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# THE DENSITY OF THE NARROW-LINE REGION OF TYPE 1 ACTIVE GALACTIC NUCLEI

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RESUMEN

Utilizamos el cociente de las líneas de [S II] $\lambda\lambda 6716, 6731$ para medir sistemáticamente la densidad de la región de líneas delgadas en una muestra numerosa de galaxias Seyfert 1 de líneas delgadas (NLS1). Comparamos nuestros resultados con los obtenidos para una muestra de galaxias Seyfert 1 de líneas anchas (BLS1). Los resultados indican que entre las galaxias BLS1 no hay objetos con densidad baja, mientras que las galaxias NLS1 tienen una distribución amplia en densidad, que incluye un número significativo de objetos de baja densidad. También se ha encontrado una anticorrelación entre el cociente de Eddington $L/L_{\rm Edd}$ y la densidad. Para explicar estos resultados favorecemos a los efectos producidos por vientos, ya que estos son más fuertes en galaxias NLS1.

ABSTRACT

We utilize the diagnostic power of the [S II] $\lambda\lambda 6716, 6731$ intensity ratio to measure the density of the narrow-line region (NLR) systematically for a large sample of narrow-line Seyfert 1 (NLS1) galaxies, and we perform a comparison with a sample of broad-line Seyfert 1 (BLS1) galaxies. The key detection is the discovery of a '*zone of avoidance*' in density in the sense that AGN with broad lines (FWHM(H$\beta$) $> 2000\,{\rm km\,s^{-1}}$) avoid low densities, while NLS1 galaxies show a wider distribution in the NLR density, including a significant number of objects with low densities. A correlation analysis further shows that the Eddington ratio $L/L_{\rm Edd}$ anti-correlates with density. We tentatively favor the effects of winds/outflows, stronger in NLS1 galaxies than in BLS1 galaxies, to explain the observed trends.

*Key Words:* galaxies: active — galaxies: emission lines — galaxies: ISM — galaxies: Seyfert



## 1. INTRODUCTION

NLS1 galaxies (e.g., Gaskell 1984; Osterbrock & Pogge 1985) are intriguing due to their extreme emission line and continuum properties (e.g., Komossa 2008, for a review). Their optical broad lines are narrower (FWHM H$\beta \leq 2000$ km s$^{-1}$) than in 'normal' BLS1 galaxies and they show strong Fe II emission. They lie at one extreme end of the Boroson & Green (1992, hereafter BG92) eigenvector 1 (EV1) which governs the correlations among AGN properties. The most common interpretation is that this regime is governed by the highest Eddington accretion rates and/or lowest black hole masses (e.g., BG92).

Among other parameters (see Komossa et al. 2006; Komossa 2008), the *density* of an outflowing wind was firstly speculated to be a prominent driver of EV1 by Lawrence et al. (1997), given the connection of Fe II strength with the presence of low-ionization, blueshifted broad absorption lines, and with blue-asymmetric emission lines. Regarding NLS1 galaxies, their high ratios of $L/L_{\rm Edd}$ are likely particularly efficient in driving outflows. However, only few previous estimates on the *density* of the emission-line regions of NLS1 galaxies exist (e.g., Rodriguez-Ardila et al. 2000; Sulentic, Marziani, & Dultzin-Hacyan 2000). Those which do exist, actually lead to partially conflicting results.

We present for the first time a study of the NLR density for one of the largest homogeneously analyzed NLS1 samples to date based on SDSS Data Release 3 spectra (Abazajian 2005), and compare it with that of BLS1 galaxies. Only objects with redshift $z$ less than 0.3 are taken into account. In order to get an accurate measurement, we require the density-sensitive ratio [S II] $\lambda\lambda$6716,6731 to have a signal-to-noise ratio (S/N) greater than 5. A total of 55 objects with FWHM of the broad component of H$\beta$ (hereafter H$\beta_{\rm b}$) $\leq 2000\,{\rm km\,s^{-1}}$ are included in the NLS1 sample, while 39 with FWHM(H$\beta_{\rm b}$) $> 2000\,{\rm km\,s^{-1}}$ are included in the BLS1 sample.

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## 2. A ZONE OF AVOIDANCE IN THE NLR DENSITY

One of our main goals is to examine whether or not there is a difference in electron density $n_e$ between NLS1 galaxies and BLS1 galaxies, in order to test different NLS1 models. We use the *density* diagnostic [S II] $\lambda6716/\lambda6731$ to measure the NLR electron density. The [S II] line ratio also depends on temperature. However, the dependence is only weak in the range of temperatures of the regions studied. We fix the electron temperature at $T_e = 10,000$K, typical for photoionized gas in the NLR.

The [S II] $\lambda6716/\lambda6731$ line ratio in our sample ranges from 0.87 to 1.47. NLS1 galaxies show ratios in the range from 0.94 to 1.43. 17 out of 55 NLS1 galaxies have a ratio higher than 1.28, while only one out of 39 BLS1 galaxies has a high ratio(i.e., 1.47)[3]. The other 38 BLS1 galaxies occupy the range from 0.87 to 1.27. We plot the ratio versus the FWHM of $H\beta_b$ in Figure 1 (upper panel).

We find that the sources do not homogeneously populate the $n_e$–FWHM($H\beta_b$) diagram (Figure 1, lower panel). The key detection is a '*zone of avoidance*' in the diagram. While the 38 BLS1 galaxies avoid low average densities, and all show $n_e > 140\,\mathrm{cm}^{-3}$ (regime C), NLS1 galaxies show a larger scatter in density in the range $n_e = 2 \sim 770\,\mathrm{cm}^{-3}$, including a significant number of objects with low densities. 17 out of the 55 NLS1 galaxies under study show $n_e < 140\,\mathrm{cm}^{-3}$ (regime A) and are clearly separated from the range occupied by BLS1 galaxies. The other 38 NLS1 galaxies overlap well with the range in density for BLS1 galaxies (regime B).

## 3. ON THE ORIGIN OF THE ZONE OF AVOIDANCE

In order to search for possible origins of the observed trends, we investigate a number of different explanations for the '*zone of avoidance*' in density. We find that supersolar metallicities and temperature effects, a strong starburst contribution in NLS1 galaxies, and the effect of NLR extent are unlikely explanations. Consequences of the fraction of matter in bounded clouds, and different properties of the ISM in the host galaxies, can only be further judged with future observations (see details in Xu et al. 2007).

There are indications that many (but not all; e.g., Xu et al. 2003; Williams, Mathur, & Pogge 2004) NLS1 galaxies accrete close to or even above the Eddington limit (e.g., BG92; Grupe & Mathur 2004). If the associated outflows still propagate up into the NLR, then we may expect that the NLR gas in such objects is actually more tenuous. Radiation-pressure driven wind models predict a decrease of accretion rate with increasing width of the broad component of $H\beta$ (e.g., Nicastro 2000). Among the NLS1 population itself, it should then be the objects with accretion rates closer to Eddington that drive the stronger winds and thus have more tenuous, *low-density* NLR components. In order to test this, in Figure 2, we plot Eddington ratio $L_{\mathrm{bol}}/L_{\mathrm{Edd}}$ as a function of density $n_e$. We find that $L_{\mathrm{bol}}/L_{\mathrm{Edd}}$ is higher in NLS1 galaxies than in BLS1 galaxies. An anti-correlation

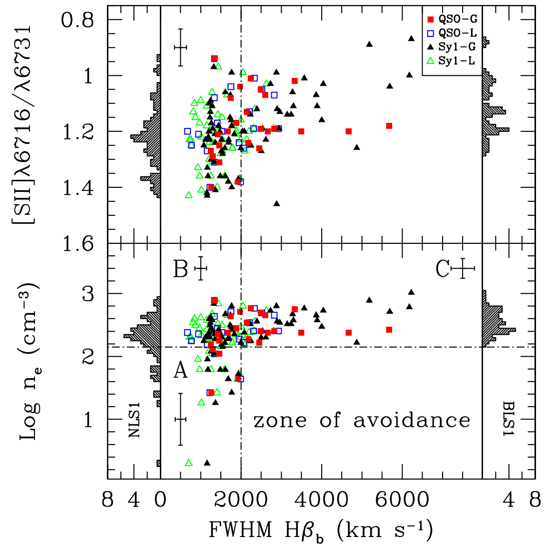


Fig. 1. *Top*: [S II] $\lambda6716/\lambda6731$ intensity ratio vs. FWHM of the broad component of $H\beta$ for our sample. Filled and open symbols represent the broad $H\beta$ components modeled by Gaussian (G) and Lorentzian (L) profiles, respectively. Squares correspond to QSOs; triangles to Seyfert 1s. The median error bar is given at the upper left corner. The vertical dot-dashed line marks the boundary between NLS1 galaxies and BLS1 galaxies in terms of FWHM($H\beta_b$). Histograms of the [S II] $\lambda6716/\lambda6731$ ratio of NLS1 galaxies and BLS1 galaxies are plotted in the left and right panels, respectively. *Bottom*: Electron density obtained from the [S II] $\lambda6716/\lambda6731$ ratio in dependence of FWHM of the broad component of $H\beta$. Symbols as in the top panel. The dot-dashed lines distinguish areas populated by: (A) NLS1 galaxies with small width of $H\beta_b$ and low density; (B) NLS1 galaxies small width of $H\beta_b$ and high density; and (C) BLS1 galaxies with large width of $H\beta_b$ and high density. Median error bars of each regime are given. Distributions of the electron density of NLS1 galaxies and BLS1 galaxies are plotted in the left and right panels, respectively.

[3]It is the only outlier actually located in the zone of avoidance in density, and within the errors beyond the '*low-density*' limit.

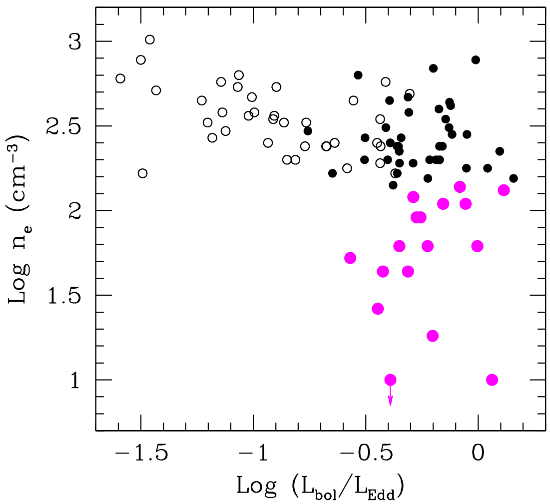


Fig. 2. Electron density vs. the Eddington ratio, $L_{\rm bol}/L_{\rm Edd}$ for NLS1 galaxies (filled circles) and BLS1 galaxies (open circles). The large filled circles represent the *low-density* objects from regime A of Figure 1.

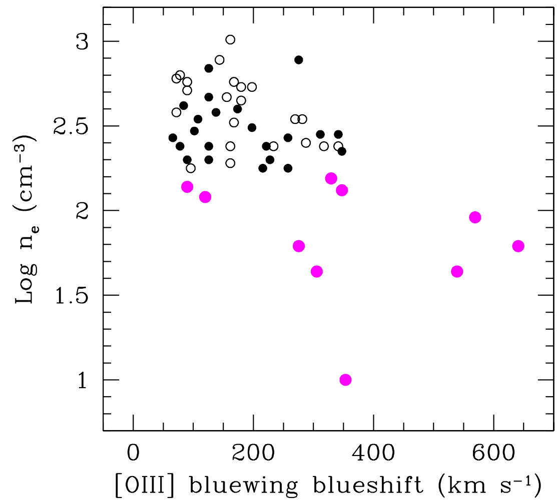


Fig. 3. Electron density plotted against the blueshift of the blue wing of [O III]. Symbols are the same as in Figure 2.

of decreasing electron density with increasing Eddington ratio can be seen across our entire sample of NLS1 and BLS1 galaxies ($r_{\rm s} = -0.42$, $P_{\rm null} = 10^{-4}$). However, among the NLS1 population itself, the *low-density* objects do not show higher-than-average $L_{\rm bol}/L_{\rm Edd}$ compared to the *high-density* NLS1 galaxies, which may suggest that higher $L_{\rm bol}/L_{\rm Edd}$ is a necessary but not a sufficient condition to lower density.

If outflow was a key mechanism to explain the lower average NLR density in NLS1 galaxies, then we would expect that the density ([S II] ratio) scales with the [O III] outflow velocity (blueshift). We checked for both, NLS1 galaxies vs. BLS1 galaxies, and within the NLS1 sample (*high-density* objects vs. *low-density* objects) whether the density correlates with the [O III] (peak) blueshift, and only found a weak correlation ($r_{\rm s} = -0.29$, $P_{\rm null} = 7 \times 10^{-3}$). However, it is interesting to note that the peak blueshift of [O III] does strongly correlate with $L_{\rm bol}/L_{\rm Edd}$ ($r_{\rm s} = 0.51$, $P_{\rm null} < 10^{-4}$). This correlation then indicates that outflows are more common in objects with high accretion rates. We also checked whether there is a correlation between density and the blueshift of the *blue wing* of [O III]. A correlation is seen with $r_{\rm s} = -0.43$ ($P_{\rm null} = 1 \times 10^{-3}$). This correlation shows that outflows are stronger in the *low-density* objects (Figure 3), even if the bulk of the NLR does not participate in the outflow.

In summary, we find several indications which point toward a link between NLR density and outflows, and we tentatively favor the role of outflows in explaining the difference in the NLR density between NLS1 galaxies and BLS1 galaxies.

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