DETECTION OF THE POLARIZED BROAD EMISSION LINE IN THE SEYFERT 2 GALAXY MARKARIAN 573

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ABSTRACT

We report the discovery of the scattered emission from a hidden broad-line region (BLR) in a Seyfert 2 galaxy, Mrk 573, based on our recent spectropolarimetric observation performed at the Subaru Telescope. This object has been regarded as a type 2 active galactic nucleus (AGN) without a hidden BLR by previous observations. However, our high-quality spectrum of the polarized flux of Mrk 573 shows prominent broad (~3000 km s⁻¹) Hα emission, broad weak Hβ emission, and subtle Fe II multiplet emission. Our new detection of these indications for the presence of the hidden BLR in the nucleus of Mrk 573 is thought to be because of the high signal-to-noise ratio of our data, but the possibility of a time variation of the scattered BLR emission is also mentioned. Some diagnostic quantities such as the IRAS color, the radio power, and the line ratio of the emission from the narrow-line region of Mrk 573 are consistent with the distributions of such quantities of type 2 AGNs with a hidden BLR. Mrk 573 is thought to be an object whose level of the AGN activity is the weakest among the type 2 AGNs with a hidden BLR. In terms of the systematic differences between the type 2 AGNs with and without a hidden BLR, we briefly comment on an interesting Seyfert 2 galaxy, Mrk 266 SW, which may possess a hidden BLR but has been treated as a type 2 AGN without a hidden BLR.

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

1. INTRODUCTION

After the discovery of scattered broad permitted lines in the polarized spectra of a Seyfert 2 galaxy (hereafter Sy2) NGC 1068 (Antonucci & Miller 1985), many attempts have been made to detect the polarized broad lines in type 2 active galactic nuclei (AGNs) up to now (e.g., 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). This is because the presence of scattered broad permitted lines is promising evidence for the AGN unified model, in which both the type 1 and type 2 AGNs possess a broad-line region (BLR) in their nucleus (see Antonucci 1993 for a review).

Although the scattered BLR emission has been found in many type 2 AGNs, it is now recognized that Sy2’s do not always exhibit broad lines in the polarized spectra (see, e.g., Tran 2001). Does this suggest that not all Sy2’s possess a BLR in their nucleus? This is a very important issue because the presence of the two distinct populations of Sy2’s, i.e., Sy2’s with and without a BLR, is inconsistent to the simple AGN unified model. Heisler et al. (1997) proposed that this dichotomy can be understood in the framework of the unified model if the scattering region resides very close to the nucleus and its visibility depends on the viewing angle (see also, e.g., Taniguchi & Anabuki 1999). On the other hand, Tran (2001) reported that the amount of the obscuration toward the central engine is indistinguishable between the Sy2’s with and without polarized BLR emission (see also Alexander 2001). This suggests the presence of AGNs without BLRs (see, e.g., Heckman et al. 1995; Dultzin-Hacyan et al. 1999; Gu et al. 2001), which contradicts the current simple unified model. Investigating this issue further is crucially important not only to examine the AGN unified model but also to understand the nature of AGN phenomena themselves.

In order to discuss this issue, we should recognize correctly which Sy2 possesses a hidden BLR and which Sy2 does not. Here we report a clear detection of the hidden BLR in a Sy2, Mrk 573, which has been regarded as a Sy2 without a hidden BLR (Tran 2001, 2003; see also Kay 1994). Its heliocentric radial velocity is 5156 ± 90 km s⁻¹ (Whittle et al. 1988), giving a projected linear scale of 0.33 h⁻⁵ kpc for 1″.

2. OBSERVATION AND DATA REDUCTION

The spectropolarimetric observation for Mrk 573 was carried out by using FOCAS (Faint Object Camera and Spectrograph; Kashikawa et al. 2002) on the 8.2 m Subaru Telescope (KAIT) at Mauna Kea, on 2003 October 5–6 (UT). The FOCAS detector is a mosaic of two 4K × 2K MIT CCDs with 15 μm pixels. All the observations were carried out through a polarimetric unit that consists of a rotating superachromatic half-wave plate and a quartz Wollaston prism. A 0.5′′ width slit, a 300 line mm⁻¹ grisms (300B), and an order-sorting filter of Y47 were used. This setting results in a wavelength resolution of R ~ 1000. We adopted a 3 pixel binning for the spatial direction on the chips, which results in the spatial sampling rate of 0.031 for a binned pixel. All of the data are 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 is 240 or 480 s, and the total on-source integration time is 208 minutes. The position angle of the slit was set to be 0°. We also obtained spectra of unpolarized standard stars (BD +28°4211 and G191B2B) and a strongly polarized star.
We extracted the spectra of Mrk 573 and the standard lamp were also obtained for the flat fielding and the wavelength calibration, respectively.

The data were reduced in the standard manner by using IRAF.\(^5\) We extracted the spectra of Mrk 573 and the standard stars by adopting the aperture size of 32 pixels (i.e., 10 binned pixels). The corresponding linear aperture size in the frame of Mrk 573 is 1.02 h\(^{-1}\) kpc x 0.13 h\(^{-1}\) kpc. The instrumental polarization was corrected by using the data of the unpolarized standard stars. The 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. The flux calibration was performed by using the data of BD +28\(^°\)4211 and G191B2B (Oke 1990). The polarization angle was calibrated by using the data of the strongly polarized star.

The Galactic interstellar polarization toward the direction of Mrk 573 is estimated to be \(P = 0.32\%\) and \(\theta = 125^\circ\) at \(B\) 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 (Table 1). Accordingly, the obtained spectrum was corrected for the Galactic interstellar polarization by adopting a Serkowski law (Serkowski et al. 1975) with \(P_{\text{max}}\) occurring at \(\lambda_{\text{max}} = 5500\ \text{Å}\). Note that the interstellar polarization might be overestimated because the Galactic reddening toward the direction of Mrk 573 estimated by the dust emissivity map is not so large, i.e., \(E_{B-V} = 0.023\ \text{mag}\) (Schlegel et al. 1998). Since the Galactic interstellar polarization is \(\sim 3E_{B-V}\%\) for typical conditions and \(\sim 9E_{B-V}\%\) at most (see Serkowski et al. 1975), the Galactic interstellar polarization for Mrk 573 is estimated to be \(\lesssim 0.21\%\), which contradicts our adopted value, \(P = 0.32\%\). However, this discrepancy may be due to the underestimation of the Galactic reddening. The spectroscopically determined Galactic reddening for HD 9740 and HD 10441 are both \(E_{B-V} = 0.10\ \text{mag}\) (Heiles 2000), about 3 times larger than that estimated from the dust emissivity map (\(E_{B-V} = 0.03\ \text{mag}\); Schlegel et al. 1998). Therefore, as for the sky region around Mrk 573, there may be a tendency that the Galactic reddening is underestimated when using the dust emissivity map. Note that, in any cases, this uncertainty does not affect the following discussion about the detection of the broad component of Balmer lines, which is the main concern of this paper.

### 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 a function of wavelength in Figure 1. The spectra displayed in this figure are uncorrected for reddening and starlight of the host galaxy, but corrected for the redshift and the Galactic interstellar polarization as described in §2. Since the optical spectrum of Mrk 573 is significantly contaminated with the starlight of the host galaxy (~80% of the continuum; Kay 1994), the presented spectrum of the polarization degree (Fig. 1b) is heavily diluted. However, we can investigate the spectropolarimetric properties of AGNs through spectra of a polarized flux, because the starlight emission of host galaxies can be regarded as unpolarized light, and thus spectra of the polarized flux are not influenced by host galaxies (see, e.g., Antonucci & Miller 1985; Miller & Goodrich 1990).

The polarization degree of the continuum emission of Mrk 573 is 1.0 ± 0.2%, which is measured in the wavelength range of 5400–6000 Å in the rest frame of Mrk 573, where no strong emission-line features are present. The polarization angle is roughly constant at all the wavelength coverage, i.e., \(\theta = 50.5^\circ \pm 7.1^\circ\) (measured at 5000–7000 Å), as shown in Figure 1c. These results are consistent with the previous observations; e.g., Kay (1994) reported \(P = 1.3\%\) and \(\theta = 48^\circ\)

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\(^5\) IRAF (Image Reduction and Analysis Facility) 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.
based on their spectropolarimetry. The observed polarization angle is roughly perpendicular to the extension of the nuclear radio jet (~125°; e.g., Ulvestad & Wilson 1984). This is the same trend as that seen in many Sy2’s (e.g., Antonucci 1983; Brindle et al. 1990). As shown in Figure 1 clearly, narrow emission lines such as [O iii] 5007 are polarized, and thus we can see the emission-line features in the spectrum of the polarized flux. We do not discuss the properties of these polarized narrow emission lines because they are investigated in the subsequent paper.

Here we focus on the polarization properties of the hidden BLR in Mrk 573, the main concern of this paper. As shown in Figure 1, a prominent broad component of the Hα emission is clearly detected in the spectrum of the polarized flux, although there is no corresponding broad Hα feature in the spectrum of the total flux. To present the properties of this hidden BLR component more clearly, we show the enlarged spectrum of the total flux and of the polarized flux around the Hα emission. The dotted thin lines in Figures 2 and 3, respectively. In addition to the observed spectra, the results of the spectral fitting by multi Gaussian components are also plotted in these figures. For the spectral features of starlight such as a Balmer absorption affect the fitting process. As for the polarized flux, on the other hand, the observed spectrum can be well reproduced by five components, i.e., a power-law component, three Gaussian components for the NLR emission, and a broad Gaussian component (Fig. 3; Table 2). The velocity width of this broad component is ~3000 km s⁻¹ in FWHM, which is typical for a width of the broad Hα component seen in spectra of Seyfert 1 galaxies.

We thus conclude that the hidden BLR is surely harbored in Mrk 573, being different from the previous reports (Tran 2001; see also Kay 1994). Note that Tran (1995) reported that the scattered BLR emission tends to shift blueward relative to the [O iii] emission (i.e., systemic receding velocity of the object) in general. As for Mrk 573, however, there is no significant difference in the recession velocity between the scattered BLR emission and the NLR emission.

It should be also remarked that there are some additional spectral features suggesting the presence of the hidden BLR in the nucleus of Mrk 573 other than the broad Hα component. One is the polarized broad Hβ component, which is clearly seen in the spectrum of the polarized flux. The presence of this scattered broad Hβ is prominently exhibited in the spectrum of the polarization degree (Fig. 1b). However, we do not make attempts to fit the spectrum for Hβ, since the data quality is not sufficiently high for the spectral modeling. Another interesting feature is the weak hump seen from ~5100 to ~5400 Å in the spectra of the polarization degree and the polarized flux (Figs. 1b and 1d). This feature is thought to be the Fe ii multiplet emission arising at the BLR, which is not seen in the spectrum of the total flux but is seen only in the scattered light. In the spectrum of the polarization degree, there might be a possible broad component at ~5900 Å, although the counterpart is not clearly seen in the spectrum of the polarized flux. This may be the scattered broad He i 5876 component, but the detection is very marginal. To see these
possible hidden BLR features visually, we show the enlarged spectra of the total flux, the polarization degree, and the polarized flux in Figure 4.

4. DISCUSSION

To examine the AGN unified model is one of the most interesting issues toward understanding the nature of the AGN phenomena. Thus, various comparative studies between Sy2’s with and without the polarized BLR emission have been performed up to now (e.g., Heisler et al. 1997; Awaki et al. 2000; Gu et al. 2001; Thean et al. 2001; Lumsden et al. 2001; Tran 2001, 2003; Gu & Huang 2002). In such studies, Mrk 573 has been regarded as a Sy2 without a hidden BLR. However, it is now evident that Mrk 573 surely possesses a hidden BLR in its nucleus. If this kind of misclassification occurs frequently, the previous comparative studies would become rather senseless. Therefore, the reason of the misclassification should be discussed here.

Kay (1994) presented the results of the spectropolarimetric observations for Mrk 573, which were performed in 1987 November–1989 December. Although it was mentioned that the H/ and the H\γ emission in the polarized flux spectrum of Mrk 573 might be slightly broader than those in the total flux spectrum, it could not be concluded because the observation did not cover the H\α wavelength range. It is therefore crucially important for exploring the hidden BLRs to investigate the profiles of the polarized H\α emission, which is the easiest spectral feature to access the hidden BLR. It should be mentioned that, however, there may be a possibility that the scattered BLR emission is temporary variable. Although there are some reports that the scattered BLR emission of type 1 AGNs varies in a few years (e.g., Young et al. 1999; Smith et al. 2002), there is no report of finding a significant temporal variation of the scattered broad BLR emission in Sy2’s, so far. This is thought to be partly because the scattered photons cannot be observed because of the obscuration by a dusty tori if the scattering region resides at very close to the nucleus, as for Sy2’s. Thus, we can see only the polarized light scattered far from the nucleus with a distance larger than the scale height of dusty tori, ~1 pc or more (e.g., Taniguchi & Murayama 1998). Therefore, we cannot detect the temporal variation of scattered BLR emission of Sy2’s unless we monitor the spectropolarimetric data for several years at least. As for Mrk 573, the comparison of the spectropolarimetric data obtained at epochs separated ~15 yr may enable us to access the temporal properties of the scattered BLR emission.

| Line                | Wavelength\(\lambda\) | Line Width\(\lambda\) | Velocity Width\(V\) | Line Flux\(\lambda\) |
|---------------------|------------------------|------------------------|----------------------|----------------------|
| Unpolarized Emission Lines |
| H\(\alpha\)         | 6563.7                 | 9.4                    | 307                  | 87.20 ± 0.99         |
| [N\ ii] \(\lambda 6548\) | 6548.8                 | 10.6                   | 383                  | 23.44 ± 0.37         |
| [N\ ii] \(\lambda 6583\) | 6584.1                 | 10.7                   | 383                  | 69.14 ± 1.09         |
| Polarized Emission Lines |
| H\(\alpha\)         | 6566.0                 | 69.8                   | 3170                 | 2.14 ± 0.05          |
| [N\ ii] \(\lambda 6548\) | 6548.3                 | 6.0                    | ≤300\(f\)           | 0.78 ± 0.01          |
| [N\ ii] \(\lambda 6583\) | 6583.6                 | 6.1                    | ≤300\(f\)           | 0.53 ± 0.01          |

\(a\) Central wavelengths of the Gaussian component in the rest frame of Mrk 573.
\(b\) Measured emission-line widths (FWHM) without the correction for the instrumental broadening effect.
\(c\) Velocity widths of the emission lines. The instrumental broadening is corrected by assuming that the instrumental widths is 300 km s\(^{-1}\).
\(d\) Emission-line fluxes obtained by the best-fit models. The extinction effect is not corrected.
\(e\) The separation and the flux ratio of the [N\ ii] doublet emission are fixed to be the theoretical values in the fitting process. The velocity width is fixed to the same.
\(f\) Unresolved in the obtained spectrum.
If this is the case, most of the polarization of the hidden BLR in Mrk 573 is caused at the region within several parsecs from the nucleus where the obscuration by the dusty torus is not significant.

We discuss how our finding of the hidden BLR in Mrk 573 affects the previous studies. It is known that Sy2’s with a hidden BLR tend to show hotter MIR colors (i.e., higher $f_{25}/f_{60}$ ratios, where $f_{25}$ and $f_{60}$ are IRAS 25 and 60 μm fluxes, respectively) than Sy2’s without a hidden BLR (e.g., Heisler et al. 1997; Gu et al. 2001; Tran 2001, 2003). Although Heisler et al. (1997) interpreted this tendency as a difference of viewing angles toward a dusty torus, Alexander (2001) reported that the $f_{25}/f_{60}$ ratio is not a reliable indicator for the viewing angle (see also Murayama et al. 2000); rather it denotes the relative strength of the AGN activity compared with the nuclear star-forming activity. In order to compare the relative strength of the AGN activity between Sy2’s with and without a hidden BLR, a diagnostic diagram that consists of the $f_{25}/f_{60}$ ratio and the $S_{20}/f_{60}$ ratio (where $S_{20}$ is a radio 20 cm flux density) has been used, since the $S_{20}/f_{60}$ ratio is also expected to be a good indicator for the relative AGN activity strength (e.g., Tran 2001, 2003). In Figure 5, we plot the data of Tran (2003) on the diagnostic diagram of $f_{25}/f_{60}$ and $S_{20}/f_{60}$. This is basically the same as Figure 1 of Tran (2001; see also Fig. 4 of Tran 2003), but the data of Mrk 573 (and Mrk 266 SW, which is discussed below) is explicitly exhibited. We can see that the data of Mrk 573 is located the edge of the correlation between the two diagnostic flux ratios for the Sy2’s with a hidden BLR. Actually, the $f_{25}/f_{60}$ ratio of Mrk 573 is lower than all of the Sy2’s with a hidden BLR in the sample of Tran (2003), i.e., $f_{25}/f_{60} = 0.23$. Despite the low ratios of $f_{25}/f_{60}$ and $S_{20}/f_{60}$, Mrk 573 is thought not to be a peculiar object as a Sy2 with a hidden BLR because its data is consistent with the correlation between the two diagnostic flux ratios for the Sy2’s with a hidden BLR. The same conclusion can be seen in other diagnostic diagram; in Figure 6, we show the diagnostic diagram of $f_{25}/f_{60}$ and $[\text{O III}] \lambda 5007/\text{H}β$ in which the data of Tran (2003) are plotted. As reported by Tran (2001), there is a statistically significant difference in the distribution of the $[\text{O III}] \lambda 5007/\text{H}β$ flux ratio between Sy2’s with and without a hidden BLR (see also Tran 2003). Again, the data of Mrk 573 is consistent with the data of the Sy2’s with a hidden BLR though it is located at the edge of the distribution of the data of Sy2’s with a hidden BLR in this diagram. Note that it may be a part of the reason for the undetection of the scattered BLR emission of Mrk 573 by the previous observations that the strength of the AGN activity of Mrk 573 is very weak as inferred by the diagnostic diagrams in Figures 5 and 6.

Our study suggests that high-quality spectropolarimetric observations are crucial for dividing Sy2’s between those with and without a hidden BLR correctly. In terms of this viewpoint, we briefly comment on an interesting Sy2, Mrk 266 SW. This Sy2 has been also treated as a Sy2 without a hidden BLR (e.g., Tran 2001, 2003) but was suspected to possess the hidden BLR by Kay (1994), as was Mrk 573. Being different from Mrk 573, however, the diagnostic quantities of Mrk 266 SW are not similar to those of the Sy2’s with a hidden BLR. As seen in Figures 5 and 6, Mrk 266 SW shows lower $[\text{O III}] \lambda 5007/\text{H}β$ flux ratio than all of the Sy2’s with a hidden BLR in the sample of Tran (2003) and shows cooler IRAS color than Mrk 573. The data of Mrk 266 SW does not follow the correlation for the Sy2’s with a hidden BLR seen in Figure 5. In addition, in the diagnostic diagram of $[\text{O III}] \lambda 5007/\text{H}β$ versus $f_{25}/f_{60}$, the data of Mrk 266 SW is far from the data distribution of the Sy2’s with a hidden BLR but is consistent to the Sy2’s without a hidden BLR. Thus, we can recognize that the general properties of Mrk 266 SW is consistent with so-called “pure Sy2’s,” i.e., Sy2’s without a BLR in its nucleus, not with Sy2’s with a BLR. In order to understand the nature of the Sy2 populations, performing a high-quality spectropolarimetry for Mrk 266 SW seems important to examine whether or not...
not Mrk 266 SW possesses a hidden BLR, because Mrk 266 SW may be an atypical object if it possesses a hidden BLR in its nucleus.

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