“Low-state” Black Hole Accretion in Nearby Galaxies†

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Abstract. I summarize the main observational properties of low-luminosity AGNs in nearby galaxies to argue that they are the high-mass analogs of black hole X-ray binaries in the “low/hard” state. The principal characteristics of low-state AGNs can be accommodated with a scenario in which the central engine is comprised of three components: an optically thick, geometrically accretion disk with a truncated inner radius, a radiatively inefficient flow, and a compact jet.

1. AGNs and Black Hole X-ray Binaries

Stellar-mass black holes in X-ray binaries, in response to changes in the mass accretion rate, exhibit distinct spectral “states” (McClintock & Remillard 2005). Since many aspects of accretion flows are invariant with respect to changes in black hole mass, it is of interest to ask whether there are extragalactic analogs to X-ray binary states in massive black holes in the centers of galaxies. Nuclear black holes outweigh stellar black holes by factors of $10^5$ – $10^8$, and so their evolutionary timescales increase in the same proportion. To search for spectral states in massive black holes, one must consider the demographics of accreting nuclear black holes—AGNs—spanning a wide range of luminosity.

In recent years, much attention has been devoted to the study of “narrow-line” Seyfert 1 galaxies, which are widely believed to be the AGN counterparts of X-ray binaries in the “high/soft” state (e.g., Pounds, Done, & Osborne 1995). Indeed, this class of AGNs may be even accreting at super-Eddington rates (Collin & Kawaguchi 2004).

This contribution focuses on AGNs in the opposite extreme, namely those accreting at highly sub-Eddington rates, which I will argue are close analogs to X-ray binaries in the “low/hard” or “quiescent” states, and which dominate the population of AGNs at $z = 0$.

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2. Observational Properties of Low-luminosity AGNs

Although the physical nature of low-luminosity AGNs (LLAGNs) is still not fully understood, the bulk of the current evidence suggests that a significant fraction of them are genuinely accretion-powered sources (for a recent review, see Ho 2004). Here I highlight the most important observational properties of these objects, which, when taken collectively, point to some novel insights on the structure of their central engines.

− **Demography.** LLAGNs are very common. According to the Palomar survey (Ho, Filippenko, & Sargent 1997a), over 40% of nearby galaxies, and an even greater fraction (50%–75%) of bulge-dominated (E–Sbc) systems, contain LLAGNs.

− **Low ionization.** The dominant population (2/3) of LLAGNs have low-ionization state spectra (Ho et al. 1997a). They are classified as either LINERs (low-ionization nuclear emission-line regions) or transition objects, which are hypothesized to be related to LINERs (Ho, Filippenko, & Sargent 1993; but see complications discussed in Ho, Filippenko, & Sargent 2003 and Ho 2004).

− **Low accretion power.** LLAGNs are intrinsically faint, in most cases orders of magnitude less powerful than classical Seyferts and quasars. The optical luminosity function of LLAGNs extends to absolute magnitudes as low as $M_B \approx -6$ (Ho 2004). Figure 1a, from Ho (2005), shows the distributions of bolometric luminosities for $\sim 250$ objects from the Palomar survey. Note that nearly all the objects have $L_{\text{bol}} < 10^{44}$ erg s$^{-1}$, and most significantly less. Seyferts are on average 10 times more luminous than LINERs or transition objects.

− **Sub-Eddington.** LLAGNs are highly sub-Eddington systems, as shown in Figure 1b. Essentially all objects in the Palomar sample have $L_{\text{bol}}/L_{\text{Edd}} < 1$, with the majority falling in the region $L_{\text{bol}}/L_{\text{Edd}} \approx 10^{-5} - 10^{-3}$. Seyferts have systematically higher Eddington ratios than LINERs or transition objects, typically by 1 to 2 orders of magnitude.

− **Radiatively inefficient.** Direct measurements of accretion rates are not available, but rough estimates can be made of the likely minimum rates supplied *in situ*. Quite apart from any additional fuel furnished by the large-scale disk of the host galaxy or from external sources triggered by tidal interactions, both of which are
inconsequential for nearby galaxies (Ho et al. 1997b, 2003), galactic centers contain two reservoirs of fuel that seems inescapable. The first is mass loss from evolved stars, which is readily available from the dense stellar cusps invariably observed in the centers of bulges (e.g., Lauer et al. 1995; Ravindranath et al. 2001). Ho (2005) estimates $\dot{M}_* \sim 10^{-5} - 10^{-3}$ $M_\odot$ yr$^{-1}$. The other source of fuel is Bondi accretion of hot gas, which is ubiquitous not only in giant elliptical galaxies, but apparently also in the bulges of disk galaxies (e.g., Shirey et al. 2001; Baganoff et al. 2003). The expected contribution from Bondi accretion turns out to be roughly comparable to $\dot{M}_*$ (Ho 2005). If this gas were to be all accreted and radiates with a standard efficiency of $\eta = 10\%$, the nuclei should be $1 - 4$ orders of magnitude more luminous than observed. Three possible explanations come to mind: (1) angular momentum transfer is very inefficient, even at these small scales, so that only a tiny fraction of the available fuel makes it to the center; (2) the accretion flow is radiatively inefficient, with $\eta$ much less than $10\%$; (3) most of the gas is blown out of the system by winds or outflows, which arise naturally in radiatively (e.g., Blandford & Begelman 1999). (Note that the third option is not entirely independent from the second.) While it is difficult to rule out the first explanation, it seems plausible that these systems are radiatively inefficient.

- **Unusual SEDs.** With few exceptions, the spectral energy distributions (SEDs) of LLAGNs lack the optical–UV “big blue bump,”
a feature usually attributed to thermal emission from an optically thick, geometrically thin accretion disk (Ho 1999, 2002a; Ho et al. 2000). This is illustrated in Figure 2, which compares the average SED of LLAGNs with the canonical SEDs of radio-loud and radio-quiet quasars (Elvis et al. 1994). Instead of a blue excess, there is a maximum peaking somewhere in the mid-IR. (The exact location of the peak is poorly defined because of the current lack of high-resolution IR data.) One consequence of the deficit of optical–UV emission is that the X-rays become disproportionately important energetically. The standard $\alpha_{\text{ox}}$ parameter is typically less than 1, whereas in luminous AGNs $\alpha_{\text{ox}} \approx 1.4$. The X-ray spectra can be well described by a simple power law, with $\Gamma \approx 1.7 - 1.9$, which generally requires only little or modest intrinsic absorption, with no evidence for a soft excess at low energies (e.g., Terashima et al. 2002; Terashima & Wilson 2003; Ptak et al. 2004).

Figure 2. The average SED of low-luminosity AGNs (solid line), adapted from Ho (1999). Overplotted for comparison are the average SEDs of powerful radio-loud (dotted line) and radio-quiet (dashed line) AGNs (Elvis et al. 1994). The curves have been arbitrarily normalized to the luminosity at 10 $\mu$m.
− *Radio jets.* Another notable feature of the SEDs of LLAGNs is that they tend to be generically radio-loud. This is true of most LINERs (Ho 1999, 2002b; Ho et al. 2000; Terashima & Wilson 2003), and, contrary to persistent popular misconception, is so even in most Seyfert nuclei (Ho & Peng 2001). Detailed modeling of the SEDs (e.g., Quataert et al. 1999; Ulvestad & Ho 2001; Anderson, Ulvestad, & Ho 2004) shows that neither the radio power nor the detailed radio spectrum agrees with predictions from accretion flow models. Instead, a separate, compact jet component is required. This indicates that compact jets develop naturally in LLAGNs.

− *No broad Fe Kα line.* The 6.4 keV Fe Kα line is detected in some LLAGNs, but it is almost always narrow (Terashima et al. 2002). In well-studied cases (e.g., Ptak et al. 2004), Fe Kα emission of any breadth can be ruled out to very high significance. Insofar as the broad iron line is regarded as a signature of a standard optically thick disk, this suggests that such a disk is generically absent or truncated in LLAGNs.

− *Disklike Hα profiles.* Emission lines with broad, double-peaked profiles, taken to be the kinematic signature of a relativistically broadened disk, are found quite often in LLAGNs (Ho et al. 2000, and references therein; Shields et al. 2000; Barth et al. 2001; Eracleous & Halpern 2001). When fitted with a disk model, one infers that the disk has a relatively large inner radius ($\sim 10^3 R_S$).

### 3. A Physical Picture of the Central Engine

I propose that the above set of characteristics, common to most LLAGNs studied in detail thus far, suggest that nearby galaxy bulges contain central engines as schematically depicted in Figure 3. Most galaxies with bulges contain active nuclei because most, if not all, bulges contain massive black holes. This is consistent with the picture that has emerged from recent kinematical studies of nearby galaxies (e.g., Richstone 2004). In the present-day Universe, and especially in the centers of big bulges, the amount of gas available for accretion is quite small, plausibly well below the Eddington rate for the associated black hole mass (Ho 2005). In such a regime, the low-density, tenuous material is optically thin and cannot cool efficiently. Rather than settling into a classical optically thick, geometrically thin disk, the hot accretion flow assumes a quasi-spherical configuration, whose dynamics may be dominated by advection, convection, or outflows (see Quataert 2001 and
Figure 3. A cartoon depicting the structure of the accretion flow surrounding weakly active massive black holes. An inner low-radiative efficiency accretion flow (LRAF) irradiates an outer, truncated thin disk. An additional compact jet component is needed.

Narayan, these proceedings.) For simplicity, I follow Quataert (2001) and simply call these low-radiative efficiency accretion flows (LRAFs). The existence of LRAFs in these systems, or conversely the absence of classical thin disks extending all the way to small radii (few $R_S$), is suggested by their (1) low luminosities, (2) low Eddington ratios, (3) low inferred radiative efficiencies, (4) lack of a big blue bump, and (5) lack of relativistically broadened Fe Kα lines.

Apart from a central LRAF, two additional components generally seem to be required. First, detailed considerations of the broad-band SED show that the baseline LRAF spectrum underpredicts the observed radio power (e.g., Quataert et al. 1999; Ulvestad & Ho 2001). Most of the radio luminosity, which is substantial because these objects tend to be “radio-loud,” must come from another component, and the most likely candidate is a compact jet. Does the puffed-up structure of an LRAF, or its propensity for outflows, somehow facilitate the generation of relativistic jets? Second, an outer thin disk, truncated at perhaps $\sim 100 - 1000 R_S$, seems necessary to explain (1) the existence of the IR excess in the SED (e.g., Quataert et al. 1999) and (2) the prevalence of double-peaked broad emission lines (Chen, Halpern, & Filippenko 1989; Ho et al. 2000). A large truncation radius is also
qualitatively consistent with the weakness or absence of broad Fe Kα emission.

Lastly, we note that low-ionization spectra may emerge quite naturally in the scenario suggested above. In the context of AGN photoionization models, it is well known that LINER-like spectra can be produced largely by lowering the “ionization parameter” $U$, typically by a factor of $\sim 10$ below that in Seyferts (e.g., Halpern & Steiner 1983; Ferland & Netzer 1983). The characteristically low luminosities of LINERs (Fig. 1a), coupled with their low densities (Ho et al. 2003), naturally lead to low values of $U$. Two other effects, however, are also important in boosting the low-ionization lines. All else being equal, hardening the ionizing spectrum (by removing the big blue bump) in photoionization calculations creates a deeper partially ionized zone from which low-ionization transitions, especially $[\text{O I}] \lambda\lambda 6300, 6363$, are created. Because of the prominence of the radio spectrum, cosmic-ray heating of the line-emitting gas by the radio-emitting plasma may be nonnegligible; one consequence of this process is again to enhance the low-ionization lines (Ferland & Mushotzky 1984). Both of these effects should be investigated quantitatively.

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References

Anderson, J. M., Ulvestad, J. S., & Ho, L. C. 2004, ApJ, 603, 42
Baganoff, F. K., et al. 2003, ApJ, 591, 891
Barth, A. J., Ho, L. C., Filippenko, A. V., Rix, H.-W., & Sargent, W. L. W. 2001, ApJ, 546, 205
Blandford, R. D., & Begelman, M. C. 1999, MNRAS, 303, L1
Chen, K., Halpern, J. P., & Filippenko, A. V. 1989, ApJ, 339, 742
Collin, S., & Kawaguchi, T. 2004, A&A, 426, 797
Elvis, M., et al. 1994, ApJS, 95, 1
Eracleous, M., & Halpern, J. P. 2001, ApJ, 554, 240
Ferland, G. J., & Mushotzky, R. F. 1984, ApJ, 286, 42
Ferland, G. J., & Netzer, H. 1983, ApJ, 264, 105
Halpern, J. P., & Steiner, J. E. 1983, ApJ, 269, L37
Ho, L. C. 1999, ApJ, 516, 672
——. 2002a, in Issues in Unification of AGNs, ed. R. Maiolino, A. Marconi, & N. Nagar (San Francisco: ASP), 165
——. 2002b, ApJ, 564, 120
Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1993, ApJ, 417, 63
——. 1997a, ApJ, 487, 568
——. 1997b, ApJ, 487, 591
——. 2003, ApJ, 583, 159

Ho, L. C., & Peng, C. Y. 2001, ApJ, 555, 650

Ho, L. C., Rudnick, G., Rix, H.-W., Shields, J. C., McIntosh, D. H., Filippenko, A. V., Sargent, W. L. W., & Eracleous, M. 2000, ApJ, 541, 120

Lauer, T. R., et al. 1995, AJ, 110, 2622

McClintock, J. E., & Remillard, R. A. 2005, in Compact Stellar X-ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), in press [astro-ph/0306213]

Pounds, K. A., Done, C., & Osborne, J. P. 1995, MNRAS, 277, L5

Ptak, A., Terashima, Y., Ho, L. C., & Quataert, E. 2004, ApJ, 606, 173

Quataert, E. 2001, in Probing the Physics of Active Galactic Nuclei by Multiwavelength Monitoring, ed. B. M. Peterson, R. S. Poldan, & R. W. Pogge (San Francisco: ASP), 71

Quataert, E., Di Matteo, T., Narayan, R., & Ho, L. C. 1999, ApJ, 525, L89

Ravindranath, S., Ho, L. C., Peng, C. Y., Filippenko, A. V., & Sargent, W. L. W. 2001, AJ, 122, 653

Richstone, D. 2004, in Carnegie Observatories Astrophysics Series, Vol. 1: Coevolution of Black Holes and Galaxies, ed. L. C. Ho (Cambridge: Cambridge Univ. Press), 281

Shields, J. C., Rix, H.-W., McIntosh, D. H., Ho, L. C., Rudnick, G., Filippenko, A. V., Sargent, W. L. W., & Sarzi, M. 2000, ApJ, 534, L27

Shirley, R., et al. 2001, A&A, 365, L195

Terashima, Y., Iyomoto, N., Ho, L. C., & Ptak, A. F. 2002, ApJS, 139, 1

Terashima, Y., & Wilson, A. S. 2003, ApJ, in press

Ulvestad, J. S., & Ho, L. C. 2001, ApJ, 562, L133