Emission Lines in Active Galaxies: New Methods and Techniques
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Low-Luminosity Seyfert Nuclei

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Abstract. We describe a new sample of Seyfert nuclei discovered during the course of an optical spectroscopic survey of nearby galaxies. The majority of the objects, many recognized as AGNs for the first time, have luminosities much lower than those of classical Seyferts and populate the faint end of the AGN luminosity function. A significant fraction of the nuclei emit broad Hα emission qualitatively similar to the broad lines seen in classical Seyfert 1 nuclei and QSOs.

1. Introduction

Knowledge of the faint end of the luminosity function of active galactic nuclei (AGNs) has bearing on a number of issues concerning the evolution of this class of objects. It it unclear at the moment how the luminosity of AGNs changes with time, how objects in different luminosity regimes are associated with one another, and how galaxies hosting AGNs relate to those that do not. These reasons and others serve as strong motivation for searching for low-luminosity AGNs.

Until recently, however, the data needed to tackle these issues have largely been either statistically incomplete or of inadequate quality. While there is general consensus that low-luminosity AGNs appear to be present in a substantial fraction of nearby galaxies, the existing data suffer from a number of shortcomings that make quantitative applications difficult (Ho 1996 and references therein). The situation has been vastly improved with the recent completion of an extensive optical spectroscopic survey of nearby galaxies using the Hale 5-m Telescope at Palomar Observatory (Filippenko & Sargent 1985, 1986; Ho, Filippenko, & Sargent 1995; Ho 1995, 1996). We acquired long-slit spectra of exceptional quality for the nuclear region of a magnitude-limited ($B_T \leq 12.5$ mag) sample of 486 northern ($\delta > 0°$) galaxies; this yields an excellent representation of 'typical', relatively nearby galaxies of all morphological types. The spectra are of moderate resolution (full-width at half maximum (FWHM) $\sim$ 100–200 km s^{-1}) and cover two regions of the optical window (4230–5110 Å and 6210–6860 Å) containing important diagnostic emission lines.

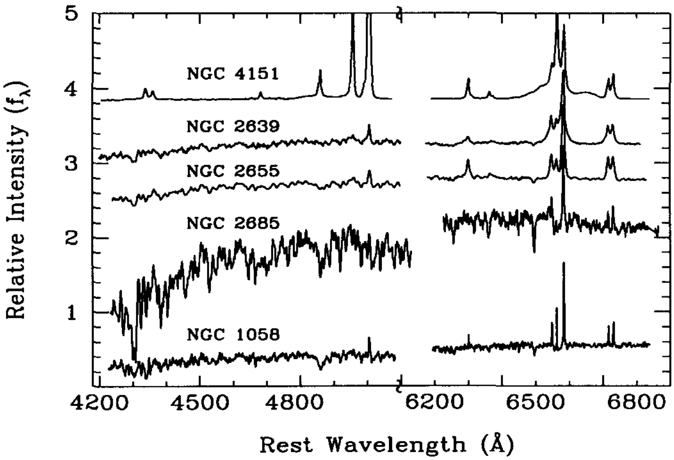

Figure 1. Sample spectra of Seyfert nuclei from the Palomar survey. Note the diversity of emission-line strengths relative to the stellar component. From Ho, Filippenko, & Sargent (1995).

Here, we take advantage of this unique data set to examine the population of Seyfert nuclei contained in it (Fig. 1) shows a few representative spectra). Some of the objects have been previously cataloged as Seyferts, but many are newly discovered. We define emission-line objects as Seyfert nuclei strictly from the line-intensity ratios of the *narrow* emission lines (see, e.g., Veilleux & Osterbrock 1987; Ho, Filippenko, & Sargent 1993; Ho 1996). Reference will be made to the broad emission lines only when further distinction into Seyferts of various subclasses (e.g., Seyfert 1, 2, and intermediate types) is called for (§3). The closely related class of low-ionization nuclear emission-line regions (LINERs; Heckman 1980) in the sample has been discussed elsewhere (Ho 1996) and will not be considered in detail here, except with reference to the subset of nuclei in which broad-line emission was detected (§4).

2. Statistics of Seyfert Nuclei in Nearby Galaxies

Objects classified as Seyfert nuclei according to their spectroscopic properties comprise 13% of the survey galaxies ($B_T \leq 12.5$ mag). The subset of 62 objects contains many nuclei of very low luminosity, with a median narrow $L(\mathrm{H}\alpha) = 6 \times 10^{38}$ ergs s^{-1}. Were it not for the high sensitivity of the Palomar survey, many of the objects would either have gone unnoticed or been misclassified. An additional, crucial factor influencing the reliability of the classification is the treatment of starlight subtraction, as described at length by Ho, Filippenko, & Sargent (1996).

Our detection rate of Seyfert nuclei is very much higher than that based on the Markarian survey (~1%; Huchra & Sargent 1973), and still significantly higher than that deduced in later studies which were more sensitive to faint nuclei than the Markarian survey (Stauffer 1982; Keel 1983; Phillips, Charles, & Baldwin 1983; Huchra & Burg 1992; Maiolino & Rieke 1995). The objects from the Palomar survey, therefore, constitute among the lowest-luminosity AGNs known.

As was known from previous studies, we find that Seyfert nuclei are preferentially hosted by galaxies of early Hubble type — 81% are found in galaxies of type Sbc or earlier. Contrary to popular belief, Seyfert nuclei do not completely shun elliptical galaxies; the detection rate in ellipticals (12%) is essentially identical to that of all disk systems (13%; S0–Sd).

As discussed in more detail by Ho (1996), several observable parameters depend on luminosity when our sample is compared with others containing sources of higher luminosity (e.g., Koski 1978). (1) The most conspicuous difference is the tendency for the narrow lines in low-luminosity objects to have smaller line widths: the median FWHM of the Seyferts in our sample is $\sim$300 km s^{-1}, whereas it is conventionally assumed to be larger than this (e.g., Shuder & Osterbrock 1981). This result reflects the known correlation between line luminosity and line width in Seyfert nuclei (Whittle 1992a). (2) The electron density, as traced by the [S II] $\lambda\lambda$6716, 6731 doublet, also exhibits a noteworthy pattern with luminosity; the density appears to decrease systematically with luminosity. (3) The level of ionization in low-luminosity Seyferts typically, but not always, falls near the low end of the distribution in Seyferts; the median [O III] λ5007/Hβ flux ratio is $\sim$ 6 in our sample, close to the 'low-ionization' regime of Seyfert 2 and narrow-line radio galaxies (Koski 1978). This is consistent with the general absence of He II λ4686 or [Fe X] λ6375 in our spectra. (4) As in other samples (Keel 1980; McLeod & Rieke 1995; Maiolino & Rieke 1995), the probability of detecting Seyfert nuclei is higher for galaxies that are more face-on; however, the inclination bias is much less pronounced in our sample, most likely because of the greater sensitivity of our survey.

3. Subtypes of Seyfert Nuclei

It has long been known that the relative strength of the broad-line component in Seyfert nuclei exhibits a continuous gradation ranging from near complete dominance of the total flux of the permitted lines (Seyfert 1s) to its virtual absence (Seyfert 2s). Osterbrock (1981) devised the so-called intermediate types (1.2, 1.5, 1.8, 1.9) to empirically categorize this diversity. Because it becomes increasingly challenging to measure a very weak broad-line component in low-luminosity AGNs, even Hα and Hβ, previous studies of intermediate-type Seyferts have concentrated mainly on fairly bright nuclei.

Our new survey is well suited for searching for weak broad-line emission, particularly that associated with the Hα line — indeed, the survey was initially designed largely with this goal in mind (Filippenko & Sargent 1985). Analysis of the starlight-subtracted spectra (Ho et al. 1996) reveals that faint broad Hα emission is detected in 33 nuclei, and with less certainty in another 16. Thus, roughly 10% (49/486) of all nearby, bright galaxies, contain an AGN with a visible broad-line region. If we adhere to the classification scheme based on the narrow-line spectrum, half of the sources strictly qualify as LINERs (i.e., because of their low [O III]/Hβ), but clearly all of the objects must be physically related.

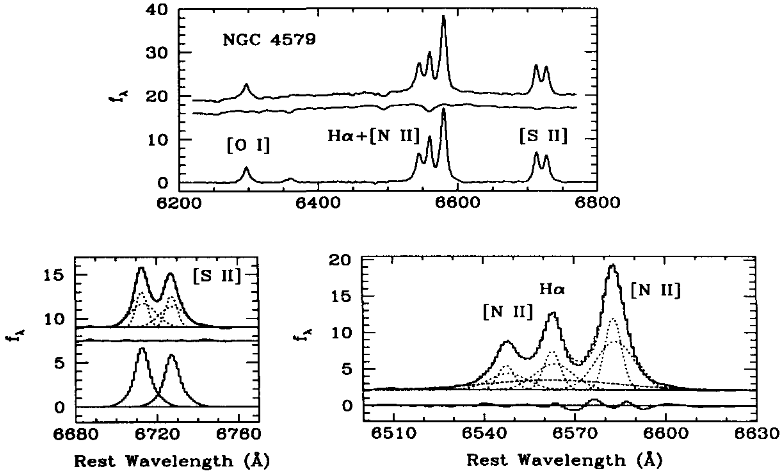

Figure 2. Example of the technique used to search for broad Hα emission in NGC 4579. The *top* panel shows the removal of starlight in order to obtain a pure emission-line spectrum. An empirical narrow-line profile is generated from the [S II] λλ6716, 6731 lines (*bottom left*), which is then used to constrain the narrow components of Hα and [N II] λλ6548, 6583 (*bottom right*). A broad component of Hα, represented as a Gaussian with FWHM = 2300 km s^{-1}, is needed to achieve a satisfactory fit.

The broad Hα emission measured typically has FWHM ~ 2200 km s^{-1}, similar to that seen in classical broad-line AGNs, but the luminosity is much lower: the median broad Hα luminosity is ~10^{39} ergs s^{-1}. Since the broad Hα component usually comprises only a small portion of the Hα+[N II] λλ6548, 6583 blend, and in general emission lines from the nucleus contribute but a minor fraction of the total integrated light in the spectrum, careful attention to starlight subtraction and line decomposition is vital to the detection of this elusive feature. Figure 2 gives an illustration of the steps involved in the analysis.

Among the 24 Seyferts in the broad-Hα sample, the numerical breakdown into the subtypes 1:1.5:1.9 = 1:10:13 (following the convention of Whittle 1992b). We did not bother to differentiate between subtypes 1.2 and 1.5, or between 1.8 and 1.9, because (1) they can vary from one to the other, (2) starlight subtraction often leaves considerable noise in the Hβ region, and (3) the classification depends on aperture size since the narrow-line region is spatially extended. If we lump all Seyferts with any degree of broad Hα as type 1, then the ratio of type 1 to type 2 is 1 to 1.6. Similarly, if we adopt a parallel classification scheme for the 25 LINERs with broad Hα emission, all the objects would be of 'type 1.9' (i.e., only broad Hα present, no broad Hβ), and the ratio of 'LINER 1s' to 'LINER 2s' is 1 to 6.4, where we have combined 'pure LINERs' and 'transition objects' (see Ho 1996) into one category. If we restrict the comparison to 'pure LINERs' alone, then the ratio is 1 to 4.2. Note that the relative numbers of LINER 1s and 2s must be interpreted with caution, since it is not clear if all narrow-lined LINERs belong to a homogeneous class (e.g., Filippenko 1993).

4. Summary

An extensive optical spectroscopic survey of the nuclei of nearby, bright galaxies has recently been completed. A large, well-defined catalog of 62 Seyfert nuclei has been identified. The results pertaining to this sample of AGNs include the following: (1) The fraction of galaxies hosting Seyfert nuclei (13%) is much higher than previously thought. (2) Most Seyfert nuclei are hosted by galaxies of early Hubble types (Sbc or earlier), although they are not restricted solely to spirals. (3) The emission-line luminosities of the overall sample are much lower than those of previously known Seyferts. Several observed properties, including the line width, electron density, ionization level, and inclination angle of the host galaxy, seem to change systematically with luminosity. (4) Weak, broad Hα emission has been detected in about 40% of the objects.

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