Note that while some late-type Seyferts lie near the low luminosity end of Whittle's 'classical' Seyferts, all Elliptical LLAGN avoid this area. Nelson and Whittle (1996) show that for Seyferts and FR radio galaxies $L_{\mathrm{rad}}^{\mathrm{core}} \propto L_{\mathrm{B}}^{3.2}$(bulge) (Fig. 3 bottom panels; dashed line) over 6 orders of magnitude. The 2 cm-detected LLAGN of all morphological types appear to follow the same slope as this relationship, but for a given bulge magnitude, they are a ~ half an order weaker in magnitude in the radio. Some of this difference can be reconciled as the lower resolution radio data used by Nelson and Whittle considerably overestimates the Seyfert core flux, which could bias the lower end of their fit.

The net result of the above two correlations with M_{B}(bulge) is that, on a log $P_{2\ \mathrm{cm}}$ vs. log $L_{\mathrm{emission\text{-}line}}$ plot, all LLAGN in elliptical hosts appear to be more closely related to radio-loud objects, consistent with

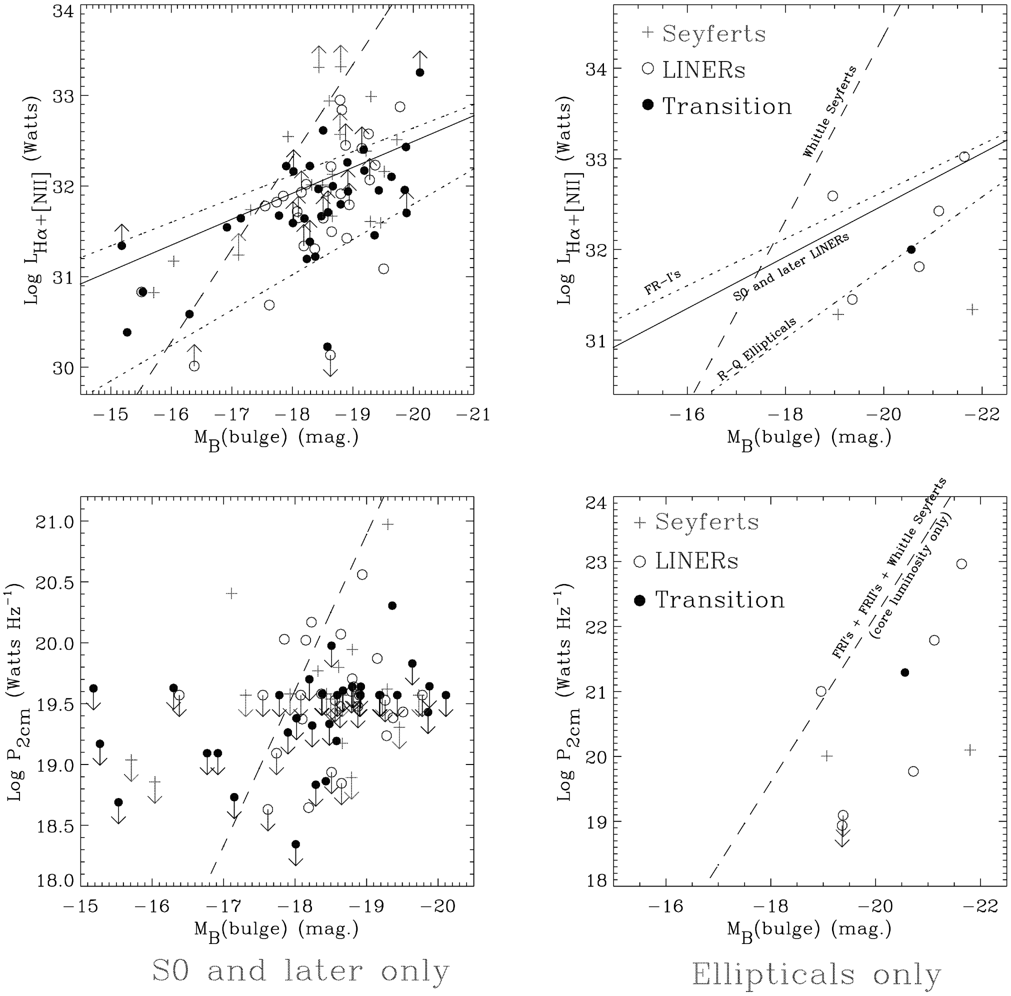

Fig. 3. The dependence of $L_{\text{emission-line}}$, and P_{radio} on bulge mass (represented here by the blue absolute magnitude M_B(bulge)). We use Hα + [NII] because [OIII] is typically very weak and noisy for LINERs and LINER + HII transition objects. Only the 96 nearest LLAGN have been plotted; the results are not significantly altered if we add more sources. The two left plots are for morphological type S0 and later, the two right plots for Ellipticals only. *Upper two panels*: the dotted lines are the best fit lines for FR I's and radio-quiet galaxies (from Zirbel and Baum, 1995) and the dashed line represents the best fit line for Seyferts from Whittle (1992); using a radio spectral index of −0.7 and standard Seyfert flux ratios to convert from [OIII] flux). The solid line is the best fit to the LINERs with morphological type S0 and later. *Lower two panels*: the dashed line is the best fit line to FRIs, FRIIs and Seyferts (using core radio powers only; Nelson and Whittle, 1996). Note how all radio detected LLAGN follow a relationship with similar slope, but displaced about half an order of magnitude towards lower radio powers.

the findings of Ho (1999). This is also true for most of the 2 cm detected LINERs and Transition objects in hosts of type S0 and later.

3. Uncited references

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