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Black Hole Demography from Nearby Active Galactic Nuclei

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Abstract

A significant fraction of local galaxies show evidence of nuclear activity. I argue that the bulk of this activity, while energetically not remarkable, derives from accretion onto a central massive black hole. The statistics of nearby active galactic nuclei thus provide an effective probe of black hole demography. Consistent with the picture emerging from direct dynamical studies, the local census of nuclear activity strongly suggests that most, perhaps all, galaxies with a significant bulge component contain a central massive black hole. Although late-type galaxies appear to be generally deficient in nuclear black holes, there are important exceptions to this rule. I highlight two examples of dwarf, late-type galaxies that contain active nuclei powered by intermediate-mass black holes.

1.1 Introduction

The search for massive black holes (BHs) has recently enjoyed dramatic progress, to the point that the statistics of BH detections have begun to yield useful clues on the connection between BHs and their host galaxies, the central theme of this Symposium. Lest one becomes complacent, however, we should recognize that our knowledge of the demographics of BHs in nearby galaxies—on which much of the astrophysical inferences depends—remains highly incomplete. Direct measurements of BH masses based on resolved gas or stellar kinematics, while increasingly robust, are still far from routine and presently are available only for a limited number of galaxies (see Barth 2004 and Kormendy 2004). Certainly nothing approaching a "complete" sample exists yet. More importantly, it is far from obvious that the current statistics are unbiased. As discussed by Barth (2004), most nearby galaxies possess chaotic nuclear rotation curves that defy simple analysis. Stellar kinematics provide a powerful alternative to the gas-based method, but in practice this technique thus far has been limited to relatively dust-free systems and, for practical reasons, to galaxies of relatively high central surface brightness. The latter restriction selects against luminous, giant ellipticals. Lastly, current surveys severely underrepresent disk-dominated (Sbc and later) galaxies, because the bulge component in these systems is inconspicuous and star formation tends to perturb the velocity field of the gas.

Given the above limitations, it would be important to consider alternative constraints on BH demography. This contribution discusses the role that active galactic nuclei (AGNs) can play in this regard. The commonly held, but by now well-substantiated premise that AGNs derive their energy output from BH accretion implies that an AGN signifies the presence of a central BH in a galaxy. The AGN signature in and of itself provides no direct information on BH masses, but AGN statistics can inform us, effectively and efficiently, some key aspects of BH demography. For example, what fraction of all galaxies contain BHs? Do BHs exist preferentially in galaxies of certain types? Does environment matter? Under what conditions do BHs light up as AGNs and how long does the active phase last? What is their history of mass build-up? These and many other related issues are inextricably linked with the statistical properties of AGNs as a function of cosmological epoch. This contribution concentrates on the local ($z \approx 0$) AGNs; Osmer (2004) considers the high-redshift population.

This review is structured as follows. I begin with an overview of the basic methodology of the spectral classification of emission-line nuclei (§1.2) by describing the currently adopted system, its physical motivation, the complications of starlight subtraction, and some practical examples. Section 1.3 briefly summarizes past and current spectroscopic surveys and introduces the Palomar survey. The demographics of nearby AGNs is the subject of §1.4, covering detection rates based on optical surveys, detection rates based on radio work, the detection of weak broad emission lines, issues of robustness and completeless in current surveys, the local AGN luminosity function, the statistics of accretion luminosities, host galaxy properties and environmental effects, and intermediate-mass black holes. No discussion on nearby AGNs would be complete without a proper treatment on LINERs (§1.5). I focus on what I believe are the three most important topics, namely the current evidence that the majority of LINERs are indeed powered by accretion, AGN photoionization as their dominant excitation mechanism and the demise of competing alternatives, and the largely still-unresolved nature of the so-called transition objects. Section 1.6 gives a synopsis of the main points.

1.2 Spectral Classification of Galactic Nuclei

1.2.1 Physical Motivation

AGNs can be identified by a variety of methods. Most AGN surveys rely on some aspect of the distinctive AGN spectrum, such as the presence of strong or broad emission lines, an unusually blue continuum, or strong radio or X-ray emission. While all of these techniques are effective, none is free from selection effects. To search for AGNs in nearby galaxies, where the nonstellar signal of the nucleus is expected to be weak relative to the host galaxy, the most effective and least biased method is to conduct a spectroscopic survey of a complete, optical-flux limited sample of galaxies. To be sensitive to weak emission lines, the survey must be deep and of sufficient spectral resolution. To obtain reliable line intensity ratios, on which the principal nuclear classifications are based, the data must have accurate relative flux calibration, and one must devise a robust scheme to correct for the starlight contamination. These issues are discussed below. But first, I must cover some basic material on spectral classification.

The most widely used system of spectral classification of emission-line nuclei follows the method outlined by Baldwin, Phillips, & Terlevich (1981), and later modified by Veilleux & Osterbrock (1987). The basic idea is that the relative strengths of certain prominent emission lines can be used to probe the nebular conditions of a source. In the context of the present discussion, the most important diagnostic is the source of excitation, which broadly falls into two categories: stellar photoionization or photoionization by a centrally located, spectrally hard radiation field, such as that produced by the accretion disk of a massive BH.

The latter class of sources are generically called AGNs, which are most relevant to issues of BH demography.

How does one distinguish stellar from nonstellar photoionization? The forbidden lines of the doublet [O I] $\lambda\lambda$6300, 6364 rise from collisional excitation of O^0 by hot electrons. Since the ionization potential of O^0 (13.6 eV) is nearly identical to that of hydrogen, in an ionization-bounded nebula [O I] is produced predominantly in the "partially ionized zone," wherein both neutral oxygen and free electrons coexist. In addition to O^0, the conditions of the partially ionized zone are also favorable for S^+ and N^+, whose ionization potentials are 23.3 eV and 29.6 eV, respectively. Hence, in the absence of abundance anomalies, [N II] $\lambda\lambda$6548, 6583 and [S II] $\lambda\lambda$6716, 6731 are strong (relative to, say, Hα) whenever [O I] is strong, and *vice versa*.

In a nebula photoionized by young, massive stars, the partially ionized zone is very thin because the ionizing spectrum of OB stars contains few photons with energies greater than 1 Rydberg. Hence, in the optical spectra of H II regions and starburst nuclei (hereinafter H II nuclei*) the low-ionization transitions [N II], [S II], and especially [O I] are very weak. By contrast, a harder radiation field, such as that of an AGN power-law continuum that extends into the extreme-ultraviolet (UV) and X-rays, penetrates much deeper into an optically thick cloud. X-ray photoionization and Auger processes release copious hot electrons in this predominantly neutral region, creating an extensive partially ionized zone. The spectra of AGNs, therefore, exhibit relatively strong low-ionization forbidden lines.

1.2.2 Sample Spectra

The spectra shown in Figure 1.1 illustrate the empirical distinction between AGNs and H II nuclei. In NGC 7741, which has a well-known starburst nucleus (Weedman et al. 1981), [O I], [N II], and [S II] are weak relative to Hα. The [O III] $\lambda\lambda$4959, 5007 doublet is quite strong compared to [O II] λ3727 or Hβ because the metal abundance of NGC 7741's nucleus is rather low, although the ionization level of H II nuclei can span a wide range, depending on metallicity (Ho, Filippenko, & Sargent 1997c). On the other hand, the low-ionization lines are markedly stronger in the other two objects shown, both of which qualify as AGNs. NGC 1358 is an example of a galaxy with a "high-ionization" AGN or "Seyfert" nucleus. NGC 1052 is the prototype of the class known as "low-ionization nuclear emission-line regions" or "LINERs." The ionization level can be judged by the relative strengths of the oxygen lines, but in practice is most easily gauged by the [O III]/Hβ ratio. In the commonly adopted system of Veilleux & Osterbrock (1987), the division between Seyferts and LINERs occurs at [O III] λ5007/Hβ = 3.0. Ho, Filippenko, & Sargent (2003) stress, however, that this boundary has no strict physical significance. The ionization level of the narrow-line region (NLR) in large, homogeneous samples of AGNs spans a wide and apparently continuous range; contrary to the claims of some studies (e.g., Véron-Cetty & Véron 2000) there is no evidence for any clear-cut transition between Seyferts and LINERs (Ho et al. 2003; Heckman 2004).

The classification system discussed above makes no reference to the profiles of the emission lines. Luminous AGNs such as quasars and many "classical" Seyfert galaxies ex-

* As originally defined (Weedman et al. 1981; Balzano 1983), a star*burst* nucleus is one whose current star formation rate is much higher than its past average rate. This terminology presupposes knowledge of the star formation history of the system. Since this information is usually not available for any individual object, I will adopt the more general designation of "H II nucleus."

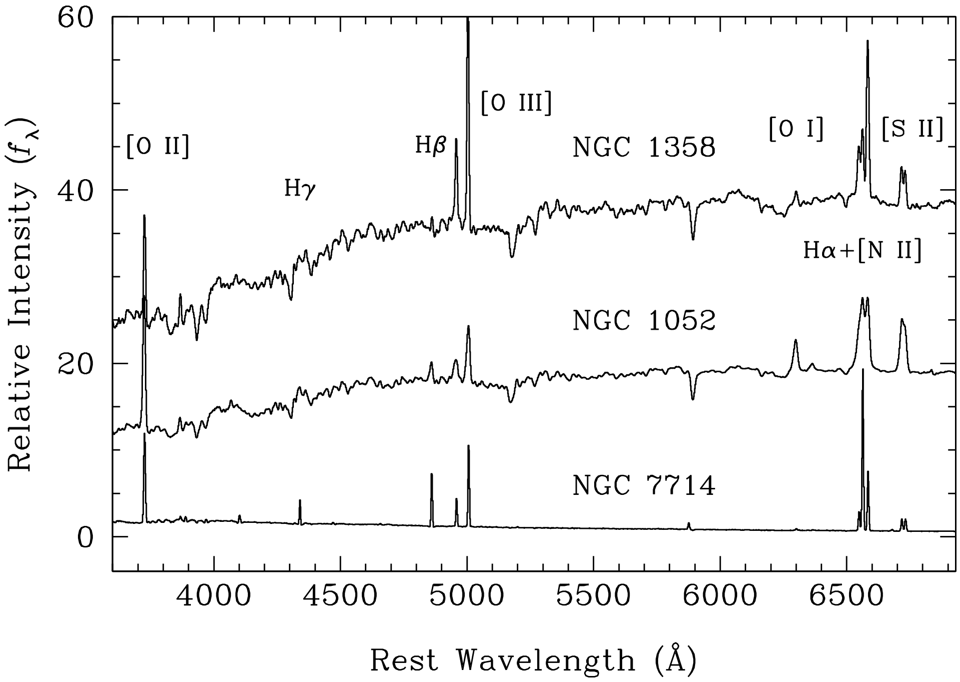

Fig. 1.1. Sample optical spectra of the various classes of emission-line nuclei. NGC 1358 = Seyfert; NGC 1052 = LINER; NGC 7714 = H II. The prominent emission lines are identified. (Based on Ho et al. 1993a and unpublished data.)

hibit permitted lines with a characteristically broad component, with FWHM widths of $\sim 1000-10,000\,\mathrm{km\,s^{-1}}$. This component arises from the broad-line region (BLR), which is thought to be physically distinct from the NLR responsible for the narrow lines. Following Khachikian & Weedman (1974), it is customary to refer to Seyferts with and without (directly) detectable broad lines as "type 1" and "type 2" sources, respectively. As discussed in § 1.4.3, this nomenclature can also be extended to include LINERs, which also contain broad emission lines. Figure 1.2 gives some examples. The spectrum of the bright Seyfert galaxy NGC 4151 is familiar to all: strong, broad permitted lines superposed on an unambiguous featureless, nonstellar blue continuuum. But this object is not typical. Even within the Seyfert class, most objects resemble NGC 5273, where the broad component is easily visible only for Hα and the featureless continuum is heavily diluted by the host galaxy light. The same applies to LINERs (e.g., NGC 3998), where the host galaxy dilution is even more extreme; nonetheless, with careful starlight subtraction (§ 1.2.4) and profile modeling (§ 1.4.3), one can detect broad Hα emission in many LINERs.

1.2.3 Diagnostic Diagrams

The classification system of Veilleux & Osterbrock (1987), which I adopt throughout this paper, is based on two-dimensional line-intensity ratios constructed from [O III]

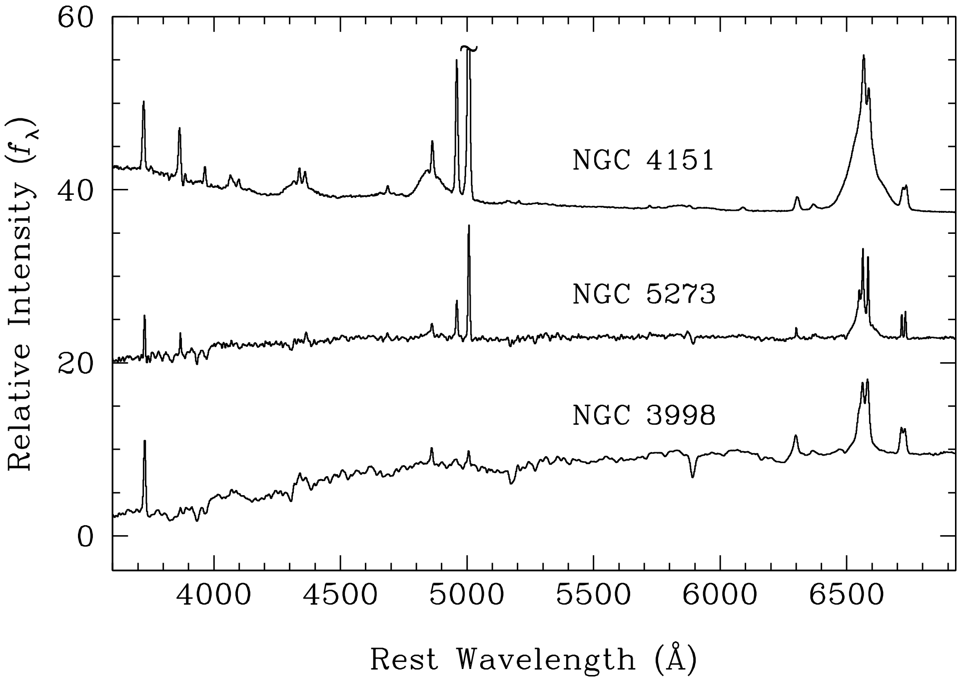

Fig. 1.2. Sample optical spectra of broad-line AGNs. NGC 4151 = "classical" Seyfert 1; NGC 5273 = typical low-luminosity Seyfert 1; NGC 3998 = LINER 1. (Based on Ho et al. 1993a and unpublished data.)

λ5007, Hβ λ4861, [O I] λ6300, Hα λ6563, [N II] λ6583, and [S II] $\lambda\lambda$6716, 6731 (here Hβ and Hα refer only to the narrow component of the line). The main virtues of this system, shown in Figure 1.3, are (1) that it uses relatively strong lines, (2) that the lines lie in an easily accessible region of the optical spectrum, and (3) that the line ratios are relatively insensitive to reddening corrections because of the close separation of the lines. The definitions of the various classes of emission-line objects are given in Ho, Filippenko, & Sargent (1997a)*. In addition to the three main classes discussed thus far—H II nuclei, Seyferts, and LINERs—Ho, Filippenko, & Sargent (1993a) identified a group of "transition objects" whose [O I] strengths are intermediate between those of H II nuclei and LINERs. Since they tend to emit weaker [O I] emission than classical LINERs, previous authors have called them "weak-[O I] LINERs" (Filippenko & Terlevich 1992; Shields 1992; Ho & Filippenko 1993). Ho et al. (1993a) postulated that transition objects are composite systems having both an H II region and a LINER component; I will return to the nature of these sources in § 1.5.3.

I note that my definition of LINERs differs from that originally proposed by Heckman (1980b), who used solely the oxygen lines: [O II] λ3727 $>$ [O III] λ5007 and [O I] λ6300

* The classification criteria adopted here differ slightly, but not appreciably, from those proposed by Kewley et al. (2001) based on theoretical models.

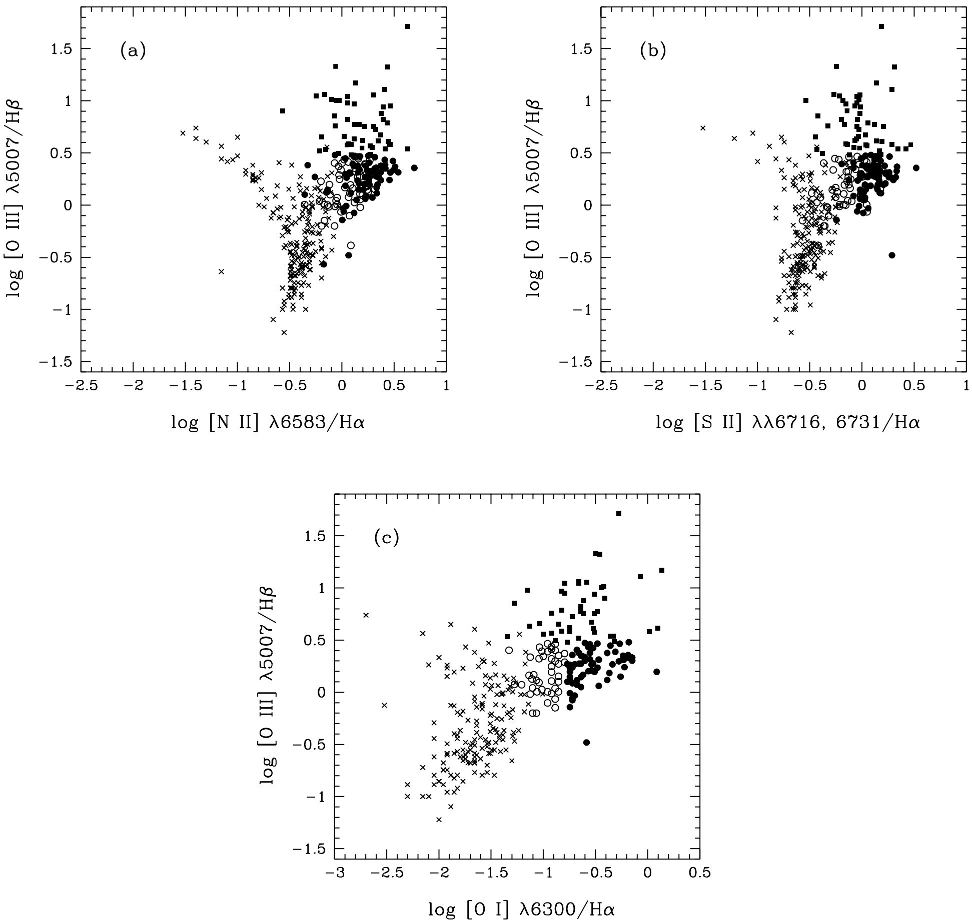

Fig. 1.3. Diagnostic diagrams plotting (*a*) log [O III] λ5007/Hβ versus log [N II] λ6583/Hα, (*b*) log [O III] λ5007/Hβ versus log [S II] $\lambda\lambda$6716, 6731/Hα, and (*c*) log [O III] λ5007/Hβ versus log [O I] λ6300/Hα. The nuclear spectral classes shown are H II nuclei (*asterisks*), Seyfert nuclei (*squares*), LINERs (*solid circles*), and transition objects (*open circles*). (Adapted from Ho et al. 1997a.)

$>$ 0.33 [O III] λ5007. The two definitions, however, are nearly equivalent. Inspection of the full optical spectra of Ho et al. (1993a), for example, reveals that emission-line nuclei classified as LINERs based on the Veilleux & Osterbrock diagrams almost invariably also satisfy Heckman's criteria. This is a consequence of the inverse correlation between [O III]/Hβ and [O II]/[O III] in photoionized gas with fairly low excitation ([O III]/Hβ $\lesssim$3; see Fig. 2 in Baldwin et al. 1981).

1.2.4 Starlight Subtraction

The scheme outlined above, while conceptionally simple, overlooks one key practical complication. The integrated spectra of galactic nuclei include emission from stars, which in most nearby systems overwhelms the nebular line emission. This can be seen in Figure 1.1, or from a cursory examination of the spectral atlas of Ho, Filippenko, & Sargent (1995). Any reliable measurement of the emission-line spectrum of galactic nuclei, therefore, *must* properly account for the starlight contamination.

An effective strategy for removing the starlight from an integrated spectrum is that of "template subtraction," whereby a template spectrum devoid of emission lines is suitably scaled to and subtracted from the spectrum of interest to yield a continuum-subtracted, pure emission-line spectrum. A number of approaches have been adopted to construct the template. These include (1) using the spectrum of an off-nuclear position within the same galaxy (e.g., Storchi-Bergmann, Baldwin, & Wilson 1993); (2) using the spectrum of a different galaxy devoid of emission lines (e.g., Costero & Osterbrock 1977; Filippenko & Halpern 1984; Ho et al. 1993a); (3) using a weighted linear combination of the spectra of a number different galaxies, chosen to best match the stellar population and velocity dispersion (Ho et al. 1997a); (4) using the spectrum derived from a principal-component analysis of a large set of galaxies (Hao & Strauss 2004); and (5) using a model spectrum constructed from population synthesis techniques, using as input a library of spectra of either individual stars (e.g., Keel 1983a) or star clusters (e.g., Bonatto, Bica, & Alloin 1989; Raimann et al. 2001).

Figure 1.4 illustrates the starlight subtraction process for the H II nucleus in NGC 3596 and for the Seyfert 2 nucleus in NGC 7743, using the method of Ho et al. (1997a). Given a list of input spectra derived from galaxies devoid of emission lines and an initial guess of the velocity dispersion, a χ^2-minimization algorithm solves for the systemic velocity, the line-broadening function, the relative contribution of the various input spectra, and the general continuum shape. The best-fitting model is then subtracted from the original spectrum, yielding a pure emission-line spectrum. In the case of NGC 3596, the model consisted of the combination of the spectrum of NGC 205, a dE5 galaxy with a substantial population of A-type stars, and NGC 4339, an E0 galaxy having a K-giant spectrum. Note that in the original observed spectrum (top), Hγ, [O III] $\lambda\lambda$4959, 5007, and [O I] λ6300 were hardly visible, whereas after starlight subtraction (bottom) they can be easily measured. The intensities of both Hβ and Hα have been modified substantially, and the ratio of the two [S II] $\lambda\lambda$6716, 6731 lines changed. The effective template for NGC 7743 made use of NGC 205, NGC 4339, and NGC 628, an Sc galaxy with a nucleus dominated by A and F stars.

Some studies (e.g., Kim et al. 1995) implicitly assume that only the hydrogen Balmer lines are contaminated by starlight, and that the absorption-line component can be removed by subtracting a constant equivalent width (2–3 Å). This procedure is inadequate for a number of reasons. First, the stellar population of nearby galactic nuclei, although relatively uniform, is by no means invariant (Ho et al. 2003). Second, the equivalent widths of the different Balmer absorption lines within each galaxy are generally not constant. Third, the Balmer absorption lines affect not only the strength but also the shape of the Balmer emission lines. And finally, as the above examples show, starlight contaminates lines other than just the Balmer lines.

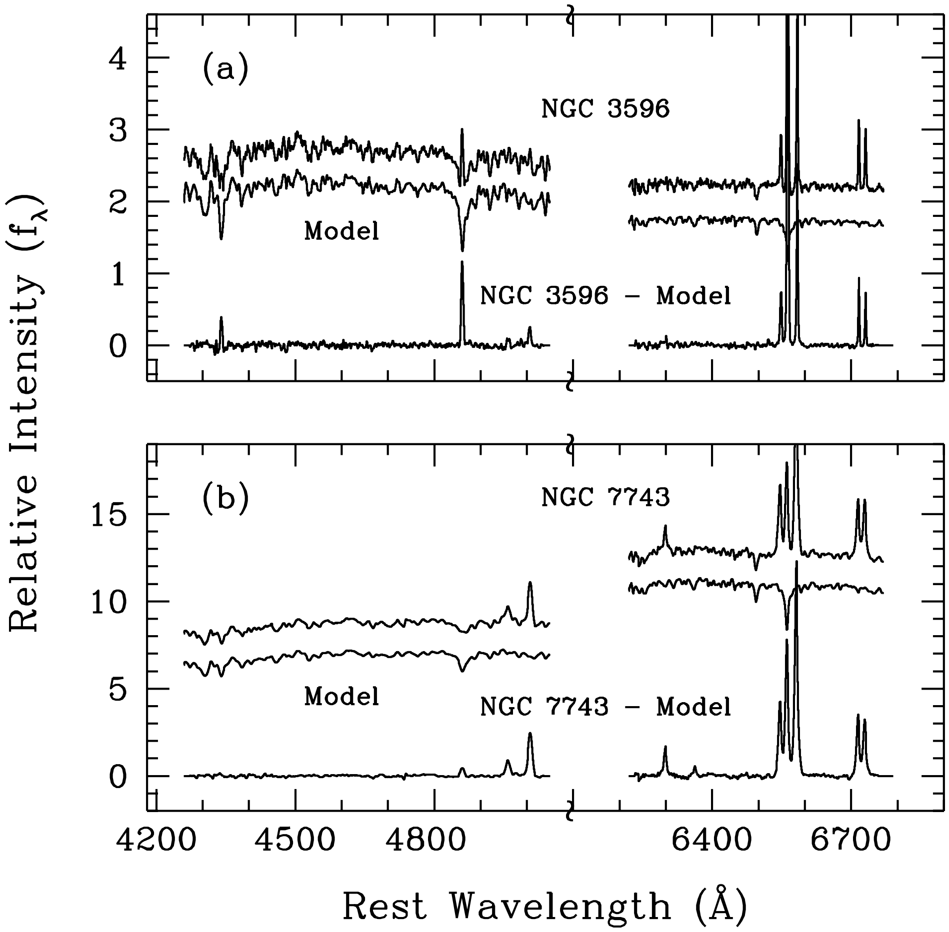

Fig. 1.4. Illustration of the method of starlight subtraction. In each panel, the top plot shows the observed spectrum, the middle plot the best-fitting "template" used to match the stellar component, and the bottom plot the difference between the object spectrum and the template. In the case of NGC 3596 (*a*), the model was constructed from NGC 205 and NGC 4339, while for NGC 7743 (*b*), the model was derived from a linear combination of NGC 205, NGC 4339, and NGC 628. (Adapted from Ho et al. 1997a.)

1.3 Spectroscopic Surveys of Nearby Galactic Nuclei

It was apparent from some of the earliest redshift surveys that the central regions of galaxies often show evidence of strong emission lines (e.g., Humason, Mayall, & Sandage 1956). A number of studies also indicated that in many instances the spectra revealed abnormal line-intensity ratios, most notably the unusually great strength of [N II] relative to Hα (Burbidge & Burbidge 1962, 1965; Rubin & Ford 1971). That the optical emission-line spectra of some nuclei show patterns of low ionization was noticed from time to time, primarily by Osterbrock and his colleagues (e.g., Osterbrock & Miller 1975; Koski & Osterbrock 1976; Costero & Osterbrock 1977; Grandi & Osterbrock 1978; Phillips 1979), but also by others (e.g., Disney & Cromwell 1971; Danziger, Fosbury, & Penston 1977; Fosbury et al. 1977, 1978; Penston & Fosbury 1978; Stauffer & Spinrad 1979).

Most of the activity in this field culminated in the 1980s, beginning with the recognition (Heckman, Balick, & Crane 1980; Heckman 1980b) of LINERs as a major constituent of the extragalactic population, and then followed by further systematic studies of larger samples of galaxies (Stauffer 1982a, b; Keel 1983a, b; Phillips et al. 1986; Véron & Véron-Cetty 1986; Véron-Cetty & Véron 1986; see Ho 1996 for more details). These surveys established three important results: (1) a large fraction of local galaxies contain emission-line nuclei; (2) many of these sources are LINERs; and (3) LINERs may be accretion-powered systems.

Despite the success of these seminal studies, there was room for improvement. Although most of the surveys attempted some form of starlight subtraction, the accuracy of the methods used tended to be fairly limited (see discussion in Ho et al. 1997a), the procedure was sometimes inconsistently applied, and in some of the surveys starlight subtraction was largely neglected. The problem is exacerbated by the fact that the apertures used for the observations were quite large, thereby admitting an unnecessarily large amount of starlight. Furthermore, most of the data were collected with rather poor spectral resolution (FWHM $\approx$ 10 Å). Besides losing useful kinematic information, blending between the emission and absorption components further compromises the ability to separate the two.

Thus, it is clear that much would be gained from a survey having greater sensitivity to the detection of emission lines. The sensitivity can be improved in at least four ways—by taking spectra with higher signal-to-noise ratio and spectral resolution, by using a narrower slit to better isolate the nucleus, and by employing more effective methods to handle the starlight correction.

The Palomar spectroscopic survey of nearby galaxies (Filippenko & Sargent 1985, 1986; Ho et al. 1995, 1997a–e, 2003) was designed with these goals in mind. Using a double CCD spectrograph mounted on the Hale 5-m reflector at Palomar Observatory, high-quality, moderate-resolution, long-slit spectra were obtained for a magnitude-limited ($B_T \leq 12.5$ mag) sample of 486 northern ($\delta > 0°$) galaxies. The spectra simultaneously cover the wavelength ranges 6210–6860 Å with $\sim$2.5 Å resolution (FWHM) and 4230–5110 Å with $\sim$4 Å resolution. Most of the observations were obtained with a narrow slit (generally $2''$, and occasionally $1''$), and the exposure times were suitably long (up to 1 hr or more for some objects with low central surface brightness) to secure data of high signal-to-noise ratio. This survey contains the largest database to date of homogeneous and high-quality optical spectra of nearby galaxies. It is also the most sensitive; the detection limit for emission lines is $\sim$0.25 Å, roughly an order-of-magnitude improvement compared to previous work. The selection criteria of the survey ensure that the sample gives a fair representation of the local ($z \approx 0$) galaxy population, and the proximity of the objects (median distance = 17 Mpc) enables relatively good spatial resolution to be achieved (typically $\lesssim$200 pc). These properties of the Palomar survey make it ideally suited to address issues on the demographics and physical properties of nearby, and especially low-luminosity, AGNs. Unless otherwise noted, the main results presented in the rest of this paper will be taken from the Palomar survey.

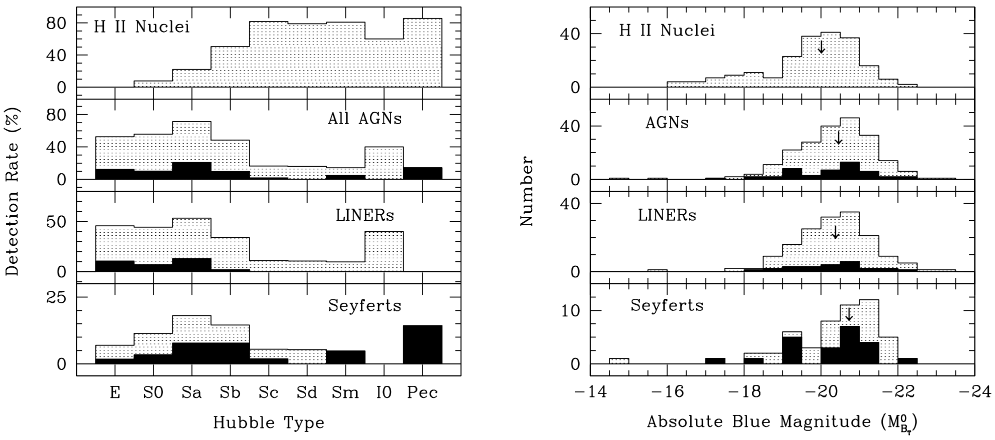

Fig. 1.5. (*Left*) Percentage of galaxies with the various classes of emission-line nuclei detected as a function of Hubble type. (*Right*) Distribution of the classes of emission-line nuclei as a function of the absolute *B* magnitude of the host galaxy. The arrow in each panel marks the median of the distribution. The solid and hatched histograms denote type 1 and type 1 + type 2 sources, respectively. (Adapted from Ho et al. 1997b.)

1.4 Demographics of Nearby AGNs

1.4.1 Detection Rates

In qualitative agreement with previous surveys, the Palomar survey finds that a substantial fraction (86%) of all galaxies contain detectable emission-line nuclei (Ho et al. 1997b). The detection rate is essentially 100% for all disk (S0 and spiral) galaxies, and over 50% for elliptical galaxies. One of the most surprising results is the large fraction of objects classified as AGNs or AGN candidates. Summed over all Hubble types, 43% of all galaxies that fall in the survey limits can be considered "active" (Fig. 1.5). This percentage becomes even more remarkable for galaxies with an obvious bulge component, rising to $\sim$50%–70% for Hubble types E–Sbc. By contrast, the detection rate of AGNs drops dramatically toward later Hubble types (Sc and later), which almost invariably (80%) host H II nuclei. This strong dependence of nuclear spectral class on Hubble type has been noticed in earlier studies (Heckman 1980a; Keel 1983a; Terlevich, Melnick, & Moles 1987).

Among the active sources, 11% have Seyfert nuclei, at least doubling older estimates (Stauffer 1982b; Keel 1983b; Phillips, Charles, & Baldwin 1983; Huchra & Burg 1992). LINERs constitute the dominant population of AGNs. "Pure" LINERs are present in $\sim$20% of all galaxies, whereas transition objects, which by assumption also contain a LINER component, account for another $\sim$13%. Thus, if all LINERs can be regarded as genuine AGNs (see § 1.5), they truly are the most populous constituents—they make up 1/3 of all galaxies and 2/3 of the AGN population (here taken to mean all objects classified as Seyferts, LINERs, and transition objects).

The sample of nearby AGNs emerging from the Sloan Digital Sky Survey (SDSS) (Kauffmann et al. 2003; Hao & Strauss 2004; Heckman 2004) far surpasses that of the Palomar survey in number. Within the magnitude range $14.5 < r < 17.7$, Kauffmann et al. (2003) report an overall AGN fraction (for narrow-line sources) of $\sim$40%, of which $\sim$10% are Seyferts, the rest LINERs and transition objects. Using a different method of starlight subtraction, Hao & Strauss (2004) obtain very similar statistics for their sample of Seyfert galaxies. Although these detection rates broadly resemble those of the Palomar survey, one should recognize important differences between the two surveys. The Palomar objects extend much farther down the luminosity function than the SDSS. The emission-line detection limit of the Palomar survey, 0.25 Å, is roughly 10 times fainter than the cutoff chosen by Hao & Strauss (2004). The faint end of the Palomar Hα luminosity function reaches 1×10^{38} erg s^{-1}, again a factor of 10 lower than the SDSS counterpart. Moreover, the $3''$-diameter fibers used in the SDSS subtend a physical scale of $\sim$5.5 kpc at the typical redshift $z \approx 0.1$, 30 times larger than in the Palomar survey. The SDSS spectra, therefore, include substantial contamination from off-nuclear emission, which would dilute, and in some cases inevitably confuse, the signal from the nucleus.

Contamination by host galaxy emission has two consequences. First, only relatively bright nuclei have enough contrast to be detected; this is consistent with the sensitivity difference described above. But second, it can introduce a more pernicious systematic effect that can be hard to quantify. Apart from normal H II regions, galactic disks are known to contain emission-line regions that exhibit low-ionization, LINER-like spectra, which can be confused with genuine *nuclear* LINERs. Examples include gas shocked by supernova remnants (e.g., Dopita & Sutherland 1995), ejecta from starburst-driven winds (Armus, Heckman, & Miley 1990), and diffuse ionized plasma (e.g., Lehnert & Heckman 1994; Collins & Rand 2001). Massive, early-type galaxies, though generally lacking in ongoing star formation, do often possess X-ray emitting atmospheres that exhibit extended, low-ionization emission-line nebulae (e.g., Fabian et al. 1986; Heckman et al. 1989). These physical processes, while interesting in their own right, are not directly related, and thus irrelevant, to the AGN phenomenon. Thus, "LINERs" selected from samples of distant galaxies should be regarded with considerable caution.

1.4.2 Statistics from Radio Surveys

The prevalence of weak AGNs in nearby galaxies is corroborated by high-resolution radio continuum surveys. Sadler, Jenkins, & Kotanyi (1989) and Wrobel & Heeschen (1991) report a relatively high incidence ($\sim$50%) of compact radio cores in complete, optical flux-limited samples of elliptical and S0 galaxies. The radio powers are quite modest, generally in the range of $10^{19}-10^{21}$ W Hz^{-1} at 5 GHz. When available, the spectral indices tend to be relatively flat (e.g., Slee et al. 1994). The optical counterparts of the radio cores are usually spectroscopically classified as LINERs (Phillips et al. 1986; Ho 1999a).

1.4.3 Broad Emission Lines

Broad emission lines, a defining attribute of classical Seyferts and quasars, are also found in nuclei of much lower luminosities. The well-known case of the nucleus of M81 (Peimbert & Torres-Peimbert 1981; Filippenko & Sargent 1988), for example, has a broad (FWHM $\approx$ 3000 km s^{-1}) Hα line with a luminosity of only 2×10^{39} erg s^{-1} (Ho, Filippenko, & Sargent 1996), and many other less conspicuous cases have been discovered in the Palomar survey (Ho et al. 1997e; Fig. 1.6). Searching for broad Hα emission in nearby nuclei is nontrivial, because it entails measurement of a (generally) weak, low-contrast, broad

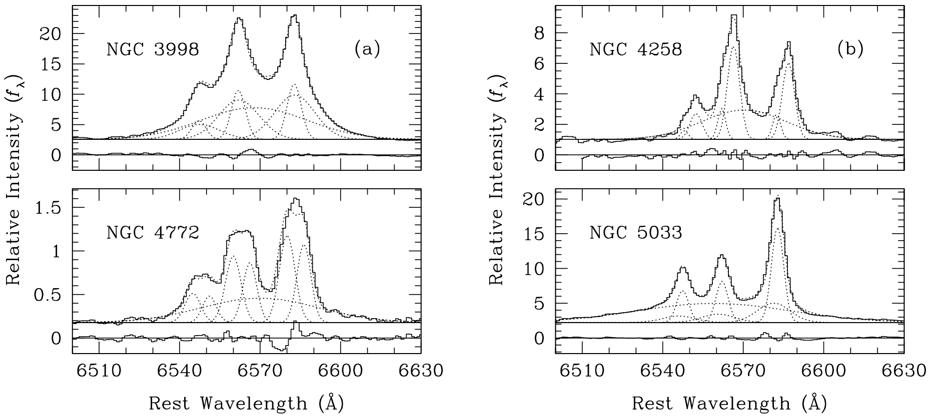

Fig. 1.6. Examples of (*a*) LINERs and (*b*) Seyferts with broad Hα emission. [N II] $\lambda\lambda$6548, 6583 and the narrow component of Hα are assumed to have the same shape as [S II] $\lambda\lambda$6716, 6731, and the broad component of Hα is modeled as a single Gaussian. Residuals of the fit are shown on the bottom of each panel. (Adapted from Ho et al. 1997e.)

emission feature superposed on a complicated stellar background. Thus, the importance of careful starlight subtraction cannot be overemphasized. Moreover, even if one were able to perfectly remove the starlight, one still has to contend with deblending the Hα + [N II] $\lambda\lambda$6548, 6583 complex. The narrow lines in this complex are often heavily blended together, and rarely do the lines have simple profiles. The strategy adopted by Ho et al. (1997e) is to use the empirical line profile of the [S II] lines to model [N II] and the narrow component of Hα.

Of the 221 emission-line nuclei in the Palomar survey classified as LINERs, transition objects, and Seyferts, 33 (15%) definitely have broad Hα, and an additional 16 (7%) probably do. Questionable detections were found in another 8 objects (4%). Thus, approximately 20%–25% of all nearby AGNs are type 1 sources. These numbers, of course, should be regarded as lower limits, since undoubtedly there must exist AGNs with even weaker broad-line emission that fall below the detection threshold.

It is illuminating to consider the incidence of broad Hα emission as a function of spectral class. Among objects formally classified as Seyferts (according to their narrow-line spectrum), approximately 40% are Seyfert 1s. The implied ratio of Seyfert 1s to Seyfert 2s (1:1.6) has important consequences for some models concerning the evolution and small-scale geometry of AGNs (e.g., Osterbrock & Shaw 1988; Lawrence 1991). Despite claims to the contrary (Krolik 1998; Sulentic, Marziani, & Dultzin-Hacyan 2000), broad emission lines emphatically are *not* exclusively confined to Seyfert nuclei. Within the Palomar sample, nearly 25% of the "pure" LINERs have detectable broad Hα emission. By direct analogy with the familiar nomenclature established for Seyferts, LINERs can be divided into "type 1" and "type 2" sources according to the presence or absence of broad-line emission, respectively (Ho et al. 1997a, 1997e). The detection rate of broad Hα, however, drops drastically for transition objects. The cause for this dramatic change is unclear, but a possible explana-

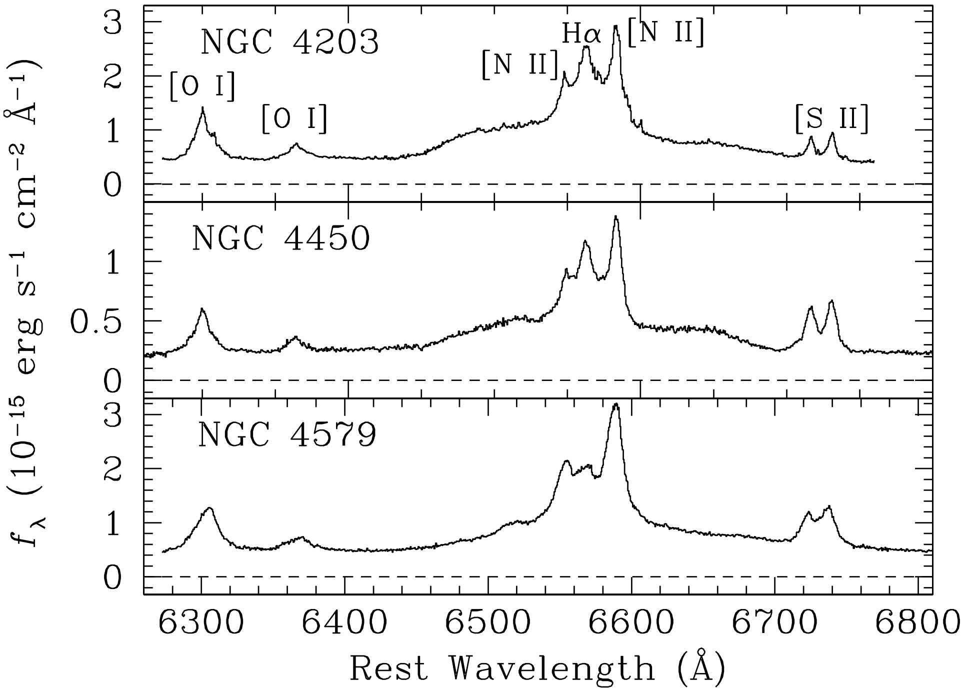

Fig. 1.7. Examples of LINERs with broad, double-peaked Hα emission discovered with *HST*. (Adapted from Ho et al. 2000, Shields et al. 2000, and Barth et al. 2001.)

tion is that the broad-line component is simply too weak to be detected in the presence of substantial contamination from the H II region component.

A subset of LINERs contain broad lines with *double-peaked* profiles (Fig. 1.7), analogous to those seen in a minority of radio galaxies (Eracleous & Halpern 1994), where they are often interpreted as a kinematic signature of a relativistically broadened accretion disk (Chen & Halpern 1989). Most of the nearby cases have been discovered serendipitously, either as a result of the broad component being variable (e.g., Storchi-Bergmann et al. 1993) or because of the increased sensitivity to weak, broad features afforded by small-aperture measurements made with the *Hubble Space Telescope (HST)* (Shields et al. 2000; Ho et al. 2000, and references therein).

1.4.4 Robustness and Completeness

To gain confidence in the current AGN statistics, one must have some handle on whether the existing AGN detections are trustworthy and whether there are many AGNs that have been missed. The robustness issue hinges on the question of whether the weak, nearby sources classified as AGNs are truly accretion-powered. As summarized in § 1.5, this appears to be largely the case. The completeness issue can be examined in two regimes. Among bulged (Sbc and earlier) galaxies, for which the spectroscopic AGN fractions are already very high ($\sim$50%–75%; Fig. 1.5), there is no room for a large fraction of missing AGNs. The same does not necessarily hold for galaxies of Hubble types Sc and later. While the majority of these systems are spectroscopically classified as H II nuclei, one must be wary that weak AGNs, if present, may be masked by brighter off-nuclear H II regions or H II regions projected along the line of sight. After all, some very late-type galaxies *do* host *bona fide* AGNs (see §1.4.8).

The AGN content of late-type galaxies can be independently assessed by using a diagnostic less prone to confusion by star-forming regions. The presence of a compact, nuclear radio or X-ray core turns out to be a useful AGN filter, since genuine AGNs almost always possess compact emission in these bands. Because of the expected weakness of the nuclei, however, any search for core emission must be conducted at relatively high sensitivity and angular resolution ($\lesssim 1''$). In practice, this requires *Chandra* for the X-rays and an interferometer such as the Very Large Array (VLA) for the radio.

Ulvestad & Ho (2002) have performed a VLA survey for radio cores in a distance-limited sample of 40 Palomar Sc galaxies classified as hosting H II nuclei. To a sensitivity limit of $P_{6\mathrm{cm}} \approx 10^{18} - 10^{20}$ W Hz^{-1} at $\sim 1''$ resolution, they found that *none* of the galaxies contain radio cores. They detected nuclear emission in three galaxies, but in all cases the morphology was diffuse, consistent with that seen in nearby circumnuclear starbursts such as NGC 253. The VLA study of Filho, Barthel, & Ho (2000) also failed to detect radio cores in a more heterogeneous sample of 12 H II nuclei.

Information on nuclear X-ray cores in late-type galaxies is much more limited because to date there has been no systematic investigation of these systems with *Chandra*. A few studies, however, have exploited the High Resolution Imager (HRI) on *ROSAT* to resolve the soft X-ray (0.5–2 keV) emission in late-type galaxies (Colbert & Mushotzky 1999; Lira, Lawrence, & Johnson 2000; Roberts & Warwick 2000). Although the resolution of the HRI ($\sim 5''$) is not ideal, it is nonetheless quite effective for identifying point sources given the relatively diffuse morphologies of late-type galaxies. Compact X-ray sources, often quite luminous ($\gtrsim 10^{38}$ erg s^{-1}), are frequently found, but generally they do *not* coincide with the galaxy nucleus; the nature of these "ultraluminous X-ray sources" is discussed by van der Marel (2004).

To summarize: unless H II nuclei in late-type galaxies contain radio and X-ray cores far weaker than the current survey limits—a possibility worth exploring—they do not appear to conceal a significant population of undetected AGNs.

1.4.5 The $z \approx 0$ AGN Luminosity Function

Many astrophysical applications of AGN demographics benefit from knowing the AGN luminosity function, $\Phi(L,z)$*. Whereas $\Phi(L,z)$ has been reasonably well charted for high L and high z using quasars (Osmer 2004), it is very poorly known at low L and low z. Indeed, until very recently there has been no reliable determination of $\Phi(L,0)$.

The difficulty in determining $\Phi(L,0)$ can be ascribed to a number of factors, as discussed in Huchra & Burg (1992). First and foremost is the challenge of securing a reliable, spectroscopically selected sample, as discussed in §§ 1.2–1.4. Since nearby AGNs are expected to be faint relative to their host galaxies, most of the traditional techniques used to identify quasars cannot be applied without introducing large biases. The faintness of nearby AGNs presents another obstacle, namely how to disentangle the nuclear emission—the only component relevant to the AGN—from the usually much brighter contribution from the host galaxy. Finally, most optical luminosity functions of bright, more distant AGNs are speci-

* For the purposes of this paper, I will only consider the optical luminosity function.

fied in terms of the nonstellar optical continuum (usually the B band), whereas spectroscopic surveys of nearby galaxies generally only reliably measure optical line emission (e.g., Hα) because the featureless nuclear continuum is often impossible to detect in ground-based, seeing-limited apertures.

Huchra & Burg (1992; see also Osterbrock & Martel 1993) presented the first optical luminosity function of nearby Seyfert galaxies, based on the sample of AGNs selected from the CfA redshift survey. They also calculated the luminosity function of LINERs, but it was known to be highly incomplete. Huchra & Burg, however, did not have access to true nuclear luminosities for their sample; their luminosity function was based on *total* (nucleus plus host galaxy) magnitudes.

A different strategy can be explored by taking advantage of the fact that Hα luminosities are now available for nearly all of the AGNs in the Palomar survey (Ho et al. 1997a, 2003). Ho et al. (2004) begin by calculating the nuclear Hα luminosity function using Schmidt's (1968) $V/V_{\rm max}$ method, where for each source V is the volume it occupies given its distance and $V_{\rm max}$ is the maximum volume it could occupy were it to lie within the flux limit of the survey, taken to be the larger of the two volumes as calculated from the total optical magnitude limit of the survey (B_T = 12.5 mag) and the flux limit for detecting emission lines. Next, Ho et al. (2004) exploit the fact that luminous AGNs obey a tight correlation between the luminosity of the optical, nonstellar continuum and the luminosity of the hydrogen Balmer lines, a relation that follows naturally from simple photoionization arguments (Searle & Sargent 1968; Weedman 1976; Yee 1980; Shuder 1981). Using *nuclear* continuum magnitudes extracted from high-resolution *HST* images, Ho & Peng (2001) showed that low-luminosity AGNs, too, obey the correlation established by the more luminous sources, albeit with somewhat greater scatter.

Figure 1.8 presents the B-band nuclear luminosity function for the Palomar AGNs, computed by translating the extinction-corrected Hα luminosities to B-band absolute magnitudes with the aid of the empirical calibration between Hβ luminosity and M_B of Ho & Peng (2001) and an assumed Hα/Hβ ratio of 3.1. Two versions are shown, each representing an extreme view of what kind of sources should be regarded as *bona fide* AGNs. The open circles include only type 1 nuclei, sources in which broad Hα emission was detected and hence whose AGN status is incontrovertible. This may be regarded as the most conservative assumption and a lower bound, since we know that genuine narrow-lined AGNs do exist (e.g., M104 or NGC 4261). The solid circles lump together all sources classified as LINERs, transition objects, or Seyferts, both type 1 and type 2. This represents the most optimistic view and an upper bound, since undoubtedly *some* narrow-lined sources must be stellar in origin but masquerading as AGNs. The true space density of local AGNs most likely lies between these two possibilities. In either case, the differential luminosity function is reasonably well approximated by a single power law from $M_B \approx -5$ to -18 mag, roughly of the form $\Phi \propto L^{-1.2\pm0.2}$. The slope may flatten for $M_B \gtrsim -7$ mag, but the luminosity function is highly uncertain at the faint end because of density fluctuations in our local volume.

For comparison, I have overlaid the luminosity function of $z \lesssim 0.3$ quasars and Seyfert 1 nuclei as determined by Köhler et al. (1997) from the Hamburg/ESO UV-excess survey*. This sample extends the luminosity function from $M_B \approx -18$ to -26 mag. Although the two samples do not strictly overlap in luminosity, it is apparent the two samples roughly

* Scaled to our adopted cosmological parameters of H_0 = 75 km s^{-1} Mpc^{-1}, $\Omega_{\rm m}$ = 0.3, and Ω_Λ = 0.7.

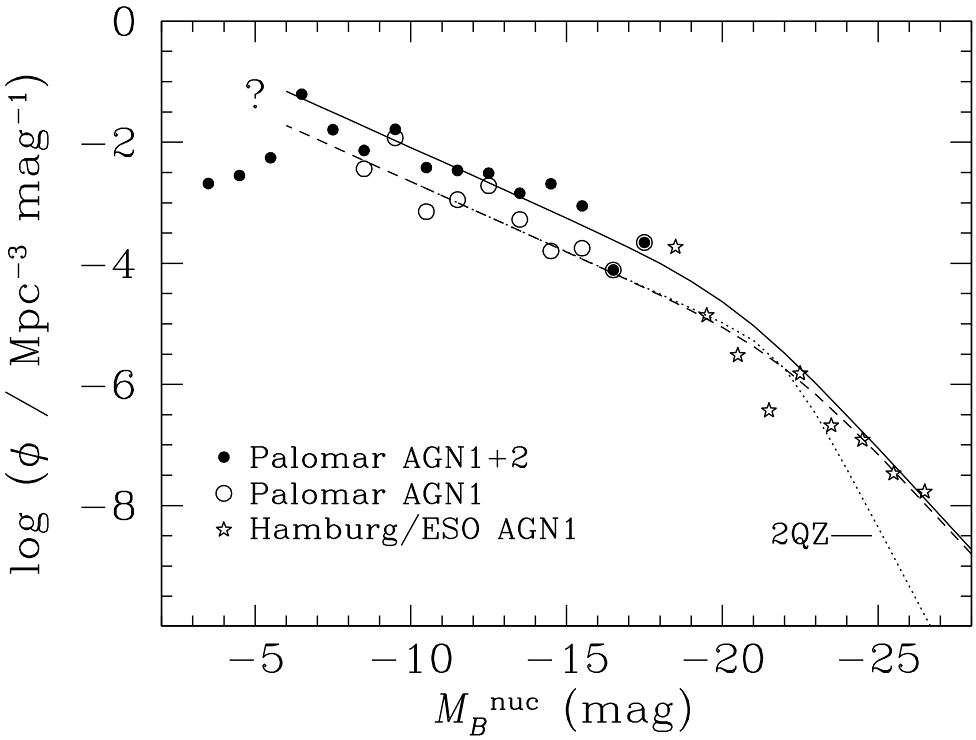

Fig. 1.8. The *B*-band nuclear luminosity function of nearby AGNs derived from the Palomar survey. The filled circles include all (type 1 + type 2) sources, while the open circles include only type 1 sources. The sample of luminous Seyfert 1s and quasars from the Hamburg/ESO survey of Köhler et al. (1997) is shown as stars. A double power-law fit to the Palomar and Hamburg/ESO samples is shown as a solid (type 1 + type 2) and dashed (type 1) curve. The dotted curve represents the quasar luminosity function derived from the 2dF quasar redshift survey (2QZ), shifted to $z = 0$ according to the luminosity evolution model of Boyle et al. (2000). (Adapted from Ho et al. 2004.)

merge, and that the break in the combined luminosity function most likely falls near $M_B^* \approx -19$ mag, where the space density $\phi \approx 1 \times 10^{-4}$ Mpc^{-3} mag^{-1}. I also plotted the quasar luminosity function obtained from the 2dF quasar redshift survey (2QZ), after evolving it to $z = 0$ following the luminosity evolution prescription of Boyle et al. (2000). The faint-end slope matches that of the local value quite well, but the break the 2QZ luminosity function drops much more sharply than the local sample.

1.4.6 Bolometric Luminosities and Eddington Ratios

To gain further insight into the physical nature of nearby AGNs, it is more instructive to examine their bolometric luminosities, rather than their luminosities in a specific band or emission line. Because AGNs emit a very broad spectrum, their bolometric lu-

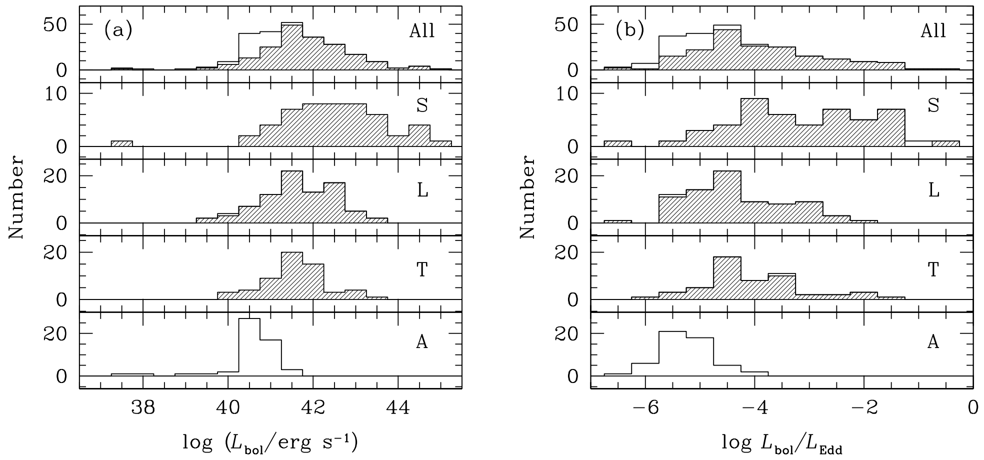

Fig. 1.9. Distribution of (*a*) bolometric luminosity, $L_{\rm bol}$, and (*b*) ratio of bolometric luminosity to the Eddington luminosity, $L_{\rm bol}/L_{\rm Edd}$, for all objects, Seyferts (L), LINERs (L), transition nuclei (T), and absorption-line nuclei (A). The hatched and open histograms denote detections and upper limits, respectively. (Adapted from Ho 2004.)

minosities ideally should be measured directly from their full spectral energy distributions (SEDs). In practice, however, complete SEDs are not readily available for most AGNs, and one commonly estimates the bolometric luminosity by applying bolometric corrections derived from a set of well-observed calibrators. As discussed in more detail in §1.5, the SEDs of low-luminosity AGNs differ quite markedly from those of conventionally studied AGNs. Nonetheless, they do exhibit a characteristic shape, which enables bolometric corrections to be calculated. AGN researchers customarily choose as the reference point either the optical *B* band or an X-ray band. While the same strategy may be used for low-luminosity AGNs (e.g., Ho et al. 2000), it cannot yet be widely employed because nuclear optical or X-ray fluxes are not yet available for large samples. What is available, by selection, is nuclear emission-line fluxes, and upper limits thereof. Although the Hα luminosity comprises only a small percentage of the total power, its fractional contribution to the bolometric luminosity, as Ho (2003, 2004) notes, turns out to be fairly well defined.

Figure 1.9 shows the distributions of bolometric luminosities and their values normalized with respect to the Eddington luminosity for Palomar galaxies with measurements of Hα luminosity and central stellar velocity dispersions. The $M_\bullet - \sigma$ relation of Tremaine et al. (2002) was used to obtain $L_{\rm Edd}$. Whereas LINER and transition nuclei both have a median $L_{\rm bol} \approx 2\times10^{41}$ erg s^{-1}, Seyfert nuclei are typically an order of magnitude more luminous (median $L_{\rm bol} \approx 2\times10^{42}$ erg s^{-1}). The upper limits for the objects lacking any detectable line emission (absorption-line nuclei) cluster near $L_{\rm bol} \approx 3\times10^{40}$ erg s^{-1}. These systematic trends persist when I consider the Eddington ratios. One again, the distribution of $L_{\rm bol}/L_{\rm Edd}$ for LINERs is rather similar to that of transition objects (median $L_{\rm bol}/L_{\rm Edd} \approx 2\times10^{-5}$ and 3×10^{-5}, respectively), but both are quite distinct from Seyferts (median $L_{\rm bol}/L_{\rm Edd} \approx 4\times10^{-4}$). Notably, the vast majority of nearby nuclei have highly sub-Eddington luminosities.

1.4.7 Host Galaxy Properties

The near dichotomy in the distribution of Hubble types for galaxies hosting active versus inactive nuclei (Fig. 1.5) leads to the expectation that the two populations ought to have fairly distinctive global, and perhaps even nuclear, properties. Moreover, a detailed examination of the host galaxies of AGNs may shed light on the origin of their spectral diversity. These issues were recently examined by Ho et al. (2003) using the database from the Palomar survey. The main results are summarized here.

The host galaxies of Seyferts, LINERs, and transition objects display a remarkable degree of homogeneity in their large-scale properties. After factoring out spurious differences arising from slight mismatches in Hubble type distribution, all three classes have essentially identical total luminosities ($\sim L^*$), bulge luminosities, sizes, and neutral gas content. The only exception is that, relative to LINERs, transition objects may show a mild enhancement in the level of star formation, and they may be preferentially more inclined. This is consistent with the hypothesis that the transition class arises from spatial blending of emission from a LINER and H II regions.

Theoretical studies (e.g., Heller & Shlosman 1994) suggest that large-scale stellar bars can be highly effective in delivering gas to the central few hundred parsecs of a spiral galaxy, thereby potentially leading to rapid star formation. Further instabilities result in additional inflow to smaller scales. Thus, provided that an adequate reservoir of gas exists, the presence of a bar might be expected to influence the BH fueling rate, and hence the level of nonstellar activity. The Palomar sample is ideally suited for statistical tests of this nature, which depend delicately on issues of sample selection effects and completeness. Ho et al. (1997d) find that while the presence of a bar indeed does enhance both the probability and rate of star formation in galaxy nuclei, it appears to have no impact on either the frequency or strength of AGN activity. Bearing in mind the substantial uncertainties introduced by sample selection (see discussion in Appendix B of Ho & Ulvestad 2001), other studies broadly come to a similar conclusion (see review by Combes 2003).

In the same vein, dynamical interactions with neighboring companions should lead to gas dissipation, enhanced nuclear star formation, and perhaps central fueling (e.g., Hernquist 1989). Schmitt (2001) and Ho et al. (2003) studied this issue using the Palomar data, parameterizing the nearby environment of each object by its local galaxy density and the distance to its nearest sizable neighbor. After accounting for the well-known morphology-density relation, it was found that the local environment, like bars, has little impact on AGNs.

The uniformity in host galaxy properties extends even to small, nuclear (~ 200 pc) scales, in two important respects. First, the velocity field of the ionized gas, as measured by the width and asymmetry of the narrow emission lines, appears to be crudely similar among the three classes, an observation that argues against the proposition that fast shocks primarily drive the spectral variations observed in nearby galactic nuclei. Second, the homogeneity among the three AGN classes is seen in their nuclear stellar content, which nearly always appears evolved. The general dearth of young or intermediate-age stars presents a serious challenge to proposals that seek to account for the excitation of the emission lines in terms of starburst or post-starburst models.

1.4.8 Do Intermediate-mass Black Holes Exist?

As summarized by Barth (2004) and Kormendy (2004), the observational evidence for supermassive BHs in the mass range $M_\bullet \approx 10^6 - 10^{9.5}\, M_\odot$ has become quite secure, to the

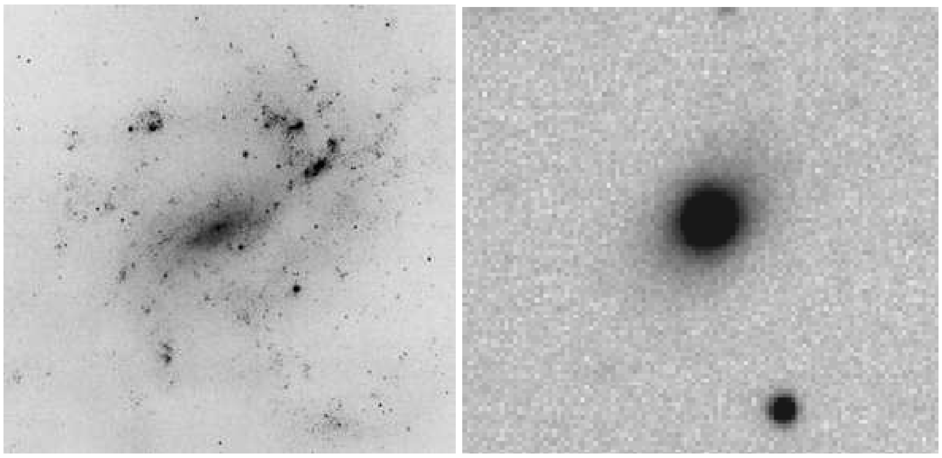

Fig. 1.10. Two examples of AGNs in late-type galaxies. The *left* panel shows an optical image of NGC 4395, adapted from the Carnegie Atlas of Galaxies (Sandage & Bedke 1994); the image is $\sim 15'$ (17 kpc) on a side. The *right* panel shows an *R*-band image of POX 52, adapted from Barth et al. (2004); the image is $\sim 25''$ (11 kpc) on a side.

point that important inferences on their demographics can be drawn (Richstone 2004). Do central (nonstellar) BHs with masses below 10^6 $M_\odot$ exist? The current low end of the mass scale may reflect observational limitations rather than a true physical limit. There is certainly no compelling theory that prohibits the existence of BHs in the large gap between the stellar regime of 10 $M_\odot$ and 10^6 $M_\odot$. The recent dynamical studies of Gerssen et al. (2002) and Gebhardt, Rich, & Ho (2002) suggest that some massive star clusters may contain BHs in the mass range $10^3 < M_\bullet < 10^4$ $M_\odot$ (see review by van der Marel 2004).

The existence of intermediate-mass BHs is further supported by the detection of AGNs in at least some very late-type and dwarf galaxies. Two examples are particularly noteworthy (Fig. 1.10). The nearby ($\sim$4 Mpc) galaxy NGC 4395 contains all the usual attributes of a respectable AGN: broad optical and UV emission lines (Filippenko & Sargent 1989; Filippenko, Ho, & Sargent 1993), a compact radio core (Ho & Ulvestad 2001; Wrobel, Fassnacht, & Ho 2001), and rapidly variable hard X-ray emission (Moran et al. 1999, 2004; Shih, Iwasawa, & Fabian 2003). Contrary to expectations, however, NGC 4395 is a bulgeless, extremely late-type (Sdm) spiral, whose central stellar velocity dispersion does not exceed $\sim$ 30 km s^{-1} (Filippenko & Ho 2003). If NGC 4395 obeys the $M_\bullet - \sigma$ relation, its central BH should have a mass $\lesssim 10^5$ $M_\odot$. This limit agrees surprisingly well with the value of $M_\bullet$ estimated from its broad Hβ line width and X-ray variability properties ($\sim 10^4 - 10^5$ $M_\odot$; Filippenko & Ho 2003).

As first noted by Kunth, Sargent, & Bothun (1987), the presence of a Seyfert-like nucleus in POX 52 is unusual because of the low luminosity of the host galaxy. Barth et al. (2004) show that POX 52 bears a close spectroscopic resemblance to NGC 4395. Based on the broad profile of Hβ, these authors derive a virial BH mass of 1.6×10^5 $M_\odot$ for POX 52, again remarkably close to the value of 1.3×10^5 $M_\odot$ predicted from the $M_\bullet - \sigma$ relation given the measured central stellar velocity dispersion of 35 km s^{-1}. Deep images reveal POX 52 to be most akin to a dwarf elliptical galaxy, to date an unprecedented morphology for an AGN host galaxy.

The two objects highlighted above demonstrate that the mass spectrum of nuclear BHs very likely extends below 10^6 $M_\odot$. Furthermore, they provide great leverage for anchoring the $M_\bullet - \sigma$ at the low end. But how common are such objects? AGNs hosted in high-surface brightness, late-type spirals appear to be quite rare in the nearby Universe. Within the comprehensive Palomar survey, NGC 4395 emerges as a unique case, and as argued in §1.4, the late-type galaxy population probably does not conceal a large number of misidentified AGNs. The majority of late-type spirals do possess compact, photometrically distinct nuclei (Böker et al. 2002), morphologically not dissimilar from NGC 4395, but these nuclei are compact star clusters, not AGNs (Walcher et al. 2004). The true incidence of AGNs like POX 52 is more difficult to assess. Most spectroscopic surveys of blue-selected emission-line objects do not have sufficient signal-to-noise ratio to identify weak, broad emission lines. On the other hand, Greene & Ho (2004), in a preliminary analysis of the first data release from SDSS, have uncovered a number of broad-line AGNs in low-luminosity, presumably low-mass, host galaxies. These appear to be excellent candidates for late-type galaxies with intermediate-mass BHs.

1.5 The Nature of LINERs

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. The principal alternatives are shocks and hot stars (see reviews by Barth 2002 and Filippenko 2003). 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), the AGN content in the majority of LINERs continues to be debated. Determining the physical origin of LINERs is more than of mere phenomenological interest. Because LINERs are so numerous, they have repercussions on many issues related to AGN demographics.

1.5.1 Evidence for an AGN Origin

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*. The discussion first focuses on "pure" LINERs, returning later to the class of transition objects, whose nature remains more obscure.

(1) *Detection of broad emission lines:* Luminous, unobscured AGNs distinguish themselves unambiguously by their characteristic broad permitted lines. The detection of broad Hα emission in $\sim$25% of LINERs (Ho et al. 1997e) thus constitutes strong evidence in favor of the AGN interpretation of these sources. LINERs, like Seyferts, evidently come in two flavors—some have a visible BLR (type 1), and others do not (type 2). The broad component becomes progressively more difficult to detect in ground-based spectra for permitted lines

* Note that this paper is concerned only with compact, *nuclear* LINERs ($r \lesssim 100$ pc), which are most relevant to the AGN issue. I do not consider LINER-like extended nebulae such as those associated with cooling flows, nuclear outflows, starburst-driven winds, and circumnuclear disks. LINERs selected from samples of distant, interacting, or infrared-bright galaxies are particularly vulnerable to confusion from these extended sources. (See also discussion in § 1.4.1.)

weaker than Hα. Where available, however, broad, higher-order Balmer lines as well as UV lines such as Lyα, C IV λ1549, Mg II λ2800, and Fe II multiplets can be seen in *HST* spectra (Barth et al. 1996; Ho et al. 1996). I further recall the double-peaked broad lines mentioned in § 1.5.3.

(2) *Detection of hidden BLRs:* An outstanding question, however, is what fraction of the more numerous LINER 2s are AGNs. By analogy with the Seyfert 2 class, surely *some* LINER 2s must be genuine AGNs—that is, LINERs whose BLR is obscured along the line of sight to the viewer. There is no *a priori* reason why the unification model, which has enjoyed such success in the context of Seyfert galaxies, should not apply equally to LINERs. The existence of an obscuring torus does not obviously depend on the ionization level of the NLR. 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 1.6:1 in the Palomar survey, we can reasonably surmise that the AGN fraction in LINERs may be as high as $\sim$60%. That at least some LINER 2s *do* contain a hidden BLR was demonstrated by the spectropolarimetric observations of Barth, Filippenko, & Moran (1999a, b).

(3) *Naked LINER 2s:* The BLR in some LINER 2s may be intrinsically absent, not obscured. If BLR clouds arise from condensations in a radiation-driven, outflowing wind (e.g., Murray & Chiang 1995), a viewpoint now much espoused, then it is reasonable to expect that very low-luminosity sources would be incapable of generating a wind, and hence of sustaining a BLR. A good example of such a case is NGC 4594 (the "Sombrero" galaxy). Its nucleus, although clearly an AGN, shows no trace of a broad-line component, neither in direct light (Ho et al. 1997e), not even when very well isolated with a small *HST* aperture (Nicholson et al. 1998), nor in polarized light (Barth et al. 1999b). Its Balmer decrement indicates little reddening to the NLR. For all practical purposes, the continuum emission from the nucleus looks unobscured: it is detected in the UV (Maoz et al. 1998) and in the soft and hard X-rays (Fabbiano & Juda 1997; Nicholson et al. 1998; Ho et al. 2001; Pellegrini et al. 2002; Terashima et al. 2002), with evidence for only moderate intrinsic absorption (Pellegrini et al. 2003). In short, there is no sign of anything being hidden or much doing the hiding. So where is the BLR? It is not there. A number of authors have also emphasized the existence of unabsorbed Seyfert 2 nuclei (e.g., Panessa & Bassani 2002; Gliozzi et al. 2004). These considerations lead to the conclusion that the mere absence of a BLR does not constitute evidence against the AGN pedigree of an object.

(4) *Compact cores:* AGNs, at least when unobscured, traditionally reveal themselves as point-like nuclear sources at virtually all wavelengths. This fact can be exploited by searching for compact cores in LINERs. To overcome the contrast problem, imaging observations of this kind are only meaningful for sufficiently high angular resolution. Moreover, in practice certain spectral windows are more advantageous than others. Nuclear point sources turn out to be surprisingly difficult to extract from optical and near-infrared images of nearby galaxies, even at the $0\farcs1$ resolution of *HST* (see, e.g., Ho & Peng 2001; Ravindranath et al. 2001; Peng et al. 2002). This is due to a number of factors, chiefly the dominance of the host galaxy bulge and the complexity of dust structures in nuclear regions at these wavelengths. The bulge light largely disappears in the UV, but the detection rate of nuclear cores in the UV is only $\sim$25% for LINERs (Maoz et al. 1995; Barth et al. 1998). This band is especially hard to work with because it is particularly susceptible to dust extinction, to confusion from young stars when present (Maoz et al. 1998), and to intrinsic variations due to the form of the SEDs of low-luminosity AGNs (Ho 1999b; see point 5 below).

Compact nuclei can be detected most cleanly in the X-rays and radio (see also § 1.4.4).

These regions are least sensitive to obscuration and provide the highest contrast between nonstellar and stellar emission. There have been a number of attempts to systematically investigate LINERs using X-ray data obtained from *ROSAT* (Koratkar et al. 1995; Komossa, Böhringer, & Huchra 1999; Roberts & Warwick 2000; Halderson et al. 2001; Roberts, Schurch, & Warwick 2001), *ASCA* (Ptak et al. 1999; Terashima, Ho, & Ptak 2000; Terashima et al. 2000, 2002), and *BeppoSAX* (Georgantopoulos et al. 2002). While these efforts have been enormously useful in delineating the basic X-ray properties of LINERs, particularly in the spectral domain, they suffer from two crucial limitations. First, the angular resolutions of all the above X-ray facilities, with the possible exception of the *ROSAT*/HRI under some circumstances (§1.4.4), are grossly incapable of properly isolating any but the brightest nuclei. And second, the faintness of the typical targets compels most investigators to study only limited, inevitably biased, samples.

The advent of *Chandra* has dramatically improved this situation. The high angular resolution of the telescope ($\sim 1''$) and the low background noise of the CCD detectors allow faint point sources to be detected with brief (few ks) exposures (Ho et al. 2001; Terashima & Wilson 2003). This makes feasible, for the first time, X-ray surveys of large samples of galaxies selected at non-X-ray wavelengths. Ho et al. (2001) used the ACIS camera to image a distance-limited sample of Palomar AGNs. Their analysis of a preliminary subset indicates that X-ray cores, some as faint as $\sim 10^{38}$ erg s^{-1} in the 2–10 keV band, are found in $\sim$75% of LINERs; the detection rate is roughly similar for LINER 1s and 2s.

As in the X-rays, AGNs nearly universally emit at some level in the radio. Although most AGNs are radio quiet, they are seldom radio silent when observed with sufficient sensitivity and angular resolution. For example, Seyfert galaxies generally contain radio cores, which are often accompanied by linear, jetlike features (e.g., Ulvestad & Wilson 1989; Kukula et al. 1995; Thean et al. 2000; Ho & Ulvestad 2001; Schmitt et al. 2001). The complete sample of Seyferts selected from the Palomar survey shows a detection rate of $\sim$80% at 5 GHz and $1''$ resolution (Ho & Ulvestad 2001; Ulvestad & Ho 2001a); their radio powers span $10^{18} - 10^{21}$ W Hz^{-1}.

LINERs have been surveyed somewhat less extensively than Seyferts. As mentioned in § 1.4.2, radio interferometric surveys of nearby elliptical and S0 galaxies detect a high fraction of low-power cores, most of which are optically classified as LINERs. VLA studies of well-defined subsamples of LINERs chosen from the Palomar survey show qualitatively similar trends (Van Dyk & Ho 1997; Nagar et al. 2000, 2002). At 5 and 8 GHz, where the sensitivity is highest, $\sim$60%–80% of LINERs, independent of type, contain radio cores. VLBI observations of the brighter, VLA-detected sources generally reveal brightness temperatures $\gtrsim 10^{6-8}$ K (Falcke et al. 2000; Ulvestad & Ho 2001b; Filho, Barthel, & Ho 2002b; Anderson, Ulvestad, & Ho 2004).

To summarize: the majority of LINERs, both type 1 and 2, photometrically resemble AGNs insofar as they emit compact, pointlike hard X-ray and radio emission.

(5) *Spectral energy distributions:* The broad-band spectrum of luminous, unabsorbed AGNs follows a fairly universal shape (e.g., Elvis et al. 1994). The SED from the infrared to the X-rays can be roughly represented as the sum of an underlying power law ($L_\nu \propto \nu^{-1}$) and a few distinct components, the most prominent of which is the "big blue bump" usually attributed to thermal emission from an optically thick, geometrically thin accretion disk (Shields 1978; Malkan & Sargent 1982). The SEDs of LINERs deviate markedly from the standard form of high-luminosity AGNs (Ho 1999b, 2002b; Ho et al. 2000), as shown in Figure 1.11. The most conspicuous difference can be seen in the apparent absence of a UV excess. The SEDs

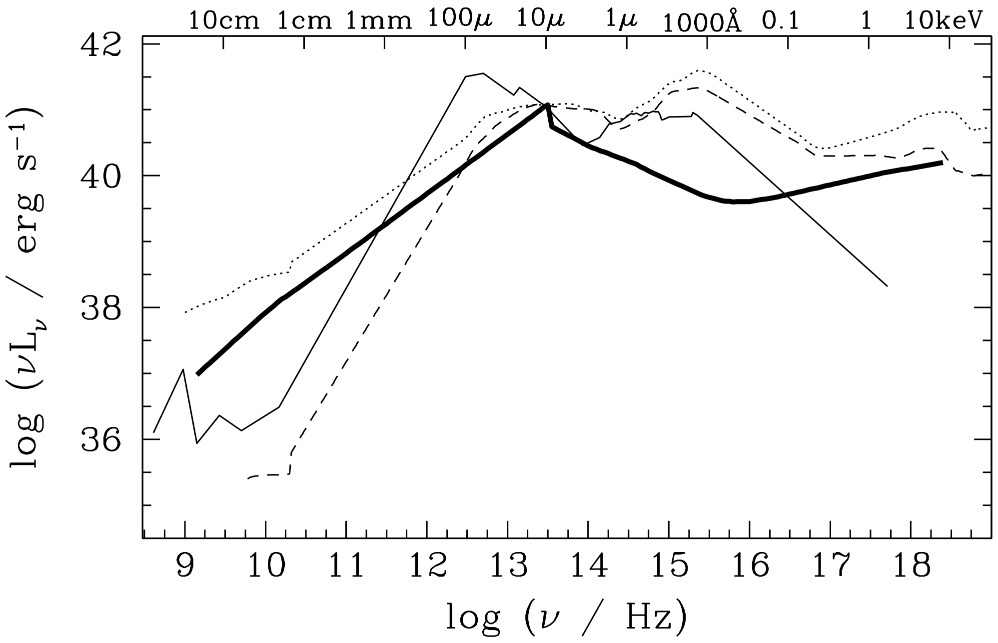

Fig. 1.11. The average SED of low-luminosity AGNs (*heavy solid line*), adapted from Ho (1999b). Overplotted for comparison are the average SEDs of powerful radio-loud (*dotted line*) and radio-quiet (*dashed line*) AGNs (Elvis et al. 1994), and of low-extinction starburst galaxies (*light solid line*; Schmitt et al. 1997). The curves have been arbitrarily normalized to the luminosity at 10 μm.

of these sources also tend to be generically "radio loud," defined here by the convention that the radio-to-optical luminosity ratio exceeds a value of 10. In fact, radio loudness seems to be a property common to essentially *all* nearby weakly active nuclei (Ho 2002a) and a substantial fraction of Seyfert nuclei (Ho & Peng 2001). Using a definition of radio loudness based on the relative strength of the X-ray and radio emission, Terashima & Wilson (2003) also find that LINERs tend to be radio loud.

While the SEDs of LINERs differ from those of those of traditional AGNs, it is important to emphasize that they *do* approximate the SEDs predicted for radiatively inefficient accretion flows onto BHs (e.g., Quataert et al. 1999; Ptak et al. 2004). At the same time, they definitely bear little resemblance to SEDs characteristic of "normal" stellar systems (see, e.g., Schmitt et al. 1997). Inactive galaxies or starburst systems not strongly affected by dust extinction emit the bulk of their radiation in the optical–UV and in the thermal infrared regions, with only an energetically miniscule contribution from X-rays (Fig. 1.11). Indeed, the decidedly *nonstellar* nature of the SEDs of LINERs can be regarded as compelling evidence that LINERs are accretion-powered sources, albeit of an unusual ilk.

(6) *Host galaxies:* As discussed in § 1.4.7, LINERs and Seyferts live in virtually identical host galaxies. To the extent that Seyferts are regarded as AGNs, the close similarity of their hosts

with those of LINERs lends supporting, if albeit indirect, evidence that the two classes share a common origin.

(7) *Detection of massive BHs:* Finally, I note the obvious fact that a significant fraction of the galaxies with detected BHs are, in fact, well-known LINERs. These include M81, M84, M87, NGC 4261, and NGC 4594. Although certainly no statistical conclusions can yet be drawn from such meager statistics, these examples nevertheless illustrate that at least some LINERs seem to be directly connected with BH accretion.

1.5.2 Excitation Mechanisms

The above arguments lend credence to the hypothesis that a sizable fraction of LINERs—indeed the *majority*—are directly related to AGNs. In this context, photoionization by a central AGN surfaces as the most natural candidate for the primary excitation mechanism of LINERs. The optical spectra of LINERs can be readily reproduced in AGN photoionization calculations by adjusting the ionization parameter, U, defined as the ratio of the density of ionizing photons to the density of nucleons at the illuminated face of a cloud. Whereas the NLR spectrum of Seyferts can be well fitted with $\log U \approx -2.5 \pm 0.5$ (e.g., Ferland & Netzer 1983; Stasińska 1984; Ho, Shields, & Filippenko 1993b), that of LINERs requires $\log U \approx -3.5 \pm 1.0$ (Ferland & Netzer 1983; Halpern & Steiner 1983; Péquignot 1984; Binette 1985; Ho et al. 1993a). What factors contribute to the lower ionization parameters in LINERs? Ho et al. (2003) identify the central luminosity and gas density as two relevant factors. According to the statistics from the Palomar survey, LINERs on average have lower luminosities and lower gas densities than Seyferts. For a given volume filling factor, this leads to lower ionization parameters in LINERs compared to Seyferts, although not at a level sufficient to account for the full difference between the two classes.

Despite the natural appeal of AGN photoionization, alternative excitation mechanisms for LINERs have been advanced. Collisional ionization by shocks has been a popular contender from the outset (Koski & Osterbrock 1976; Fosbury et al. 1978; Heckman 1980b; Dopita & Sutherland 1995; Alonso-Herrero et al. 2000; Sugai & Malkan 2000). Dopita & Sutherland (1995) showed that the diffuse radiation field generated by fast ($\upsilon \approx$ 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 shocked gas should produce a higher excitation spectrum, most readily discernible in the UV, than photoionized gas. In all the cases studied so far, however, 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; Maoz et al. 1998; Nicholson et al. 1998; Gabel et al. 2000). Dopita et al. (1997) used the spectrum of the circumnuclear *disk* of M87 to advance the view that LINERs are shock excited. This argument is misleading because their analysis deliberately avoids the nucleus. Sabra et al. (2003) demonstrate that the UV–optical spectrum of the *nucleus* of M87 is best explained by a multi-component photoionization model.

A recent analysis of the emission-line profiles of the Palomar nuclei further casts doubt on the viability of the shock scenario (Ho et al. 2003). The velocity dispersions of the nuclear gas generally fall short of the values required for shock excitation to be important.

Furthermore, the close similarity between the velocity field of LINERs and Seyferts, as deduced from their line profiles, contradicts the basic premise that shocks are primarily responsible for the spectral differences between the two classes of objects.

Another widely discussed class of models invokes hot stars, formed in a short-duration burst of star formation, to supply the primary ionizing photons. Ordinary O-type stars with effective temperatures typical of those inferred in giant H II regions in galactic disks do not produce sufficiently strong low-ionization lines to account for the spectra of LINERs. The physical conditions in galactic nuclei, on the other hand, may be more favorable for generating LINER-like spectra. For example, Terlevich & Melnick (1985) postulate that the high-metallicity environment of galactic nuclei may be particularly conducive to forming very hot [$T \approx (1-2) \times 10^5$ K], luminous Wolf-Rayet stars, whose ionizing spectrum would effectively mimic the power-law continuum of an AGN. The models of Filippenko & Terlevich (1992) and Shields (1992) appeal to less extreme conditions. These authors show that photoionization by ordinary O stars embedded in an environment with high density and low ionization parameter can explain the spectral properties of transition objects. Barth & Shields (2000) extended this work by modeling the ionizing source not as single O-type stars but as a more realistic evolving young star cluster. They confirm that young, massive stars can indeed generate optical emission-line spectra that match those of transition objects, and, under some plausible conditions, even those of *bona fide* LINERs. But there is an important caveat: the star cluster must be formed in an instantaneous burst, and its age must coincide with the brief phase ($\sim$3–5 Myr after the burst) during which sufficient Wolf-Rayet stars are present to supply the extreme-UV photons necessary to boost the low-ionization lines. The necessity of a sizable population of Wolf-Rayet stars is also emphasized in the recent study by Gabel & Bruhweiler (2002). As discussed in Ho et al. (2003), the main difficulty with this scenario, and indeed with all models that appeal to young stars (e.g., Taniguchi, Shioya, & Murayama 2000), is that the nuclear stellar population of the host galaxies of the majority of nearby AGNs, irrespective of spectral class, is demonstrably *old*. Stellar absorption indices indicative of young or intermediate-age stars are seldom seen, and the telltale emission features of Wolf-Rayet stars are notably absent. These empirical facts seriously undermine stellar-based photoionization models of AGNs.

1.5.3 Transition Objects

The physical origin of transition nuclei continues to be a thorny, largely unresolved problem. Since these objects make up a significant fraction of emission-line nuclei, this complication unfortunately casts some uncertainty into the demography of local AGNs.

In two-dimensional optical line-ratio diagrams (Fig. 1.3), transition nuclei are empirically defined to be those sources that lie sandwiched between the loci of "normal" H II regions and LINERs. This motivated Ho et al. (1993a) to proposed that transition objects may be composite systems consisting of a LINER nucleus plus an H II region component. The latter could arise from neighboring circumnuclear H II regions or from H II regions randomly projected along the line of sight. A similar argument, based on decomposition of line profiles, has been made by Véron, Gonçalves, & Véron-Cetty (1997) and Gonçalves, Véron-Cetty, & Véron (1999).

If transition objects truly are LINERs sprinkled with a frosting of star formation, one would expect that their host galaxies should be largely similar to those of LINERs, namely bulge-dominated systems (§ 1.4.7), modulo minor differences due to the "excess" contaminating star formation. The study of Ho et al. (2003) largely supports this picture. The host galaxies of transition nuclei exhibit systematically higher levels of recent star formation, as indicated by their far-infrared emission and broad-band optical colors, compared to LINERs of matched morphological types. Moreover, the host galaxies of transition nuclei tend to be slightly more inclined than LINERs. Thus, all else being equal, transition-type spectra seem to be found precisely in those galaxies whose nuclei have a higher probability of being contaminated by extra-nuclear emission from star-forming regions.

This story, however, has some holes. If simple spatial blending of circumnuclear H II regions is sufficient to transform a regular LINER into a transition object, the LINER nucleus should reveal itself unambiguously in spectra taken with angular resolution sufficiently high to isolate it. This test was performed by Barth, Ho, & Filippenko (2003), who obtained *HST*/STIS spectra, taken with a $0\rlap{.}''2$-wide slit, of a well-defined subsample of 15 transition objects selected from the Palomar catalog. To their surprise, the small-aperture spectra of the nuclei, for the most part, look very similar to the ground-based spectra; they are *not* more LINER-like.

The "masqueraded-LINER" hypothesis can be further tested by searching for compact radio and X-ray cores using high-resolution images. Recall that this is a highly effective alternative method to filter out weak AGNs (§ 1.4.4 and § 1.5.1). Filho et al. (2000, 2002a, 2004) have systematically surveyed the full sample of Palomar transition objects using the VLA. They find that ∼25% of the population contains arcsecond-scale radio cores. These cores appear to be largely nonstellar in nature. The brighter subset of these sources that are amenable to follow-up VLBI observations (Filho et al. 2004) all reveal more compact (milliarcsecond-scale) cores with flat radio spectra and high brightness temperatures ($T_B \gtrsim 10^7$ K). In their preliminary analysis of a *Chandra* survey of Palomar galaxies, Ho et al. (2001) noted that transition objects show a marked deficit of X-ray cores. Although based on small-number statistics, the frequency of X-ray cores for the transition objects in the Ho et al. study also turns out to be 25%.

The above considerations suggest a conservative lower limit of ∼25% for the AGN fraction in transition objects, or a reduction from 13% to ∼3% of the overall galaxy population. In turn, the total AGN fraction (LINERs, Seyferts, and accretion-powered transition objects) for all local galaxies decreases from 43% to 33%. These revised rates are lower limits because of the imperfect correspondence between "genuine" AGNs and the presence of radio and X-ray cores. After all, for reasons that are not yet understood, clearly not all Seyfert nuclei are detected in the radio (e.g., Ho & Ulvestad 2001; Ulvestad & Ho 2001), and X-rays in the 2–10 keV band will be extinguished for gas with sufficiently large column densities ($\gtrsim 10^{24}$ cm^{-2}). Such low-luminosity Compton-thick nuclei, if present, can be uncovered with sensitive, high-resolution observations at harder X-ray energies.

If the majority of transition objects are not AGNs, we are faced with a new conundrum. What are they? For the reasons explained above, the source of their line excitation is unlikely to be shock heating or photoionization by hot, massive stars. Here I suggest two possibilities worth considering. First, the ionizing radiation field might originate from hot, *evolved* stars. This idea has been advocated by Binette et al. (1994), who proposed that post-asymptotic giant branch stars, which can attain effective temperatures as high as $\sim 10^5$ K, might be responsible for photoionizing the extended ionized gas often observed in elliptical galaxies. The emission-line spectrum of these nebulae, in fact, tend to be of relatively low ionization (Demoulin-Ulrich, Butcher, & Boksenberg 1984; Phillips et al. 1986; Zeilinger et al. 1996). Invoking evolved stars has the obvious appeal of not conflicting with the dominant old stellar population found in the centers of nearby galaxies. Second, the integrated (off-nuclear) X-ray emission of the central regions of galaxies may contribute nonnegligibly to the ionizing photon budget. Recent *Chandra* and *XMM-Newton* images of the centers of nearby, "ordinary" galaxies have resolved the X-ray emission into two components: discrete sources and diffuse, hot gas. The discrete X-ray source population consists mainly of X-ray binaries, mostly of the low-mass variety (see Fabbiano & White 2004 for a review). While X-ray–emitting plasma has long been known to be pervasive in giant elliptical galaxies, it now appears that it may be a generic constituent even in spheroids of lower mass. For example, diffuse, hot gas has been detected in the central regions of the Milky Way (Baganoff et al. 2004), M31 (Shirey et al. 2001), and M32 (Ho, Terashima, & Ulvestad 2003). Since X-ray binaries and X-ray–emitting gas have "hard" spectra (compared to, say, O-type stars), they would naturally be conducive to producing strong low-ionization optical lines when used as an ionizing source. These unconventional sources of ionization—hot, evolved stars, X-ray binaries, and X-ray plasma—*must* contribute at some level, insofar as we know empirically that they exist. Their ubiquitous presence likely maintains a pervasive, diffuse, ionizing radiation field, which may be sufficient to sustain a "baseline" level of weak optical line emission. It would be fruitful to further explore these issues quantitatively with photoionization models.

1.6 Summary

This review argues that the demographics of AGN activity in nearby galaxies can inform us much about the demographics of massive BHs. While ultimately there is no substitute for direct dynamical mass measurements, such an approach is often neither practical nor feasible. AGN statistics provide important complementary information. The following points are the most germane to BH demography.

(1) Nuclear activity is extremely common in the nearby Universe. Over 40% of all nearby galaxies qualify as AGNs or AGN candidates according to their emission-line spectral properties.
(2) LINERs are the most common variety of local AGN candidates.
(3) The majority of LINERs appear to be genuinely accretion-powered systems. Thus, most LINERs should be considered AGNs.
(4) Nuclear activity preferentially occurs in bulge-dominated galaxies. Galaxies with Hubble types later than Sbc become progressively dominated by nuclear star formation.
(5) The physical origin of the so-called transition objects remains largely unknown, although at least 25% of them appear to be AGNs. This uncertainty affects the quantitative conclusions from (1) and (2), but the qualitative picture remains unchanged.
(6) Inasmuch as central BHs are a precondition for AGN activity, the detection rate of AGNs establishes a lower limit on the incidence of massive BHs in nearby galactic nuclei. The above findings support the prevailing belief, based on dynamical studies and energy arguments (see Barth 2004; Kormendy 2004; Richstone 2004), that massive BHs are a ubiquitous feature of massive galaxies.
(7) Central massive BHs, while perhaps uncommon in pure-disk or dwarf galaxies, do not completely shun such environments. Some late-type galaxies definitely harbor lightweight nuclear BHs, which extend the BH mass function down to the regime of $M_\bullet \approx 10^4 - 10^5\ M_\odot$, although the frequency of such objects is not yet well established. These intermediate-mass BHs seem to obey the $M_\bullet$-σ relation established by the supermassive ($10^6 - 10^{9.5}\ M_\odot$) BHs.

(8) Local AGNs are generically weak, characterized by highly sub-Eddington luminosities. Most central BHs in nearby galaxies are either quiescent or only weakly active.

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