Carnegie Observatories Astrophysics Series, Vol. 1:
Coevolution of Black Holes and Galaxies, 2004
ed. L. C. Ho (Pasadena: Carnegie Observatories,
http://www.ociw.edu/ociw/symposia/series/symposium1/proceedings.html)

Black Holes as Traced by Weak Active Nuclei

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Abstract

The centers of many nearby galaxies show low levels of emission-line activity in their nuclei. While some of these sources exhibit properties that clearly trace accretion onto a black hole, many of these objects are less certain in their interpretation. Understanding the nature of these ambiguous cases is of interest for extending the local census of black holes and their growth rates. Spectroscopy with *HST* provides a means of resolving the inner emission regions of galaxy nuclei and reducing contaminating emission from circumnuclear sources. Here we report the results of such observations obtained in the Survey of Nearby Nuclei with STIS (SUNNS). We find, rather surprisingly, that emission-line ratios within the central 20 pc often show little difference from the emission measured over apertures an order of magnitude larger in size, containing 10 – 100 times as much emission. These results cast doubt on whether the ambiguous objects are accretion powered in general, and instead suggest an important role for distributed sources of ionization in the centers of some of these galaxies.

1.1 Introduction

In the standard paradigm, the detection of an active galactic nucleus is an efficient means of discovering an accreting supermassive black hole. The extent to which we can build a census of black holes in this way depends on our ability to detect and recognize AGN behavior at low as well as high luminosities.

Optical spectroscopic surveys capable of revealing weak AGNs have demonstrated that a large fraction of bright galaxies exhibit nebular emission in their nuclei. For one of the most extensive surveys, the Palomar survey of 486 nearby galaxies (Filippenko & Sargent 1985; Ho, Filippenko & Sargent 1997), the fraction of nuclei showing detectable emission lines is 86%. Of these sources, $\sim 18\%$ are Seyfert nuclei or Low Ionization Nuclear Emission-line Regions (LINERs) with broad Hα, which are thus unambiguously quasar-like objects presumably powered by accretion onto a supermassive black hole. However, another $\sim 33\%$ are "LINER 2s" (lacking broad lines, by analogy with Seyfert 2s) or H II/LINER "transition"objects, for which the power source is potentially ambiguous. A variety of mechanisms other than accretion power can in some situations give rise to LINER 2 emission; transition objects lie intermediate to H II regions and LINERs in line-ratio diagnostic diagrams, and hence are particularly uncertain in their underlying energetics. Determining whether accretion power is important in these sources is thus of interest for identifying the local incidence and growth rates for supermassive black holes.

A possible means of discerning the presence or absence of accretion sources in ambiguous emission nuclei is by inspection of their nebular emission on small scales. Measurement of the nuclear spectra through reduced apertures will diminish contaminating starlight and make it easier to discover weak broad Balmer emission that may be missed in ground-based studies. For LINER 2s powered by a central photoionizing source, we might also expect gradients in ionization on small scales tracing the r^{-2} dilution of the radiation field. For transition objects, several researchers have posited that these sources are composite systems consisting of a central accretion-powered nucleus surrounded by H II regions that are spatially unresolved (Kennicutt, Keel, & Blaha 1989; Ho, Filippenko, & Sargent 1993); this model can be tested using spectra with angular resolution sufficient to resolve the central emission nebula and isolate the two putative components.

1.2 New Results from *HST*

The Survey of Nearby Nuclei with STIS (SUNNS) employed the *Hubble Space Telescope* to study the spectroscopic properties of nearby galaxy nuclei exhibiting emission lines in the Ho et al. (1997a) survey. A distance-limited sample ($d \leq 17$ Mpc for $H_0 = 75$ km s^{-1} Mpc^{-1}) of 24 galaxies was employed; one source was lost due to a target acquisition error. The Palomar spectra for these sources, obtained with a $2'' \times 4''$ aperture, yielded spectroscopic classifications with nearly equal numbers of Seyfert, LINER 1, LINER 2, transition, and H II sources among the sample. (The Seyfert nuclei are classified as Seyfert 1.9 or 2.) The *HST* spectra were obtained with a $0.2''$ slit.

Here we focus on the emission-line properties of the nuclei, and make use of measurements obtained through the central $0.2'' \times 0.25''$, corresponding to a typical metric scale of ~ 20 pc. G750M spectra spanning 6300–6850 Å are employed. Emission line fluxes were measured after subtraction of a best-fitting continuum template generated by spectral synthesis from individual stellar spectra. Several interesting comparisons can be made between the SUNNS results and the Palomar measurements, which sample nuclear size scales an order of magnitude larger for the same galaxies.

1.2.1 Spatial Extent of Emission

One question relevant to understanding the nuclear emission is simply its spatial extent. Figure 1.1 shows ratios of Hα flux measured by SUNNS relative to Palomar. The smaller SUNNS aperture leads to significant reductions in the measured nebular flux; the decrease is generally less than the simple ratio of aperture areas (−2.2 dex), however, indicating that the nebular surface brightness typically shows some degree of central concentration.

The results in Figure 1.1 are sorted according to spectroscopic classification of the nucleus, and thereby reveal some interesting trends. The nuclei that are unambiguously accretion-powered, the LINER 1 (L1) and Seyfert (S) nuclei, show the largest ratios, indicating the highest degree of central concentration of emission. The H II, transition (T), and LINER 2 (L2) nuclei show smaller values, indicating a more distributed surface brightness distribution. The difference is not due to characteristically different metric apertures for the two subsets of objects; the distribution of distances is very similar. In the Palomar spectra the different object types show substantial overlap in Hα luminosity, indicating that the difference is likewise not due to some underlying luminosity dependence. The degree of concentration is evidently linked to the ionization process, and is consistent with the expectation that

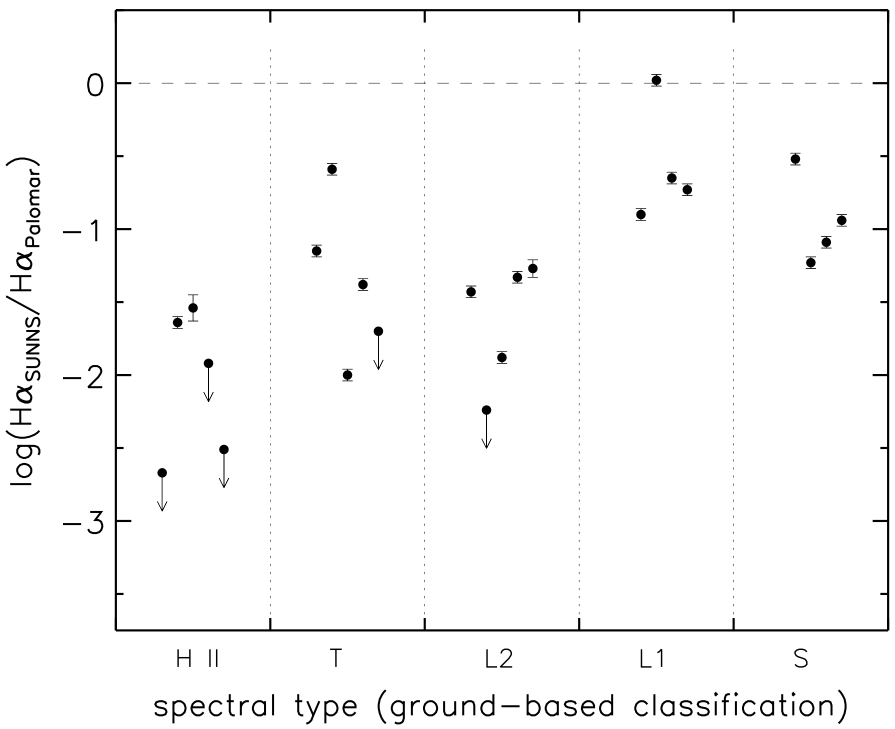

Fig. 1.1. Ratio of Hα flux measured by SUNNS and by Palomar, as a function of nuclear spectral class.

accretion-powered objects are dominated by a central power source, while other objects may be influenced by spatially distributed energetic phenomena.

The behavior of H II nuclei in Figure 1.1 is particularly noteworthy. Three of the five H II nuclei in this sample showed no detectable Hα emission in the SUNNS aperture, at levels even less than predicted by scaling down the Palomar flux by the aperture ratio. "Nuclear" star formation is evidently spread over radial scales of tens of pc, and may not even continue into the actual center of many galaxies.

1.2.2 Broad Emission

In addition to decreasing narrow nebular emission, the SUNNS aperture leads to a substantial reduction in circumnuclear starlight, which is the limiting factor in searching for quasar-like broad emission components in the Balmer lines. SUNNS produced two noteworthy results early on that reflect this increase in sensitivity, namely the discovery of broad Hα emission with dual shoulders or peaks in two of the sample sources (Shields et al. 2000; Ho et al. 2000). This emission component can potentially be interpreted as a signature of a relativistic disk, and is of interest for understanding the central accretion structure in low-luminosity AGNs.

A more general question is whether a larger fraction of nuclei are classified as broad-line objects when viewed at *HST* resolution compared to ground-based surveys. We searched for broad Hα emission with the SUNNS data, using a careful removal of the underlying starlight and deblending of the narrow nebular emission. In the end we found no examples of objects changing their identity from narrow-line to broad-line objects. The two sources in which the double-shouldered emission was discovered were already seen from the ground to exhibit "normal" broad Hα, leading to their classification as LINER 1s. The hunt for broad emission thus does little to clarify whether the ambiguous L2 and T objects are in fact accretion-powered.

1.2.3 Nebular Excitation

A simple comparison of nebular line ratios between the SUNNS and Palomar spectra provides another diagnostic of the central emission structure and energetics. Ratios of collisionally excited forbidden lines relative to a Balmer recombination line are sensitive to nebular temperature, and have a key role in standard spectroscopic classification diagrams. With the present data, the ratio that presents the strongest lines for this purpose is [N II] λ6583/Hα. Figure 1.2 shows a "ratio of ratios" comparing the $R \equiv$ [N II]/Hα ratio measured by SUNNS to that from Palomar. The scatter about unity is clearly asymmetric, with more objects showing $R_{\rm SUNNS}/R_{\rm Palomar} > 1$, and with larger amplitude variations upward than downward. The general pattern seen in Figure 1.2 is also found for other forbidden lines measured in these data (i.e. [O I]λ6300 and [S II]$\lambda\lambda$6717, 6731).

Higher ratios in the smaller aperture may stem from several causes. Comparisons of the [S II] $\lambda\lambda$6717/6731 ratio as measured by SUNNS and Palomar indicate that the electron density is larger for all nucleus types at smaller radii; larger density may lead to suppression of fine-structure line cooling, with a resulting boost in optical forbidden lines such as [N II]. The enhancement may also indicate that the small aperture emission is dominated to a greater degree by a central accretion-powered source. This behavior would be consistent with the interpretation of transition nuclei as composite systems with circumnuclear star formation contributing to the larger aperture measurements.

What is surprising, however, and contrary to our expectations, is the degree to which the line ratios do *not* change between the Palomar and SUNNS measurements. This finding is all the more striking given that the flux sampled in the SUNNs aperture is typically a small fraction of that contributing to the Palomar measurements, as described earlier, and the spatial scale observed differs by an order of magnitude. The objects clearly hosting an accretion source, the S and L1 nuclei, show little evidence for radial gradients in ionization or excitation; we also do not see objects changing their identity from LINERs to Seyfert nuclei as the aperture shrinks. Radial variations that might be expected from r^{-2} variation of the radiation field may be diluted by gradients in particle density, and possibly also a range of densities at each radius.

Approximately half of the T and L2 nuclei are consistent with no difference in measured line ratios between the large and small apertures. This result calls into question whether the composite picture is applicable to the majority of transition nuclei. Some form of distributed ionization mechanism may be important in these objects, or alternatively physical conditions may conspire to reduce the expected gradients, as seems to be the case for the L1 and S nuclei.

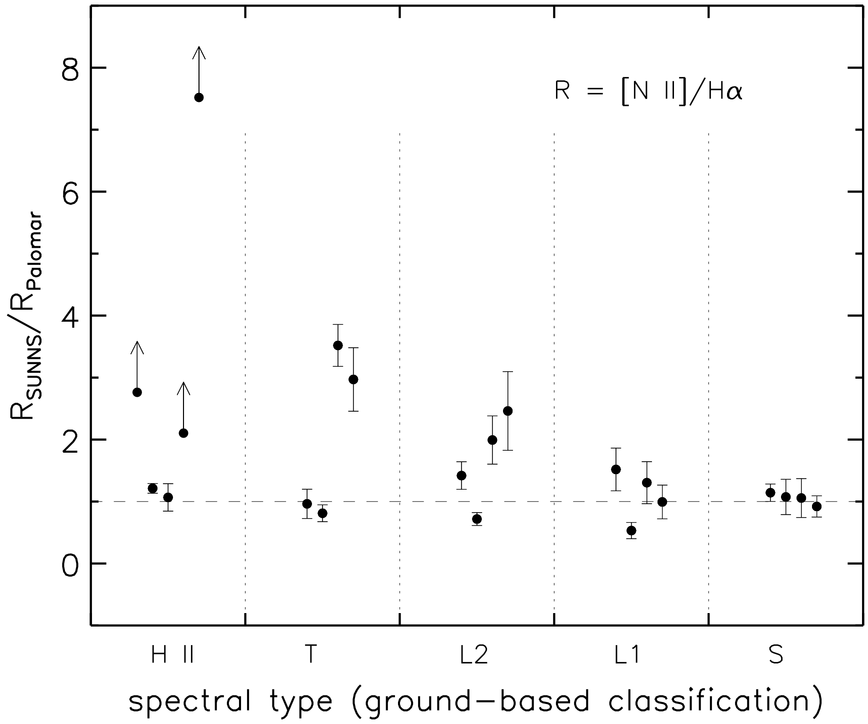

Fig. 1.2. [N II]/Hα from SUNNS ratioed to the Palomar value, as a function of nuclear spectral class.

1.3 Discussion

The SUNNS results do not provide a clear answer as to whether nuclei with T or L2 spectra should be regarded as accreting black holes. While some objects show emission-line trends consistent with increasing domination by a central power source on small scales, many do not. No new examples of broad Hα emission among these object types were found by SUNNS, despite the enhanced sensitivity of this survey. The significance of these results is limited by the small numbers of sources within each spectral class. Preliminary results from a STIS survey of 15 additional transition nuclei confirm that these objects often show weak gradients in emission-line ratios, and no evidence of broad emission (Barth et al., in preparation). Further observational study as well as theoretical consideration of these results is needed before we can fully translate detections of nuclear nebulosity into a census of accreting black holes.

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