Revealing AGN by Polarimetry

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Abstract.

Polarimetric study in the UV and optical has been one of the keys to reveal the structure and nature of active galactic nuclei (AGN). Combined with the HST’s high spatial resolution, it has directly confirmed the predicted scattering geometry of $\sim 100$ pc scale and accurately located the hidden nuclear position in some nearby active galaxies. Recently, we are using optical spectropolarimetry to reveal the nature of the accretion flow in the central engine of quasars. This is to use polarized light to de-contaminate the spectrum and investigate the Balmer edge spectral feature, which is otherwise buried under the strong emission from the outer region surrounding the central engine.

1. Introduction

We will describe the UV/optical polarimetric contributions to the AGN studies in two spatial scales, namely $\sim 100$ pc and $\sim 0.001$ pc scale. Broadly, active nuclei of galaxies consist of (1) the central engine, which we refer here to the region emitting a strong UV/optical continuum, probably of the scale of $\sim 100 R_S \sim 0.001$ pc for the black hole mass $M_{BH} = 10^8 M_\odot$ where $R_S = 2GM_{BH}/c^2$; (2) the broad-line region (BLR) of $\sim 0.1$ pc scale, emitting the broad permitted emission lines (FWHM $\sim 5000$ km/s); (3) the narrow-line region (NLR) of $\gtrsim 100$ pc scale, emitting the narrow permitted and forbidden lines ($\sim 500$ km/s). Generally, one observes both the BLR and NLR in type 1 AGNs, while only NLR in type 2s.

2. Inner Narrow-Line Region: $\sim 100$ pc scale structure

One of the most important results in understanding the structure of AGNs is that at least some of the type 2 AGNs are indistinguishable from type 1s if they are looked in scattered light, or polarized flux spectra (Antonucci 1993). Based on this and many other facts, it is widely believed that at least part of the type 1 and 2 distinction is simply orientation: the central engine and BLR are surrounded by torus-like obscuring matter ($\sim 1$ pc scale), and our line of sight
to type 2s is edge-on so that we don't see the nucleus directly. However, light escapes along the torus axis direction (and this is directly seen in type 1s) and partly reflected above or below the torus.

The spectropolarimetry would suggest that the spatial scale of the scattering region is rather comparable to that of the NLR: the continuum and broad lines are polarized in the same way but narrow lines are often polarized differently (and at a much lower level), meaning that the scattering region directly seen in type 2s is well outside the scale of the BLR but not the NLR.\(^1\)

The HST UV imaging polarimetry has spatially resolved this scattering region. One clearest example is for the Seyfert 2 galaxy NGC1068 by Capetti et al. (1995a,b). Similar work has been done for other type 2s (e.g. Capetti et al. 1996, Kishimoto et al. 2002). Highly polarized UV light with centrosymmetric PA pattern is observed to be extended roughly in a cone shape. This is seen in the inner NLR, so the size is consistent with the spectropolarimetric suggestion above. The hidden nuclear location can be robustly determined as the symmetric center of this pattern, and no bright UV/optical source is found at this position. For NGC1068, there was some deviation from the centrosymmetric pattern in the original map of Capetti et al. (1995a), but this was shown to be essentially entirely instrumental and the hidden nuclear location was refined accordingly (Kishimoto 1999). This scattering center should be quite robust, and turned out to be consistent with many subsequent high-resolution investigations in the IR (e.g. Galliano et al. 2003; Bock et al. 2000).

In NGC 1068, there is evidence that the UV continuum is rather purely dominated by scattered light (Antonucci, Hurt, & Miller 1994; Tran 1995), and nuclear scatterers are thought to be electrons. In this case, since the morphology of the scattering region is resolved to be quite clumpy, we can actually estimate the viewing angle of each resolved clump from its observed UV polarization, and construct a 3D structure map of the 100 pc scale region (Kishimoto 1999).

### 3. Unresolved nucleus: \(~0.001\) pc scale

#### 3.1. The Balmer edge observed

The central engine can't be spatially resolved yet, but polarimetry may provide a very important clue to its understanding. It has been well known that many normal quasars (luminous type 1s) have 1% level polarization (e.g. Stockman et al. 1984; Berriman et al. 1990). At least in some cases with spectropolarimetry data of a limited S/N, this polarization has been shown to be confined to continuum and not shared by emission from the BLR (Antonucci 1988, showing the data of Miller and Goodrich; Schmidt & Smith 2000). Our new data with a higher S/N now give a much tighter limit on unpolarized broad lines. Fig.1 shows our 5 best objects taken with the Keck and VLT. Each panel shows the polarized flux, with the dotted line being the total flux scaled to match the polarized flux.

\(^1\)The NLR low polarization can also be affected by the transmission through aligned dust grains in the host galaxy (e.g. Goodrich 1992). At least for NGC1068, however, the scattering origin seems to be favored by the HST optical imaging polarimetry data (Capetti et al. 1995a).
at the red side. In the polarized flux, there is almost nothing in the broad line wavelengths.

However, more importantly, the polarized flux shows definitely a spectral feature in the Balmer edge wavelengths: in the wavelengths longer than $\sim 4000\,\AA$, the shape of the polarized flux is the same as that of the total flux continuum, but it turns over at $\sim 4000\,\AA$, and then turns up below $\sim 3600\,\AA$ (thus, the polarized flux has a local maximum at $\sim 4000\,\AA$ and a local minimum at $\sim 3600\,\AA$). This seems to be a Balmer edge feature seen in absorption. In fact, this is actually what our observations were aiming for, as we explain below.

### 3.2. De-contaminating the spectra

It is well known that the continuum emission from the central engine does not seem to show a Lyman edge in general (e.g. Antonucci, Kinney, & Ford 1989; Koratkar, Kinney, & Bohlin 1992). The UV/optical continuum is usually thought to be from an accretion disk around the central supermassive black hole, and naively we should see a Lyman edge feature, as many disk atmosphere models predict. In some individual cases and composites (e.g. Kriss et al. 1999; Zheng et al. 1997), there seems to be a slope change near the Lyman edge wavelength, but the theoretical predictions are still not in a good agreement with these observations (Blaes et al. 2001). This apparent lack of the expected Lyman edge has been one of the major difficulties in understanding the UV/optical continuum: this component is energetically the most dominant, thus crucial to understand.

One reason for the apparent lack could be that the Lyman edge is relativistically smeared, since it is thought to originate from the inner region of the disk. Lyman foreground absorption also complicates/confuses the spectral region. On the other hand, the Balmer edge is better in these two respects, since it would originate farther out in radius and it is not a resonant feature; the only problem is that the emission from the BLR heavily contaminates this spectral region.

Our idea is to use the polarized flux to remove this contamination. It is simply based on the empirical fact that the polarization is confined to the continuum and the emission from the BLR isn’t polarized. Our interpretation here is that the polarization is probably due to electron scattering interior to the BLR$^2$. If the scattering region scale is much larger than the BLR, then we would clearly see the broad lines polarized in the same way as the continuum, just like the broad lines in type 2s.

Therefore, in the objects shown in Fig.1 and possibly in many other quasars, the polarized flux is likely to originate interior to the BLR. Then, by studying the polarized flux, we would be able to effectively scrape off the contamination from the BLR and investigate the BLR-emission-free continuum shape. If this simple interpretation is correct, the observed Balmer edge feature is attributed to be intrinsic to the continuum emitter (the feature might be simply copied by scattering, or polarization itself might be intrinsic to the emitter, e.g. disk atmosphere), indicating that the emission is indeed thermal and the emitter is

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$^2$We discuss and disfavor the synchrotron possibility in Kishimoto et al. (2003). Scattering is supposed to be by electrons and not by dust since it is within the dust sublimation radius.
optically thick. In addition, this opens up a totally new way to look at the physical state of the accretion flow.

3.3. Puzzles left

However, we still cannot rule out the case where the Balmer edge absorption signature is imprinted by the scatterers themselves (“scatterer/absorber” case). In fact, this is thought to be the case in the circumstellar disks of Be stars (J. Bjorkman, K. Bjorkman in these proceedings). However, the fact that essentially no feature (either in emission or absorption) is seen in the broad line wavelengths seems to be against any simple scatterer/absorber models. In addition, the observed edge feature looks quite broadened, and this might require quite specific conditions including a high velocity dispersion. Whatever is producing the feature might thus be considered as a part of the continuum emitter. A detailed disk atmosphere model incorporating the Balmer lines and metal lines is now being developed.

Many Seyfert 1 galaxies show broad lines which are polarized differently from the continuum (J. Smith in these proceedings). In this case, the spatial scale of the scattering region is thought to be comparable to that of the BLR. These Seyfert galaxies are quite different in optical luminosity and radio loudness from the objects in Fig. which are all radio-loud quasars. We note, however, that luminous radio-loud type 1 object such as 3C382 also show polarized broad lines like Seyfert 1s. Therefore, the distinction is not yet clear.

Finally, we note that there seems to be more spectral features in the shorter wavelength region of the polarized flux, though they are less clear: a local peak at \( \sim 3050\AA \) and/or absorption feature shortward of \( \sim 3050\AA \), and at \( \sim 2600\AA \). Those are clearer in the composite spectrum which is constructed from the average of the 5 objects with equal weighting (see Fig. and its caption). The interpretation isn’t clear yet, but they might be related to FeII absorption.

4. Conclusion

Polarimetry has played a key role in understanding AGN. This has been intensively done for type 2 objects, while polarization of type 1 objects is still under-exploited and has a potential to yield a very new insight. The Balmer edge feature observed and presented here is entirely a new finding, and we definitely need a much larger sample to investigate this further.

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Figure 1. Our spectropolarimetric data for five quasars taken with the Keck and VLT (from Kishimoto et al. 2004). Flux has been corrected for Galactic reddening. The wavelengths shown are all in the rest frame. Note that the data for all the objects except Ton 202 and B2 1208+32 have been corrected for the interstellar polarization in our Galaxy. Left—The solid line represents the polarized flux, and the dotted line is the total flux scaled to roughly match at the red side. Top-right—In the upper panel, the five polarized flux spectra, normalized by the mean at 2800-5000Å, are over-plotted with a larger wavelength bin (20Å). In the lower panel the average of these five spectra with equal weighting is shown. Both panels are in $F_\lambda$. Bottom-right—The same as top-right but in $\nu F_\nu$ with both axes in log scale.