ABSTRACT

We report the results of our high-quality spectropolarimetric observation of the narrow-line region in a nearby Seyfert 2 galaxy, Mrk 573, with the Subaru Telescope. The polarized flux spectrum of Mrk 573 shows not only prominent scattered broad Hα emission but also various narrow forbidden emission lines. We find that the measured polarization degree of the observed forbidden emission lines is positively correlated with the ionization potential of the corresponding ions and the critical density of the corresponding transitions. We discuss some possible origins of these correlations, and then we point out that the correlations are caused by the obscuration of the stratified narrow-line region in Mrk 573 by the optically and geometrically thick dusty torus, matching findings of a previous study of NGC 4258.

Key words: galaxies: active — galaxies: individual (Markarian 573) — galaxies: nuclei — galaxies: Seyfert — polarization

1. INTRODUCTION

Active galactic nuclei (AGNs) can be broadly classified into types 1 and 2, based on the presence or absence of broad permitted emission lines in their spectra. This dichotomy can be understood as follows: because high-velocity photoionized clouds in broad-line regions (BLRs) are surrounded by an optically thick, dusty torus, the BLR can be seen only when we view the AGN face-on toward the dusty torus, and they are hidden by the torus when our view is edge-on. This scheme, termed a unified AGN model (see Antonucci 1993 for a review), is supported by a variety of observational findings, including the detection of hidden BLRs in some type 2 AGNs observed in polarized light (e.g., Antonucci & Miller 1985; Miller & Goodrich 1990; Tran et al. 1992, 1995, 2000; Young et al. 1993; Tran 1995, 2001; Young et al. 1996; Kay & Moran 1998; Barth et al. 1999a, 1999b; Kishimoto et al. 2001; Lumsden et al. 2001; Nagao et al. 2004). This unified model now provides one of the most important frameworks for AGN studies.

Differing from BLR emission, narrow forbidden and permitted emission lines are seen in spectra of both type 1 and type 2 AGNs. This suggests that narrow-line regions (NLRs) are located far from the nucleus and implies that their visibility should not depend on a viewing angle toward dusty tori. Recent imaging observations with the Hubble Space Telescope (HST) have indeed clarified the spatially extended feature of NLRs on the scale of $\sim$10$^{-3}$ pc (e.g., Capetti et al. 1995, 1997; Schmitt & Kinney 1996; Falcke et al. 1998; Ferruit et al. 1999; Schmitt et al. 2003). However, it has also been recognized that high-ionization forbidden emission lines, such as [Fe vii] and [Fe x], and high critical density transitions, such as [O iii] $\lambda$4363, are statistically stronger in type 1 AGNs than in type 2 AGNs (e.g., Murayama & Taniguchi 1998a; Schmitt 1998; Nagao et al. 2000, 2001a, 2001b). Does this suggest the breakdown of the AGN unified model? Murayama & Taniguchi (1998b) showed that these observed differences can be understood within the framework of the unified model as follows: the highly ionized dense gas clouds, which radiate [O iii] $\lambda$4363 and high-ionization lines selectively, are located near the nucleus, where they can be hidden by the tori, as well as by the BLRs (see also Nagao et al. 2001a, 2001b). Since this “high-ionization nuclear emission-line region (HINER)” plays a crucial role in the construction of realistic multizone photoionization models for NLRs, it is very important to investigate the nature of this HINER component.

However, it is far from feasible to resolve such a small scale, comparable to the inner radius of the tori ($<$1 pc; e.g., Taniguchi & Murayama 1998; see also Minezaki et al. 2004 and references therein for the inferred inner radius of the tori by the dust reverberation technique). This is an area in which the unique capacities of spectropolarimetry become apparent, as already mentioned by Goodrich (1992). Note that few spectropolarimetric studies of NLRs have been conducted as of yet, although many spectropolarimetric studies have been performed regarding BLRs and the continuum emission. One of the few AGNs whose NLR has been extensively investigated in a spectropolarimetric manner is a LINER galaxy, NGC 4258 (Barth et al. 1999e). This object exhibits the following three interesting aspects: (1) the polarization degrees of forbidden lines are positively correlated with critical densities and ionization potentials of the line transitions; (2) the forbidden-line widths are broader in the polarized spectrum than those in the total flux spectrum; and (3) the gas density traced by the line ratio of the [S ii] doublet is higher using the polarized spectrum than the total flux spectrum. These observational facts are perfectly consistent with the HINER hypothesis; that is, these three results can be consistently explained by introducing relatively high-velocity, high-density, and highly ionized clouds. Their radiation contributes significantly to the polarized...
spectrum in the innermost region of NLRs whose visibility depends on a viewing angle toward the dusty tori. The same results are also obtained for a quasar-hosted ultraluminous infrared galaxy IRAS 09104+4109 (Tran et al. 2000). Unfortunately, however, NLRs in Seyfert galaxies, the most typical population of AGNs in the local universe, have not yet been investigated in such a spectropolarimetric manner.

Therefore, we have started this project to perform spectropolarimetric observations of NLRs in type 2 Seyfert galaxies by using the Subaru Telescope to explore the innermost region of NLRs. Although many spectropolarimetric observations have been performed for type 2 Seyfert galaxies historically, their data quality is not high enough to be useful for our purposes. This is because most of the previous studies were designed to search for scattered BLR emission, which can be detected more easily than the scattered components of weak forbidden lines. Since we require very high quality spectropolarimetric data, the large aperture size of the Subaru Telescope is absolutely necessary. In this paper, we present the initial result of our project on the Seyfert 2 galaxy Mrk 573.

2. OBSERVATION AND DATA REDUCTION

The details of observations and the data reduction procedure are described in Nagao et al. (2004). However, we offer a brief description here for the convenience of the readers.

The spectropolarimetric observation of Mrk 573 was carried out by using the Faint Object Camera and Spectrograph (FOCAS; Kashikawa et al. 2002) on the 8.2 m Subaru Telescope (Kaifu et al. 2000; Iye et al. 2004) at Mauna Kea, on 2003 October 5–6 (UT). All of the observations were carried out through a polarimetric unit that consists of a rotating superachromatic half-wave plate and a quartz Wollaston prism. A 0.4′′ wide slit, a 300 line mm\(^{-1}\) grism (300B), and a V47 order-sorting filter were used. This setting results in a wavelength resolution of \(R \approx 1000\). We adopted 3 pixel binning for the spatial direction on the chips, which results in a spatial sampling rate of 0.3′′ per binned pixel. All of the data were obtained at four wave-plate position angles, 0°, 45°, 22.5°, and 67.5°. The integration time of each exposure for the observation of Mrk 573 was 240 or 480 s, and the total on-source integration time was 208 minutes. The position angle of the slit was set to 0°. We also obtained spectra of unpolarized standard stars (BD +28°4211 and G191B2B) and a strongly polarized star (HD 204827). Spectra of a halogen lamp and a thorium-argon lamp were also obtained for flat fielding and wavelength calibration, respectively.

The data were reduced by the standard manner using IRAF. We extracted the spectra of Mrk 573 and the standard stars by adopting the aperture size of 3′′ (i.e., 10 binned pixels). The corresponding linear aperture size in the frame of Mrk 573 is 1.02 h\(_{\text{75}}\)^{-1} kpc \times 0.13 h\(_{\text{75}}\)^{-1} kpc. Instrumental polarization was corrected by using the data from the unpolarized standard stars. Instrumental depolarization was not corrected because it has been confirmed experimentally that the amount of the instrumental depolarization of the FOCAS is less than a few percent. Flux calibration was performed by using the data of BD +28°4211 and G191B2B (Oke 1990). The polarization angle was calibrated using the data from the strongly polarized star. Galactic interstellar polarization toward Mrk 573 is estimated to be \(P = 0.32\%\) and \(\theta = 125°\) in the B band, based on the polarimetric properties of the two stars near the line of sight toward Mrk 573 (i.e., HD 9740 and HD 10441; see Table I of Nagao et al. 2004). Accordingly, the spectrum obtained was corrected for Galactic interstellar polarization by adopting a Serkowski law (Serkowski et al. 1975) with \(P_{\text{max}}\) occurring at \(\lambda_{\text{max}} = 5500\ \text{Å}\).

3. RESULTS

The total flux \((I)\), the polarization degree \((P)\), the position angle of polarization \((\theta)\), and the polarized flux \((I \times P)\) of Mrk 573 are shown as functions of wavelength in Figure 1. The spectra shown in this figure are uncorrected for reddening and starlight of the host galaxy. Top to bottom: Total flux \(I\), polarization degree \(P\), position angle of polarization \(\theta\), and polarized flux \((I \times P)\).

The heliocentric radial velocity of Mrk 573 is 5156 ± 90 km s\(^{-1}\) (Whittle et al. 1988), which gives a projected linear scale of 0.33 h\(_{\text{75}}\)^{-1} kpc for 1″.

\footnote{The heliocentric radial velocity of Mrk 573 is 5156 ± 90 km s\(^{-1}\) (Whittle et al. 1988), which gives a projected linear scale of 0.33 h\(_{\text{75}}\)^{-1} kpc for 1″.}

\footnote{IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.}

\footnote{Mrk 0573

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{spectrum.png}
\caption{Data obtained from Mrk 573 plotted as a function of wavelength. The data are corrected for interstellar polarization and redshift but not for reddening and starlight of the host galaxy. Top to bottom: Total flux \(I\), polarization degree \(P\), position angle of polarization \(\theta\), and polarized flux \((I \times P)\).}
\end{figure}
total flux in Figure 2. The strong stellar features such as Mg $\text{i} b$ 5177, Fe $\text{i}$ 5270, Na $\text{i}$ D 5893, and the TiO$_2$ molecular band at 6235 Å are clearly seen. Thus, it should be kept in mind that the spectrum of the polarization degree shown in Figure 1b ($P = 1.0\% \pm 0.2\%$ at 5400–6000 Å; see Nagao et al. 2004) is heavily diluted by the unpolarized starlight emission.

As clearly exhibited in the second and bottom panels of Figure 1, a prominent broad component of the H$\alpha$ emission is detected in the spectrum of the polarized flux, although there is no corresponding broad H$\alpha$ feature in the spectrum of the total flux (Fig. 1a). We do not discuss this hidden BLR emission in this paper because it is discussed in detail in a companion paper (Nagao et al. 2004). In addition to the broad emission lines, strong forbidden lines, such as [O $\text{iii}$] $\lambda\lambda$4959, 5007, [N $\text{i}$] $\lambda$6548, 6583, and [S $\text{ii}$] $\lambda\lambda$6717, 6731, are clearly seen in the polarized flux spectrum, and thus the polarization degree of these strong forbidden emission lines can be measured rather easily. However, two difficulties arise in measuring the polarization degrees for rather weak but important forbidden lines.

One is the insufficient signal-to-noise ratio (S/N) of the polarized flux spectrum. It is generally very difficult to obtain high-quality spectra of polarized flux even using 8 m class telescopes because a huge number of photons are required. To improve this situation, we apply 15 pixel (which corresponds to 0.5 Å) smoothing on the spectrum of the polarized flux. The resulting polarization degrees for rather weak but important forbidden lines.

As for the model spectrum, we adopt the simple stellar population (SSP) of Bruzual & Charlot (2003). We examine five SSPs as candidate stellar populations of the host galaxy of Mrk 573; that is, (Age = 5 Gyr, Z = 0.0 Z$_\odot$), (10 Gyr, 0.4 Z$_\odot$), (10 Gyr, 1.0 Z$_\odot$), (10 Gyr, 2.5 Z$_\odot$), and (15 Gyr, 1.0 Z$_\odot$). Since the spectral resolution of the SSP spectra ($\approx$2000; see Bruzual & Charlot 2003) is not as high as the same data obtained by our observation, we use the Gaussian kernel to match the spectral resolution of the models to the FOCAS data, R = 1000. The smoothed spectra of the five SSPs are shown in Figure 4. To judge which SSP is better as a template of the starlight of the host galaxy, we focus on two stellar absorption features: Na $\text{i}$ D 5893 and the TiO$_2$ molecular band at $\approx$6235 Å (in the rest frame). Among the five SSPs, those with (Age, Z) = (5 Gyr, 0.0 Z$_\odot$), (10 Gyr, 0.4 Z$_\odot$), (10 Gyr, 1.0 Z$_\odot$), and (10 Gyr, 2.5 Z$_\odot$) are not appropriate for the host galaxy spectrum. This is because the equivalent widths of Na $\text{i}$ D 5893 and the TiO$_2$ molecular band of these three SSPs are too small. In the remaining two SSPs, the one with (Age, Z) = (10 Gyr, 2.5 Z$_\odot$) cannot eliminate the absorption features of Na $\text{i}$ D 5893 and the TiO$_2$ molecular band simultaneously. Thus, we finally adopt the SSP with (Age, Z) = (15 Gyr, 1.0 Z$_\odot$) as the template spectrum of the host galaxy of Mrk 573. Close-ups of the total flux spectra before and after the subtraction of the model galaxy spectrum are shown in Figure 5.

The other difficulty in measuring the polarization degrees of weak emission lines is the contamination of the starlight from the host galaxy in the total flux spectrum. Since the continuum emission of the total flux of Mrk 573 is heavily contributed by the host galaxy, as mentioned above (see also Kay 1994), the fluxes of weak emission lines are hard to measure accurately because of the complex spectral features of the starlight. Thus, in order to measure the fluxes of the weak emission lines in the total flux spectrum correctly, we must remove the starlight contribution in the total flux spectrum by using the model spectrum. The stellar population of a host galaxy of an AGN is generally hard to determine accurately (see, e.g., Schmitt et al. 1999; Raimann et al. 2003). However, we are not interested in accurately determining the stellar population of the host galaxy of Mrk 573 but only in removing the stellar features approximately, in order to measure the polarization degree of the emission lines. We thus try to remove the stellar features by only using some of the template galaxy spectra.

As for the model spectrum, we adopt the simple stellar population (SSP) of Bruzual & Charlot (2003). We examine five SSPs as candidate stellar populations of the host galaxy of Mrk 573; that is, (Age = 5 Gyr, Z = 0.0 Z$_\odot$), (10 Gyr, 0.4 Z$_\odot$), (10 Gyr, 1.0 Z$_\odot$), (10 Gyr, 2.5 Z$_\odot$), and (15 Gyr, 1.0 Z$_\odot$). Since the spectral resolution of the SSP spectra ($\approx$2000; see Bruzual & Charlot 2003) is not as high as the same data obtained by our observation, we use the Gaussian kernel to match the spectral resolution of the models to the FOCAS data, R = 1000. The smoothed spectra of the five SSPs are shown in Figure 4. To judge which SSP is better as a template of the starlight of the host galaxy, we focus on two stellar absorption features: Na $\text{i}$ D 5893 and the TiO$_2$ molecular band at $\approx$6235 Å (in the rest frame). Among the five SSPs, those with (Age, Z) = (5 Gyr, 0.0 Z$_\odot$), (10 Gyr, 0.4 Z$_\odot$), (10 Gyr, 1.0 Z$_\odot$), and (10 Gyr, 2.5 Z$_\odot$) are not appropriate for the host galaxy spectrum. This is because the equivalent widths of Na $\text{i}$ D 5893 and the TiO$_2$ molecular band of these three SSPs are too small. In the remaining two SSPs, the one with (Age, Z) = (10 Gyr, 2.5 Z$_\odot$) cannot eliminate the absorption features of Na $\text{i}$ D 5893 and the TiO$_2$ molecular band simultaneously. Thus, we finally adopt the SSP with (Age, Z) = (15 Gyr, 1.0 Z$_\odot$) as the template spectrum of the host galaxy of Mrk 573. Close-ups of the total flux spectra before and after the subtraction of the model galaxy spectrum are shown in Figure 5.
After treating the data in these two ways to improve measurement accuracy, we are now ready to measure the polarization degree of the weak emission lines of Mrk 573. To measure the emission-line fluxes, we use the IRAF task SPECFIT (developed by Kriss 1994), assuming a Gaussian profile for the emission lines. We measure the unpolarized fluxes of the emission lines by using the total flux spectrum after removing the contribution of starlight by the host galaxy. The flux ratios and the velocity separations of the doublets of [O ii], [O i], and [N ii] are fixed at the theoretical values. As for the doublets of [S ii] and [O i], however, the velocity separations are not fixed at the theoretical values because the two emission lines in each doublet generally arise from different clouds in the NLR (see, e.g., Ferguson et al. 1997). For the measurement at the wavelength region around [O i]+[Fe x], we include the [S ii] λ6312 emission in the multi-Gaussian spectral modeling process because the [O i] λ6300 emission is blended by that emission, as seen in Figure 3. The measured flux ratio of [S ii] λ6312/[O i] λ6300 is ~0.26. As for the polarized emission-line spectrum, the measurement is performed using the polarized flux spectrum smoothed by 15 pixels, except for the [N ii] doublet, which cannot be measured in the smoothed spectrum because it is blended with the Hα emission. For the [N ii] flux, we thus refer to the value presented in Nagao et al. (2004), for which no smoothing was performed for the polarized flux spectrum. The adjacent pairs of emission lines, [O i] λ6300+[S ii] λ6312, [O i] λ6363+[Fe x] λ6374, [S ii] λ6717+[S ii] λ6731, and [O ii] λ7320+[O i] λ7330, cannot be deblended in the smoothed spectrum. Thus, we adopt a single Gaussian profile for each pair for a rough measurement of the sum of the emission-line fluxes.

The measured total flux and polarized flux, as well as the polarization degree for each forbidden emission line, are given in Table 1. The derived polarization degree of the [O i] emission is higher than the previously reported value, 0.27%±0.09% (Goodrich 1992). This may be due to the difference in the aperture size used to make the one-dimensional spectra. Note that our adopted slit width is far narrower than that of the observation of Goodrich (1992), 2″. The upper limit value of 1.4% for the polarization degree of [O i] λ6300 is obtained by assuming that the [S ii] λ6312 emission is unpolarized. Under this assumption we can estimate the polarized flux of the [Fe x] λ6374 emission to be 8.5×10^{-17} ergs s^{-1} cm^{-2}, which corresponds to a polarization degree of 3.4%. On the other hand, if the flux ratio of [S ii] λ6312/[O i] λ6300 in the polarized flux spectrum is the same as that in the total flux spectrum, the polarized flux of [O i] λ6300 would be 8.1×10^{-17} ergs s^{-1} cm^{-2}. In this case the polarization degrees of [O i] and [Fe x] are estimated to be 1.1% and 3.7%, respectively.

4. DISCUSSION

To interpret the results obtained, we plot in Figure 7 the polarization degrees of the forbidden emission lines as functions of the ionization potential of the corresponding ions and the critical density of the corresponding transitions. As shown in this figure, positive correlations are seen both between the polarization degree and the ionization potential and between the polarization degree and the critical density. Note that the typical error for the polarization degree is 0.1% at most for faint emission lines. These correlations appear to be very similar to those seen in
NGC 4258 (Barth et al. 1999c) and IRAS P09104+4109 (Tran et al. 2000). To investigate whether these positive correlations are statistically significant, we apply a Spearman rank test, for which the null hypothesis is that the obtained polarization degree is not correlated with either the ionization potential or the critical density. The calculated probabilities of the data being consistent with the null hypothesis are 0.313 and 0.038 for the correlations of the polarization degree on either the ionization potential or the critical densities, respectively, if the [S iii] 6312 emission is not polarized. As for the case in which the polarization degree of the [S iii] 6312 emission is the same as the [O ii] 6300 emission, the probabilities are calculated to be 0.213 and 0.033, respectively. These results suggest that the correlation between the polarization degree and the ionization potential is statistically insignificant, although that between the polarization degree and the critical density is statistically significant. This tendency seems to resemble the situation seen in NGC 4258 (see Fig. 3 of Barth et al. 1999c). This result does not depend strongly on the assumption about the polarization property of the [S iii] 6312 emission. Note that if the [S iii] 6312 emission is more polarized than the [O ii] 6300 emission, the [O ii] 6300 and [Fe x] 6374 polarization are correspondingly estimated to be less than 1.1% and greater than 3.7%, respectively. Even in this case, the correlations seen in Figure 7 do not disappear. However, the [S iii] 6312 emission may be not so strongly polarized because its critical density is lower than the critical density of the [O ii] 6300 emission.

We next discuss the origin of the correlations. Sometimes NLR emission lines appear to be polarized because of Galactic interstellar polarization; i.e., narrow emission lines without intrinsic polarization can be seen in the polarized flux spectrum when the Galactic interstellar polarization is not properly corrected for. If the NLR polarization and its dependence on the ionization potential and the critical density are significantly

---

**TABLE 1**

| Line      | Total Flux\(^a\) (10\(^{-15}\) erg s\(^{-1}\) cm\(^{-2}\)) | Polarized Flux\(^b\) (10\(^{-15}\) erg s\(^{-1}\) cm\(^{-2}\)) | Polarization Degree (%) |
|-----------|---------------------------------------------------|---------------------------------------------------|-------------------------|
| [O ii] \(\lambda 6300\) | 108.011 ± 0.517 | 1.161 ± 0.007 | 1.1 |
| [O ii] \(\lambda 6583\) | 312.151 ± 1.495 | 3.356 ± 0.019 | 1.1 |
| [O i] \(\lambda 6300\) | 6.234 ± 0.092 | 0.116 ± 0.007 | 1.9 |
| [O i] \(\lambda 6364\) | 7.490 ± 0.113 | 0.102 ± 0.006 | <1.4 |
| [O i] \(\lambda 6374\) | 2.389 ± 0.038 | 0.118 ± 0.008 | <1.4 |
| [Fe x] \(\lambda 6374\) | 2.503 ± 0.075 | >3.4 |
| [N ii] \(\lambda 6548\) | 23.439 ± 0.365 | 0.181 ± 0.004 | 0.8 |
| [N ii] \(\lambda 6538\) | 69.145 ± 1.077 | 0.533 ± 0.012 | 0.8 |
| [S ii] \(\lambda 6717\) | 17.514 ± 0.364 | 0.316 ± 0.014 | 0.8 |
| [S ii] \(\lambda 6731\) | 20.844 ± 0.408 | 0.8 |
| [Ar iii] \(\lambda 7136\) | 7.309 ± 0.223 | 0.043 ± 0.004 | 0.6 |
| [O ii] \(\lambda 7320\) | 1.609 ± 0.062 | 0.049 ± 0.005 | 1.4 |
| [O ii] \(\lambda 7330\) | 2.012 ± 0.069 | 1.4 |

\(^a\) Measured from the total flux spectrum corrected for the contamination of the starlight of the host galaxy by the manner described in the text.

\(^b\) Measured from the polarized flux spectrum on which a 15 pixel smoothing is performed except for [N ii] \(\lambda 6548\), 6583, which are taken from Nagao et al. (2004); see text.

\(^c\) The flux ratios and the velocity separations of the doublets of [O ii], [O i], and [N ii] are fixed at the theoretical values. Note that this is not the case for the [O i] doublet in the polarized flux spectrum (see text).

\(^d\) The velocity separations of the doublets of [S ii] and [O ii] are not fixed at the theoretical values.

\(^e\) Including the contribution of the polarized [S ii] 6312 emission.

\(^f\) Excluding the contribution of the [S ii] 6312 emission.

\(^g\) Including the contribution of the polarized [S ii] 6312 emission.

\(^h\) Sum of the polarized [O i] \(\lambda 6364\) and [Fe x] \(\lambda 6374\) emission.

\(^i\) Sum of the polarized [S ii] 6717 and [S ii] 6731 emission.

\(^j\) Sum of the polarized [O ii] 7320 and [O ii] 7330 emission.

---

**Fig. 7.**—Polarization degrees of the forbidden emission lines as functions of the ionization potential of corresponding ions and the critical density of corresponding transitions. The polarization degrees of [O i] and [Fe x] are upper and lower limits, respectively (see text).
caused by improper correction of the Galactic interstellar polarization, the polarization degree of the lines should be a function of the wavelength. Thus, in Figure 8 we plot the polarization degrees of the forbidden emission lines as a function of the line wavelength. As shown in this figure, the polarization degree is not correlated with the line wavelength. This result strongly suggests that the observed NLR polarization and the correlations seen in Figure 7 are intrinsic and are not due to Galactic interstellar polarization. Finding no clear correlation between the line flux and the polarization degree (see Table 1) is also consistent with this idea.

The correlations may be caused by nuclear star-forming activity, because H II regions radiate lower ionization emission lines than NLRs in AGNs. Since emission from nuclear star-forming regions is thought to show a very small or no polarization, the observed polarization degree of lower ionization emission lines may be more diluted by the nebular emission of the star-forming regions than that of higher ionization emission lines. Therefore, the dependence of the dilution on the ionization potential of the forbidden lines could cause the observed correlations shown in Figure 7. However, this is not a probable scenario for Mrk 573. This is because the spectral properties of the host galaxy of Mrk 573 suggest that the stellar population of the host galaxy is very old and does not contain a significant number of young stars, as suggested by the result of our SSP fitting (§ 3). González Delgado et al. (2001), using a more quantitative method than ours, also reported that the stellar emission of Mrk 573 is dominated by a old stellar population component (see also Cid Fernandes et al. 2001; Raimann et al. 2003). Mouri & Taniguchi (2002) reported that the far-infrared emission of Mrk 573 is dominated by the AGN emission, not by the nuclear or circumnuclear starburst activity, which also supports the idea that the NLR emission of Mrk 573 is not diluted so significantly by emission attributed to the star-forming activities.

A possible origin of the correlations inferred from the AGN unified model is that the highly ionized, dense part of NLRs (i.e., HINERs) is hidden by an edge-on, geometrically and optically thick torus. If the NLRs possess a stratified structure, highly ionized and/or high-density gas clouds should be more effectively hidden by the thick torus. In that case, emission lines with a higher ionization potential and/or a higher critical density should be much more visible in the polarized flux spectrum, which would result in the positive correlations of the polarization degree of the forbidden emission lines with the ionization potential and the critical density. Since this scenario has been discussed for IRAS 20210+1121 (Young et al. 1996), NGC 4258 (Barth et al. 1999c), and IRAS P09104+4109 (Tran et al. 2000), it is very interesting to investigate whether it is also the case for Mrk 573.

First, we focus on how significantly the HINERs are hidden by the dusty torus in Mrk 573. Nagao et al. (2001a) demonstrated that the emission-line diagnostic diagram of [O III] λ4363/[O III] λ5007 versus [Fe II] λ6087/[O III] λ5007 is useful for examining the obscuration of HINERs (see Fig. 12 of Nagao et al. 2001a). The optical spectrum of Mrk 573 shows only weak HINER emission ([O III] λ4363/[O III] λ5007 ~ 0.18 and [Fe II] λ6087/[O III] λ5007 ~ 0.013; Nagao et al. 2000, 2001a), which is explained by the HINER in Mrk 573 being very obscured compared with other Seyfert galaxies. Second, we refer to the previous literature regarding spatially resolved observations of the NLRs. As for the HINER emission, Winge et al. (2000) argued, based on their near-infrared spectroscopy, that the [S II] λ1.252 μm emission is unresolved, although the neighboring [Fe II] λ1.257 μm emission is clearly extended in Mrk 573. Low-ionization emission lines such as [O III] λ5007 are, on the contrary, clearly extended around the central engine of Mrk 573 (e.g., Unger et al. 1987; Haniff et al. 1988; Tsvetanov & Walsh 1992; Pogge & De Robertis 1995; Capetti et al. 1996; Schmitt et al. 2003). Since the polarization of the emission from this extended NLR is thought to be very small, the polarization degrees of the low-ionization emission lines are diluted, and thus the observed correlations created. Third, we check where the polarization of the NLR emission occurs in Mrk 573. It is known that the polarization angle of the nuclear continuum emission of type 2 AGNs tends to be perpendicular to the direction of extended NLRs and radio jets (e.g., Antonucci 1983; Brindle et al. 1990). This is due to the fact that the polarization is caused by the scattering of free electrons in the opening cone above the torus. As for Mrk 573, the polarization angle of the nuclear continuum emission obeys the same tendency as the other type 2 AGNs (e.g., Nagao et al. 2004), which suggests that the observed polarization of the forbidden emission lines is also caused in the opening cone above the torus. Thus, the obscured HINER emission can be seen in the polarized light, which is scattered at the electron-scattering region above the torus.

If the polarization mechanism of the forbidden lines is the same as that of the broad permitted lines and the continuum emission, the position angle of the polarization of the forbidden lines should be similar to that of the broad lines and continuum emission. However, as expected from Figure 1c, the S/N of our data is not sufficient to allow an independent comparison of the position angles of the weaker forbidden lines, although some strong forbidden lines may show somewhat different position angles (Fig. 1c). This issue should therefore be examined on the basis of another deeper observation.

Taking all of the above matters into account, we conclude that the observed correlations presented in Figure 7 are caused by the obscuration of the stratified NLR of Mrk 573 by the thick dusty torus, as found in previous studies of NGC 4258 and IRAS P09104+4109. This result is important as evidence of the stratification of NLRs in AGNs. The velocity profiles of polarized forbidden emission lines are more useful for further investigations of this issue (Barth et al. 1999c), but the quality and the velocity resolution of our data are not high enough for us to carry out such an analysis.

It might be possible that the correlations seen in Figure 7 are present without any obscuration effect. If NLRs are stratified and thus HINERs reside in the innermost part of NLRs,
scattered photons arising at HINERs move along a longer optical path than the photons arising at the outer, low-ionization NLRs. The correlation of the polarization degree with the ionization potential and the critical density may be attributed to this difference. If this effect is the dominant source of the correlations seen in Figure 7 and the obscuration by the torus is not significant enough to create them, then the correlations should also be discovered in type 1 AGNs, just as in type 2 AGNs such as Mrk 573 and NGC 4258. Further spectropolarimetry of NLRs in AGNs by 8 m class telescopes will bring us useful information about the structure of the innermost part of NLRs, which cannot be fully resolved spatially by current observational facilities.

Finally, we remark that the measured polarization degrees of the forbidden emission lines, ~0.6%–3.4%, are comparable to or larger than the polarization degree of the continuum emission (~1.0%), although the nuclear continuum emission arises from a more compact region than the NLR emission. This problem can be completely solved by recalling the dilution effect caused by the starlight of the host galaxy on the polarization degree of the continuum emission. We can correct the dilution effect by adopting the fraction of the starlight in the continuum emission. If we adopt 84% as a starlight fraction of the continuum emission (see § 3), the intrinsic polarization degree of the continuum emission is calculated to be 1.0/(1 – 0.84) ~ 6.3%, which is roughly consistent with the previous result of Kay (1994). This corrected polarization degree of the nuclear continuum emission is significantly larger than the polarization degrees of all forbidden emission lines. Note that the difference in the polarization degree between the NLR emission and the starlight-corrected continuum emission is due to the dilution effect caused by the unobscured part of the NLR. As mentioned above, some forbidden lines of Mrk 573 have been observed to be spatially extended (see, e.g., Unger et al. 1987; Haniff et al. 1988; Tsvetanov & Walsh 1992; Pogge & De Robertis 1995; Capetti et al. 1996; Schmitt et al. 2003). Emission-line imaging observations with high quality and a high spatial resolution for higher ionization forbidden lines are important to further interpret the polarization properties of the NLR emission.

We are grateful to everyone on the staff of the Subaru Telescope, especially to the FOCAS instrument team. We thank the referee, R. Goodrich, for his comments, which helped improve this paper. We also thank K. Matsuda and M. Seki for useful comments. T. N. acknowledges financial support from the Japan Society for the Promotion of Science (JSPS) through JSPS Research Fellowships for Young Scientists. A part of this work was financially supported by Grants-in-Aid for the Scientific Research (10044052, 10304013, and 13740122) of the Japanese Ministry of Education, Culture, Sports, Science, and Technology.

REFERENCES

Antonucci, R. R. J. 1983, Nature, 303, 158
Antonucci, R. R. J., & Miller, J. S. 1985, ApJ, 297, 621
Barth, A. J., Filippenko, A. V., & Moran, E. C. 1999a, ApJ, 515, L61
Barth, A. J., Tran, H. D., Brotherton, M. S., Filippenko, A. V., Ho, L. C., van Breugel, W., Antonucci, R., & Goodrich, R. W. 1999c, AJ, 118, 1609
Brindle, C., Hough, J. H., Bailey, J. A., Axon, D. J., Ward, M. J., Sparks, W. B., & McLean, I. S. 1990, MNRAS, 244, 577
Brualdi, G., & Charlot, S. 2003, MNRAS, 344, 1000
Capetti, A., Axon, D. J., & Macchetto, F. 1997, ApJ, 487, 560
Capetti, A., Axon, D. J., Macchetto, F., Sparks, W. B., & Boksenberg, A. 1996, ApJ, 469, 554
Capetti, A., Macchetto, F., Axon, D. J., Sparks, W. B., & Boksenberg, A. 1995, ApJ, 448, 600
Cid Fernandes, R., Heckman, T., Schmitt, H., González Delgado, R. M., & Storchi-Bergmann, T. 2001, ApJ, 558, 81
Falcke, H., Wilson, A. S., & Simpson, C. 1998, ApJ, 502, 199
Ferguson, J. W., Korista, K. T., Baldwin, J. A., & Ferland, G. J. 1997, ApJ, 487, 122
Ferruit, P., Wilson, A. S., Falcke, H., Simpson, C., Pécontal, E., & Durret, F. 1999, MNRAS, 309, 1
González Delgado, R. M., Heckman, T., & Leitherer, C. 2001, ApJ, 546, 845
Goodrich, R. W. 1992, ApJ, 399, 50
Haniff, C. A., Wilson, A. S., & Ward, M. J. 1988, ApJ, 334, 104
Iye, M., et al. 2004, PASJ, 56, 381
Kafu, N., et al. 2000, PASJ, 52, 1
Kashikawa, N., et al. 2002, PASJ, 54, 819
Kay, L. E. 1994, ApJ, 430, 196
Kay, L. E., & Moran, E. C. 1998, PASP, 110, 1003
Kishimoto, M., Antonucci, R. R. J., Cimatti, A., Hurt, T., Dey, A., van Breugel, W., & Spinrad, H. 2001, ApJ, 547, 667
Kris, G. A. 1994, in ASP Conf. Ser. 61, Astronomical Data Analysis of Software and Systems III, ed. D. R. Crabtree, R. J. Hanisch, & J. Barnes (San Francisco: ASP), 437
Lumsden, S. L., Heisler, C. A., Bailey, J. A., Hough, J. H., & Young, S. 2001, MNRAS, 327, 459
Miller, J. S., & Goodrich, R. W. 1990, ApJ, 355, 456
Minezaki, T., Yoshii, Y., Kobayashi, Y., Enya, K., Suganuma, M., Tomita, H., Aoki, T., & Peterson, B. A. 2004, ApJ, 600, L35
Mouri, H., & Taniguchi, Y. 2002, ApJ, 565, 786
Murayama, T., & Taniguchi, Y. 1998a, ApJ, 497, L9
———. 1998b, ApJ, 503, L115
Nagao, T., Kawabata, K. S., Murayama, T., Ohyama, Y., Taniguchi, Y., Sumiya, R., & Sasaki, S. S. 2004, AJ, 128, 109
Nagao, T., Murayama, T., & Taniguchi, Y. 2001a, ApJ, 549, 155
———. 2001b, PASJ, 53, 629
Nagao, T., Taniguchi, Y., & Murayama, T. 2000, AJ, 119, 2605
Oke, J. B. 1990, AJ, 99, 1621
Osterbrock, D. E. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Mill Valley: University Science Books)
Pogge, R. W., & De Robertis, M. M. 1995, ApJ, 451, 585
Raimann, D., Storchi-Bergmann, T., González Delgado, R. M., Cid Fernandes, R., Heckman, T., Leitherer, C., & Schmitt, H. 2003, MNRAS, 339, 772
Schmitt, H. R. 1998, ApJ, 506, 647
Schmitt, H. R., Donley, J. L., Antonucci, R. R. J., Hutchings, J. B., & Kinney, A. L. 2003, ApJS, 148, 327
Schmitt, H. R., & Kinney, A. L. 1996, ApJ, 463, 498
Schmitt, H. R., Storchi-Bergmann, T., & Cid Fernandes, R. 1999, MNRAS, 303, 173
Serkowski, K., Mathewson, D. L., & Ford, V. L. 1975, ApJ, 196, 261
Taniguchi, Y., & Murayama, T. 1998, ApJ, 501, L25
Tran, H. D. 1995, ApJ, 440, 565
———. 2001, ApJ, 554, L19
Tran, H. D., Cohen, M. H., & Goodrich, R. W. 1995, AJ, 110, 2597
Tran, H. D., Cohen, M. H., & Villar-Martin, M. 2000, AJ, 120, 562
Tran, H. D., Miller, J. S., & Kay, L. E. 1992, ApJ, 397, 452
Tsvetanov, Z., & Walsh, J. R. 1992, ApJ, 386, 485
Unger, S. W., Pedlar, A., Axon, D. J., Whittle, M., Meurs, E. J. A., & Ward, M. J. 1987, MNRAS, 228, 671
Whittle, M., Pedlar, A., Meurs, E. J. A., Unger, S. W., Axon, D. J., & Ward, M. J. 1988, ApJ, 326, 125
Winge, C., Storchi-Bergmann, T., & Cid Fernandes, R. 1999, MNRAS, 303, 173
Young, S., Hough, J. H., Bailey, J. A., Axon, D. J., & Ward, M. J. 1993, MNRAS, 260, L1
Young, S., Hough, J. H., Efstathiou, A., Wills, B. J., Bailey, J. A., Ward, M. J., & Axon, D. J. 1996, MNRAS, 281, 1206