MULTIPLE REGRESSION ANALYSIS OF THE VARIABLE COMPONENT IN THE NEAR-INFRARED REGION FOR TYPE 1 AGN MCG +08-11-011

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ABSTRACT

We propose a new method of analyzing a variable component for type 1 active galactic nuclei (AGNs) in the near-infrared wavelength region. This analysis uses a multiple regression technique and divides the variable component into two components originating in the accretion disk at the center of an AGN and from the dust torus that far surrounds the disk. Applying this analysis to the long-term VHK monitoring data of MCG +08-11-011 that were obtained by the MAGNUM project, we found that the (H − K) color temperature of the dust component is $T = 1635 \pm 20$ K, which agrees with the sublimation temperature of dust grains, and that the time delay of $K$ to $H$ variations is $\Delta t \approx 6$ days, which indicates the existence of a radial temperature gradient in the dust torus. As for the disk component, we found that the power-law spectrum of $f_\nu \propto \nu^{-a}$ in the $V$ to near-infrared $HK$ bands varies with a fixed index of $a \approx -0.1$ to $+0.4$, which is broadly consistent with the irradiated standard disk model. The outer part of the disk therefore extends out to a radial distance where the temperature decreases to radiate the light in the near-infrared.

Subject headings: accretion, accretion disks — dust, extinction — galaxies: active — galaxies: individual (MCG +08-11-011)

1. INTRODUCTION

The existence of massive black holes at the centers of accretion disks in AGNs is well accepted in current AGN research. The so-called big blue bump, which is observed in the UV to optical wavelength region of the spectral energy distribution (SED) of many AGNs, is regarded as an evidence of the accretion disk (e.g., Shields 1978; Malkan & Sargent 1982; Czerny & Elvis 1987). Based on another distinct feature of near-infrared bumps in their SED, the existence of a surrounding dust torus, which is heated to the sublimation temperature of dust by the accretion disk, is also accepted now (e.g., Sanders et al. 1989; Barvainis 1987; Kobayashi et al. 1993).

In practice, however, it is known that composite SEDs constructed from a huge number of AGNs obtained by large surveys show their optical colors to be significantly redder than predicted by the standard accretion disk model (see Francis et al. [1991] for the composite SED from the Large Bright Quasar Survey; Vanden Berk et al. [2001] for the composite SED from the Sloan Digital Sky Survey). Since AGNs are superimposed on host galaxies, how serious this discrepancy depends on how reliably the nuclear SED has been separated from the SED of the galaxy component.

In addition to the problem of SED decomposition, a possible contamination of near-infrared light from the accretion disk and dust torus further complicates the interpretation of the SED. In fact, it is reported that the SED of the accretion disk extends to the near-infrared wavelength region (Kishimoto et al. 2005; Minezaki et al. 2006) and that the temperature gradient exists in the dust torus of which the inner part is hotter than the outer part (e.g., Barvainis 1987; Glass 1992; Alloin et al. 1995). These two factors cause similar effects such that variations at shorter near-infrared wavelengths are less delayed behind the optical variations, when compared to variations at longer near-infrared wavelengths. Therefore, unless the above factors are taken into account simultaneously in the analysis, the time delay of near-infrared variations behind the optical is liable to be underestimated.

In order to overcome such complications as well as the problem of SED decomposition, we propose a new method of analyzing the variable SEDs of accretion disks and dust tori, based on a multiple regression technique. In § 2, we describe the assumptions and methods of the analysis. In § 3, we apply the analysis to the long-term VHK monitoring data of MCG +08-11-011 obtained by the MAGNUM project (Yoshii 2002; Kobayashi et al. 2003; Yoshii et al. 2003). Finally, in § 4, we describe the applicability of the analysis and discuss the results.

2. MULTIPLE REGRESSION ANALYSIS

2.1. Overview of the Analysis

Let $F_\lambda(t)$ be the observed flux at wavelength $\lambda$ and time $t$; then it is decomposed as

$$F_\lambda(t) = F_{\lambda, \mathrm{disk}}^{\mathrm{var}}(t) + F_{\lambda, \mathrm{dust}}^{\mathrm{var}}(t) + F_{\lambda, \mathrm{const}}^{\mathrm{const}},$$  \hspace{1cm} (1)

where the first two are the variable components from the accretion disk and dust torus, respectively, and the last component is a constant, partly offset including the contribution from the host galaxy.

Kobayashi et al. (1993) showed that all 14 QSOs in their sample have almost the same blackbody spectra of 1500 K. This indicates that the flux in the near-infrared wavelength region is mainly radiated from the innermost part of the dust torus, where the temperature is near the sublimation temper-
nature of dust grains. Hence, as we observe for each AGN, the near-infrared light curves in different bands have almost the same shape and overlap each other by shifting the lag time between the variations in different bands (e.g., Suganuma et al. 2006). When there is a short lag time of \( \tau \) between variations in two near-infrared bands, \( H(1.7 \text{ \mu m}) \) and \( K(2.2 \text{ \mu m}) \), for example, which are intrinsic to the dust torus, the situation considered here corresponds to

\[
F_{H_{\text{var,disk}}}(t - \tau)/F_{H}(t) = a. \tag{2}
\]

Winkler et al. (1992) and Winkler (1997) claimed that the optical colors of the variable component for Seyfert galaxies remain constant as their brightness changes, while recent studies report that QSOs get bluer as they get brighter (e.g., Trevese & Vagnetti 2002; Giveon et al. 1999). For our analysis focusing on Seyfert galaxies below, we then assume that the variable component synchronized with optical variation, which comes from the accretion disk, has constant optical \( V(0.55 \text{ \mu m}) \) to near-infrared \( H \) and \( K \) colors, i.e.,

\[
F_{V_{\text{var,disk}}}(t)/F_{V}(t) = b, \quad F_{K_{\text{var,disk}}}(t)/F_{K}(t) = c. \tag{3}
\]

Substitution of equations (2) and (3) in equation (1) therefore gives

\[
F_{B}(t - \tau) - bF_{V}(t - \tau) = a[F_{K}(t) - cF_{V}(t)] + d, \tag{4}
\]

where \( a, b, c, \) and \( d \) are the constant parameters to be determined by the fit to the \( VHK \) monitoring data, based on a multiple regression technique described below.

### 2.2. Details of Calculation

For calculation of the multiple regression, Jefferys (1980) provides the most generalized multivariate least-squares process. This process allows errors to appear in all variables, which is desirable for astronomical observations. In practice, we adopted the Marquardt method described in Jefferys (1981), which is robust for the case that the initial trial for the fit is far from the true solution.

The calculation of the regression with a given value of lag time \( \tau \) requires interpolation of the monitoring data in time, because such data are usually discrete. We here adopt the linear interpolation scheme, and smaller weights are assigned to the data produced with large interpolation. We estimate the uncertainties of the interpolation, using the structure function (SF) of AGN variabilities (Collier & Peterson 2001; Suganuma et al. 2004):

\[
\sigma_{\text{SF}} = \text{SF}(l) = \frac{1}{N(l)} \sum_{i,j} [f(t_i) - f(t_j)]^2 - 2\sigma^2, \tag{5}
\]

where the summation runs over all \((i,j)\)-pairs, \( l = t_i - t_j \) is the length of interpolation, \( N(l) \) is the number of pairs at \( l, f(t) \) is the flux at time \( t, \) and \( \sigma \) is the mean observational error for the data used for the SF calculation. We adopted a length nearer to the neighboring data point as the length of interpolation \( l. \)

While we naturally use the observational error as the weight for the data with no interpolation, we adopt the larger of the SF error or the observational error as representing the uncertainty of the interpolated data in the regression analysis. In order to determine whether or not the fit well represents the observations, the \( \chi^2 \)-test is performed. The \( \chi^2 \)-value is computed by doubling equation (8) of Jefferys (1980), and this doubled value follows the \( \chi^2 \) distribution of \( N = m - 4 \) degrees of freedom, where \( m \) is the number of data sets.

Finally, the value of lag time \( \tau \) that gives the best fit is estimated at the peak of the multiple correlation coefficient that measures the strength of association between the independent and dependent variables.

### 3. Application of the Analysis

The \( BVHK \) monitoring data for MCG +08-11-011 were obtained by the MAGNUM project in the period from 2001 September 8 to 2002 December 31 (Fig. 1). Aperture photometry was used throughout. An aperture size of 8.3′′ was adopted for all images. The flux of MCG +08-11-011 was measured relative to a reference star (\( \alpha_{2000} = 05^h 54^m 47.9^s, \delta_{2000} = +46°23′5′′ \)) whose flux was absolutely calibrated using Landolt standard stars (Landolt 1992) in \( BV \) and Hunt standard stars (Hunt et al. 1997) in \( HK \) during the monitoring observations. The host galaxy flux was estimated using the GALFIT program (Peng et al. 2002) and was subtracted from the measured flux of MCG +08-11-011. The estimated magnitudes of the host galaxy were 16.5 mag at \( B, \)
15.5 mag at \( V \), 12.0 mag at \( H \), and 11.5 mag at \( K \). A small error of 0.003 mag caused by the seeing effect, arising from the profile difference between the AGN and the reference star, was taken into account. Galactic extinction was corrected according to Schlegel et al. (1998).

We performed the regression analysis comparing the observed \( H \)-band light curve with the predicted \( H \)-band light curve in equation (4). We adopted only the data set where observations in \( V \), \( H \), and \( K \) were carried out on the same night in order to decrease the effect of interpolation. The parameters used for \( SF(l) = S_0 l^n \) were \( S_0 = 0.033 \) mJy and \( \beta = 1.1 \) for \( V \), and \( S_0 = 0.0077 \) mJy and \( \beta = 2.0 \) for \( K \). Zero correlation was assumed between the data in any two bands, and the standard error was used for the error of the fitted parameters.

We carried out the regression analysis for a range of \( \tau \) from -10 to 60 days. The value of the multiple correlation coefficient was calculated as a function of \( \tau \), and its peak was found to occur at \( \tau = 6.0 \) days with the \( \chi^2 \)-value of 12.5 for \( m = 26 \) (Fig. 2). The reduced \( \chi^2 \)-value becomes \( \approx 0.5 \), which indicates that the fit is good enough to represent the observations. The regression at \( \tau = 6.0 \) days yielded that the \(( H - K )\) color temperature for the dust component is 1635 ± 20 K, and the index of power-law SED for the accretion disk component \(( f \propto \nu^\alpha )\) is \( \alpha = +0.36^{+0.34}_{-0.23} \) from \( V \) to \( H \) and \( \alpha = -0.06^{+0.35}_{-0.24} \) from \( V \) to \( K \).

4. DISCUSSION

The \(( H - K )\) color temperature of 1635 K here derived for MCG +08-11-011 agrees well with the sublimation temperature of 1500–1800 K for graphite/silicate grains (Salpeter 1977; Huffman 1977). Hence, this component represents the innermost part of the dust torus heated to the sublimation temperature by the accretion disk.

Following Winkler et al. (1992), we performed the flux variation gradient (FVG) analysis for the \( BV\) monitoring data (Fig. 3). We converted the FVG \(( B - V )\) color to the index of the power-law SED and obtained \( \alpha = +0.21 \pm 0.1 \). Combining this and the results in § 3 from the regression analysis, we found that the power-law SED with \( \alpha = -0.1 \sim +0.4 \) prevails in the optical to near-infrared wavelength region (Fig. 4).

For comparison, we computed theoretical colors of the standard accretion disk model (Shakura & Sunyaev 1973) with a black hole mass of \( M = 10^7 M_\odot \) and an outer disk radius of \( R = 10^4 R_\odot \), where \( R_\odot = G M/\sigma^2 \). Figure 4 shows \( \alpha \) as a function of frequency \( \nu \) for two cases of accretion rate \( \dot{M} = 0.1 M_\odot \) yr\(^{-1}\) (upper thick line) and 0.001 \( M_\odot \) yr\(^{-1}\) (lower thick line). These predicted SEDs have an approximate value of \( \alpha = \frac{1}{2} \) and agree with our finding of \( \alpha = -0.1 \sim +0.4 \) for MCG +08-11-011.

The standard disk model has a critical difficulty for explaining the variability. Although many UV/optical monitoring observations have so far been made, all of them have failed to detect significant lags between UV and optical variations, except for NGC 7469 (Peterson et al. 1998; Wanders et al. 1997; Collier et al. 1998) and Ark 564 (Collier et al. 2001). The expected lag time is too short for the energy to flow at sound speed within the standard viscous disk. However, such a lag time is sufficient for the incident radiation to transfer the energy to any distant parts of the disk (Krolik et al. 1991). Hence, the irradiated accretion disk model has been invoked, where the central X-ray energy source illuminates a geometrically thin disk, and UV/optical light is radiated at the outer part of the disk. The predicted spectrum of the irradiated standard disk model has an index of \( \alpha = \frac{1}{2} \) at the radii where the height of

Fig. 3.—\( B \)-flux to \( V \)-flux diagram for MCG +08-11-011. The straight line is the least-squares fit to the data.

Fig. 4.—Values of power index \( \alpha \) plotted against the rest-frame frequency of radiation. Filled circles are our results for MCG +08-11-011 from the data of \( BV \), \( VH \), and \( VK \). Vertical bars indicate the estimated error of \( \alpha \), and horizontal bars correspond to the wavelength range between two bands used for the calculation of \( \alpha \). For reference, open circles show the values of \( \alpha \) for other AGNs by Winkler et al. (1992), and the two thick lines show the predictions of two standard accretion disk models. See text for details.

Fig. 5.—Fractional contribution of near-infrared flux from the accretion disk component throughout the monitoring observations of MCG +08-11-011. Shown are the values of \( F_{\nu}^\text{in} \propto \nu^\alpha \phi_{\nu}(\tau) \) for the \( H \) band (open squares) and for the \( K \) band (filled squares).
the X-ray source is negligible compared to the radial distance from the center. This spectrum is exactly the same as that of the standard viscous disk model. Furthermore, the detected wavelength-dependent lag time agrees with $r \propto \lambda^{0.7}$ in the UV to optical region for NGC 7469 and Ark 564, which is the same as the prediction for the irradiated standard disk model (Collier et al. 1998, 2001). Consequently, we conclude that the power-law SED obtained by our analysis reinforces evidence that irradiated standard disks exist in the centers of AGNs.

Our analysis showed that the power-law SED extends to the near-infrared wavelength region. By the standard accretion disk model, the near-infrared $K$-emitting region in the disk is located at a radial distance of $R \approx 10^3 R_g$, from the center of a typical Seyfert galaxy, which is close to the inner part of the broad-line region (BLR) where high-ionization lines originate. Collin & Hure (2001) showed that the disk would become gravitationally unstable at $R > R_{\text{crit}} \approx 2 \times 10^3 R_g (M/10^7 M_\odot)^{-0.46}$. Based on this estimation, the $K$-emitting region in the disk could be gravitationally stable, and the existence of such a stable extended disk could distort the Kepler motion of BLR gas clouds. This may explain the significant scatter of observed virial relationships of AGNs with high Eddington ratio, the $K$-emitting region in the disk would be farther away from the centers of AGNs, and the outer disk edges might be observable (Collin et al. 2002; Kawaguchi 2003; Kawaguchi et al. 2004).

The accretion disk component contributes to the near-infrared flux by 15%–30% in the $H$ band and by 15%–25% in the $K$ band (Fig. 5). Since the observational errors are of order 1% only, these disk contributions are significant and cannot be ignored in deriving accurate and reliable results from near-infrared observations of AGNs. For a long time, however, separation of accretion disk components in the near-infrared region has been considered difficult, because the thermal emission from the dust torus component is the dominant source there. In this context, the multiple regression analysis for multicolor monitoring observations is indeed a promising method for extracting the accretion disk component from near-infrared data and will be useful for investigating the physical conditions and emission mechanisms of both components of accretion disk and dust torus simultaneously.

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