LINERs AS LOW-LUMINOSITY ACTIVE GALACTIC NUCLEI

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ABSTRACT. Many nearby galaxies contain optical signatures of nuclear activity in the form of LINER nuclei. LINERs may be the weakest and most common manifestation of the quasar phenomenon. The physical origin of this class of objects, however, has been ambiguous. I draw upon a number of recent observations to argue that a significant fraction of LINERs are low-luminosity active galactic nuclei.

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1. AGN CENSUS IN NEARBY GALAXIES

The local space density of active galactic nuclei (AGNs) has bearing on a number of issues in extragalactic astronomy, including the fraction of galaxies hosting massive black holes, the cosmological evolution of quasars, and the contribution of AGNs to the cosmic X-ray background. It is therefore of fundamental importance to establish the extent and nature of nuclear activity in nearby galaxies. This contribution summarizes recent efforts to survey nearby galactic nuclei, discusses complications regarding the interpretation of the results, and presents a variety of fresh observational perspectives that help toward reaching a coherent understanding of nuclear activity in nearby galaxies.

Optical surveys find that a large fraction of nearby galaxies have nuclei that emit weak emission lines with a spectrum unexpected for photoionization by normal stars. Heckman (1980) identified low-ionization nuclear emission-line regions (LINERs) as a major constituent of the extragalactic population, particularly among early-type galaxies. The optical spectra of LINERs broadly resemble those of traditional AGNs such as Seyfert nuclei, except that they have characteristically lower ionization levels. These findings were strengthened by a number of subsequent studies, as reviewed by Ho (1996).

The latest and most sensitive survey of this kind was completed by Ho et al. (1997a, and references therein) using the Hale 5 m telescope at Palomar Observatory. Long-slit spectra of exceptional quality were taken of the nuclear region of a magnitude-limited ($B_T \lesssim 12.5$ mag) sample of 486 northern ($\delta > 0°$) galaxies that constitutes an excellent representation of the typical nearby galaxy population. The spectra are of moderate resolution (full-width at half maximum [FWHM] ~ 100-200 km s^{-1}) and cover two regions of the optical window (4230-5110 Å and 6210-6860 Å) containing important diagnostic emission lines. The main results of the Palomar survey are the following. (1) AGNs are very common in nearby galaxies (Fig. 1). At least 40% of all galaxies brighter than $B_T = 12.5$ mag emit AGN-like spectra. The emission-line nuclei are classified as Seyferts, LINERs, or LINER/H II-region composites, and most have very low luminosities compared to traditionally studied AGNs. The luminosities of the Hα emission line range from 10^{37} to 10^{41} ergs s^{-1}, with a median value of ~ 10^{39} ergs s^{-1}. (2) The detectability of AGNs depends strongly on the morphological type of the galaxy, being most common in early-type systems (E-Sbc). The detection rate of AGNs reaches 50%-75% in ellipticals, lenticulars, and bulge-dominated spirals but drops to $\lesssim 20\%$ in galaxies classified as Sc or later. (3) LINERs make up the bulk (2/3) of the AGN population and a sizable fraction (1/3) of all galaxies. (4) A significant number of objects show a faint, broad (FWHM $\gtrsim$ 1000-4000 km s^{-1}) Hα emission line that qualitatively resembles emission arising from the conventional broad-line region of ``classical'' Seyfert 1 nuclei and QSOs.
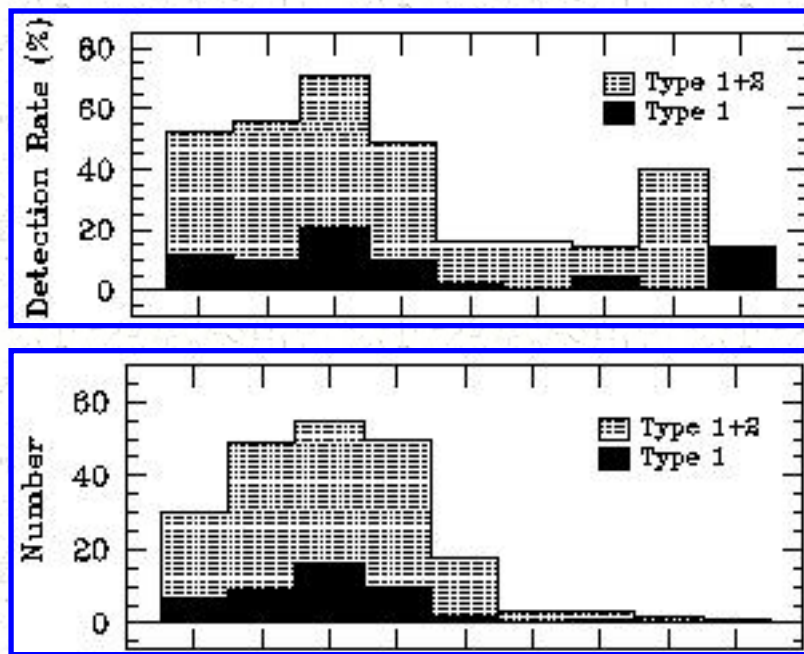
Figure 1. Detection rate (*left*) and number distribution (*right*) of AGNs as a function of Hubble type in the Palomar survey. ``Type 1'' AGNs (those with broad Hα) are shown separately from the total population (types 1 and 2).

Radio observations provide further support for the prevalence of nuclear activity (see the contribution of E. Sadler in these proceedings). Weak radio cores with powers of 10^{19}-10^{21} W Hz^{-1} at 5 GHz are found in ~ 50% of nearby elliptical and S0 galaxies (Sadler et al. 1989; Wrobel and Heeschen 1991). Where information is available, the cores have relatively flat spectral indices and nonthermal brightness temperatures (Slee et al. 1994), and the optical spectra of most of these sources are classified as LINERs (Sadler et al. 1989; Ho 1998a).

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2. RECENT OBSERVATIONAL RESULTS ON LINERs

If LINERs are powered by a nonstellar source, then LINERs clearly would be the most common type of AGNs known in the nearby regions of the universe. However, ever since their discovery, the physical origin of LINERs has been hotly debated. The recognition and definition of LINERs is based on their spectroscopic properties at optical wavelengths. In addition to the AGN scenario, the optical spectra of LINERs unfortunately can be interpreted in several other ways that do not require an exotic energy source (e.g., shocks, hot stars; see Ho et al. 1993 and Filippenko 1996 for reviews). As a consequence, it has often been suggested that LINERs may be a mixed-bag, heterogeneous collection of objects. While the nonstellar nature of some well-studied LINERs is incontrovertible (e.g., M81, M87, M104), the AGN content in the majority of LINERs remains unknown. Determining the physical origin of LINERs is more than of mere phenomenological interest. Because LINERs are so numerous, they have a tremendous impact on the specification of the faint end of the local AGN luminosity function, which itself bears on a range of issues. A number of recent developments provide considerable new insight into the origin of LINERs. I outline these below, and I use them to advance the proposition that *most* LINERs are truly AGNs [1]

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[1] Note that this paper is concerned only with compact, *nuclear* LINERs ($r \lesssim 200$ pc), which are most relevant to the AGN issue. LINER-like spectra are often also observed in extended nebulae such as those associated with cooling flows, nuclear outflows, and circumnuclear disks. Back.

2.1. *Host Galaxy Properties*

LINERs and Seyferts live in virtually identical host galaxies ([Fig. 2](#)). The vast majority of both classes occupy bulge-dominated, early-type systems (87% are found in types E-Sbc), which clearly differ from the population of galaxies whose nuclear spectrum indicates photoionization by current star formation (the so-called H II-nuclei), which is dominated by late-type hosts (63% are Sc's and later). The only noticeable difference in the distribution of morphological types of LINERs and Seyferts is that LINERs occupy a higher proportion of ellipticals. Bars exist with roughly the same frequency within the subsample of disk galaxies in both groups.

The similarity in the host galaxy properties of LINERs and Seyferts becomes even more apparent when we examine their absolute magnitude distributions ([Fig. 2](#)); they are statistically indistinguishable. Both peak at $M_{B_T}^0 \simeq$ -20.5 mag (for $H_0 = 75$ km s^{-1} Mpc^{-1}), about 0.4 mag brighter than $M_{B_T}^*$, the typical absolute magnitude of the field-galaxy luminosity function. The parent galaxies of H II-nuclei, on the other hand, are systematically fainter than the other two groups by ~ 0.5 mag in the median.
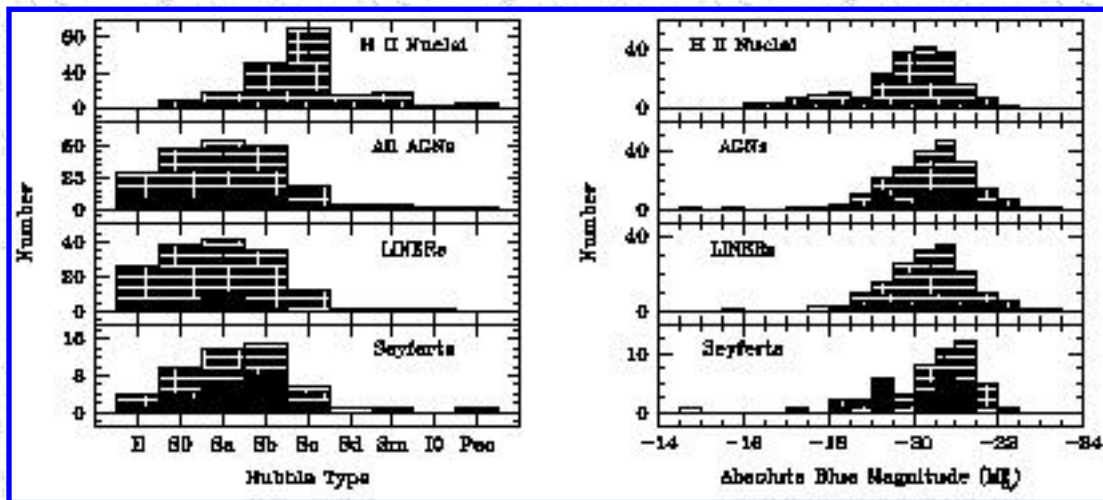

Figure 2. Number distribution of morphological types (*left*) and total absolute blue magnitudes (*right*) for H II nuclei, all AGNs (LINERs + Seyferts), and LINERs and Seyferts separately. The median of each distribution is marked by an arrow. Adapted from [Ho et al. (1997a)](#).

2.2. *Detection of Massive Black Holes*

There has been considerable recent progress in the detection of dark masses, plausibly interpreted as massive black holes, in nearby galactic nuclei (see Ho 1998c and the contribution by S. Faber). A significant fraction of the known black hole candidates, albeit still a small number, in fact are well known LINERs. These include M81 ($M_{BH} \approx 4 \times 10^6\ M_\odot$), M84 ($1.5 \times 10^9\ M_\odot$), M87 ($3 \times 10^9\ M_\odot$), the ``Sombrero'' galaxy ($1 \times 10^9\ M_\odot$), NGC 4261 ($5 \times 10^8\ M_\odot$), and Arp 102B ($2 \times 10^8\ M_\odot$). Although certainly no statistical conclusions can yet be drawn, these examples nevertheless serve as a powerful proof-of-concept that at least *some* LINERs are incontrovertibly accretion-powered sources.

2.3. *Detection of Broad-Line Regions*

Bona fide AGNs such as QSOs and luminous Seyfert 1 nuclei distinguish themselves unambiguously by their characteristic broad (FWHM ~ few thousand km s^{-1}) permitted lines which arise from the broad-line region (BLR). The detection of such broad lines in LINERs would constitute strong evidence in favor of the AGN interpretation of these sources. Since the strongest permitted line at optical wavelengths is expected to be Hα, one of the primary goals of the Palomar survey was to search for broad Hα emission. Of the sample of objects with broad Hα emission (22% of the AGN candidates), more than half belong to the LINER category (Ho et al. 1997b; see Fig. 3). This is a very important finding, because it implies that LINERs, like Seyferts, evidently come in two flavors - some have a visible BLR, and others do not. By direct analogy with the nomenclature established for Seyferts, we might extend the ``type 1" and ``type 2" designations to include LINERs. Approximately 15%-25% of the LINER population are LINER 1s, the appropriate fraction depending on whether the so-called transition objects (Ho et al. 1993) are regarded as LINERs.
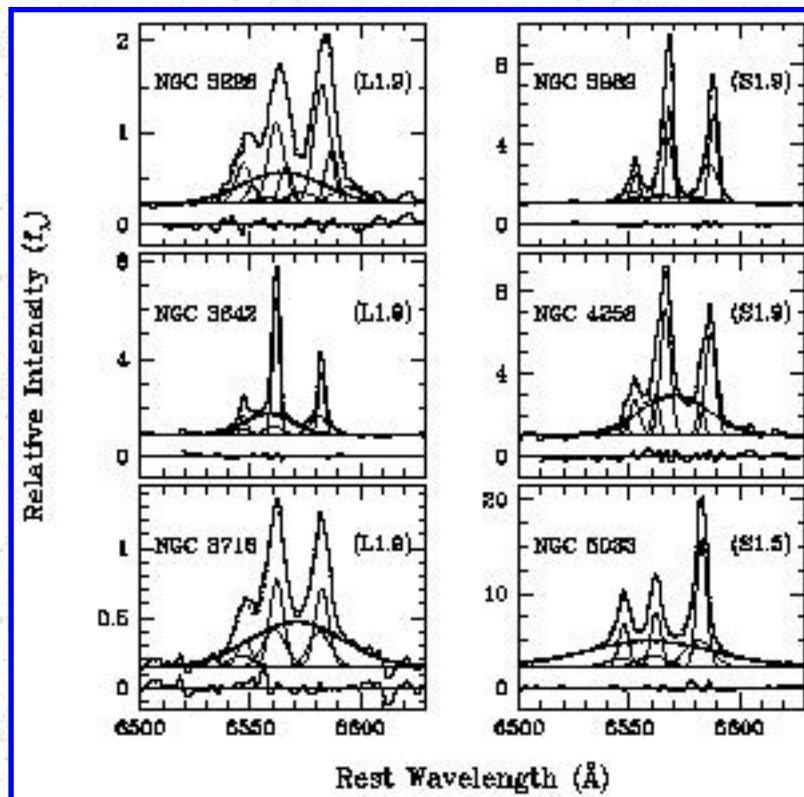

Figure 3. Decomposition of the Hα + N II region for LINERs and Seyferts. The broad Hα component is shown as a heavy line. Adapted from Ho et al. (1997b).

A remaining, outstanding question, however, is what fraction of the LINER 2s are AGNs. Again, by analogy with the Seyfert 2 class, surely *some* LINER 2s must be genuine AGNs - that is, LINERs that

happen to have no BLR or have an obscured BLR. There is no *a priori* reason why the unification model, which has enjoyed such popular support in the context of Seyfert galaxies, should not equally apply to LINERs. The existence of an obscuring torus does not obviously depend on the value of the ionization level of the line-emitting regions. If we suppose that the ratio of LINER 2s to LINER 1s is the same as the ratio of Seyfert 2s to Seyfert 1s, that ratio being 1.4:1 in the Palomar survey, we might argue that the AGN fraction in LINERs may be as high as ~ 40%-60%. What evidence is there, however, that the unified model is applicable to LINERs? The faintness of the sources in question renders application of the classical spectropolarimetric test (e.g., Antonucci and Miller 1985) impractical for moderate-sized telescopes. An important breakthrough was recently achieved by Barth (1998), who successfully used the Keck 10 m telescope to detect a polarized broad Hα line in the prototypical LINER NGC 1052 (Fig. 4). Weak broad Hα wings were previously found in the total-light spectrum after very careful profile decomposition (Ho et al. 1997b), but the broad line is undeniable in scattered light. Some LINER 2s evidently *do* harbor obscured BLRs. It would be highly desirable to extend these observations to larger samples.
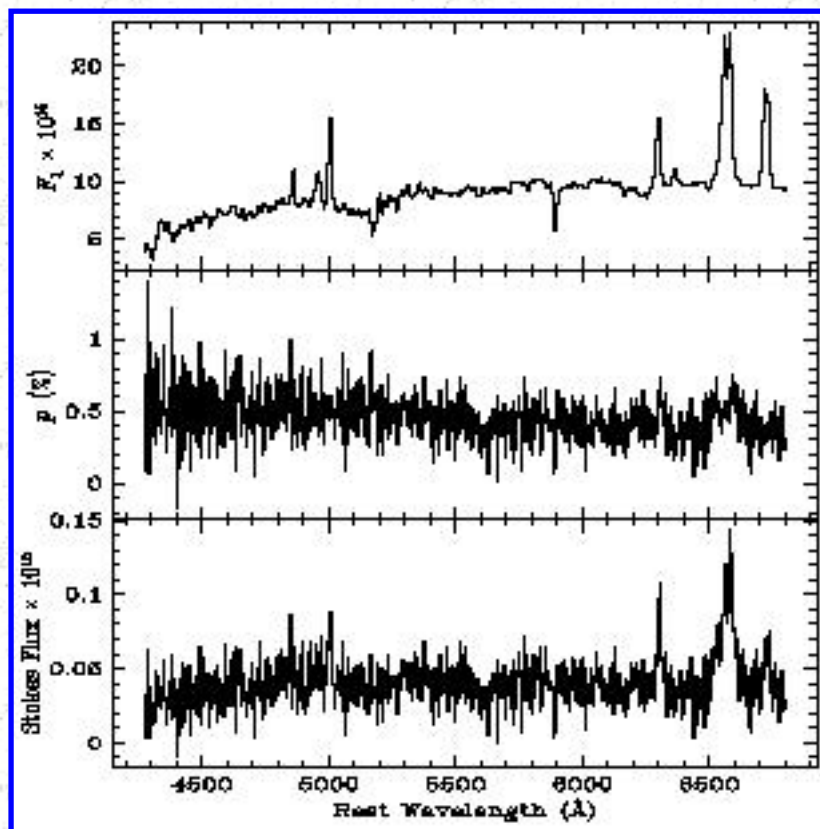

Figure 4. Keck spectra of NGC 1052 from Barth (1998). Top panel - Total flux spectrum. Middle panel - Percent polarization. Bottom panel - Stokes flux obtained from $F\lambda *$ *p*.

Lest one doubts that the existence of BLRs can be established with the detection of a single broad line, it should be remembered that broad lines are seen in other transitions as well, particularly in the ultraviolet (UV) where contamination by old stars poses less of a problem. The two best examples are M81 (Ho et

al. 1996) and NGC 4579 (Barth et al. 1996) which were observed with the *Hubble Space Telescope (HST)*. Finally, note that the minority of AGNs that display so-called double-peaked broad emission lines, whose origin is widely thought to lie in a relativistically rotating accretion disk, in fact very often exhibit LINER-like narrow-line spectra (Eracleous 1998 an references therein).

2.4. *Ultraviolet Emission and Constraints on Shock Excitation*

The nonstellar nature of LINERs might be revealed through the presence of a central compact source responsible for the photoionizing continuum. The UV band is preferred over the optical because it minimizes contamination from old stars, although it is much more adversely affected by dust extinction. Two imaging surveys performed with the *HST* (Maoz et al. 1995; Barth et al. 1998) find that LINERs in fact do contain compact UV emission, but in only 20%-25% of the cases. By itself, however, this result is ambiguous. Are the central UV sources in most LINERs obscured by dust, are they in the ``off'' state of a duty cycle most of the time as suggested by Eracleous et al. (1995), or do the majority of LINERs simply lack a pointlike ionizing source because they are not AGNs after all? There is some indication that the sources detected in the UV tend to be in more face-on galaxies than the undetected sources (Barth et al. 1998). Moreover, as discussed below, LINERs seem to be *intrinsically* weak in the UV, and this may further contribute to the low detection rates. Mere morphological information, of course, cannot specify definitively the physical origin of the UV emission. For example, the point sources could be simply very compact nuclear star clusters. Indeed, follow-up spectroscopy indicates that the bulk of the UV emission in some sources comes from young massive stars (Maoz et al. 1998). Others, on the other hand, exhibit featureless, power-law continua as expected for an energetically significant AGN component (M81: Ho et al. 1996; NGC 4579: Barth et al. 1996; M87: Tsvetanov et al. 1998).

Collisional ionization by shocks has been considered a plausible energy source for LINERs since the discovery of these objects (Fosbury et al. 1978; Heckman 1980). Dopita and Sutherland (1995) recently showed that the diffuse radiation field generated by fast ($v \simeq$ 150-500 km s^{-1}) shocks can reproduce the optical narrow emission lines seen in both LINERs and Seyferts. In their models, LINER-like spectra are realized under conditions in which the precursor H II region of the shock is absent, as might be the case in gas-poor environments. The postshock cooling zone attains a much higher equilibrium electron temperature than a photoionized plasma; consequently, a robust prediction of the shock model is that it should produce a higher excitation spectrum, most readily discernible in the UV, than photoionization models. In all the cases studied so far, the UV spectra are inconsistent with the fast-shock scenario because the observed intensities of the high-excitation lines such as C IV λ1549 and He II λ1640 are much weaker than predicted (Barth et al. 1996, 1997; Nicholson et al. 1998; Maoz et al. 1998). [The case of M87 presented by Dopita et al. (1997) is irrelevant to the present discussion because those observations explicitly avoided the nucleus of the galaxy.] The data, however, cannot rule out contributions from slower shocks ($v \lesssim$ 150 km s^{-1}), although the viability of shock ionization in luminous AGNs has been criticized on energetic grounds by Laor (1998).

2.5. *Clues from the X-rays*

Compact soft X-ray emission on the scale of the *ROSAT* HRI camera (~ 5") has now been detected in a handful of LINERs (e.g., Worral and Birkinshaw 1994; Koratkar et al. 1995; Fabbiano and Juda 1997), although no statistical conclusions can yet be drawn based on the scant data available. Most of the core sources have luminosities clustering near L(0.5-2 keV) $\approx 10^{40}$-10^{41} ergs s^{-1} because of selection effects. The pointlike morphology of the *ROSAT* images certainly agrees with our expectation for an AGN source, but we must remember that the 5" point-spread function of the HRI subtends an uncomfortably large region (several hundred parsecs) at the typical distances of these objects. Images taken at much higher angular resolution and ideally at harder energies, such as would be possible with the ACIS camera on *AXAF* (see the concluding remarks at the end of the paper), are needed to put more stringent constraints on the nature of the X-ray emission.

In the meantime, progress can be made by examining the *ASCA* hard X-ray spectra of LINERs whose X-ray structure is found to be compact on HRI images. These data, again, are scarce, and current constraints by necessity bias the sample in favor of the brightest targets. Nonetheless, when the observations are considered collectively (Serlemitsos et al. 1996; Terashima et al. 1997; Ptak 1998; Ptak et al. 1998; Iyomoto et al. 1998; Nicholson et al. 1998; see contributions by H. Awaki and Y. Terashima), the following trends appear. (1) The 2-10 keV continuum can generally be modeled as a single power-law function modified by cold absorption; the best-fitting photon index, $\gamma \approx 1.7$-1.8, agrees well with values normally measured in luminous AGNs. In some cases the fits require an additional soft thermal component with a temperature of $kT \approx 1$ keV. (2) There is no evidence for significant amounts of cold material along the line of sight. Any measurable absorbing column in excess of the Galactic contribution usually does not exceed $N_H \approx 10^{21}$ cm^{-2}. (3) Broad Fe Kα emission at 6.4 keV, a feature common to many luminous Seyfert 1 nuclei, is usually either absent or unusually weak. The composite LINER spectrum of Terashima et al. (1997) shows no detectable Fe Kα line to an equivalent-width limit of 140 eV. In the few cases where an iron line has been detected, the rest energy is ~ 6.7 keV, consistent with ionized instead of neutral iron. And (4), these sources do not undergo rapid X-ray variability at the level expected from extrapolation of the variability behavior established for more luminous sources.

2.6. *Compact Radio Cores*

Finally, further verisimilitude with the AGN phenomenon can be sought by means of high-resolution radio continuum observations. As already mentioned above, compact, flat-spectrum cores of low power are often found in radio continuum surveys of nearby elliptical and S0 galaxies. Less certain is the incidence of the similar phenomenon in spirals, which in general tend to be rather weak radio sources. A large subsample of LINERs from the Palomar survey is being systematically mapped at 2, 3.6, and 6 cm using the the Very Large Array in its most extended configuration. The highest angular resolution achieved is comparable to that of *HST*, and faint, sub-mJy compact sources can be routinely detected with ease. The preliminary analysis, reported in Van Dyk and Ho (1997), finds that the 6 cm maps nearly always detect a single, compact core spatially coincident with the optical nucleus. Most of the radio cores have relatively steep spectral indices consistent with optically thin synchrotron emission, but a significant fraction has flat, presumably optically thick, spectra (Falcke et al. 1997).

2.7. *The Spectral Energy Distributions of LINERs*

Luminous AGNs generally display a fairly ``universal'' spectral energy distribution (SED) (e.g., Elvis et al. 1994). The SED from the infrared to the X-rays, roughly flat in log ν $F\nu$ - log ν space, can be represented by an underlying power law ($\alpha \approx 1$, where $F\nu \propto \nu^{-\alpha}$) superposed with several distinct components, the most prominent of which is a broad UV excess. This so-called big blue bump is conventionally interpreted as thermal emission from an optically thick, physically thin accretion disk (Malkan and Sargent 1982). As multiwavelength data for LINERs and other low-luminosity AGNs become more readily available, we can begin to piece together their SEDs. Comparing SEDs of AGNs of various luminosities might yield clues to physical processes that depend on luminosity.

The SEDs of the low-luminosity AGNs share a number of common traits, and yet they differ markedly from the SEDs of luminous AGNs (Ho 1998b). To illustrate this point, Figure 5 normalizes the SEDs of seven low-luminosity objects (mostly LINERs) with the median SED of radio-loud and radio-quiet AGNs from Elvis et al. (1994). Several features are noteworthy. (1) The optical-UV slope is quite steep. The power-law indices for the seven low-luminosity objects average $< \alpha > \approx 1.8$, whereas in luminous AGNs $\alpha \approx 0.5\text{-}1$. (2) The UV band is exceptionally dim relative to the optical and X-ray bands; there is no evidence for a big blue bump component. Indeed, the SED reaches a local minimum somewhere in the far-UV or extreme-UV region. The mean value of α_{ox}, the two-point spectral index between 2500 Å and 2 keV, is ~ 0.9, to be compared with $< \alpha_{ox} > = 1.2\text{-}1.4$ for luminous Seyferts and QSOs. (3) There is tentative evidence for a maximum in the SED at mid-IR wavelengths. (4) The nuclei have radio spectra that are either flat or inverted. (5) All sources, including the three spiral galaxies in the sample, qualify as being *radio-loud*. This finding runs counter to the usual notion that only elliptical galaxies host radio-loud AGNs. (6) The bolometric luminosities of the sources range from $L_{bol} = 2 \times 10^{41}$ to 8×10^{42} ergs s^{-1}, or ~ $10^{-6}\text{-}10^{-3}$ times the Eddington rate for the black hole masses estimated for these objects.
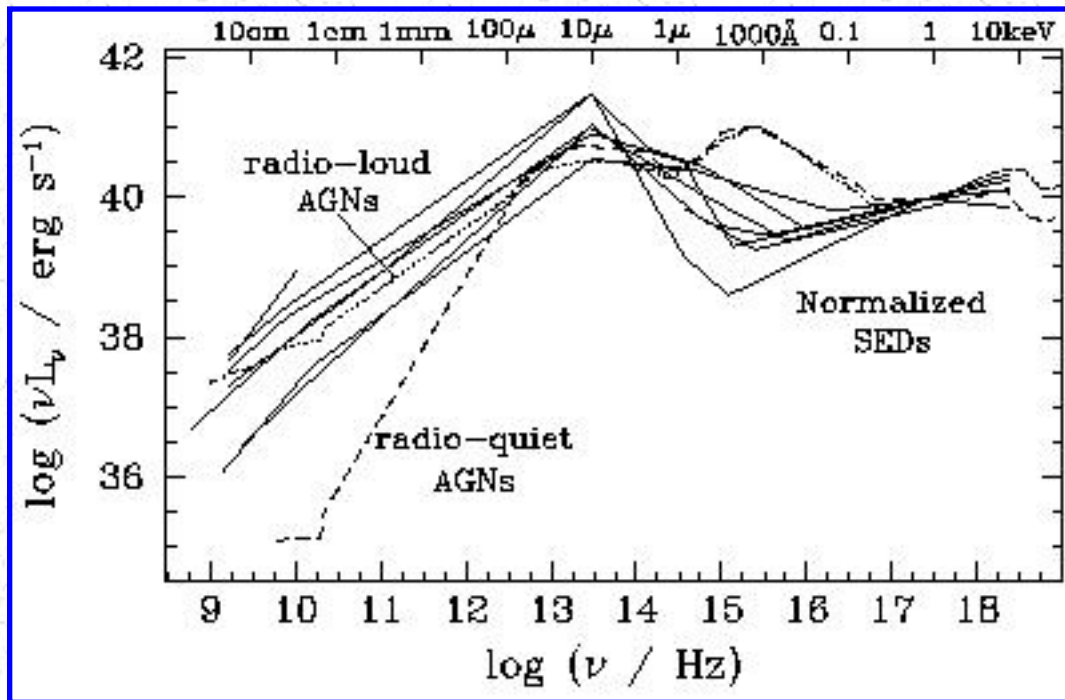
Figure 5. Interpolated SEDs of seven low-luminosity AGNs (*solid lines*) normalized to the 1 keV luminosity of M81. The median SEDs of radio-loud (*dotted line*) and radio-quiet (*dashed line*) AGNs of Elvis et al. (1994), normalized in the same way, have been overplotted for comparison. From Ho (1998b).

The overall characteristics of these nonstandard SEDs can be explained by models of ``advection-dominated accretion flows" (ADAFs; see Narayan et al. 1998 for a review). The accretion flow equations admit a stable advection-dominated, optically thin solution when the accretion rate falls to very low values ($\dot{M} \lesssim 10^{-2} \dot{M}_{\rm Edd}$). Under these conditions, the low density and low optical depth of the accreting material lead to inefficient cooling, and the resulting radiative efficiency is much less than the canonical value of 10%. This accounts for the low observed luminosities. Moreover, the predicted SEDs of ADAFs look radically different from the SEDs of optically thick disks but provide a good match for the observations of low-luminosity AGNs (Ho and Narayan 1998).

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3. A PHYSICAL DESCRIPTION OF LINERs

The evidence summarized in the preceding sections paints the following picture for the physical nature of LINERs. For reasons yet to be fully understood, the narrow emission-line regions of AGNs evidently can allow a wide range of ionization parameters (the ratio of the density of ionizing photons to the density of gas at the illuminated face of a cloud; $U \equiv L_{ion} / 4\pi\, cnr^2$). Those with $U \approx 10^{-2}$-10^{-1} are conventionally denoted ``Seyferts;'' low-ionization objects with $U \approx 10^{-3.5}$-$10^{-2.5}$ are called ``LINERs'' ([Halpern and Steiner 1983](#); [Ferland and Netzer 1983](#); [Ho et al. 1993](#)). There is no sharp division, other than that imposed for sheer taxonomical convenience, between the two groups. Like Seyferts, some LINERs (~ 20%) come equipped with a BLR. The others either do not have BLRs, or their BLRs are obscured from the observer. At least some of the type 2 LINERs definitely have hidden BLRs that can only be seen in scattered light.

Most LINERs inhabit large, bulge-dominated galaxies, the very galaxies that evidently are most prone to host supermassive black holes. Thus, LINERs can be identified with the quiescent black-hole remnants from the quasar era. In the present epoch, the supply of gas available for powering the central engines is much curtailed, and the resulting low accretion rates lead to an advection-dominated mode of accretion that manifests itself in the low luminosity output and in the peculiar SEDs of the nuclei. The diminished nuclear power naturally accounts for the low values of U in LINERs, and the likely preponderance of ADAFs in nearby galactic nuclei may explain why LINERs are so ubiquitous. Two additional effects may help to further reduce the ionization state of the line-emitting gas. The modification of the SED from UV to X-ray energies, most noticeable by the absence of the UV excess, leads to an overall hardening of the ionizing spectrum. The exceptional strength of the radio component, on the other hand, increases the effectiveness of cosmic-ray heating of the gas by the energetic electrons (e.g., [Ferland and Mushotzky 1984](#)). Both effects result in an enhancement of the low-ionization lines.

4. FUTURE DIRECTIONS

Future studies should refine the statistical completeness of the current AGN surveys. The Palomar survey, while a significant improvement compared to previous optical surveys, is nonetheless limited by ground-based seeing and by host galaxy contamination. In early-type galaxies, where the contamination from starlight is strong, there is a practical limit to which weak emission lines can be extracted from the total spectrum. On the other hand, in late-type galaxies the strong emission from H II regions in and near the nucleus can easily mask the fainter signature of a weak AGN that might be present. The reported low incidence of AGNs in late-type galaxies, therefore, may be misleading and needs to be verified. A significant increase in sensitivity to weak nuclear emission can be achieved with high-angular resolution spectroscopy with *HST*. A follow-up program to assess the completeness of the Palomar survey is being performed with the Space Telescope Imaging Spectrograph.

The recent availability of high-quality multiwavelength observations has provided important clues toward resolving the LINER mystery. As outlined in this review, while the data collectively, and in some instances even individually, do support the AGN interpretation for LINERs, it is still premature to draw quantitative, statistical conclusions concerning the AGN content in LINERs. The most outstanding unanswered question is the fraction of the LINER 2 population which are genuine AGNs. The cleanest test of the AGN hypothesis must rely on high-resolution observations in the hard X-ray band, which is the least affected by absorption and by confusion from young stars. Detection of a single compact hard X-ray source coincident with the nucleus would constitute strong evidence for the existence of an accretion-powered source. Such an experiment is being planned for the ACIS camera (resolution ~ 0".5) on *AXAF*.

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