**O III** emission line in narrow-line Seyfert 1 galaxies

Weihao Bian,1* Qirong Yuan1 and Yongheng Zhao2

1Department of Physics and Institute of Theoretical Physics, Nanjing Normal University, Nanjing 210097, China
2National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

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Abstract

Three sets of two-component profiles are used to simultaneously model the [O III]λλ4959, 5007 and Hβ lines for the Fe II-subtracted spectra of 149 narrow-line Seyfert 1 galaxies (NLS1s) from the Sloan Digital Sky Survey (SDSS). Using the linewidth of the narrow/core component of [O III]λ5007 to trace the stellar velocity dispersion instead of using the total linewidth of [O III]λλ4959, 5007, we found that the SDSS NLS1s are still deviated from the \( M_{bh} - \sigma \) relation found in the nearby inactive galaxies. This suggests that the linewidth of the [O III] narrow/core component is likely not a good tracer of bulge velocity dispersion in NLS1s, since some other studies indicate that NLS1s, like other active galactic nuclei (AGN), should follow the \( M_{bh} - \sigma \) relation. If we assume that the [O III]5007/Hβ line ratio emitted in the narrow-line region (NLR) ranges from one to 10, 63 objects are found to be satisfied with this criterion, and their Hβ broad components should be used to calculate their virial black hole masses. These 63 objects are statically consistent with the \( M_{bh} - \sigma \) relation. With the Chandra observation of some SDSS NLS1s, we find that one of these 63 objects (J143030.22-001115.1) cannot be classified as a genuine NLS1. Its narrow component of Hβ is coming from NLRs. This is consistent with its very flat hard X-ray spectrum found by researchers.

Key words: galaxies: active – galaxies: individual: J143030.22-001115.1 – galaxies: nuclei – quasars: emission lines.

1 INTRODUCTION

There is a strong relation between the central black hole mass and the bulge velocity dispersion (the \( M_{bh} - \sigma \) relation) for inactive nearby galaxies (Gebhardt et al. 2000a; Ferrarese & Merritt 2000; Tremaine et al. 2002), suggesting that the formation and evolution of host galaxies and their active nuclei are intimately related. For active galactic nuclei (AGNs), the reverberation mapping method and the empirical size–luminosity relation are usually used to measure the black hole mass, instead of the gas and stellar dynamics used in nearby galaxies (Peterson 1993; Kaspi et al. 2000). Broad-line AGNs follow this relation (Gebhardt et al. 2000b; Ferrarese et al. 2001; Nelson 2001; Boroson 2003; Shields et al. 2003; Bonning et al. 2005; Greene & Ho 2005c). Many theoretical models are presented to explain the established \( M_{bh} - \sigma \) relation, considering the regulation of the bulge growth by the feedback from the accretion around the black hole (e.g. Silk & Rees 1998; King 2003; Hopkins et al. 2005).

However, for an interesting subclass of AGNs, narrow-line Seyfert 1 galaxies (NLS1s), their locus in \( M_{bh} - \sigma \) plane is still a question of debate. NLS1s are defined with the following characteristics: Hβ full width at half-maximum (FWHM) less than 2000 km s\(^{-1}\); strong optical Fe II multiplets; line ratio of [O III]λ5007 to Hβ less than 3 (Osterbrock & Pettigrew 1985; Goodrich 1998); steep, soft X-ray excess (Puchnarewicz et al. 1992; Boller, Brandt & Fink 1996) and rapid soft/hard X-ray variability (Leighly 1999). We also note that the soft X-ray photon indices of some NLS1s observed by Chandra are found to be not too steep compared with those normally observed in NLS1s (Williams et al. 2004). NLS1s are believed to have less massive black holes with higher Eddington ratios, suggesting that they might be in the early stage of AGN evolution (Grupe 1996; Mathur 2000; Bian & Zhao 2003).

NLS1s seemed not to follow the \( M_{bh} - \sigma \) relation if the [O III] linewidth is used to trace the bulge velocity dispersion \( \sigma \) (Mathur, Kuraszkiewicz & Czerny 2001; Bian & Zhao 2004a; Grupe & Mathur 2004). The locus of NLS1s in the \( M_{bh} - \sigma \) plane possibly depends on some parameters, such as their accretion ratios (Mathur & Grupe 2005). Greene & Ho (2004) presented a sample of 19 AGNs with low-mass black holes from the Sloan Digital Sky Survey (SDSS) Data Release One (DR1). These 19 AGNs can be classified as NLS1s because their Hα FWHM is less than 2000 km s\(^{-1}\). Barth, Greene & Ho (2005) measured \( \sigma \) in these 19 NLS1s. They found that these NLS1s follow the \( M_{bh} - \sigma \) relation. The linewidth of [O III] indeed typically overestimates \( \sigma \) compared with the direct measurement of \( \sigma \). Botte et al. (2005) also reaches this result.

As we know, the [O III] profile is usually bluewards asymmetric, i.e. with more flux on the short-wavelength side of line than...
on the long-wavelength side (Peterson 1997). Also, the strong Fe \( \Pi \) multiples would blend the [O III] and H\( \beta \) lines in NLS1s. A multicomponent profile and Fe \( \Pi \) template are needed to model the [O III] lines in NLS1s. Greene & Ho (2005a) recently suggested that the core of [O III], after removing its asymmetric blue wing, can trace \( \sigma \) in narrow-line (type 2) galaxies. Is this true for NLS1s?

We used the largest published sample, of 150 NLS1s, to investigate this problem (Williams, Pogge & Mathur 2002). Their spectra have been analysed using a multicomponent model to investigate the [O III] blueshift in NLS1s, and we found seven ‘blue outliers’ (Bian & Zhao 2005a). In this paper, we want to investigate whether NLS1s follow the \( M_{\text{BH}}-\sigma \) relation when we used the narrow/core component of the [O III] line to trace \( \sigma \). In Section 2, we briefly introduce the data and the analysis. Our results and discussion are given in Section 3. A conclusion is presented in the final section. All of the cosmological calculations in this paper assume \( H_0 = 75 \, \text{km s}^{-1} \, \text{Mpc}^{-1}, \Omega_M = 0.3 \) and \( \Omega_\Lambda = 0.7 \).

2 DATA AND ANALYSIS

There are many samples of NLS1s: (i) an optically selected sample of 46 NLS1s with extremely steep soft X-ray spectra observed with ROSAT (Boller et al. 1996); (ii) a compiled sample of 64 NLS1s (Veron-Cetty, Verron & Cloncalves 2001); (iii) a sample of 150 NLS1s found within the SDSS Early Data Release (EDR; Williams et al. 2002); (iv) 50 NLS1s from a complete sample of 110 soft X-ray selected AGNs (Grupe & Mathur 2004); and (v) 19 AGNs with low-mass black holes from SDSS DR1 presented by Greene & Ho (2004). Here, we used the 150 SDSS NLS1s sample because it is the largest published NLS1 sample. Because of the lack of the [O III] line, SDSS J153243.67-004342.5 is ignored in our analysis.

Considering strong Fe \( \Pi \) multiples and the asymmetry of [O III]/H\( \beta \) lines, we reduced their SDSS spectra by the multicomponent fitting task SPECFIT (Kris 1994 in the IRAF-STS package. The components are (i) the Galactic interstellar reddening curve; (ii) Fe \( \Pi \) template; (iii) power-law continuum and (iv) three sets of two-Gaussian profiles for [O III]\( \lambda \lambda 4959, 5007 \), H\( \beta \) lines. For the doublet [O III]\( \lambda \lambda 4959, 5007 \), we take the same linewidth for each component, and fix the flux ratio of [O III]\( \lambda 4959 \) to [O III]\( \lambda 5007 \) to be 1:3. We didn’t consider the starlight contribution because there were no obvious stellar lines (Gu et al. 2006). For more details, please refer to Bian et al. (2005a).

3 RESULTS AND DISCUSSION

3.1 Distribution of \( \Delta \lambda = \lambda_{\text{broad}} - \lambda_{\text{narrow}} \) for the H\( \beta \) and [O III] lines

As we mentioned above, the [O III] profile is usually bluewards asymmetric. We calculated the blueshift of the broad component relative to the narrow component \( \Delta \lambda = \lambda_{\text{broad}} - \lambda_{\text{narrow}} \) for the [O III] and H\( \beta \) lines. In Fig. 1, we show the distribution of \( \Delta \lambda \) for the H\( \beta \) and [O III] lines. It is obvious that the [O III] profiles tend to be bluewards while the H\( \beta \) profiles tend to be bluewards or redwards.

3.2 \( M_{\text{BH}} - \text{FWHM}^*([\text{O III}]) \)

In our two-component model, we found that for some objects the optical Fe \( \Pi \) multiples seriously blend with the lines of H\( \beta \) and [O III]\( \lambda \lambda 4959, 5007 \). In some cases, Fe \( \Pi \) multiples showed almost the same magnitude of flux as that of [O III] line (see fig. 3 in Bian et al. 2005a).

Bian & Zhao (2004a) directly measure the [O III]\( \lambda 5007 \) linewidth [hereafter FWHM\( ^*([\text{O III}]) \)] using a one-Gaussian profile model. The spectrum resolution \( R \) is about 1800, which is equivalent to 166 km s\(^{-1} \). The typical error of FWHM\( ^*([\text{O III}]) \) is about 10 per cent. For the width of narrow component of [O III]\( \lambda 5007 \) line [hereafter FWHM\( ^*([\text{O III}]) \)] from two-component model, the typical error is about 10 per cent.

Figure 1. The distribution of \( \Delta \lambda = \lambda_{\text{broad}} - \lambda_{\text{narrow}} \) for the H\( \beta \) and [O III] lines.

Figure 2. The relation between the black hole masses and the width of the narrow component of [O III] line. Left-hand side: the black hole masses are calculated using FWHM of H\( \beta \) derived from one-Gaussian profile fitting, which are adopted from Bian & Zhao (2004a). The red circle denotes the object with [O III]\( \lambda 5007/H\beta \) line ratio larger than 1. The solid line shows the \( M_{\text{BH}}-\sigma \) relation defined by Tremaine et al. (2002). Right-hand side: the black hole masses are corrected for the objects with [O III]\( \lambda 5007/H\beta \) line ratio larger than 1, which are calculated using FWHM of the broad component of H\( \beta \) line.
In the left-hand panel of Fig. 2, we plot the central black hole masses (\(M_{\text{bh}}\)) versus FWHM\(^{\text{max}}\) ([O III]). The mass versus FWHM\(^{\text{max}}\) ([O III]) is shown in fig. 1 in Bian & Zhao (2004a). We adopted the same range of \(x\) and \(y\) axes so that we can compare the results with those in fig. 1 in Bian & Zhao (2004a). The masses are calculated from the H\(\beta\) linewidth using a one-Gaussian fit, which are form Bian & Zhao (2004a).

Grupe & Mathur (2004) also plot the \(M_{\text{bh}}-\sigma_{\text{[O III]}}\) relation for a complete sample of 75 soft X-ray selected AGNs: 43 broad-line AGNs and 32 NLS1s. They found that the locus of NLS1s obviously deviates from the \(M_{\text{bh}}-\sigma_{\text{[O III]}}\) relation defined by Tremaine et al. (2002). Considering the blue asymmetry of the [O III] profile, they remeasured the width of the [O III] line as twice the half-width-at-half-maximum of the red part of the emission line and found that the deviation indeed exists. In the left-hand panel of Fig. 2, we still find this result, which is consistent with Grupe & Mathur (2004).

### 3.3 Mass correction

When we use the linewidth of H\(\beta\) or H\(\alpha\) to trace the virial velocity around a black hole, we should subtract the contribution from NLRs. The template built from [O III] or [S II] is used to model narrow H\(\alpha\) and H\(\beta\) (Grupe et al. 1998; Grupe, Thomas & Leighly 1999; Greene & Ho 2005a,b). For seven NLS1s, Rodriguez-Ardila et al. (2000) found that the narrow component of H\(\beta\) is about 50 per cent of the total line flux and the [O III] \(\lambda5007/\text{H}\beta\) ratio emitted in the narrow-line regions (NLRs) varies from 1 to 5, instead of the universally adopted value of 10. We also found that the [O III] is not too weak in many SDSS NLS1s. This is consistent with the results of a sample of 64 NLS1s presented by Veron-Cetty et al. (2001). There are 63 SDSS NLS1s with [O III] \(\lambda5007/\text{H}\beta\) line ratios larger than 1. If we assume that the narrow H\(\beta\) component is emitted from NLRs for these objects, we should use the linewidth of the H\(\beta\) broad component to calculate the virial black hole masses, which are shown in the right-hand panel of Fig. 2.

We also calculated the black hole mass, \(M_{\text{[O III]}}\), using the FWHM of narrow component of the [O III] line as the indicator of \(\sigma\), i.e. \(\sigma_{\text{[O III]}} = \text{FWHM}^{\text{max}}([\text{O III}])/2.35\).

\[
M_{\text{[O III]}} = 10^{\Delta11}\left[\sigma_{\text{[O III]}}/(200\text{ km s}^{-1})\right]^{4.62} M_\odot.
\]

The distributions of \(\log(M_{\text{bh}}/M_{\text{[O III]}})\) for 149 SDSS NLS1s are shown in Table 1, where \(M_{\text{bh}}\) is calculated from the H\(\beta\) FWHM using one-Gaussian fitting. These 149 NLS1s statically deviated the \(M_{\text{bh}}-\sigma_{\text{[O III]}}\) relation defined by Tremaine et al. (2002) (see Fig. 2). Considering the spectrum resolution, the intrinsic \(\sigma\) derived from FWHM\(^{\text{max}}\) ([O III]) may be instrumentally broadened by about 60 km s\(^{-1}\) (hereafter \(\sigma_{\text{obs}}\)) (Greene & Ho 2005a). The values of \(\sigma\) derived from FWHM\(^{\text{max}}\) ([O III]) for all objects in Fig. 1 are larger than 60 km s\(^{-1}\). To the first order, the intrinsic \(\sigma\) value can be approximated by \(\sigma = (\sigma_{\text{obs}}^2 - \sigma_{\text{inst}}^2)^{1/2}\). We found that the logarithm value of the intrinsic \(\sigma\) value would be lowered by 0.08 dex, which is small relative to the deviation in Fig. 2 (also see Table 1). Subsample A consists of 63 objects with a [O III] \(\lambda5007/\text{H}\beta\) line ratio larger than 1. Subsample B consists of the rest 86 NLS1s. If we used the width of the H\(\beta\) broad component to calculate the black hole masses, we found that these 63 objects in Subsample A follow the \(M_{\text{bh}}-\sigma_{\text{[O III]}}\) relation. In these 63 objects, we found nine objects with the linewidth of the H\(\beta\) broad component less than 2000 km s\(^{-1}\). If we excluded these nine objects from Subsample A, i.e. Subsample C, the mean value of log\(M_{\text{bh}}/M_{\text{[O III]}}\) would be smaller, \(-0.09 \pm 0.07\) with a standard deviation of 0.53. Therefore, it is possible that these 54 objects in Subsample C are not genuine NLS1s. It needs a more careful H\(\beta\) subtraction from the NLR contribution in future.

### 3.4 FWHM\(^{\text{max}}\) ([O III]) is not a good tracer in NLS1s?

From Fig. 2, we found that the locus of NLS1s obviously deviates from the \(M_{\text{bh}}-\sigma_{\text{[O III]}}\) relation defined by Tremaine et al. (2002). If the linewidth of the [O III] narrow/core component overestimates \(\sigma\) and [O III] is not a good tracer of \(\sigma\), it suggests the particular environment of NLRs in NLS1s compared with other AGNs. On the other hand, if the narrow [O III] component does trace \(\sigma\), then our results show that NLS1s possibly do lie below the \(M_{\text{bh}}-\sigma\) relation (Mathur & Grupe 2005).

However, the values of \(\sigma\) for some NLS1s are directly measured from the Ca\(\alpha\)/Mg b absorption lines (Filippenko & Ho 2003; Barth et al. 2004, 2005; Botte et al. 2005); these NLS1s follow the \(M_{\text{bh}}-\sigma\) relation in a statistical sense, where the mass is calculated from the H\(\beta\) FWHM. Bian & Zhao (2004b) also found that the mass from the soft X-ray bump luminosity is consistent with that from the H\(\beta\) FWHM for NLS1s. Therefore, there is no underestimate in mass calculation using H\(\beta\) FWHM. This showed that the [O III] line is probably not a good tracer of bulge velocity dispersion.

Greene & Ho (2005a) investigated the relation between the velocity dispersion and the linewidth of [O III] with the sample of narrow-line (Type 2) AGNs from SDSS DR2. They found that, after the asymmetric blue wing is properly removed, the width of the [O III] core component can be used as a tracer of stellar velocity dispersion. They also looked for the secondary parameters for \(\Delta\sigma \equiv \log \sigma_{\text{[O III]}} - \log \sigma\) and found a correction equation; \(\Delta\sigma = 0.072 \log L_{\text{bol}}/L_{\text{Edd}} + 0.08\). Considering \(L_{\text{bol}}/L_{\text{Edd}}\) is in the range of \(-1 \sim 1\) (see fig. 1 in Bian et al. 2005a), the \(\sigma\) correction would be 0.008 \sim 0.152, which is small relative to the deviation in Fig. 2 (also see Table 1). Mathur & Grupe (2005) also used this correction to derive \(\sigma\) from \(\sigma_{\text{[O III]}}\). However, they found that NLS1s and BL AGNs are still significantly different (see their fig. 1). They suggested some NLS1s with high Eddington ratios that deviate from the \(M_{\text{bh}}-\sigma_{\text{[O III]}}\) relation and reside preferentially in relatively late-type galaxies.

### 3.5 J143030.22–001115.1 with flat X-ray spectrum

Williams et al. (2004) suggested that the soft X-ray photon indices of some SDSS NLS1s observed by \textit{Chandra} are found to be not too steep compared with that normally observed in NLS1s. There are two objects with photon indices of less than one. One is J125943.59+031115.1 (\(\Gamma = 0.25^{+0.08}_{-0.07}\)) and the other

| Type       | Number | \(\log(M_{\text{bh}}/M_{\text{[O III]}})\) | SD |
|------------|--------|----------------------------------------|----|
| Total      | 149    | -0.77±0.06                             | 0.70 |
| Subsample A| 63     | -0.90±0.06                             | 0.51 |
| Subsample A| 63     | -0.13±0.07a                           | 0.53 |
| Subsample B| 86     | -0.67±0.09                             | 0.79 |
| Subsample C| 54     | -0.09±0.07                            | 0.53 |

\(\alpha\) : the corrected black hole mass from the FWHM of the H\(\beta\) broad component.

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is J143030.22–001115.1 (γ = 0.92 ± 0.64). They belong to our
149 SDSS NLS1s. For J125943.59+010255.1, the net 0.5–8 keV
count rate is smallest among the Chandra observations, and the
uncertainty in γ is too large. The [O III] line is too weak in the SDSS
spectrum of J1259+0102. For J143030.22–001115.1, its [O III] line is
obvious. The [O III]λ5007/Hβ, line ratio is 9.236, the largest one
in these 149 SDSS NLS1s. However, the Fe II line is very weak.
Therefore, we think the narrow component of the Hβ line is coming
from NLRs. We used three components to model the Hβ line. The
widths of two narrow components of Hβ were forced to be equal
with that of [O III]λ5007 line. And the shifts between the corre-
sponding two component of Hβ and [O III] were fixed to be 146 Å.
It is found that the FWHM of the Hβ broad component is 2783 km
s⁻¹. Therefore, it is a broad-line AGN, a misclassified NLS1. Some
authors also found some incorrectly classified NLS1s (e.g. Veron-
Cetty et al. 2001; Botte et al. 2005). We should be cautious about
using the narrow component of Hβ to trace the black hole masses.
We should exclude this kind of object in the statistics of NLS1s.
For more details, please refer to Bian, Cui & Chao (2005b). It is
found by Williams et al. (2004).

Three sets of two-component profiles are used to model the
[O III]λλ4959, 5007 and Hβ lines for 149 SDSS NLS1s. The main
conclusions can be summarized as follows.

(i) Using the linewidth of the [O III] narrow/core component,
we found that 149 SDSS NLS1s still deviate from the Mbh−σ[O III]
relation found in nearby inactive galaxies. If the linewidth of the
[O III] narrow/core component overestimates σ and then [O III] is
not a good tracer of σ, this suggests the particular environment of
NLRs in NLS1s compared with other AGNs. On the other hand, if
the narrow [O III] component does trace σ, then our results show
that NLS1s possibly do lie below the Mbh−σ relation.

(ii) If the [O III]/Hβ line ratio from NLRs is between one and 10,
we found that the narrow Hβ line in 63 objects is from NLRs.
We used the broad Hβ linewidth to calculate the black hole masses.
Also, these 63 objects follow the Mbh−σ[O III] relation found in
nearby inactive galaxies. We exclude nine objects from the 63 (those
with FWHM(Hβ) of less than 2000 km s⁻¹); the other 54 objects
do not appear to be NLS1s.

(iii) J143030.22–001115.1 cannot be classified as a genuine
NLS1. Its narrow component of Hβ comes from NLRs. After the Hβ
contribution from broad line regions is removed, the Hβ FWHM is
2783 km s⁻¹. This is consistent with its very flat hard X-ray spectrum
found by Williams et al. (2004).

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