The spectral variability of UV-optical continuum emission of Active Galactic Nuclei

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Abstract

We examine whether the spectral shape of UV-optical continuum emission of AGNs changes during flux variation. The long-term optical monitoring observations of 11 nearby Seyfert galaxies and QSOs were carried out by the MAGNUM telescope. We found that the multi-epoch flux data in any two different bands obtained on the same night showed a tight linear flux-to-flux relationship, and the non-variable component of the host galaxy plus narrow emission lines was located on the fainter extension of the best-fit linear regression. The UV spectral variability was examined based on the multi-epoch photometric data of 10 luminous QSOs at $z = 1.0 - 2.4$ in the Stripe 82 observed by the SDSS Legacy Survey. We found that the rest-frame UV flux data in two different bands showed a linear relationship, but in contrast to the optical, the host galaxy flux was not located on the fainter extension of the best-fit linear regression for most targets: The host galaxy flux in longer wavelength was systematically smaller than that of the linear regression line at the same flux level in shorter wavelength. These results indicate that the spectral shape of continuum emission remains almost constant during flux variation in optical ($\lambda = 0.44 - 0.79$ μm), whereas it becomes bluer as it is brighter in UV ($\lambda = 0.14 - 0.36$ μm). This spectral variability of UV-optical continuum emission can be interpreted by the standard accretion disk model changing the mass accretion rate with a constant black hole mass, which strongly supports the standard accretion disk model for UV-optical continuum emission of AGNs (Sakata et al. 2010, ApJ, 711, 461; Sakata et al. 2011, ApJ, 731, 50).

Key words: AGN: accretion disk — AGN: variability — AGN: optical, UV

1. Introduction

It is generally accepted that a supermassive black hole is located in the center of Active Galactic Nuclei (AGNs) and that the gravitational energy released by the mass accretion onto the black hole is converted into the vast amount of UV-optical continuum emission from the accretion disk surrounding the black hole. Flux variation of AGNs in different wavelengths has been observed for many years, and studying the flux variation is considered to be a powerful tool for understanding the structure and emission mechanism of AGNs. However, the mechanism of the variability of the UV-optical continuum emission from the accretion disk is still uncertain. Many models have been proposed, but none of them successfully explained more than a few properties of UV-optical variability.

The spectral variability of the UV-optical continuum emission during flux variation is one of key properties for understanding the accretion disk and the variability mechanisms in AGNs. For example, the spectral shape of the UV-optical continuum emission is expected to vary with flux variation when the flux variation is caused by a hot spot or a local flare in the accretion disk, because the spectral energy distribution of the local flares would be different from that of the entire disk. On the other hand, if the spectral shape of the continuum emission remains constant during flux variation, a mechanism that holds the temperature structure of the accretion disk unchanged is suggested.

However, there have been two opposing observational claims for the spectral variability of the UV-optical continuum emission: spectral hardening, in which the UV-optical continuum emission becomes bluer as it becomes brighter, and a constant spectral shape during flux variation. Many observation showed that the color of an AGN became bluer as it became brighter for a number of AGNs, and Giveon et al. (1999) and Webb & Malkan

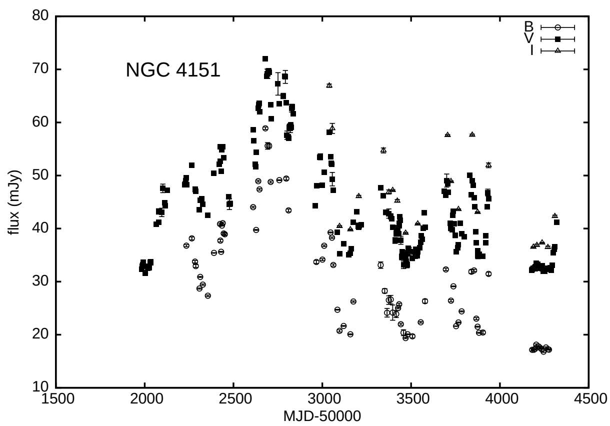

Fig. 1. The multi-waveband light curves of NGC 4151 obtained by the MAGNUM telescope. The open circles, the filled squares, and the open triangles represent the B-band, V-band, and I-band fluxes, respectively.

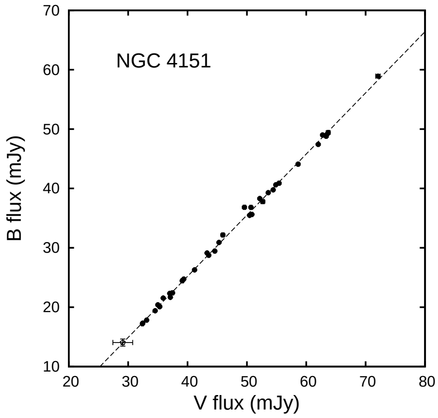

Fig. 2. The flux-to-flux plots in two different bands for NGC 4151. The filled circles represent the flux data in two different bands obtained on the same night, the open pentagon represents the sum of the host-galaxy flux and the narrow-line flux, and the dashed line represents the best-fit linear regression line for the flux data points.

(2000) concluded that the continuum emission from the accretion disk in optical wavelengths becomes bluer as it becomes brighter. However, Winkler (1997) found a linear flux-to-flux relationship between any two different bands obtained on the same night for each AGN, and interpreted the linear relationship as indicating the constant spectral shape of the continuum emission during flux variation.

When observing AGNs in UV-optical wavelengths, many components other than the continuum emission from the accretion disk such as starlight from the host galaxy always contaminate the observed flux, and therefore, it is important to estimate their fluxes to examine the spectral variability of the UV-optical continuum emission. For example, since the host-galaxy color is usually redder than that of the UV-optical continuum emission, the observing color of their combined flux would become bluer as it becomes brigher, even if the spectral shape of the UV-optical continuum emission remains constant. However, the contamination of the host galaxy in the observing flux has been considered less emphasized in most studies, and sometimes ignored or just assumed.

In this study, we focused on the spectral variability of the UV-optical continuum emission of AGNs during flux variation to obtain implications to the emission and variability mechanisms of the accretion disk. To achieve such purposes, we carefully estimate the fluxes of components other than the UV-optical continuum emission such as starlight from the host galaxy, and examine the correlation between fluxes in different wavebands obtained from the long-term multicolor monitoring obseravation of AGNs in UV and optical wavelengths.

2. Long-term optical spectral variability of nearby AGNs

First, we examined the long-term spectral variability of the optical continuum emission of nearby AGNs, based on accurate and frequent monitoring observations of 9 nearby Seyfert galaxies and 2 nearby QSOs carried out in B, V, and I bands ($\lambda = 4400$, 5500, 7900 Å) for seven years by the MAGNUM telescope. The targets were selected for which the high-resolution HST images were available, and the photometric bands were selected to avoid contamination of bright broad emission lines. The multi-epoch flux data in any two different bands obtained on the same night showed a very tight linear flux-to-flux relationship for all the target nearby AGNs. The flux of the host galaxy within the photometric aperture was carefully estimated by surface brightness fitting to available highresolution HST images and MAGNUM images. The flux of the narrow emission lines in the photometric bands was also estimated from available spectroscopic data. We present examples of the multi-waveband light curves and the flux-to-flux plots for NGC 4151 in Figures 1 and 2.

We found that the non-variable component of the host galaxy plus the narrow emission lines was located on the fainter extension of the best-fit linear regression line of the multi-epoch flux data in the flux-to-flux diagram for all the target nearby AGNs. These results indicate that the spectral shape of the optical continuum emission of AGNs does not systematically change during flux variation. Careful extraction of the AGN continuum also revealed that all AGNs showed significant flux variability, and some Seyfert galaxies showed optical flux variation by more than 10 times.

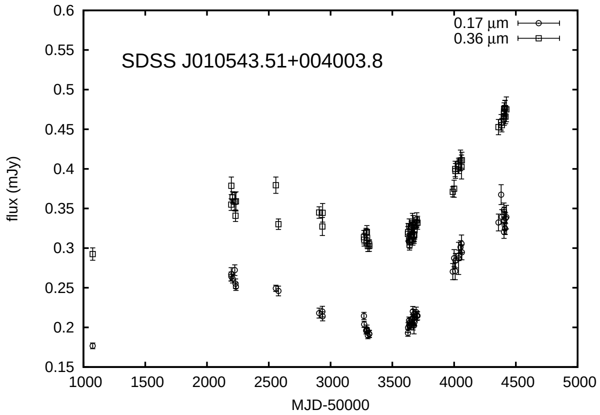

Fig. 3. The UV lightcurves of SDSS J010543.51+004003.8. The open circles represent the flux in the rest-frame wavelength of $\lambda = 0.17$ μm, and the open squares represent the flux in the rest-frame wavelength of $\lambda = 0.36$ μm.

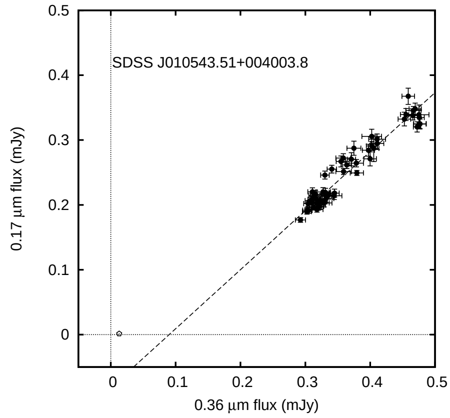

Fig. 4. The flux-to-flux plots in two different bands for SDSS J010543.51+004003.8. The filled circles represent the flux data in two different bands obtained on the same night, the open pentagon represents the sum of the host-galaxy flux, and the dashed line represents the best-fit linear regression line for the flux data points.

3. Long-term UV spectral variability of Luminous QSOs

Next, we examined the long-term spectral variability of the UV continuum emission of luminous QSOs, based on multi-epoch photometric data of QSOs in Stripe 82 observed by the Sloan Digital Sky Survey (SDSS) Legacy Survey. We selected 10 bright QSOs observed with high photometric accuracies, in the redshift range of $z = 1.05$, 1.54, 1.71, 2.35 ± 0.05 where the effective wavelength of the SDSS filters in the rest frame come in the UV region, avoiding bright broad emission lines. The multi-epoch flux data in two different bands (shorter-$\lambda_{\rm rest} \sim 1400$ or $\sim$1730 Åand longer-$\lambda_{\rm rest} \sim 2200 - 3600$ Å) obtained on the same night showed a linear flux-to-flux relationship for all the target SDSS QSOs. The host-galaxy flux was estimated based on the correlation between the stellar mass of the bulge of the host galaxy and the central black hole mass assuming the mass-to-luminosity ratio and the spectrum of the host galaxy. We present examples of the multi-waveband light curves and the flux-to-flux plots for SDSS J010543.51+004003.8 in Figures 3 and 4.

We found that the host galaxy flux of 9 of the 10 target SDSS QSOs was located differently from the fainter extension of the best-fit regression line of the multi-epoch flux data in the flux-to-flux diagram, indicating the spectral hardening of the UV continuum emission of luminous QSOs, in which it becomes bluer as it becomes brighter.

4. Discussion

4.1. Comparison with previous observations

Giveon et al. (1999) and Webb & Malkan (2000) are the two leading studies that claimed spectral hardening of intrinsic emission from AGNs in optical wavelengths, which is in opposite to our conclusion. Defining the spectral variability as the spectral-index variation per 1-magnitude flux variation, the spectral variabilities estimated by these studies are really larger than that of our study.

However, we estimate the spectral variability as $\Delta\alpha/\Delta m = -0.128^{+0.147}_{-0.137}$ for one common target with Giveon et al. (1999), PG 0844+349, which is consistent with zero and significantly smaller than the average optical spectral variability of PG quasars by Giveon et al. (1999). In addition, the host-galaxy fluxes we estimated with improved accuracy as described in Section 2 are significantly larger than those estimated by Webb & Malkan (2000) for common four targets, whose spectral variabilities estimated by our study are consistent with zero. From these considerations, the trend of spectral hardening for the optical continuum emission of nearby Seyfert galaxies and QSOs reported by Giveon et al. (1999) and Webb & Malkan (2000) is interpreted as the domination of the bluer optical continuum emission of the nearly constant spectral shape of an AGN as it brightens over the host galaxy.

Vanden Berk et al. (2004) statistically examined the properties of flux variations of QSOs from the two-epoch photometric observations of $\sim$ 25000 QSOs obtained by SDSS, and found the larger amplitude of variation at shorter wavelength in the UV region of $\lambda < 4000$ Å. Their result is consistent with ours that shows the hardening trend of spectral variability in UV wavelengths.

Assuming that the wavelength-dependent amplitude of variation always holds for the flux variation at all time for individual QSOs, a power-law function of $F_{\nu1} = \alpha \times F_{\nu2}^{\beta}$ in a flux-to-flux plot is obtained, where β is the ratio of the amplitude of variation in two different wavelengths. Then, we fit the power-law function, $F_{\nu1} = \alpha \times F_{\nu2}^{\beta}$ to the flux-to-flux plot data of the target SDSS QSOs, fixing the paramerter β as $\beta = v(\lambda1)/v(\lambda2)$

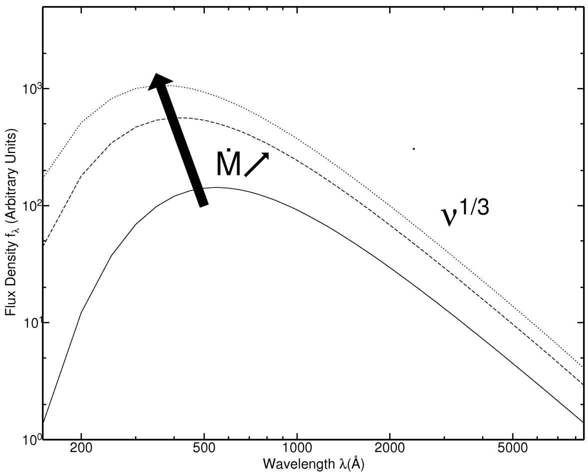

Fig. 5. The flux density spectrum of the standard accretion disk model dependent on the mass accretion rate. The mass of the black hole is fixed at 10^8 $M_\odot$. The inner and outer disk radii, R_{in} and R_{out}, are set at $3R_S$ and $1000R_S$, respectively, where R_S is the Schwarzschild radius of the black hole. Thick line, dashed line, and dotted line represent the flux density of the disk at various mass accretion rates corresponding to the Eddington ratios of 0.1, 0.3, and 0.5, respectively.

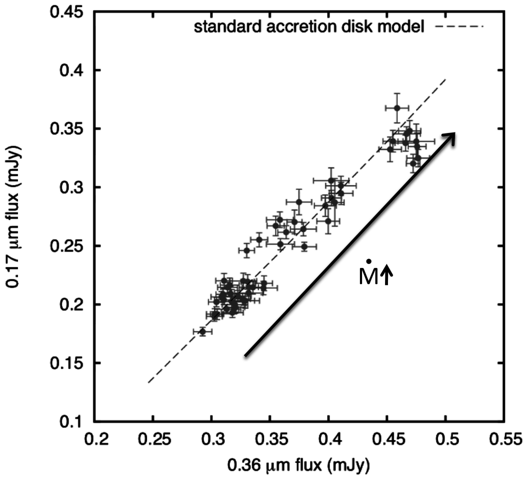

Fig. 6. The flux-to-flux plots in two different bands for SDSS J010543.51+004003.8 and the model fitting for flux variation. The filled circles represent the flux data in two different bands obtained on the same night, and the dashed line represents the track of the best-fit model of the standard accretion disk changing the mass-accretion rate with a constant black hole mass.

as presented in the Equation 11 of Vanden Berk et al. (2004), where $\lambda 1$ and $\lambda 2$ are the effective wavelengths of the observing filters in the rest frame. The reduced χ^2 value of the power-law fit is as small as that of the straight-line fit for most of the target SDSS QSOs in Stripe 82, which means that the multi-epoch UV flux data in the flux-to-flux diagram are consistent with the wavelength-dependent amplitude of variation presented by Vanden Berk et al. (2004).

4.2. Possible mechanisms for long-term AGN flux variability in UV-optical wavelengths

We examined possible models for long-term flux variation that can explain the spectral variability of the UV-optical continuum emission of AGNs. The nearly constant spectral shape of the optical continuum emission would rule out some model of local flares or fluctuations as the main source of the long-term flux variation. Although an X-ray reprocessing model might explain the spectral variability of the UV-optical continuum emission in a limited parameter range, the model would be difficult to explain the large variability amplitude of the UVoptical continuum emission at long timescales, because the X-ray luminosity is typically smaller than the UV-optical luminosity by about on order.

Here, we examine an phenomenological model, the standard accretion disk model with changing the global mass accretion rate. According to the model, the spectral variabilitiy of the optical continuum emission of AGNs is expected to be small, which is consistent with our results on that for the target nearby AGNs. The spectral index of the optical continuum emission predicted by the model is also consistent with those taken from the observations. On the other hand, the significant amount of spectral variability in the UV continuum emission is expected for luminous QSOs hosting large black hole by the model. We present a schematic figure of the spectral energy distribution of the standard accretion disk model dependent on the mass accretion rate in Figure 5.

Then, we found that we could fit the model well to the multi-epoch UV flux data of the target SDSS QSOs in Stripe 82 in the flux-to-flux diagram. We present an example of the flux-to-flux plots and the model fitting for SDSS J010543.51+004003.8 in Figure 6. These results strongly support the standard accretion disk for the central engine of AGNs, and also indicate that the variation of the global mass accretion rate could be a promising mechanism for explaining the long-term flux variation of UV-optical continuum emission of AGNs and its spectral variability.

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