

# AGNs in LLAGNs: High resolution radio observations of the Palomar sample

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**Abstract.** We present completed results of a high resolution radio imaging survey of the Palomar Spectroscopic Sample of all ( $\sim 470$ ) nearby bright northern galaxies. Almost half the Palomar sample's galaxies have nuclei with emission-lines characteristic of AGN but with  $L_{\text{H}\alpha} \leq 10^{40}$  erg  $\text{s}^{-1}$ . These are referred to as low-luminosity AGNs or LLAGNs. The power source of such LLAGNs has been long debated. High resolution radio surveys of the sample - with the VLA at 15 GHz (150 mas resolution), and the VLBA at 5 GHz (2 mas resolution) - have now revealed a high incidence of pc-scale radio cores with implied brightness temperatures  $\gtrsim 10^8$  K, and sub-parsec scale jets. The results support the presence of accreting black holes in  $\geq 50\%$  of all LLAGNs; there is no evidence against *all* LLAGNs being mini-AGNs. The detected parsec-scale radio nuclei are preferentially found in massive ellipticals and in type 1 nuclei (i.e. nuclei with broad  $\text{H}\alpha$  emission). These nuclei follow the usual correlations between radio and emission-line gas properties found in more powerful AGNs. The radio luminosity function (RLF) of Palomar Sample LLAGNs extends three orders of magnitude below, and is continuous with, that of 'classical' AGNs. We find marginal evidence for a low-power turnover in the RLF; nevertheless LLAGNs are responsible for a significant fraction of accretion in the local universe. Low accretion rates ( $\leq 10^{-2} - 10^{-3}$  of the Eddington rate) are implied in both advection- and jet-type models. Within the context of jet models, the accretion energy output is dominated by the energy in the observed jets rather than the radiated bolometric luminosity. These jets would be able to dump sufficient energy into the innermost parsecs to significantly slow the accretion inflow. Detailed results can be found in Nagar et al. (2002, 2004) and references therein.

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## 1. Introduction

The debate on the power source of low-luminosity active galactic nuclei (LLAGNs, i.e. low-luminosity Seyferts, LINERs, and "transition" nuclei) is a continuing one. Their low emission-line luminosities ( $L_{\text{H}\alpha} \leq 10^{40}$  erg  $\text{s}^{-1}$  by definition) can be modeled in terms of photoionization by hot, young stars, by collisional ionization in shocks, or by aging starbursts. On the other hand, evidence has accumulated that at least some LLAGNs share characteristics in common with their more powerful counterparts - radio galaxies and powerful Seyfert galaxies. These similarities include the presence of compact nuclear radio cores, water vapor megamasers, nuclear point-like UV sources, broad  $\text{H}\alpha$  lines, and broader  $\text{H}\alpha$  lines in polarized emission than in total emission. If LLAGNs are truly scaled down AGNs then the challenge is to explain their much lower accretion luminosities. This requires either very low accretion rates ( $\sim 10^{-8}$  of the Eddington accretion rate) or radiative efficiencies (the ratio of radiated energy to accreted mass) much lower than the typical value of  $\sim 10\%$  assumed for powerful AGNs.

One well-known property of some powerful AGNs is a sub-parsec, flat-spectrum nuclear radio source, usually interpreted as the synchrotron self-absorbed base of the jet which fuels larger-scale radio emission. It has been suggested that scaled-down versions

of AGN jets can produce flat-spectrum radio cores in LLAGNs. The radio spectral shape and brightness temperature can be used to distinguish such jets from the accretion inflow in advection-dominated (ADAF) or convection-dominated (CDAF) accretion flows, and from thermal emission from H II regions. Finally, the radio regime offers several advantages (e.g. high sensitivity, high resolution, and lack of obscuration) for identifying (mini-)AGNs.

## 2. Radio Observations and Results

We focus on the  $\sim 7$  AGNs and  $\sim 190$  LLAGNs in the Palomar spectroscopic survey of all ( $\sim 470$ ) northern bright galaxies (Ho *et al.* 1997). Three groups have conducted recent large radio surveys of this sample. We (Nagar *et al.* 2000, 2001, 2002, 2004; Falcke *et al.* 2000) have observed 162 LLAGNs with the A-configuration VLA at 15 GHz (150 mas resolution), and then followed up 27 LLAGNs with the VLBA at 5 GHz ( $\sim 2$  mas resolution). Ulvestad, Ho, & Anderson (Anderson *et al.* 2004 and references therein) have observed all Seyfert galaxies at arcsec resolution at 6 cm and 20 cm and followed up some of the strong detections with the VLBA. Filho and collaborators (Filho *et al.* 2004 and references therein) have completed a  $5''\text{-}0''.3$  resolution VLA survey of all transition nuclei, with VLBA follow ups of the strongest nuclei.

Tabular compilations of the results for the complete sample appear in Nagar *et al.* 2002 and Nagar *et al.* 2004. The VLA detection rates are  $\sim 50\%$  for LINERs and Seyferts. The follow up VLBA imaging of all nuclei with  $S_{15\text{GHz}}^{\text{VLA}} > 2.7$  mJy detected 42 of 43 observed LLAGNs and AGNs; implied brightness temperatures are  $\gtrsim 10^8$  K.

Four factors point strongly to a non-thermal origin of the radio nuclei in LLAGNs: (1) the brightness temperatures are too high to be explained by thermal processes; (2) many nuclei have pc-scale “jets”; (3) the radio spectral shapes support a non-thermal origin; and (4) significant flux variability is observed. Therefore, the mas-scale radio emission is likely to be either emission from the accretion inflow or synchrotron emission from the base of the radio jet. The latter explanation is supported by the presence of sub-parsec jets in many of the nuclei, and the radio spectral shape.

The nuclear radio and emission-line properties of LLAGNs fall close to the low-luminosity extrapolations of more powerful AGNs, providing further support for a common central engine. The radio luminosity function (RLF) of Palomar Sample LLAGNs extends three orders of magnitude below, and is continuous with, that of ‘classical’ AGNs. We find marginal evidence for a low-end turnover in the RLF. The nuclear radio power is correlated with both the black hole mass and the bulge luminosity. In the context of jet models, the primary accretion energy output is in the jet power; this jet power could dominate over the radiated bolometric luminosity by factor  $\sim 2$  to  $> 10^3$ . These jets can dump significant energy into the inner parsecs, significantly slowing the accretion inflow.

## References

- Anderson, J. M., Ulvestad, J. S., & Ho, L. C. 2004, *ApJ*, 603, 42  
 Falcke, H., Nagar, N.M., Wilson, A.S., & Ulvestad, J.S. 2000, *ApJ*, 542, 197  
 Filho, M., *et al.* 2004, *A&A*, 418, 429  
 Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997a, *ApJS*, 112, 315  
 Nagar, N. M., Falcke, H., Wilson, A. S., & Ho, L. C. 2000, *ApJ*, 542, 186  
 Nagar, N. M., Wilson, A. S., & Falcke, H. 2001, *ApJ*, 559, L87  
 Nagar, N. M., Falcke, H., Wilson, A. S., & Ulvestad, J. S. 2002, *A&A*, 392, 53  
 Nagar, N. M., Falcke, H., & Wilson, A. S., 2004, *A&A*, submitted