GAS METALLICITY OF NARROW-LINE REGIONS IN NARROW-LINE SEYFERT 1 GALAXIES AND BROAD-LINE SEYFERT 1 GALAXIES

TOHRU NAGAO, TAKASHI MURAYAMA, YASUHIRO SHIOYA, AND YOSHIKI TANIGUCHI

Astronomical Institute, Graduate School of Science, Tohoku University, Aramaki, Aoba, Sendai 980-8578, Japan; tohru@astr.tohoku.ac.jp, murayama@astr.tohoku.ac.jp, shioya@astr.tohoku.ac.jp, tani@astr.tohoku.ac.jp

Received 2002 February 19; accepted 2002 April 23

ABSTRACT

We investigate gas metallicity of narrow-line regions in narrow-line Seyfert 1 galaxies (NLS1’s) and broad-line ones (BLS1’s) in order to examine whether or not there is a difference in the gas metallicity between the two populations of Seyfert 1 galaxies. We apply two methods to study this issue. One is to use the emission-line flux ratio [N II] \( \lambda 6583/\mathrm{H}_\alpha \) \( \lambda 5577 \) in combination with some other optical emission line flux ratios. This method, which has been often applied to Seyfert 2 galaxies, suggests that the gas metallicity of narrow-line regions is indistinguishable, or possibly higher in BLS1’s than in NLS1’s. On the contrary, the other method, in which only forbidden emission line fluxes are used, results in that NLS1’s tend to possess metal-richer gas in the narrow-line regions than BLS1’s. We point out that this inconsistency may be owing to the contamination of the narrow component of permitted lines by the broad component in the first method. Since the results derived by using only forbidden emission line fluxes do not suffer from any uncertainty of the fitting function for the broad component of Balmer lines, the results from this method are more reliable than those derived by using permitted lines. We thus conclude that the gas metallicity of narrow-line regions tends to be higher in NLS1’s than in BLS1’s.

Subject headings: galaxies: abundances — galaxies: active — galaxies: nuclei — galaxies: Seyfert — quasars: emission lines

1. INTRODUCTION

Seyfert nuclei are typical active galactic nuclei (AGNs) in the nearby universe. They have been broadly classified into two types based on the presence or absence of broad \((\gtrsim 2000 \text{ km}^{-1})\) permitted lines in their optical spectra (Kachachian & Weedman 1974); Seyfert nuclei with broad lines are type 1 (hereafter S1’s), while those without broad lines are type 2 (S2’s). This difference can be explained by the “unified model,” in which the broad-line region (BLR) is surrounded by a dusty torus and the BLR in S2’s is obscured by the observer’s edge-on view of the torus (see, e.g., Antonucci & Miller 1985; Antonucci 1993). Therefore, only narrow \((\lesssim 2000 \text{ km}^{-1})\) lines, which arise from narrow-line regions (NLRs), are seen in the spectra of S2’s. In addition to these two types of Seyfert nuclei, narrow-line Seyfert 1 galaxies (NLS1’s) also constitute a subclass of the Seyfert nuclei. Since NLS1’s exhibit only narrow (i.e., \(\lesssim 2000 \text{ km}^{-1}\)) permitted lines in their optical spectra, NLS1’s are recognized as a distinct type of ordinary broad-line S1’s (BLS1’s). However, NLS1’s also show several characteristics of S1’s (see, e.g., Osterbrock & Pogge 1985), e.g., small line flux ratios of [O II] \( \lambda 5007 \) to H\( \beta \) \((\lesssim 3)\), strong Fe II and some high-ionization emission lines, and nonabsorbed X-ray spectra. Therefore, it is believed that the BLR of NLS1’s is not obscured but that the line width of the BLR is narrow for some reason.

One possible idea to explain the origin of the narrow BLR emission of NLS1’s is that NLS1’s have a smaller mass black hole than BLS1’s (see, e.g., Boller, Brandt, & Fink 1996; Laor et al. 1997). If the BLR in NLS1’s is the same as that in BLS1’s but the gas motion is more quiescent because of the smaller black hole mass, the narrowness of the BLR emission can be successfully explained. The steep and highly variable X-ray spectra, which are also the common properties of NLS1’s (see, e.g., Boller et al. 1996; Turner et al. 1999a; Leighly 1999a, 1999b), can be also explained by introducing the small black hole mass (see, e.g., Wang, Brinkmann, & Bergeron 1996; Hayashida 2000; Mineshige et al. 2000; Lu & Yu 2001; Puchnarewicz et al. 2001).

Recently, it has been proposed that NLS1’s may be relatively young AGNs with a black hole still in a growing phase (see, e.g., Mathur 2000a, 2000b; Mathur, Kurazhskiewicz, & Czerny 2001; see also Komossa & Mathur 2001; Mathur 2001). If NLS1’s possess a smaller mass black hole than BLS1’s while the luminosity is similar for NLS1’s and BLS1’s, the mass accretion rate for the same black hole mass is larger in NLS1’s than in BLS1’s. This implies that the mass accretion is more efficient in NLS1’s than in BLS1’s, which leads to the above hypothesis. Indeed, some observations suggest that the mass accretion rate in NLS1’s is high, close to the Eddington rate (see, e.g., Pounds, Done, & Osborne 1995; Kurazhskiewicz et al. 2000; Pounds & Vaughan 2000; Wandel 2000; Puchnarewicz et al. 2001). Moreover, Wandel (2002) reported that NLS1’s have a smaller black hole mass than the value inferred from the correlation between the black hole mass and spheroidal mass of the host galaxy (see also Wandel 1999, 2000; Mathur et al. 2001), which is consistent with the hypothesis that NLS1’s possess a growing black hole in their nucleus.

In the framework of this scheme, the gas metallicity of NLS1’s has been discussed very recently. Wills et al. (1999) found a negative correlation between the emission-line width of H\( \beta \) and the line flux ratio N \( \nu \lambda 1240/C \[ \lambda 3968 \) \( \lambda 5007 \), which can be interpreted as a result of a nitrogen overabundance in BLRs of NLS1’s (see also Wills, Shang, & Yuan 2000; Shemmer & Netzer 2002). The observed strong, fluorescent Fe K\( \alpha \) and optical Fe II emission, and the unusual spectral feature at 1 keV, which are seen in spectra of some NLS1’s, may suggest the overabundance of iron in NLS1’s.
The gas metallicity in NLRs of AGNs has been often investigated for S2’s (see, e.g., Shields & Oke 1975; Storchi-Bergmann & Pastoriza 1989, 1990; Storchi-Bergmann 1991; Alloin et al. 1992; Kraemer et al. 1994; Schmitt, Storchi-Bergmann, & Baldwin 1994; Radovich & Rafanelli 1996; Kraemer, Ruiz, & Crenshaw 1998), while it has been scarcely studied for S1’s (see, e.g., Kraemer et al. 1999). One reason for this is that accurate measurement of the narrow component of permitted lines is rather difficult for S1’s. Thus, high-quality spectra and their careful analysis are required to measure the narrow-component flux of permitted lines.

Recently, Rodríguez-Ardila, Pastoriza, & Donzelli (2000) presented high-quality optical spectra of seven NLS1’s and 16 BLS1’s. They carefully removed the underlying stellar continuum and multiple Fe ii emission lines from the observed spectra. Then they deconvolved the narrow component of permitted lines from the broad component and measured various emission-line fluxes accurately. We basically refer to the data of Rodríguez-Ardila et al. (2000) in this paper to investigate the gas metallicity of NLRs in NLS1’s and BLS1’s.

In order to see some possible correlations among narrow emission line flux ratios in a larger sample of Seyfert nuclei, we also refer to the data compiled by Nagao, Murayama, & Taniguchi (2001c). Their sample contains \( \approx 350 \) Seyfert nuclei. Since their work is based on data compilation from the literature, the measurement of emission-line flux ratios is done in heterogeneous ways. Therefore, we refer to their results only when we see general trends in emission-line flux ratios, and we never use them to discuss the difference in the properties of the NLR emission between NLS1’s and BLS1’s.

3. PREVIOUS DIAGNOSTICS FOR THE GAS METALLICITY OF NLRs

3.1. The \([\text{N} \text{ II]} \lambda 6583/\text{H} \alpha \) Method

The gas metallicity in NLRs of S2’s has sometimes been studied by using the emission-line flux ratio \([\text{N} \text{ II]} \lambda 6583/\text{H} \alpha \). \( \lambda 6583/\text{H} \alpha \) (see, e.g., Storchi-Bergmann & Pastoriza 1989, 1990; Storchi-Bergmann 1991; Radovich & Rafanelli 1996). Using photoionization models, Storchi-Bergmann & Pastoriza (1989, 1990) showed that this emission-line flux ratio is sensitive to the nitrogen abundance, but rather insensitive to the gas density and the ionization parameter (i.e., a number density ratio of ionizing photons to hydrogen atoms). Note that the nitrogen abundance is important, since the N/O abundance ratio in Galactic H ii regions is known to scale with the O/H abundance ratio (see, e.g., Shields 1976; Pagel & Edmunds 1981; Vila-Costas & Edmunds 1993; van Zee, Salzer, & Haynes 1998; Izotov & Thuan 1999). Therefore the nitrogen abundance, N/H, scales with \( Z^2 \), where Z is the gas metallicity. The data from H ii regions show that these scaling relations hold approximately for \( Z \gtrsim 0.2 \ Z_\odot \).

We show the histograms of the emission-line flux ratio \([\text{N} \text{ II]} \lambda 6583/\text{H} \alpha_{\text{narrow}} \) for the NLS1’s and the BLS1’s in the sample of Rodriguez-Ardila et al. (2000) in Figure 1. The data are not corrected for the dust extinction because the effect of the dust extinction on this flux ratio is negligibly small. The average and median values of \([\text{N} \text{ II]} \lambda 6583/\text{H} \alpha_{\text{narrow}} \) for the NLS1’s and BLS1’s are given in Table 1. There is no apparent difference in this flux ratio between the two populations. It is also suggested by the Kolmogorov-Smirnov (KS) statistical test that the two frequency distri- 

---

1 CTS H34.06, Mrk 1239, CTS J03.19, CTS J04.08, NGC 4748, CTS J13.12, and I1 1934–063.

2 CTS C16.16, MCG –5–13–17, CTS H34.03, CTS B31.01, Fairall 1146, CTS M02.50, CTS J07.02, CTS J10.09, CTS R12.15, CTS J14.05, CTS J15.22, CTS M17.17, CTS G03.04, I1 2107–097, CTS A08.12, and CTS F10.01. Note that we do not use the data for CTS A08.12 in the following analysis, since the flux of the \([\text{N} \text{ II]} \lambda 6583 \) emission of this object is not presented in Rodriguez-Ardila et al. (2000).

3 Note that there is a typesetting error in the Rodríguez-Ardila et al. (2000) paper; i.e., a second header in Table 4 was cut in the editing process. The second set of line fluxes (when the object names are repeated) correspond, in fact, to other emission lines, organized as follows: [O i] \( \lambda 6300, \lambda 6369, \lambda 6374, \lambda 6548, \lambda 6584, [\text{S} \text{ II]} \lambda 6717, [\text{S} \text{ II]} \lambda 6731, [\text{Ar} \text{ II]} \lambda 7135, [\text{O} \text{ III]} \lambda 7325, [\text{S} \text{ III]} \lambda 9069, and E(B–V).

---

**Fig. 1.**—Frequency distributions of the emission-line flux ratio \([\text{N} \text{ II]} \lambda 6583/\text{H} \alpha \) for the NLS1’s and the BLS1’s in the sample of Rodriguez-Ardila et al. (2000). The data are not corrected for the dust extinction.
butions of the flux ratio $[\text{N} \ii] \lambda 6583/H_\alpha$ are statistically indistinguishable ($P_{KS} = 0.912$). As shown in Figure 2, we cannot find an apparent correlation between the flux ratio $[\text{N} \ ii] \lambda 6583/H_\alpha$ and the FWHM of the broad component of the $H_\alpha$ emission. The corresponding correlation coefficient is 0.009, which implies that there is no meaningful correlation between the two quantities. This result seems contrary to the result of Wills et al. (1999), who found an apparent negative correlation between the emission-line flux ratio $N \gamma \lambda 1240/C \ iii \lambda 1909$, which is sensitive to the nitrogen abundance, and the FWHM of the broad component of the $H_\alpha$ emission.

### 3.2. The SSCK Method

Based on the intensive photoionization model calculations and the careful calibrations with observations, Storchi-Bergmann et al. (1998, hereafter SSCK) proposed revised diagnostics for the gas metallicity of NLRs in AGNs. They showed that the oxygen abundance of the NLR gas in AGNs can be expressed by

$$12 + \log(O/H)_{\text{SSCK1}} = 8.34 + 0.212x - 0.012x^2 - 0.002y + 0.007xy - 0.002x^2y + 6.52 \times 10^{-4}y^2 + 2.27 \times 10^{-4}xy^2 + 8.87 \times 10^{-5}x^2y^2,$$

(1)

where $x \equiv [\text{N} \ ii] \lambda 6583/H_\alpha$ and $y \equiv [\text{O} \ iii] \lambda 5007/H_\alpha$.

$$12 + \log(O/H)_{\text{SSCK2}} = 8.643 - 0.275u + 0.164u^2 + 0.655v - 0.154w - 0.021uv^2 + 0.288u^2v + 0.162uw^2 + 0.0353u^2v^2,$$

(2)

where $u \equiv \log ([\text{O} \ iii] \lambda 3727/\lambda 5007)$ and $v \equiv \log ([\text{N} \ ii] \lambda 6583/H_\alpha)$. These methods weakly depend on the gas density; the derived values should be subtracted by the correction term, $0.1 \log(n_H/300 \, \text{cm}^{-3})$, where $n_H$ is the hydrogen density (see SSCK for more details). We apply these relations to the data of Rodríguez-Ardila et al. (2000). For the objects whose gas density is not given in Rodríguez-Ardila et al. (2000) (CTS H34.03, CTS M02.30, CTS J14.05, CTS G03.04, and 1H 2107–097), we assume the gas density to be $300 \, \text{cm}^{-3}$. The average and median values of the derived $12 + \log(O/H)_{\text{SSCK1}}$ and $12 + \log(O/H)_{\text{SSCK2}}$ are given in Table 2. Here the effect of the dust extinction is corrected by adopting the values of $A_V$ presented by Rodríguez-Ardila et al. (2000) and the extinction curve of Cardelli, Clayton, & Mathis (1989). There is no tendency that the NLS1’s are metal-rich compared with the BLS1’s, as implied by some earlier studies. To the contrary, the derived oxygen abundances may be larger in the sample of BLS1’s than in the sample of NLS1’s. We show the relationships between the FWHM of the broad component of the $H_\alpha$ emission and the derived oxygen abundances in Figure 3. The object with a larger FWHM of the $H_\alpha$ emission seems to be more oxygen-abundant when equation (1) is applied, although this tendency is not significant. On the other hand, such a tendency is not seen when equation (2) is applied.

### 3.3. Remarks on the Two Methods

Do the results presented in § 3.2 suggest that the NLR of NLS1’s is not metal-rich compared with that of BLS1’s?
Recently, Véron-Cetty, Véron, & Gonçalves (2001) pointed out that the broad component of permitted lines in the optical spectra of NLS1’s is well fitted by a Lorentzian profile, rather than by a Gaussian profile. They also mentioned that the decomposition of the narrow component of permitted lines by the broad component inferred by Rodríguez-Ardila et al. (2000) may be accordingly inaccurate, since the broad components of permitted lines were fitted by a Gaussian profile by Rodríguez-Ardila et al. (2000; see also Moran, Halpern, & Helfand 1996; Leighly et al. 1999b; Gonçalves, Véron, & Véron-Cetty 1999; Sulentic et al. 2002). If this is the case, the flux ratio \( \frac{[\text{N} \text{II}]}{\text{C} \text{II}} \) may be inappropriate for the metallicity diagnostics, because the selection of the fitting function for the broad component of permitted lines affects the measurement of not only the broad component but also the narrow component of permitted lines.

Indeed, the oxygen abundances of the NLR gas of the NLS1’s and the BLS1’s derived by using equations (1) and (2) should be suspect if we take account of the following two facts. First, most of the derived oxygen abundances suggest very subsolar metallicities. This is especially remarkable when equation (1) is adopted: the median value of the derived oxygen abundances corresponds to \( Z \simeq 0.32 \) \( Z_\odot \). Second, the derived oxygen abundances are not consistent with each other. That is, the average and median values of the derived oxygen abundances are systematically different: the oxygen abundances derived by using equation (2) are larger than those from equation (1) by \( \sim 0.3 \) dex. This difference is more clearly shown in Figure 4, in which we compare the two kinds of inferred oxygen abundances. Although SSCK also mentioned that the oxygen abundance derived by equation (2) tends to be higher than the one derived by equation (1) by \( \sim 0.11 \) dex, the difference in the sample of Rodríguez-Ardila et al. (2000) is much larger than that reported by SSCK. This may imply that the methods proposed by SSCK are inappropriate to estimate the gas metallicities of NLRs, at least for S1’s. Thus, it seems to be safe to avoid using the narrow component of permitted lines for the investigation of the gas properties of NLRs in S1’s.

**TABLE 2**

| NLS1 | BLS1 |
|------|------|
| **Abundance** | **Average** | **Median** | **Average** | **Median** |
| \( 12 + \log \frac{[\text{O} \text{II}]}{\text{H} \text{II}} \) SSCK1 | 8.420 | 8.384 | 8.517 | 8.512 |
| \( 12 + \log \frac{[\text{O} \text{II}]}{\text{H} \text{II}} \) SSCK2 | 8.679 | 8.739 | 8.654 | 8.752 |

* Calculated by eqs. (1) and (2), which are derived by SSCK.

![Fig. 3. Oxygen abundances estimated by the equations given by SSCK vs. the FWHM of the broad component of the Hα emission (top, from eq. [1]; bottom, from eq. [2]). Symbols are as in Fig. 2.](image-url)

![Fig. 4. Oxygen abundance estimated by eq. (1) vs. that estimated by eq. (2). The loci of equal values for the two quantities are shown by a dotted line for comparison. Symbols are as in Fig. 2.](image-url)
4. NEW DIAGNOSTICS FOR THE GAS METALLICITY OF NLRs

4.1. Correlations among Forbidden Emission Line Flux Ratios

As mentioned in the last section, it seems desirable to use only forbidden lines for studies of the gas metallicity of NLRs in S1’s. Furthermore, it seems ideal to use only low-ionization forbidden emission lines to discuss the gas properties. This is because low- and high-ionization line emitting regions may be spatially segregated (see, e.g., Baker 1997; Murayama & Taniguchi 1998a, 1998b; Nagao, Taniguchi, & Murayama 2000; Nagao, Murayama, & Taniguchi 2001b; Nagao et al. 2001c; see also Hes, Barthel, & Fosbury 1993). Taking the above two constraints into account, we examine whether or not the forbidden emission line flux ratios \([\text{[O} \text{I}] \lambda 6300]/[\text{[N} \text{II}] \lambda 6583, [\text{[O} \text{II}] \lambda 3727]/[\text{[N} \text{II}] \lambda 6583, and [\text{[S} \text{II}] \lambda \lambda 6717, 6731]/[\text{[N} \text{II}] \lambda 6583\) can be useful estimators for the nitrogen abundance of gas clouds in the NLRs.

In Figure 5, we show the relationship among the three forbidden emission line flux ratios. Here we use the data of Nagao et al. (2001c) in order to find possible correlations among the three flux ratios. Since the data are not corrected for dust reddening, we also show the effect of the reddening correction, which is calculated by adopting the extinction curve of Cardelli et al. (1989), in Figure 5. Apparently, positive correlations are seen among the three flux ratios. The corresponding correlation coefficients are 0.674 and 0.561 for \([\text{[O} \text{I}] \lambda 6300]/[\text{[N} \text{II}] \lambda 6583\) versus \([\text{[O} \text{II}] \lambda 6300]/[\text{[N} \text{II}] \lambda 6583\) and \([\text{[S} \text{II}] \lambda \lambda 6717, 6731]/[\text{[N} \text{II}] \lambda 6583\) versus \([\text{[O} \text{I}] \lambda 6300]/[\text{[N} \text{II}] \lambda 6583\), respectively. These correlation coefficients imply that there are meaningful correlations among the three flux ratios. What makes these correlations? Or can these correlations be interpreted as sequences of the nitrogen abundance? In order to investigate these issues, we perform photoionization model calculations. The model methods and the results are presented in the following sections.

4.2. Photoionization Models

To investigate the origin of the correlations presented in the last section, we carry out photoionization model calculations by using the publicly available code CLOUDY, version 94.00 (Ferland 1996, 2000). Here we assume uniform density gas clouds with a plane-parallel geometry. The parameters for the calculations are (1) the hydrogen density of a cloud \((n_\text{H})\), (2) the ionization parameter \((U)\), (3) the chemical composition of the gas, and (4) the shape of the spectral energy distribution (SED) of the input continuum radiation. We perform several model runs covering the following ranges of parameters: \(10^{2.0} \text{ cm}^{-3} \leq n_\text{H} \leq 10^{5.0} \text{ cm}^{-3}\) and \(10^{-3.5} \leq U \leq 10^{-2.0}\).

For the chemical composition of the gas clouds, we assume that the metals are all scaled keeping solar proportions, except for nitrogen; the nitrogen abundance scales with \(Z^2\) (this assumption is altered in some calculations presented in § 5). We calculate the models covering a metallicity range of \(0.25 \leq Z/Z_\odot \leq 3.0\), which corresponds to \(8.27 \leq 12 + \log(O/H) \leq 9.35\) and \(6.77 \leq 12 + \log(N/H) \leq 8.92\). The adopted solar elemental abundances relative to hydrogen are taken from Grevesse & Anders (1989), with extensions by Grevesse & Noels (1993). We also examine the case in which a part of the heavy elements is depleted into dust grains. In this case, 90% of Mg, Si, and Fe, 50% of C and O, and 25% of N and S are locked into dust grains, as estimated for the Orion H II region (see, e.g., Baldwin et al. 1991, 1996). This corresponds to the case in which the gas clouds in NLRs contain nonnegligible dust grains. However, we ignore grain opacity, heating, and cooling, since their properties in photoionized gases are highly uncertain. Although the heating process by grain photoelectrons is important for enhancing some high-ionization emission lines (see, e.g., Shields & Kennicutt 1995), it does not affect our results significantly, since we use only low-ionization emission lines.
We adopt two types of SED for the calculations; for both the SEDs, we adopt the function

\[ f_\nu = \nu^{\alpha_{UV}} \exp \left( -\frac{\hbar \nu}{kT_{BB}} \right) \exp \left( -\frac{kT_{IR}}{\hbar \nu} \right) + a\nu^{\alpha_{OX}} \]  

(3)

(see Ferland 1996). We adopt the following parameter set (see Nagao, Murayama, & Taniguchi 2001a for more details): (1) the infrared cutoff of the big blue bump component, \( kT_{IR} = 0.01 \) ryd; (2) the slope of the low-energy side of the big blue bump, \( \alpha_{UV} = -0.5 \); (3) the UV-to-X-ray spectral index, \( \alpha_{OX} = -1.35 \); (4) the slope of the X-ray power-law continuum, \( \alpha_X = -0.85 \) or \(-1.15\); and (5) the characteristic temperature of the big blue bump, \( T_{BB} = 4.9 \times 10^5 \) or \( 11.8 \times 10^5 \) K. Hereafter, continua with \( (\alpha_X, T_{BB}) = (-0.85, 4.9 \times 10^5 \) K\) and \( (-1.15, 11.8 \times 10^5 \) K\) are denoted “BLS1-like SED” and “NLS1-like SED,” respectively. Note that the parameter \( a \) in equation (3) is determined from the adopted value of \( \alpha_{OX} \). The last term in equation (3) is not extrapolated below 1.36 eV or above 100 keV. Below 1.36 eV the last term is simply set to zero. Above 100 keV the continuum is assumed to fall off as \( \nu^{-3} \).

The calculations are stopped when the temperature falls to 3000 K, below which the gas does not contribute significantly to the observed optical emission line spectra.

### 4.3. Results of Model Calculations

In Figure 6, we present the results of the models with metallicity of \( Z = Z_{\odot} \). These model results are used to investigate whether the gas density, the ionization parameter, or the combination of both two parameters drives the correlations presented in §4.1. Here the models with the NLS1-like and BLS1-like SEDs are presented. It is apparently shown that the emission-line flux ratios \([\text{O} \, i] \lambda 6300/[\text{N} \, ii] \lambda 6583\), \([\text{O} \, ii] \lambda 3727/[\text{N} \, ii] \lambda 6583\), and \([\text{S} \, ii] \lambda 6717, 6731/[\text{N} \, ii] \lambda 6583\) are insensitive to the ionization parameter for any...
type of the adopted ionizing SEDs. The predicted emission-line flux ratios vary by less than a factor of 2 when the ionization parameter is changed between $10^{-3.5}$ and $10^{-2.0}$. This is mainly because we use only low-ionization forbidden emission lines. Although the three emission-line flux ratios are rather sensitive to the gas density, the model grids for varying gas densities are perpendicular to the observed correlations for any type of the adopted ionizing SEDs, as shown in Figure 6. These results do not depend on whether or not the heavy elements are depleted into dust grains, as shown in Figure 6. Therefore, we conclude that the observed correlations among the three emission-line flux ratios are not significantly attributed to the effects of the gas density, the ionization parameter, or both.

Then are the correlations attributed to the nitrogen abundance (i.e., the gas metallicity)? In Figure 7, we show the results of model calculations in which the gas metallicity is varied in the range $0.25 \leq Z/Z_\odot \leq 3.0$. Here the NLS1-like and BLS1-like SEDs are adopted for the ionizing continuum, together with $U = 10^{-3.0}$. It is shown that the metallicity sequences can well explain the observed correlations in the flux ratios of the low-ionization forbidden lines for both models with nondepleted abundances and those with depleted abundances. We thus conclude that the observed correlations among the flux ratios of the low-ionization forbidden lines are mainly attributed to the variety of the gas metallicity. Since the narrow component of permitted lines is not used and only forbidden lines are used, the diagrams presented in Figure 7 can be powerful diagnostics for the gas metallicity in the NLR of AGNs, especially for S1’s.

Here we mention that the flux ratio $[O\,i] \lambda 6300/[N\,ii] \lambda 6583$ seems to be the most appropriate diagnostic for gas metallicity among the three emission-line flux ratios. This is because the flux ratios $[O\,ii] \lambda 3727/[N\,ii] \lambda 6583$ and $[S\,ii] \lambda\lambda 6717, 6731/[N\,ii] \lambda 6583$ are sensitive to the gas density, while $[O\,i] \lambda 6300/[N\,ii] \lambda 6583$ is not, unless the gas density is high ($\gtrsim 10^4\text{ cm}^{-3}$). In addition, the flux ratio $[O\,ii] \lambda 3727/[N\,ii] \lambda 6583$ is sensitive to the dust extinction.
4.4. Application to NLRs in NLS1’s and BLS1’s

Now we apply our new method to the investigation of the gas metallicity of NLRs in NLS1’s and BLS1’s. In Figure 8, we plot the data of Rodríguez-Ardila et al. (2000) on the diagnostic diagrams presented in § 4.3. It appears that the NLS1’s have smaller flux ratios $[\text{O} \, \text{i}] \lambda 6300/\text{C} \, \text{II} \lambda 6583$, $[\text{O} \, \text{ii}] \lambda 3727/\text{N} \, \text{ii} \lambda 6583$, and $[\text{S} \, \text{ii}] \lambda 6717, 6731/\text{N} \, \text{ii} \lambda 6583$ than the BLS1’s. The average and median values of these three emission-line flux ratios for the NLS1’s and BLS1’s are given in Table 1. These values imply that there are differences in the emission-line flux ratios between the NLS1’s and BLS1’s, although the statistical significance is low; i.e., $P_{\text{KS}} = 0.133, 0.533,$ and 0.767 for the flux ratios $[\text{O} \, \text{i}] \lambda 6300/\text{N} \, \text{ii} \lambda 6583$, $[\text{O} \, \text{ii}] \lambda 3727/\text{N} \, \text{ii} \lambda 6583$, and $[\text{S} \, \text{ii}] \lambda 6717, 6731/\text{N} \, \text{ii} \lambda 6583$, respectively (see Table 1). Here it should be noted that the photoionization models predict larger values of $[\text{O} \, \text{i}] \lambda 6300/\text{N} \, \text{ii} \lambda 6583$ for NLS1’s than for BLS1’s, if the difference in the SEDs of ionizing photons between NLS1’s and BLS1’s is taken into account. The data of Rodríguez-Ardila et al. (2000) exhibit the opposite trend from the prediction of the photoionization models. It is thus suggested that the gas metallicity in NLRs of the NLS1’s is possibly higher than that of the BLS1’s, at least for the sample of Rodríguez-Ardila et al. (2000).

In Figure 9, we show the relationship between the FWHM of the broad component of the $\text{H} \alpha$ emission and the flux ratio $[\text{O} \, \text{i}] \lambda 6300/\text{N} \, \text{ii} \lambda 6583$ for the sample of Rodríguez-Ardila et al. (2000). By contrast with Figures 2 and 3, there appears to be a positive correlation between them. Its correlation coefficient is 0.681, which implies that there is a meaningful correlation between them. This is consistent with the result of Wills et al. (1999); that is, the object with narrower BLR emission tends to exhibit higher nitrogen abundance.

5. DISCUSSION

As investigated in §§ 3 and 4, the inferred difference in the gas metallicity of NLRs between NLS1’s and BLS1’s...
Gaussian profile, which Rodríguez-Ardila et al. (2000) adopted. In order to see how the underestimation of the flux ratios \([\text{N ii}] \lambda6583/\text{H}α_{\text{narrow}}\) and \([\text{O iii}] \lambda5007/\text{H}β_{\text{narrow}}\) affects the inferred oxygen abundance, we consider the case in which the two flux ratios are underestimated by a factor of 10. We assume \([\text{N ii}] \lambda6583/\text{H}α_{\text{narrow}} = 2.0\), \([\text{O iii}] \lambda5007/\text{H}β_{\text{narrow}} = 10.0\), and \([\text{O ii}] \lambda3727/[\text{O iii}] \lambda5007 = 0.1\), which would be measured as \([\text{N ii}] \lambda6583/\text{H}α_{\text{narrow}} = 0.2\), \([\text{O iii}] \lambda5007/\text{H}β_{\text{narrow}} = 1.0\), and \([\text{O ii}] \lambda3727/[\text{O iii}] \lambda5007 = 0.1\), respectively. In this situation, the oxygen abundances are also underestimated by a factor of \(0.28\) for \(\log (O/H)_{\text{SSCK1}}\) and by a factor of \(0.30\) for \(\log (O/H)_{\text{SSCK2}}\). This result suggests that we might underestimate the oxygen abundance in §3 if the Lorentzian profile is the representative function for the broad component of permitted lines. This may be the reason why the results derived in §§3 and 4 are inconsistent; the oxygen abundance of gas in NLS1’s may be selectively underestimated when the SSCK method is applied, because of the Lorentzian profile of broad components of permitted lines in the spectra of NLS1’s. Although the reason why the broad component of the permitted lines is well fitted by Lorentzian is not clear, Dumont & Collin-Souffrin (1990) showed that the Lorentzian profile could be produced if the BLR emission is produced at gas clouds in a disklike geometry around a supermassive black hole (see also Veron-Cetty et al. 2001; Sulentic et al. 2002). We do not discuss the origin of the Lorentzian profile further, since this issue is beyond the purpose of this paper. Since the diagnostics investigated in §4 consist of only forbidden lines and thus are free from the above uncertainties, we conclude that the results obtained in §4 are more reliable than those obtained in §3. Therefore, it can be concluded that the metallicity of gas clouds in NLRs is higher in NLS1’s than in BLS1’s.

Here we mention that the diagnostics investigated in §4 may also have a possible drawback. As shown in Figure 7, the correlations among the emission-line flux ratios \([\text{O i}] \lambda6300/[\text{N ii}] \lambda6583\), \([\text{O ii}] \lambda3727/[\text{N ii}] \lambda6583\), and \([\text{S ii}] \lambda6717, 6731/[\text{N ii}] \lambda6583\) can be explained by the photoionization models in the parameter ranges of \(n_\text{H} \approx 10^2\) to \(10^3\) cm\(^{-3}\) and \(0.5 \lesssim Z/Z_\odot \lesssim 3.0\). The inferred range of the gas density is consistent with the previously reported values (see, e.g., Tsvetanov & Walsh 1992; Storchi-Bergmann, Wilson, & Baldwin 1992; Schmitt et al. 1994). However, the model values of metallicity would contain possible uncertainties if the nitrogen production is delayed relative to the oxygen production. The delay is significant if the timescale for the increase in the metallicity by star formation activity is comparable to or shorter than the lifetime of the nitrogen-producing stars, i.e., \(\approx 10^8\) yr (see, e.g., Hamann & Ferland 1993, 1999; Henry, Edmunds, & Köppen 2000; see also Hamann et al. 2002). The result of this effect is that the abundance ratio \(N/H\) becomes subsolar at \(Z = Z_\odot\). Although this offset is only weakly present in the data for \(\text{H} ii\) regions (van Zee et al. 1998), it could be substantial in AGNs (see, e.g., Hamann & Ferland 1999). Taking this effect into account, one can formulate the nitrogen abundance of the gas as

\[
\log([\text{N}/\text{H}]/[\text{N}/\text{H}]_0) = 2 \log(Z/Z_\odot) - q,
\]

where \(q\) is the logarithmic offset. Hamann et al. (2002) mentioned that the \(q\)-value might reach up to \(\approx 0.2\) to 0.5 for gas in AGNs. In order to investigate the effect of this delay on our
diagnostics, we perform further model calculations. The adopted parameters are the same as those of the models presented in Figures 7 and 8 except for the \(q\)-value, which is altered from 0 to 5. The results are shown in Figure 10. The diagrams in Figure 10 suggest that the gas metallicity of NLRs is \(1.0 \leq Z/Z_\odot \leq 3.0\) for the BLS1’s, while \(Z/Z_\odot \geq 2.5\) for the NLS1’s. These values are larger than those suggested by the diagrams in Figure 8. Therefore, the diagnostics investigated in §4 may be invalid when we estimate the absolute values of the gas metallicity, since the true \(q\)-value for the NLR in AGNs is unclear. We can, however, use the diagnostics to compare the gas metallicities of NLS1’s and BLS1’s, unless the \(q\)-value is systematically different between the two populations. Since there is no reason for such a difference to exist, the conclusion that the gas metallicity in NLRs tends to be relatively higher in NLS1’s than in BLS1’s seems valid, even if the uncertainty of the \(q\)-value is taken into account.

Finally, we discuss the effect of the inhomogeneity of NLRs on our results. It is known that there are significant density gradients in NLRs (see, e.g., Kraemer et al. 2000). Since the [O I] \(\lambda 6300\) transition has higher critical density \((1.8 \times 10^6 \text{ cm}^{-3})\) than the transitions of [O II] \(\lambda 3727\), [N II] \(\lambda 6583\), [S II] \(\lambda 6717\), and [S II] \(\lambda 6731\) \((4.5 \times 10^4, 8.7 \times 10^4, 1.5 \times 10^5, \text{and } 3.9 \times 10^5 \text{ cm}^{-3}\), respectively), gas clouds with \(n_H > 10^5 \text{ cm}^{-3}\) may selectively radiate the [O I] \(\lambda 6300\) emission. Therefore our one-zone photoionization models may be inappropriate to investigate the gas metallicity of NLRs, if such a high-density gas cloud contributes to emission-line spectra of NLS1’s and BLS1’s differently. Indeed, there are significant differences in the emission-line fluxes of some high-ionization emission lines, such as [Fe vii] \(\lambda 6087\) and [Fe x] \(\lambda 6374\), between S1’s and S2’s, due to the different contribution of dense gas clouds in NLRs (see, e.g., Murayama & Taniguchi 1998a; Nagao et al. 2000, 2001c). However, it has already been shown by Nagao et al. (2000, 2001c) that there is no systematic difference in the high-ionization emission lines between NLS1’s and BLS1’s. This suggests that the contribution from the dense gas clouds to emission-line spectra is not so different between NLS1’s and BLS1’s. Therefore, our conclusions seem valid, even if possible density inhomogeneity is taken into account.

Fig. 10.—Same as Fig. 8, but using models with \(q = 0.5\) instead of those with \(q = 0\).
6. SUMMARY

In order to explore possible differences in the gas metallicity between NLS1’s and BLS1’s, we have focused on the gas in NLRs. It is found that the results depend on the diagnostics applied. The emission-line flux ratio $[\text{N} II]/[\text{H} \alpha]$ has been often used to discuss the gas metallicity of NLRs in S2’s, but is not significantly different between NLS1’s and BLS1’s. Some other diagnostics, in which the narrow component of permitted lines is used, also suggest that there is little or no systematic difference in the gas metallicity between NLS1’s and BLS1’s. On the other hand, the diagnostics that consist of only forbidden emission lines, which are newly proposed in this paper, suggest that the gas metallicity of NLRs in NLS1’s tends to be higher than that in BLS1’s. This complex situation may be solved if the Lorentzian profile, rather than the Gaussian profile, is the representative function for the broad component of permitted lines in the spectra of NLS1’s. Since the results derived by using only forbidden emission line fluxes do not suffer from the uncertainty of the fitting function for the broad component of permitted lines, it can be concluded that the gas metallicity of NLRs tends to be higher in NLS1’s than in BLS1’s.

We would like to thank Gary Ferland for providing his code CLOUDY to the public. We also thank the anonymous referee for useful comments and suggestions. Alberto Rodriguez-Ardila kindly provided information about the emission-line flux ratios of some Seyfert galaxies. Y. S. is supported by a Research Fellowship from the Japan Society for the Promotion of Science for Young Scientists. This work was financially supported in part by Grants-in-Aid for Scientific Research 10044052, 10304013, and 13740122 from the Japanese Ministry of Education, Culture, Sports, Science, and Technology.

REFERENCES

Alloin, D., Bica, E., Bonatto, C., & Prugniel, P. 1992, A&A, 266, 117
Antonucci, R. R. J. 1993, ARA&A, 31, 473
Antonucci, R. R. J., & Miller, J. S. 1985, ApJ, 297, 621
Baker, J. C. 1997, MNRAS, 286, 23
Baldwin, J. A., Ferland, G. J., Martin, P. G., Corbin, M. R., Cota, S. A., Peterson, B. M., & Slettebak, A. 1991, ApJ, 374, 580
Baldwin, J. A., et al. 1996, ApJ, 468, L115
Boller, T., Brandt, W. N., & Fink, H. 1996, A&A, 305, 53
Boller, T., et al. 2002, MNRAS, 329, L1
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Collin, S., & Joly, M. 2000, NewA Rev., 44, 531
Dumont, A.-M., & Collin-Souffrin, S. 1990, A&A, 229, 313
Hamann, F., & Ferland, G. J. 1993, ARA&A, 31, 487
Hamann, F., & Ferland, G. J. 1993, ApJ, 418, 11
Hamann, F., Korista, K. T., Ferland, G. J., Warner, C., & Baldwin, J. 2002, ApJ, 564, 592
Hayashi, K. 2000, NewA Rev., 44, 419
Henry, R. B., Edmunds, M. G., & Köppen, J. 2000, ApJ, 519, 160
Hes, R., Barthel, P. D., & Fosbury, R. A. E. 1993, Nature, 362, 326
Izotov, Y. I., & Thuan, T. X. 1999, ApJ, 511, 639
Kasliwal, E. Y., & Weedman, D. W. 1974, ApJ, 192, 581
Kraemer, S. B., Wu, C.-C., Crenshaw, D. M., & Harrington, J. P. 1994, ApJ, 435, 171
Kuraszkiewicz, J., Wilkes, B. J., Czerny, B., & Mathur, S. 2000, ApJ, 542, 692
Laor, A., Fiore, F., Elvis, M., Wilkes, B. J., & McDowell, J. C. 1997, ApJ, 477, 93
Leighly, K. M. 1999a, ApJS, 125, 297
Leighly, K. M. 1999b, ApJS, 125, 317
Lu, Y., & Yu, Q. 2001, MNRAS, 324, 653
Mathur, S. 2000a, MNRAS, 314, L17
———. 2000b, NewA Rev., 44, 469
———. 2001, AJ, 122, 1688
Mathur, S., Kuraszkiewicz, J., & Czerny, B. 2001, NewA, 6, 321
Mineshige, S., Kawaguchi, T., Takeuchi, M., & Hayashida, K. 2000, PASJ, 52, 499
Moran, E. C., Halpern, J. P., & Helfand, D. J. 1996, ApJS, 106, 341
Murayama, T., & Taniguchi, Y. 1998a, ApJ, 497, L9
———. 1998b, ApJ, 503, L115
Nagao, T., Murayama, T., & Taniguchi, Y. 2001a, ApJ, 546, 744
———. 2001b, ApJ, 549, 155
———. 2001c, PASJ, 53, 629
Nagao, T., Taniguchi, Y., & Murayama, T. 2000, ApJ, 119, 2605
Osterbrock, D. E., & Pogge, R. W. 1985, ApJ, 297, 166
Pagel, B. E. J., & Edmunds, M. G. 1981, ARA&A, 19, 77
Pounds, K., Done, C., & Osborne, J. P. 1995, MNRAS, 277, L5
Pounds, K., & Vaughan, S. 2000, NewA Rev., 44, 431
Puchnarewicz, E. M., Mason, K. O., Siemiginowska, A., Fruscione, A., Comastri, A., Fiore, F., & Cagnoni, L. 2001, ApJ, 550, 644
Radovich, M., & Rafanelli, P. 1996, A&A, 306, 97
Rodriguez-Ardila, A., Pastoriza, M. G., & Donzelli, C. J. 2000, ApJS, 126, 63
Schmitt, H. R., Storchi-Bergmann, T., & Baldwin, J. A. 1994, ApJ, 423, 237
Shemmer, O., & Netzer, H. 2002, ApJ, 567, L19 (erratum, 569, L59)
Shields, G. A. 1976, ApJ, 204, 530
Shields, G. A., & Oke, J. B. 1975, ApJ, 197, 5
Shields, J. C., & Kennicutt, R. C., Jr. 1995, ApJ, 454, 807
Storchi-Bergmann, T. 1991, MNRAS, 249, 404
Storchi-Bergmann, T., & Pastoriza, M. G. 1999, ApJ, 347, 195
———. 1990, PASP, 102, 1359
Storchi-Bergmann, T., Schmitt, H. R., Calzetti, D., & Kinney, A. L. 1998, AJ, 115, 909 (SSCK)
Storchi-Bergmann, T., Wilson, A. S., & Baldwin, J. A. 1992, ApJ, 396, 345
Sulentic, J. W., Zamanov, R., Bachev, R., Calvani, M., & Dultzin-Hacyan, D. 2002, ApJ, 566, L17
Tsvetanov, Z., & Walsh, J. R. 1992, ApJ, 386, 485
Turner, T. J., George, I. M., Nandra, K., & Turcan, D. 1999a, ApJ, 524, 667
———. 2002, ApJ, 568, 427
Ultrich, M.-H., Comastri, A., Komossa, S., & Crane, P. 1999, A&A, 350, 816
van Zee, L., Salzer, J. J., & Haynes, M. P. 1998, ApJ, 497, L1
Ve´ron-Cetty, M.-P., Ve´ron, P., & Gonc¸alves, A. C. 2001, A&A, 372, 730
Vila-Costas, M. B., & Edmunds, M. G. 1993, MNRAS, 265, 199
Wandel, A. 1999b, ApJ, 519, L39
———. 2000, NewA Rev., 44, 427
———. 2002, ApJ, 565, 762
Wang, T., Brinkmann, W., & Bergeron, J. 1996, A&A, 309, 81
Wills, B. J., Brotherton, M. S., Laor, A., Wills, D., Beland, G. J., & Chang, Z. 1999, in ASP Conf. Ser. 162, Quasars and Cosmology, ed. G. Ferland & J. Baldwin (San Francisco: ASP), 373
———. 2000b, ApJ, 549, 155