Chandra Snapshot Observations of LINERs with a Compact Radio Core

Y. Terashima\textsuperscript{1,2} and A.S. Wilson\textsuperscript{2,3}

\textsuperscript{1} Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan
\textsuperscript{2} Astronomy Department, University of Maryland, College Park, MD 20742, USA
\textsuperscript{3} Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

Abstract. The results of Chandra snapshot observations of 11 LINERs (Low-Ionization Nuclear Emission-line Regions), three low-luminosity Seyfert galaxies, and one HII-LINER transition object are presented. Our sample consists of all the objects with a flat or inverted spectrum compact radio core in the VLA survey of 48 low-luminosity AGN (LLAGN) by Nagar et al. (2000). An X-ray nucleus is detected in all galaxies except one and their X-ray luminosities are in the range $5 \times 10^{38}$ to $8 \times 10^{41}$ ergs s$^{-1}$. The X-ray to H$\alpha$ luminosity ratios for 11 out of 14 objects are in good agreement with the value characteristic of LLAGNs and more luminous AGNs, and indicate that their optical emission lines are predominantly powered by a LLAGN. For three objects, this ratio is less than expected. Comparing with multi-wavelength results, we find that these three galaxies are most likely to be heavily obscured AGN. We compare the radio to X-ray luminosity ratio of LLAGNs with those of more-luminous AGNs, and confirm the suggestion that a large fraction of LLAGNs are radio loud.

1. Introduction

Low-Ionization nuclear emission-line regions (LINERs) are found in many nearby bright galaxies (e.g., Ho, Filippenko, & Sargent 1997a). Extensive studies in various wavelengths have shown that type 1 LINERs (LINER 1s, i.e., those galaxies having broad H$\alpha$ and possibly other broad Balmer lines in their nuclear optical spectra) are powered by a low-luminosity AGN (LLAGN) with a bolometric luminosity less than $\sim 10^{42}$ ergs s$^{-1}$ (Ho et al. 2001; Terashima, Ho, & Ptak 2000a; Ho et al. 1997b). On the other hand, the energy source of LINER 2s is likely to be heterogeneous. Some LINER 2s show clear signatures of the presence of an AGN, while others are most probably powered by stellar processes, and the luminosity ratio $L_X/L_{H\alpha}$ can be used to discriminate between these power sources (e.g., Terashima et al. 2000b). It is interesting to note that currently there are only a few LINER 2s known to host an obscured AGN (e.g., Turner et al. 2001). This paucity of obscured AGN in LINERs may indicate that LINER 2s are not simply a low-luminosity extension of luminous Seyfert 2s, which often show heavy obscuration with a column density averaging $N_H \sim 10^{23}$ cm$^{-2}$ (e.g., Turner et al. 1997). Alternatively, biases against finding heavily obscured LLAGNs may be important. For example, objects selected through optical emission lines or X-ray fluxes are probably biased in favor of less absorbed ones, even if one uses the X-ray band above 2 keV.

In contrast, radio observations, particularly at high frequency, are much less affected by absorption. Nagar et al. (2002) have reported a VLA 2 cm radio survey of all 96 LLAGNs within a distance of 19 Mpc. These LLAGNs come from the Palomar spectroscopic survey of bright galaxies (Ho et al. 1997a). As a pilot study of the X-ray properties of LLAGNs, we report here a Chandra survey of a subset, comprising 14 galaxies, of Nagar et al’s (2002) sample. We have detected 13 of the galactic nuclei with Chandra. We also examine the “radio loudness” of our sample and compare it with other classes of AGN.

2. The Sample and Observations

Our sample is based on the 15 GHz VLA observations by Nagar et al. (2000). Their sample of 48 objects consists of 22 LINERs, 18 transition objects between LINERs and HII nuclei, and eight low-luminosity Seyferts selected from the optical spectroscopic survey of Ho et al. (1997a).

We selected 14 objects showing a flat to inverted spectrum radio core ($\alpha \geq -0.3$, $S_\nu \propto \nu^{\alpha}$) according to Nagar et al. (2000)’s comparison with longer wavelength radio data published in literature. The targets are summarized in Table 1. The sample consists of seven LINER 1s, three LINER 2s, two Seyfert 1s, one Seyfert 2, and one transition 2 object. 12 out of these 14 objects have been observed with the VLBA and high brightness temperature ($T_b > 10^7$ K) radio cores were detected in all of them (Falcke et al. 2000; Ulvestad & Ho 2001; Nagar et al. 2002).

The exposure time was typically two ksec each. All the objects were observed with the ACIS-S3 back-illuminated CCD chip. Eight objects were observed in 1/8 sub-frame mode (frame time 0.4 s) to minimize effects of pileup. 1/2
sub-frame modes were used for three objects. Detailed results are given in Terashima & Wilson (2002c).

3. Results

An X-ray nucleus is seen in all the galaxies except for NGC 5866. The X-ray luminosities corrected for absorption are in the range $5 \times 10^{38}$ to $8 \times 10^{41}$ erg s$^{-1}$. The positions of the X-ray nuclei coincide with the radio core positions to within the positional accuracy of Chandra.

Spectral fits were performed for relatively bright objects. The pileup effect for the three objects with the largest count rate per frame (NGC 4203, NGC 4579, and NGC 5033) is serious and we did not attempt detailed spectral fits. Instead, we use the spectra and fluxes measured with ASCA for these three objects (Terashima et al. 2002b and references therein) in the following discussions. We confirmed that the nuclear X-ray source dominates the hard X-ray emission within the beam size of ASCA.

A power-law model modified by absorption was applied and acceptable fits were obtained in all cases. The photon indices of the nuclear sources are generally consistent with the typical values observed in LLAGNs (photon index $\Gamma = 1.6 - 2.0$, e.g., Terashima et al. 2002a, 2002b), although errors are quite large due to the limited photon statistics. The two objects (LINER 2s NGC 3169 and NGC 4548) show large absorption column density $N_H = 1.1 \times 10^{23}$ cm$^{-2}$ and $1.6 \times 10^{22}$ cm$^{-2}$, respectively, while NGC 3226 is less absorbed ($N_H = 9.3 \times 10^{21}$ cm$^{-2}$). Others have small column densities which are consistent with ‘type 1’ AGNs. NGC 2787 has only 8 detected photons in the 0.5–8 keV band and is too faint to obtain spectral information.

4. Discussion

4.1. Power Source of LINERs

We test whether the detected X-ray sources are the power source of their optical emission lines by examining the luminosity ratio $L_X/L_{H \alpha}$. The H$\alpha$ luminosities ($L_{H \alpha}$) were taken from Ho et al. (1997a) and corrected for the reddening estimated from the Balmer decrement for the narrow lines. The X-ray luminosities ($L_X$) in the 2–10 keV band, and corrected for absorption, were used. The resulting $L_X/L_{H \alpha}$ ratios of most objects are in the range of AGNs ($\log L_X/L_{H \alpha} \gtrsim 1$) and in good agreement with the strong correlation between $L_X$ and $L_{H \alpha}$ for LLAGNs, luminous Seyferts, and QSOs presented in Terashima et al. (2000a) and Ho et al. (2001). This indicates that their optical emission lines are predominantly powered by a LLAGN.

The three objects NGC 2787, NGC 5866, and NGC 6500, however, have much lower $L_X/L_{H \alpha}$ ratios ($\log L_X/L_{H \alpha} \lesssim 0$) than expected from the correlation, and their X-ray luminosities are not enough to power the H$\alpha$ luminosities. This X-ray faintness could indicate one or more of several possibilities such as (1) an AGN is the power source, but is heavily absorbed at energies above 2 keV, (2) an AGN is the power source, but is currently switched-off or in a faint state, and (3) the optical narrow emission lines are powered by some other source(s) than an AGN.

If an AGN is present in these X-ray faint objects and absorbed in the hard energy band above 2 keV, only scattered and/or highly absorbed X-rays can be observed, and then the intrinsic luminosity would be much higher than that observed. This can account for the low $L_X/L_{H \alpha}$ ratios and high radio to X-ray luminosity ratios ($\nu L_\nu (5$ GHz)/$L_X$). If the intrinsic X-ray luminosities are about one or two orders of magnitude higher than those observed, as is often inferred for Seyfert 2 galaxies, their X-ray luminosities are not enough to power the H$\alpha$ emission, as is often inferred for Seyfert 2 galaxies.

4.2. Obscured LLAGNs

In our sample, we found at least two highly absorbed LLAGNs (NGC 3169 and NGC 4548). In addition, if the X-ray faint objects discussed in the previous subsection are indeed AGNs, they are most probably highly absorbed with $N_H > 10^{23}$ cm$^{-2}$. Among these absorbed objects, NGC 2787 is classified as a LINER 1.9, NGC 3169, NGC 4548, and NGC 6500 as LINER 2s, and NGC 5866 as a transition 2 object. Thus, heavily absorbed LINER 1.9s/2s, of which few are known, are found in the present observations demonstrating that radio selection is


Fig. 1. Examples of Chandra spectra. (a) NGC 3169 and (b) NGC 4548

a valuable technique for finding obscured AGNs. Along with heavily obscured LLAGNs known in low-luminosity Seyfert 2s (e.g., NGC 2273, NGC 2655, NGC 3079, NGC 4941, and NGC 5194; Terashima et al. 2002a), our observations show that at least some type 2 LLAGNs are simply low-luminosity counterparts of luminous Seyferts in which heavy absorption is often observed. Some LINER 2s (e.g., NGC 4594, Terashima et al. 2002a; NGC 4374, Finoguenov & Jones 2001; NGC 4486, Wilson & Yang 2002) and low-luminosity Seyfert 2s (NGC 3147) show no strong absorption. Therefore, the orientation dependent unification scheme does not always apply to AGNs in the low-luminosity regime.

4.3. Radio Loudness of LLAGNs

Earlier studies have suggested that LLAGNs tend to be radio loud compared to more luminous AGNs based on the spectral energy distributions of seven LLAGNs (Ho 1999) and, for a larger sample, on the conventional definition of radio loudness $R_O = L_\nu (5 \text{ GHz})/L_\nu (B)$ (the subscript “O” stands for optical), with $R_O > 10$ being radio loud (Ho & Peng 2001). Ho & Peng (2001) measured the luminosities of the nuclei by spatial analysis of optical images obtained with HST to reduce the contribution from stellar light. A caveat in the use of optical measurements for the definition of radio loudness is extinction, which will lead to an overestimate of $R_O$. Although Ho & Peng (2001) used only type 1–1.9 objects, some objects of these types show high absorption columns in their X-ray spectra. In this subsection, we study radio loudness by comparing radio and hard X-ray luminosities. Since the unabsorbed luminosity for objects with $N_H \gtrsim 10^{23} \text{ cm}^{-2}$ (equivalent to $A_V \gtrsim 50$ mag for a normal gas to dust ratio) can be reliably measured in the 2–10 keV band, it is clear that replacement of optical by hard X-ray luminosity potentially yields considerable advantages.

In the following analysis, radio data at 5 GHz taken from the literature are used since fluxes at this frequency are widely available for various classes of objects. We used the radio luminosities primarily obtained with the VLA at $\lesssim 1^\prime$ resolution for the present sample. High resolution VLA data at 5 GHz are not available for several objects. For four objects among such cases, VLBA observations at 5 GHz with 150 mas resolution are published in the literature (Falcke et al. 2000) and are used here. For two objects, we estimated 5 GHz fluxes from 15 GHz data by assuming a spectral slope of $\alpha = 0$ (cf. Nagar et al. 2001). Since our sample is selected based on the presence of a compact radio core, the sample could be biased to more radio loud objects. Therefore, we constructed a larger sample by adding objects taken from the literature for which 5 GHz radio, 2–10 keV X-ray, and $R_O$ measurements are available.

First, we introduce the ratio $R_X = \nu L_\nu (5 \text{ GHz})/L_X$ as a measure of radio loudness and compare the ratio with the conventional $R_O$ parameter. The X-ray luminosity $L_X$ in the 2–10 keV band (source rest frame), corrected for absorption, is used. We examine the behavior of $R_X$ using samples of AGN over a wide range of luminosity, including LLAGN, the Seyfert sample of Ho & Peng (2001) and PG quasars which are also used in their analysis. The X-ray luminosities (mostly measured with ASCA) are compiled from the literature.

Fig. 2 compares the parameters $R_O$ and $R_X$ for the Seyferts and PG sample. These two parameters correlate well for most Seyferts. Some Seyferts have higher $R_O$ values than indicated by most Seyferts. This could be a result of extinction. Seyferts showing X-ray spectra absorbed by a column greater than $10^{22}$ cm$^{-2}$ (NGC 2639, 4151, 4258, 4388, 4395, 5252, and 5674) are shown as open circles in Fig. 2. At least four of them have larger $R_O$ than indicated by the correlation. The correlation between log $R_O$ and log $R_X$ for the less absorbed Seyferts can be described as log $R_O = 0.88 \log R_X + 5.0$. According to this relation, the boundary between radio loud and radio quiet object (log $R_O = 1$) corresponds to log $R_X = -4.5$.

The PG quasars show systematically lower $R_O$ values than those of Seyferts at a given log $R_X$. For the former objects, log $R_O = 1$ corresponds to log $R_X = -3.5$. This apparently reflects a luminosity dependence of the shape of the SED: luminous objects have steeper optical-X-ray slopes $\alpha_{ox} = 1.4 - 1.7$ ($S \propto \nu^{-\alpha}$), where $\alpha_{ox}$ is often measured as the spectral index between 2200 A and 2 keV, while less luminous AGNs have $\alpha_{ox} = 1.0 - 1.2$ (Ho
Fig. 2. Comparison between $R_O = L_\nu(5 \, \text{GHz})/L_\nu(\text{B})$ and $R_X = \nu L_\nu(5 \, \text{GHz})/L_X$ for Seyferts and PG quasars. The conventional boundary between “radio loud” and “radio quiet” objects (log $R_O = 1$) is shown as a horizontal dashed line.

1999). This is related to the fact that luminous objects show a more prominent “big blue bump” in their spectra. Figure 8 of Ho (1999) demonstrates that low-luminosity objects are typically 1–1.5 orders of magnitude fainter in the optical band than luminous quasars for a given X-ray luminosity.

The definition of radio loudness using the hard X-ray flux ($R_X$) appears to be more robust because X-rays are less affected by both extinction at optical wavelengths and the detailed shape of the blue bump. Further, measurements of nuclear X-ray fluxes are much easier than measurements of nuclear optical fluxes, since in the latter case the nuclear light must be separated from the surrounding starlight.

Fig. 3 shows the X-ray luminosity dependence of $R_X$. In this plot, the LLAGN sample discussed in the present paper is shown in addition to the Seyfert and PG samples used above. This is an “X-ray version” of the log $R_O$-$M_B^{10^{10}}$ plot (Fig. 4 in Ho & Peng 2001). Our plot shows that a large fraction of LLAGNs ($L_X < 10^{42}$ erg s$^{-1}$) are radio loud. This is a confirmation of Ho & Peng’s (2001) finding. Since radio emission in LLAGNs is likely to be dominated by emission from jets (Nagar et al. 2001; Ulvestad & Ho 2001), these results suggest that, in LLAGN, the fraction of the accretion energy that powers a jet, as opposed to electromagnetic radiation, is larger than in more luminous Seyfert galaxies and quasars.

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Fig. 3. X-ray luminosity dependence of $R_X = \nu L_\nu(5 \, \text{GHz})/L_X$ for the present LLAGN sample, Seyfert galaxies, and PG quasars. The boundary between “radio loud” and “radio quiet” objects (log $R_X = -4.5$) is shown as a horizontal dashed line.