The properties of LLAGN inferred from high resolution observations

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Abstract. Supermassive black holes (SMBHs) gain most of their mass during their brief, 100 Myr, luminous phases as efficiently radiating quasars and Seyfert galaxies. However, the total mechanical energy that is released by a SMBH during its quiescent phase, in which it spends 99 percent of the time, may be comparable to or even greater than the total radiative energy released during luminous phases. As such, the low-luminosity AGNs (LLAGNs) that are found in a large a fraction of all massive galaxies could have a significant role in regulating galaxy growth and establishing the observed relations between galaxies and SMBHs. Almost by definition, however, LLAGNs are difficult to study observationally, with their feeble signals easily lost or confused with other nuclear emission. As a result, much less is known, compared to luminous AGNs, about the phenomenology of low-luminosity activity, let alone its physics. For example, there are widely disparate views about the accretion mode at low-luminosities: do quiescent SMBHs undergo a transition to a geometrically thick RIAF phase that is distinct in its physics and emergent spectrum from those of the thin accretion disks invoked for quasars? Or does non-thermal jet emission become the dominant component at all wavelengths in LLAGNs? Multi-wavelength high-angular-resolution data that isolate the AGN emission are critical for answering these questions. Additional gain is obtained by combining high resolution with the time domain; the variability that seems to be endemic to all AGNs permits isolating weak non-stellar nuclear emission at all wavelengths, even when it is dwarfed by brighter, but constant, non-nuclear emission. I will review recent progress in understanding the properties of LINERs, the most common form of LLAGNs, based on such data. I will argue that there is actually more similarity than contrast between the observed spectral properties of different AGNs, with only a mild and continuous change in the properties as a function of decreasing accretion rate, going from quasars to the faint LINERs in nearby galaxies. This suggests a persistence of thin accretion disks at low accretion rates, in analogy to some recent findings for stellar-mass BHs. At the same time, a relatively larger fraction of the energy emerges in radio bands, suggesting an increasing role for jets/outflows, and their associated mechanical input, at low AGN luminosities.

1. Introduction

Supermassive black holes (BHs), whose existence has been postulated since the discovery of quasars, are now believed to reside in the nuclei of all massive galaxies, with a correlation between the masses of the BHs and the masses of their host bulges (as evidenced by the stellar luminosities or the velocity dispersions of the bulges; e.g., Häring & Rix 2004; Tremaine et al. 2002). Following an argument by Soltan (1982), the active galactic nucleus (AGN) luminosity density from recent X-ray and optical surveys, integrated over cosmic time, when compared to the present-day space density of nuclear BHs, provides strong evidence that the BHs have grown...
primarily during relatively brief ($\sim 10^8$ yr) active periods when they accreted in a radiatively efficient mode as Seyfert nuclei and quasars (Marconi et al. 2004; Shankar et al. 2004, Cao 2007). The favored mechanism for achieving the required high rest-mass-to-energy conversion efficiencies ($\epsilon \approx 0.1$) is a geometrically thin, optically thick, accretion disc (Shakura & Sunyaev 1973). A less efficient accretion mode during the Seyfert/quasar phase would overpredict the currently observed BH space density. Semi-direct evidence for the existence of such discs in AGNs has come from the presence of an optical to ultraviolet (UV) “big blue blump” in the spectral energy distributions (SEDs) of luminous AGNs (e.g., Shang et al. 2005; Kishimoto et al. 2005) – presumably the thermal radiation from the disc (Shields 1978; Malkan 1983), as well as from the profiles of iron X-ray emission lines, interpreted as gravitationally redshifted and relativistically Doppler-broadened and -boosted emission from the inner regions of the disc (see Nandra et al. 2006, for a review). Estimates of the BH masses in Seyferts and quasars indicate, furthermore, that the thin discs are often radiating at luminosities near the Eddington limit, $L_E$, corresponding to the BH mass (Kaspi et al. 2000; Kollmeier et al. 2006; Netzer & Trakhtenbrot 2007).

Compared to the radiatively efficient, high-rate, accretion mode of BHs in their short-lived, high-luminosity, phases, much less is known about BH behavior during their long, quiescent, stages. In the presence of a central BH, and given the ubiquity of gas from the mass loss accompanying normal stellar evolution of the bulge population, it appears unavoidable that accretion on to the BH at some finite rate still takes place (e.g., Soria et al. 2006a,b). However, it has been a challenge to explain how this accretion can be accompanied by only the feeble radiative signatures that are observed in non-active galaxies. During their quiescent stage, BHs may switch to a different accretion mode, characterized by a low accretion rate and low-radiative efficiency. In most models of such radiatively inefficient accretion flows (RIAFs; see, e.g., Yuan 2007, and references therein), the kinetic energy associated with the gas is either advected with the matter into the BH, or redirected into an outflow. The funnels in the geometrically thick structures, such as tori, invoked by such models, also provide a plausible mechanism for collimating axial outflows and jets. Observationally, AGNs show some evidence for a transition from a low-accretion-rate state, with an associated low luminosity and a hard X-ray spectrum, to a high-accretion-rate, high-luminosity, soft-X-ray state, analogous to behavior observed in Galactic stellar-mass accreting BHs (e.g., Done & Gierliński 2005). However, direct observational evidence for the existence of RIAFs has been sparse, and some authors have argued against such structures based on the observed spectral slopes in specific wavelength regimes (e.g., Done & Gierliński 2005; Körding, Falcke, & Corbel 2006), when compared to the predictions of RIAF models.

Understanding the quiescent BH stage is important for a variety of reasons. It is not known what triggers the active stage of luminous AGNs, with galaxy interactions, or tidal disruption and accretion of stars being favorite contenders (e.g., Volonteri et al. 2006), and details about the quiescent stage could provide clues. The existence of the BH-bulge correlations and results of galaxy-formation simulations have led to proposals that AGNs provide “feedback” that can regulate star formation and can affect galactic structure (e.g., Springel et al. 2005; Silk 2005). These ideas have been reinforced by the recent discovery of large cavities of hot gas that have been formed in the intracluster medium by jets from the nuclei of central cluster galaxies (e.g., Dunn & Fabian 2006; Nusser et al. 2006). This feedback could well take place mainly during the quiescent stage of BH activity (e.g., Heinz et al. 2007). For example, for the low-luminosity AGN in M87, the total energy radiated during the efficient growth of its BH, and the total kinetic energy released during its quiescent phase (assuming the Heinz et al. scaling between radio and kinetic luminosity, and a quiescent phase lasting of order a Hubble time), are both of order $10^{62}$ erg.

The low-level nuclear activity of the quiescent stage can manifest itself observationally in
the form of compact, often-variable, sources of radio, UV, or X-ray emission, or as emission-line nuclei with line ratios uncharacteristic of stellar excitation, or with broad Balmer lines reminiscent of Seyfert 1 spectra (see below). Jets, generally seen in radio, but sometimes in other bands as well (e.g., as in M87) are another unambiguous indicator of nuclear activity seen in some galaxies. The weakness of these radiative signals from quiescent BHs make their study difficult, almost by definition. Problems include confusion with brighter, non-AGN, components, obscuration by dust, and selection effects. Fortunately, it is becoming clear that a large fraction of all galactic nuclei do show some weak signs of activity that can be associated with the central BH, and in this sense most galaxies can be considered to host a low-luminosity AGN. The ubiquity and nearness of these objects (including the one in our own Galaxy) often permits separating their weak signals from the various possible backgrounds, such as radiation from stars in the optical to the UV range, and from circumnuclear accreting binaries in X-rays. In radio, high-angular resolution can help separate between jet emission and an unresolved nuclear source that could be coming directly from the accretion flow.

Probably the most common manifestation of low-luminosity AGN appears in the form low-ionization nuclear emission-line regions (LINERs; Heckman 1980; see Ho 2008 for a recent review), which are detected in the nuclei of a large fraction of bright nearby galaxies (Ho et al. 1997; Kauffmann et al. 2003). As their name implies, LINERs are characterized by collisionally excited lines of neutral and singly-ionized species, indicators of the presence of hot but largely neutral gas. Theoretical studies that attempted to model LINER spectra have generally agreed that LINERs are photoionized objects. Recently, Kewley et al. (2006) have used Sloan Digital Sky Survey (SDSS) data to show that LINERs occupy a well-defined “cloud” in emission-line ratio diagnostic diagrams, a cloud that is distinct from the regions occupied by H II and Seyfert nuclei. These results largely overcome previous sentiments that LINERs are a “mixed bag” of objects, with some photoionized by stars, some by AGNs, and some perhaps excited by shocks. By assuming a BH mass for every galaxy based on the BH-bulge mass relation, Kewley et al. (2006) further showed that the transition from the Seyfert region to the LINER region in the diagnostic diagrams corresponds to a decrease in the Eddington ratio, \( L/L_E \), confirming earlier conclusions by Ho (2004). If this decrease is accompanied by a hardening of the ionizing spectrum, the spectral transition can also be explained.

In terms of actually detecting the ionizing continuum source in LINERs, observations at UV wavelengths, where the bright background from the bulge stellar population basically disappears, have proved to be useful. Hubble Space Telescope (HST) imaging showed that some 25 per cent of LINERs have compact, generally unresolved (i.e., \(< \text{few pc}\) bright UV sources in their nuclei (Maoz et al. 1995; Barth et al. 1998). Optical HST imaging of 14 LINERs (Pogge et al. 2000) revealed that in every case where a compact UV nucleus had not been detected, obscuration of the nucleus by circumnuclear dust was apparent. This strongly suggests that most nearby LINERs (including the 75 per cent that are “UV-dark”, i.e., those that do not reveal a nuclear UV source at HST sensitivity, \( \sim 10^{-17}\text{erg/s/cm}^2/\text{Ang.}\) likely have such a nuclear UV source.

Maoz et al. (2005; M05) monitored with the HST Advanced Camera for Surveys (ACS) a sample of 17 compact UV LINER nuclei at 2500 Å and 3300 Å. They found that all but three of the objects varied in UV brightness on month-long time-scales, correlated between both UV bands, or on decade-long time-scales (by comparison to flux levels measured previously [1993–2000] for these objects at bandpasses similar to the ACS 2500 Å band, usually at 2300 Å), or both. Month-scale variation amplitudes were typically \( \sim 10 \) per cent, while decadal variations were by a factor of a few. This result argues for a nonstellar UV source and, by extension to the ionizing far-UV range, for AGN excitation of the LINER emission lines. The variable UV flux provides a lower limit on the nonstellar contribution to the UV luminosity of each object.

The identification of the nonstellar emission components in LINERs permits obtaining a picture of the nuclear SEDs of these low-luminosity AGNs across the electromagnetic spectrum.
Comparison of the SEDs to theoretical predictions for different accretion modes may be the most promising avenue for understanding how BHs “sleep”. SEDs of LINERs have been compiled by many authors, starting with Ho (1999); see Maoz (2007) for a summary. The main conclusion has often been that low-luminosity AGN SEDs are markedly different from those of luminous AGNs, in that underluminous objects have a weak or absent big blue bump, and are “radio loud” in terms of the ratio of luminosity in the radio relative to other bands. Work in progress for additional LINERs has been presented in Ho (2008).

In Maoz (2007), of which this contribution is a summary with some updates, I have revisited the SEDs of low-luminosity AGNs, motivated by several recent developments. First, a larger sample of LINERs having accurate HST/ACS UV photometry is now available. Furthermore, the observed variable fraction of the UV flux found by M05 in these objects provides a firm lower limit on the nonstellar AGN flux. Second, high-resolution X-ray measurements with Chandra and Newton XMM exist for most of these objects, permitting better isolation of the compact central X-ray source. Finally, recent statistical studies of the spectral properties of AGNs (e.g., Steffen et al. 2006; Sikora et al. 2007; Panessa et al. 2006,2007) allow a clearer comparison of SEDs as a function of luminosity and Eddington ratio, and thus give a better view of low-luminosity AGNs in the greater AGN context.

2. Sample
My objective in this work was to investigate the luminosity ratios between radio, UV, and X-ray emission in low-luminosity LINER-type AGNs. High-angular-resolution UV measurements, possible only with HST, have been carried out for relatively few galaxies, and in only 25 per cent of the LINERs among them is the UV nucleus unobscured by circumnuclear dust (see § 1, above). The final sample I analyze consists of 13 LINERs with suitable measurements. The reader is referred to Maoz (2007) for details of the sample and the data compilation for the individual objects.

3. Derived Quantities
The ratio of UV to X-ray luminosity in AGNs is usually discussed in terms of $\alpha_{\text{ox}}$, the spectral index of a hypothetical power-law between $L_\nu$ at 2500 Å and at 2 keV, or

$$\alpha_{\text{ox}} = \frac{\log[L_\nu(2500 \, \text{Å})/L_\nu(2 \, \text{keV})]}{\log[\nu(2500 \, \text{Å})/\nu(2 \, \text{keV})]}$$

$$= 0.384 \log[L_\nu(2 \, \text{keV})/L_\nu(2500 \, \text{Å})]. \quad (1)$$

I derive two values of $\alpha_{\text{ox}}$ for every galaxy in the sample, one based on the “high point” UV flux, and one based on the lower limit on the UV flux from an AGN, based on the variable flux. The latter provides an upper limit on $\alpha_{\text{ox}}$. One galaxy, NGC 3486, did not vary during the M05 campaign or before it, and hence there is no lower limit on its AGN UV flux. Furthermore, the nucleus is undetected in X-rays with only an upper limit. In this case I therefore use the UV “high point” and the X-ray upper limit to derive only an upper limit on $\alpha_{\text{ox}}$.

“Radio loudness”, $R$, is usually discussed in terms of the ratio of the luminosity at 5 GHz to the luminosity in optical, UV, or X-ray bands. I will define $R_{\text{UV}}$ as the ratio of $L_\nu$ between 5 GHz and 2500 Å,

$$R_{\text{UV}} \equiv L_\nu(6 \, \text{cm})/L_\nu(2500 \, \text{Å}). \quad (2)$$

As in the case of $\alpha_{\text{ox}}$, I calculate two values of $R_{\text{UV}}$ for each galaxy, one based on its highest UV measurement, and another based on the lower limit on the nonstellar UV flux, which gives an upper limit on $R_{\text{UV}}$. In three galaxies, NGC 404, NGC 3368, and NGC 3642, no radio core has been detected. The upper limit on the radio flux in each of these cases, combined with the UV
Figure 1. Radio through X-ray spectral energy distributions for some of the 13 LINERs, in $\log \nu L_\nu$ vs. $\log \nu$. Upper limits are $3\sigma$. Lower limits in the UV are based on the variable, and hence nonstellar, flux. The solid curves show the mean SEDs of radio-loud and radio-quiet quasars from Elvis et al. (1994), normalized to pass through the high UV 2500 Å measurement of each LINER.

high point and lower limit, give two separate upper limits on $R_{UV}$. In a fourth case, NGC 3486, there is an upper limit on the radio flux, and no UV variability is detected. In this case, there is only one upper limit on $R_{UV}$, based on the constant UV flux.

4. Results

The numbers compiled and derived above permit a renewed look at the SEDs of unobscured, LINER-type, low-luminosity AGNs, particularly the ratios of their UV, X-ray, and radio luminosities.

4.1. The SED

Figure 1 displays examples of the SED data of some of the objects. Following Ho (1999), I overlay in every frame the mean SEDs of radio-loud and radio-quiet quasars from Elvis et al. (1994), normalized to pass through the high UV 2500 Å measurements for the LINERs. All the multi-wavelength measurements I use are non-simultaneous, often with many years between the measurements in different bands. Variations by factors of a few in each band are common over these time-scales in low-luminosity objects (see, e.g., M05, and references therein). This uncertainty should be kept in mind when comparing the non-simultaneous measurements of each individual object to the mean quasar SEDs.

The sample of LINERs discussed here has been selected to be unobscured, is the sense that a nuclear UV point source is detected, optical imaging, when available, has not shown evidence for foreground dust extinction, and X-ray absorbing columns are $N_H < 10^{22}$ cm$^{-2}$. From Fig. 1,
it is qualitatively evident that the SEDs of this sample are not dramatically different from those of quasars [the typical quasars used to produce the Elvis et al. (1994) templates have \( \nu L_{\nu}(2500 \text{ Å}) \sim 10^{43} \text{ erg s}^{-1} \)]. While the ratio of X-ray to UV luminosity is sometimes larger in the LINERs, the difference is by not by more than a factor of a few. Furthermore, there is no clear evidence for the absence of an optical-UV bump, only perhaps some signs that such a bump may be weaker, relative to X-rays, compared to quasars.

In the radio, Fig. 1 confirms previous assessments that, compared to quasars, most low-luminosity AGNs are radio loud, or even “super radio loud”. The radio loudness and UV-to-X ratio are examined more quantitatively below.

$4.2 \ \alpha_{\text{ox}}$

Figure 2 permits a more quantitative look at the UV-to-X ratio by showing \( \alpha_{\text{ox}} \) as a function of UV luminosity. For every object in the LINER sample, I plot the two \( \alpha_{\text{ox}} \) values obtained by using either the high UV point or the UV lower limit, and connect them with a line. The true \( \alpha_{\text{ox}} \) is therefore somewhere along these connecting lines, but possibly even below the point corresponding to the highest UV measurement, because UV measurements are so susceptible to extinction. We thus see that \( \alpha_{\text{ox}} \) for most of the sample spans the range \(-1.4 < \alpha_{\text{ox}} < -0.8\).

To place these results in the wider AGN context, I reproduce in Fig. 2 the compilation by

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**Figure 2.** The UV-to-X-ray spectral index, \( \alpha_{\text{ox}} \), vs. 2500 Å luminosity, \( \nu L_{\nu}(2500 \text{ Å}) \). For every LINER, the value obtained by using its high UV point is shown with a filled square, the value based on its UV lower limit is marked as an upper limit on \( \alpha_{\text{ox}} \), and the two are connected with a line. Small symbols reproduce the compilation by Steffen et al. (2006) of \( \alpha_{\text{ox}} \) and 2500 Å luminosity for several samples of broad-lined AGNs. The best-fitting trend between these variables found by these authors for their sample is also shown (straight line). The \( \alpha_{\text{ox}} \) values for most of the LINER sample span the range \(-1.4 < \alpha_{\text{ox}} < -0.8\), largely overlapping with that of the Seyferts in the Steffen et al. sample. The short curves are from models by Merloni & Fabian (2002; see Maoz 2007).
Steffen et al. (2006) of $\alpha_{\text{ox}}$ and 2500 Å luminosity for several samples of broad-lined AGNs. Also plotted (straight line) is the best-fitting trend between these variables, as found by Steffen et al. (2006) for their sample. While the $\alpha_{\text{ox}}$ values for the LINERs are high compared to those of luminous quasars, as we saw quantitatively in Fig. 1 (most of the quasars in the Elvis et al. 1994 sample have $-1.5 < \alpha_{\text{ox}} < -1.2$), they are actually in a similar range to those of Seyfert 1 galaxies, having luminosities up to $\sim 10^{44}$ erg/s. The $\alpha_{\text{ox}}$’s of the LINERs are clearly below the extrapolation of the Steffen et al. relation to low luminosities. Indeed, based on their data alone, Steffen et al. already noted evidence (significant at the 2$\sigma$ level) for a flattening of the relation toward low luminosities. Figure 2 shows that such a turnover is unavoidable. Similarly, the $\alpha_{\text{ox}}$’s of the LINERs in the present sample are very similar to the values found by Greene & Ho (2007), $-1.0$ to $-1.2$, for a sample of type-1 AGNs having intermediate-mass BHs ($\sim 10^{5}$–$6M_{\odot}$), with luminosities $L_{\nu}(2500 \text{ Å}) = 10^{41}$–$43$ erg s$^{-1}$. We thus see that unobscured low-luminosity LINER AGNs, as far as their UV-to-X luminosity ratios are concerned, are quite similar to AGNs that are $10^{4}$ times more luminous in UV and X-rays.

4.3. Radio Loudness

Figure 3 plots the radio-loudness parameter, $R_{\text{UV}}$, vs. UV luminosity for the LINER sample. As in Fig. 2, the two possible values, based on the two UV measurements, are shown for every galaxy, and are connected by lines. For comparison, I include in Fig. 3 data from the recent compilation by Sikora et al. (2007) for several AGN samples. I convert the luminosities and $R$ parameters, which are given by Sikora et al. for the $B$-band (4400 Å), to 2500 Å, assuming an optical-UV power-law relation $f_{\nu} \propto \nu^{-0.5}$. The Sikora et al. (2007) points for the four LINERs in common with my sample (M81, NGC 3998, NGC 4203, NGC 4579) are not plotted.

Sikora et al. (2007) noted that, as pointed out by Ho (2002), radio loudness in inversely correlated with Eddington ratio. They showed, however, that the entire (possibly bimodal) distribution in $R_{\text{UV}}$, including both radio loud and radio quiet objects, shifts to higher $R$ values when going from high to low luminosities. The radio-loud “branch” in the distribution consists exclusively of massive elliptical galaxies, with correspondingly large BHs, while the radio-quiet branch included both spirals and ellipticals. Related results have been shown by Xu et al. (1999), Laor (2001), Best et al. (2005), Chiaberge et al. (2005), Wang, Wu, & Kong (2006), Panessa et al. (2007), and Chiaberge (2007).

The LINERs in the present sample conform with this picture. While their radio-to-UV luminosity ratios are often similar to those of radio-loud quasars, and sometimes even greater (as already seen qualitatively in Fig. 1), these AGNs fall on the same two branches on the diagram, with the majority actually being on the “radio-quiet” branch, with log $R_{\text{uv}} \approx 2$. (I note that, in their compilation of radio fluxes, Sikora et al. 2007 included extended radio flux, while I have made a point of isolating, at the highest spatial resolution possible, just the unresolved nuclear flux. Inclusion of the extended flux in the LINER sample would likely move some of the points upwards in the diagram to some degree. This shift would be by up to an order of magnitude for the objects on the “radio-loud” branch, e.g., M87, which is a FRI radio galaxy, but probably not by much for the others, since they are all core-dominated radio sources.) The four LINERs that are on the “radio-loud branch”, with log $R_{\text{uv}} \approx 4$, (NGC 1052, M87, NGC 4552, and NGC 4594) indeed all have high BH masses, above $10^{8}M_{\odot}$, and two of them have masses > $10^{9}M_{\odot}$. Equivalently, all the objects on the radio-loud branch have the lowest Eddington ratios, $\nu L_{\nu}(2500 \text{ Å})/L_{E} < 10^{-6}$.

Thus, in terms of their ratios of radio to UV luminosities, low-luminosity LINERs are, again, similar to AGNs of high luminosity, in that their radio loudness spans about 4 orders of magnitude, most of them are at the low-$R$ end of the distribution, and the most radio-loud cases occur in massive early-type galaxies.
Figure 3. The radio-to-UV (5 GHz to 2500 Å) radio loudness parameter $R_{\text{UV}}$, plotted vs. 2500 Å luminosity, $\nu L_\nu(2500 \text{ Å})$. As in Fig 2, $R_{\text{UV}}$ using each LINER’s high UV point is shown with a filled square, $R_{\text{UV}}$ based on the UV lower limit is marked as an upper limit, and the two are connected with a line. Double connected upper limits are based on the two UV measurements for objects that are undetected in radio. The single upper limit is NGC 3486, which is undetected in radio, and has no variability-based UV lower limit. Small symbols reproduce the compilation by Sikora et al. (2007) of $R$ and $L_B$ for several samples of AGNs, after converting their values from 4400 Å to 2500 Å. While all low-luminosity AGNs are, on average, radio-louder by a factor $\sim 100$ than high-luminosity quasars, most of the LINERs are actually on the “radio-quiet” branch of the distribution at low luminosities.

4.4. Comparison to Previous Work
The conclusions above, that LINER SEDs are overall similar to those of higher-luminosity AGNs, are in contrast to those of most previous LINER SED studies (see § 1). It is therefore instructive to understand the source of these different conclusions.

The claims by previous authors for a distinct SED in low-luminosity AGNs, with a weak or absent big blue bump, has been based on: (1) radio loudness; (2) a low UV/X-ray ratio; and (3) a steep optical-UV slope. In this paper, I have argued that (1) and (2) are actually quite similar in AGNs at low and intermediate luminosities. In terms of measurements, the values of $\alpha_{\text{ox}}$, e.g., for the five objects in common to Ho (1999), Ho et al. (2000), and to this work (M81, M87, NGC 4579, NGC 4594) are similar. Thus, the X-ray fluxes used by those authors, which were based on Einstein, Rosat, and ASCA measurements having lower angular resolutions, did not significantly overestimate the AGN flux (due, e.g., to inclusion of diffuse X-ray emission or discrete circumnuclear sources), and hence this is not the source of the discrepancy. Rather, with the more recent data on the statistics of $\alpha_{\text{ox}}$ (e.g., Steffen et al. 2006; Greene & Ho 2007) and $R$ (e.g., Sikora et al. 2007), the values for LINERs are seen to largely overlap with those for Seyferts.

However, the main source of the discrepancy concerns (3), the optical-UV slope of the SED, which I have chosen to ignore in the present work. Typical optical-UV power-law indices in quasars (assuming $f_\nu \propto \nu^{\alpha_{\text{uv}}}$) are $\alpha_{\text{uv}} \approx -0.5$ (Shang et al. 2005), $-0.65$ (vanden Berk et al. 2001, at low redshifts), or $-1$ (Zheng et al. 1997). The exact value depends on the chosen
wavelength range (optical contamination is a problem even in quasars), the bands to which the power law is fit, and how far to the UV one looks (the spectrum is not a pure power law, and it becomes steeper toward the far UV). Furthermore the spectral slope may depend on luminosity. By comparison, among LINERs that are apparently unobscured, previous SED studies have measured typical optical-UV slopes of $\alpha_{\text{opt}} \approx -1.5$ (although some LINERs, e.g., NGC 4579, have spectra that actually flatten in the UV, to $\alpha_{\text{opt}} \approx -0.5$; Maoz et al. 1998). Is this difference in $\alpha_{\text{opt}}$ between LINERs and higher-luminosity AGNs significant?

Efforts to isolate the nonstellar optical continuum in LINERs have been based on imaging (e.g., Chiaberge et al. 2006) or on the dilution of stellar features in optical spectra (e.g., Ho et al. 2000). All of these attempts, however, extrapolated the surface brightness outside the nucleus inwards in order to subtract the starlight, and/or assumed an unchanging stellar population when going from the bulge to the nucleus at HST resolution. Many galaxies (including the Milky Way), host compact nuclear star clusters. While those clusters that are detected as such are often young, in some galaxies the clusters could be of intermediate age, and hence much harder to discern as such, photometrically or spectroscopically. Due to such residual contamination by starlight, systematic errors by factors of a few in the optical luminosity are conceivable. While such errors would have little effect on estimates of radio loudness and $\alpha_{\text{ox}}$, they would have a strong impact on the optical-UV slope.

Some of the previous studies have used spectral slopes measured in the space-UV region, where stellar contamination is less of a problem. However, these estimates are extremely sensitive to small amounts of foreground extinction. A $V$-band extinction of $A_V = 0.2$ mag is sufficient to change a UV power-law slope of $-0.5$ to $-1.5$ (see discussion in Maoz et al. 1998). The preponderance of lanes, wisps, and clumps of dust seen in the neighbourhoods of most LINERs (see, e.g., Pogge et al. 2000; Chiaberge et al. 2006) makes it likely that even relatively unobscured objects undergo some small degree of reddening. Such reddening, rather than an intrinsic lack of UV emission, could be the cause of the UV steepening of LINER SEDs. (NGC 4579, with its UV slope of $-0.5$, may be the case of an unobstructed line of sight.) Given these uncertainties, I have ignored in this work measurements of optical-UV slopes in LINERs. The remaining observables suggest a similarity, rather than a difference, between the SEDs of LINERs and those of more luminous AGNs.

5. Discussion and Conclusions

The optical-to-UV emission in luminous AGNs is widely thought to come from the inner parts of a thermally radiating, geometrically thin, accretion disc. If so, this emission provides the most direct measure of the accretion rate on to the BH. Tracking this measure to lower and lower luminosities requires reliance on the UV, which is less susceptible than the optical emission to contamination by the old stellar population of galaxy bulges.

I have used new, high-angular-resolution data, particularly recent measurements and variability-based lower limits in the UV, to re-assess the SED of low-luminosity LINER nuclei. I have focused on unobscured objects in which the faint nuclear emission has been properly isolated from surrounding contamination. I have ignored IR and optical data and optical-UV slopes, which can be strongly affected by stellar contamination and by small amounts of reddening by dust. With these choices, I have shown that the SEDs of LINERs are similar to those of Seyfert-type AGNs $10^4$ to $10^4$ more luminous. This similarity is seen quantitatively in the parameters $\alpha_{\text{ox}}$ and $R_{\text{UV}}$. The lack of any conspicuous “phase transition” as a function of luminosity or accretion rate in the SEDs of LINERs, extends similar recent results by Panessa et al. (2007) for low-luminosity Seyferts.

It is tempting to speculate, therefore, that the same combination of physical components that gives rise to the SEDs of quasars is present at luminosities and accretion rates that are $\sim 10^{5-8}$ times smaller. In particular, if radiatively efficient accretion discs produce the UV
emission in quasars, there is no compelling evidence that such discs disappear at low luminosities. Instead, the ratio of UV to X-ray emission is fairly insensitive to luminosity. It is only the ratio of luminosities between radio and other wavelengths that does increase dramatically as the luminosity decreases. However, it seems that the entire distribution of radio loudness shifts to higher values, with most objects remaining at the low side of the $R$ distribution. The decrease in the accretion rate on to a supermassive BH (as traced by the UV luminosity) could thus be manifest as a hand-in-hand decrease in the UV and X-ray luminosities, but with a much smaller decrease in radio luminosity. The sources of the UV radiation (presumably a thin accretion disc, although synchrotron emission from the jet could also contribute or dominate, e.g., Chiaberge et al. 1999; Verdoes Kleijn et al. 2002) and of the X-rays apparently persist, but are simply scaled down, with a minor increase in the prominence of the X-ray emission. At this meeting, E. Ros (these proceedings) also showed new Suzaku data of what is apparently a relativistically broadened Fe K-α line in the prototypical LINER NGC 1052. In luminous AGNs, such lines are thought to result from reflection off the innermost regions (few Schwarzschild radii) of a thin accretion disk. In fact, Ho (2008) has recently argued that the absence of broad iron lines in LINERs is more evidence for the disappearance of thin disks at low luminosities. These new results by Ros et al. cast yet more doubt on this distinction.

Interestingly, analogous results have been found recently for stellar-mass Galactic BHs. Miller et al. (2006a,b) have analysed data for three BHs (including a re-analysis of ASCA data for Cygnus X-1 in its low state) accreting at $\sim 10^{-2}$ to $\sim 10^{-3}$ of the Eddington rate. In each case, the soft X-ray spectra require the presence of a thermally radiating thin accretion disc, down to the innermost marginally stable circular orbit. There is no obvious reason why such “mass-starved” structures could not exist at even-lower low accretion rates. RIAFs were devised in order to explain the low luminosities that are observed from dormant galactic nuclei, despite the significant rates of mass infall expected on to the BHs. Instead, the evidence for the persistence of thin, radiatively efficient, but mass-flow-starved, discs suggests that some mechanism prevents gas from reaching the inner parts of the accretion flow in the first place. The radio loudness at low luminosities points to a solution in which gas joins a jet or outflow long before reaching the innermost orbits. High-resolution radio images of M87 indeed reveal a very wide base for the jet, of order $100R_S$ or more (Jnor et al. 1999; Ly et al. 2007; see also C. Walker, these proceedings), suggestive of this picture.

To summarize, I have compiled recent radio, UV, and X-ray data for a sample of 13 unobscured low-luminosity LINER AGNs. I have shown that their interband luminosity ratios are not dramatically different from those of higher luminosity AGNs. Specifically, in terms of their UV/X ratios, there is only a slightly enhanced prominence of the X-ray emission compared to intermediate-luminosity AGNs. There is thus no obvious indication for the disappearance of the big blue bump at low luminosities, suggesting the persistence of thin accretion discs in the low-accretion-rate regime. In terms of radio/UV luminosity ratios, the LINERs span a range of 4 orders of magnitude, with most of them residing at the lower end of the distribution, with $\log R_{uv} < 2$. In this sense, these low-luminosity AGNs again are part of a continuous sequence with higher luminosity objects. Since at least some, if not all, of the radio emission in AGNs is known to come from jets, this suggests a picture in which, at decreasing accretion rates, a progressively larger fraction of the inflowing mass is channeled into an outflow, and a smaller fraction into the persistent thin accretion disk. Analogous results have been obtained recently for some Galactic stellar-mass BHs.

While I have made an effort to compile the best available data, the measurements analyzed here are still crude. In particular, the fact that the measurements in different bands are often separated by years, coupled with the large fluctuations in flux that are common in low-luminosity AGNs, means that individual luminosity ratios could be off by an order of magnitude. In P. Romano et al. (in preparation) we have taken a first step in this direction by means of
contemporaneous X-ray and UV data for four of the LINERs described here using SWIFT. Repeated observations of individual objects over few-year time-scales could reveal changes in SED as a function of changing luminosity. Such monitoring would also reduce the uncertainty regarding the non-stellar contribution to the UV, another major source of error in the present work. Detection of nuclear variability also in the optical (with HST) and in the IR (with Spitzer) would permit measuring reliably the AGN component in those bands as well, significantly sharpening our view of the SED. Finally, much larger samples of unobscured low-luminosity AGNs, analyzed in similar ways, could clarify the picture considerably. A larger, UV-selected, sample of such objects could be assembled by means of UV imaging (e.g., with GALEX or with HST) and subsequent optical spectroscopic classification to identify the LINERs. UV imaging need not necessarily be from space – the UV nuclei of the current sample are prominent in the F330W band, so such objects could potentially be identified by ground-based observations near the atmospheric UV cutoff. Alternatively, one could begin with the large, optically selected, SDSS LINER sample of Kewley et al. (2006), and follow it up with sensitive multiwavelength observations.

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