Near-Infrared Intraday Variations in AGNs

Takeo Minezaki,[1] Yuzuru Yoshii,[1,2] Yukiyasu Kobayashi,[3]
Keigo Enya[4], Masahiro Suganuma[3], Hiroyuki Tomita[1], Shintaro Koshida[5],
Masahiro Yamauchi[5], Yu Sakata[5], Shota Sugawara[5], and Tsutomu Aoki[6]

[1] Institute of Astronomy, School of Science, University of Tokyo
[2] Research Center for the Early Universe, School of Science, University of Tokyo
[3] National Astronomical Observatory, Japan
[4] Institite of Space and Astronautical Science, Japan Aerospace Exploration Agency
[5] Department of Astronomy, School of Science, University of Tokyo
[6] Kiso Observatory, Institute of Astronomy, School of Science, University of Tokyo
E-mail(TM): minezaki@ioa.s.u-tokyo.ac.jp

Abstract

We carried out a one-night optical V and near-infrared JHK monitoring observation of the least luminous Seyfert 1 galaxy, NGC 4395, on 2004 May 1, and detected intraday flux variations in the V, J, and H bands. The near-infrared flux variations are almost synchronized with the flux variation in the V band. This indicates that the intraday-variable component of near-infrared continuum emission of the NGC 4395 nucleus is an extension of UV-optical power-law continuum emission and originates in an outer region of the central accretion disk. In addition, a possible time lag of ~ 7 minutes between the V-band and infrared flux variations was found by cross-correlation analysis. These results can be explained by the X-ray reprocessing model, in which X-ray flux variation propagates with light velocity and drives the flux variations in optical and near-infrared wavelengths.

We also carried out the most intense monitoring observations in the optical and near-infrared wavebands for a Seyfert 1 galaxy, NGC 5548, and examined the correlation between the X-ray and optical flux variations. The X-ray light curve was taken from Uttley et al. (2003) as observed by the Rossi X-ray Timing Explorer (RXTE). The V-band flux variation shows a clear lag of $1-2$ days behind the X-ray flux variation, which supports the X-ray reprocessing model for the optical flux variation at short timescales.

Key words: AGN: time variation — AGN : multiwavelength (X-ray, optical, and near-infrared)

1. Introduction

It is generally accepted that the continuum emission of type 1 active galactic nuclei (AGNs) in UV and optical wavebands originates in the optically thick accretion disk, and the X-ray emission originates in the optically thin hot corona in the central part of the accretion disk, respectively. Studying the relationship between flux variations in UV/optical and X-ray wavebands can provide important clues about the connection between the disk and coronal emission and the mechanisms of flux variations in those wavebands. For example, it has been proposed that the UV/optical flux variation originates in the thermal reprocessing of X-ray variability by the accretion disk (Krolik et al. 1991). In this scheme, the UV/optical flux variation should lag behind the X-ray flux variation, which explains why the UV-optical continuum emissions are highly correlated and vary almost simultaneously in different wavelengths. In more detail, light travel time arguments for a standard accretion disk predict a small time lag between the UV-optical continuum emissions that increases with wavelength (Collier et al. 1999). Alternatively, if the UV/optical emission provides the "seed" photons for the X-ray Comptonization process, the UV/optical flux variation should be followed by the X-ray flux variation.

Previous studies have presented diverse and somewhat confusing results on the relationship between the X-ray and UV/optical flux variations of AGNs (e.g., Uttley 2006; McHardy this proceeding). For some sources, good correlation between the X-ray and UV/optical flux variations was found; a time lag of the optical flux variation behind that of X-rays was reported for NGC 4051 (Mason et al. 2002) and Ark 564 (Shemmer et al. 2001). In contrast, the time lag of the X-ray flux variation behind that of the UV/optical was reported for NGC 4051 (Shemmer et al. 2003), MCG-6-30-15 (Arevalo et al. 2005), and Mrk 509 (Marshall et al. 2008). However, no apparent correlation between the X-ray and UV/optical flux variations was found for NGC 3516 (Maoz et al. 2002), or the correlation between X-ray spectral variation and UV/optical flux variations was found for NGC 7469 (Nandra et al. 2000).

In this study, we present recent results obtained by the Multicolor Active Galactic NUclei Monitoring (MAGNUM) project (Yoshii 2002), which supports the X-ray reprocessing model for the optical and near-infrared flux variations on short timescales, and then discuss the extent of the accretion disk based on the light travel time arguments. These results regarding NGC 4395 and NGC 5548 were presented in Minezaki et al. (2006) and Suganuma et al. (2006), respectively.

2. Near-Infrared Intraday Variations in NGC 4395

2.1. The least luminous Seyfert 1 galaxy, NGC 4395

NGC 4395 is a unique object known as the least luminous Seyfert 1 galaxy (Filippenko & Sargent 1989), having a bolometric luminosity of only $L_{\rm bol} \sim 10^{40-41}$ ergs s^{-1} with broad emission lines in the UV and optical spectra (Filippenko & Sargent 1989; Filippenko et al. 1993; Kraemer et al. 1999). Its spectral energy distribution from X-ray to radio wavelengths resembles those of normal type 1 AGNs rather than those of low-ionization nuclear emission-line regions (LINERs; Moran et al. 1999). Although a compact radio source has been detected, it is a radio-quiet AGN (Ho & Ulvestad 2001; Wrobel et al. 2001; Ho & Peng 2001). The mass of the central black hole measured by a reverberation-mapping observation of the C IV emission line is as small as $M_{\rm BH} = (3.6 \pm 1.1) \times 10^5\ M_\odot$ (Peterson et al. 2005).

Moreover, the NGC 4395 nucleus shows extreme variability at many wavelengths, probably because of its low luminosity and small black hole mass. Rapid large-amplitude variations were observed in X-rays (Lira et al. 1999; Iwasawa et al. 2000; Shih et al. 2003; Vaughan et al. 2005; Moran et al. 2005; O'Neil et al. 2006), and intraday variations were observed in UV and optical (Peterson et al. 2005; Skelton et al. 2005; Desroches et al. 2006).

In near-infrared, we carried out the first intensive monitoring observation and found intraday flux variations (Minezaki et al. 2006). We also carried out a long-term (more than a year) monitoring observation in optical and near-infrared wavebands; however, here we focus on the short timescale flux variations from the intensive monitoring observation.

2.2. Observations

A one-night monitoring observation was carried out on 2004 May 1 (UTC), using the multicolor imaging photometer (MIP) mounted on the 2-m telescope of the MAGNUM project at the Haleakala Observatories in Hawaii (Kobayashi et al. 1998a, 1998b). The observation started at 06:31 and ended at 12:35 on 2004 May 1 (UTC). Using the MIP's simultaneous optical and near-infrared imaging capability, a sequence of $(V,\ K)$, (V, H), and $(V,\ J)$ -bands imagings was repeated cyclically during the observation, and 59 data points for the V band and 20 data points each for the J, H, and K bands were obtained. The average monitoring interval was 6 minutes for the V band and 18 minutes for the J, H, and K bands.

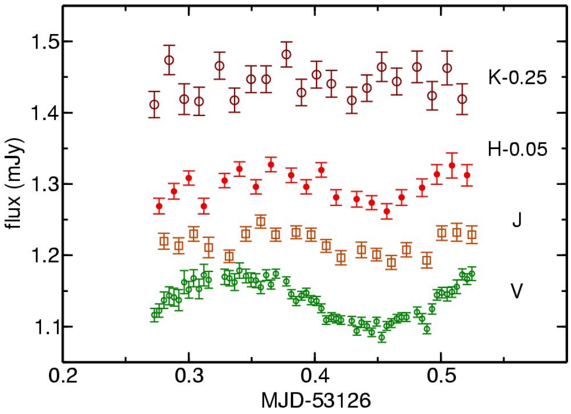

Fig. 1. Optical and near-infrared light curves of NGC 4395 on 2004 May 1 (UTC): V band (small open circles), J band (open squares), H band (small filled circles), and K band (open circles). For clarity, an offset of -0.05 mJy is applied to the H-band data points, and -0.25 mJy to the K-band data points.

2.3. Results

Figure 1 shows the optical and near-infrared light curves of NGC 4395 on 2004 May 1 (UTC). Galactic extinction was corrected for according to Schlegel et al. (1998). Clear flux variations in the V, J, and H bands were found during the six-hour monitoring period; this is the first detection of the intraday variation in the near-infrared for normal Seyfert 1 galaxies. The amplitude of the variations was $0.05 - 0.09$ mag; however, the real amplitude must be larger because nonvariable fluxes, such as the host galaxy flux and narrow-line flux, were not subtracted from the data. On the other hand, intraday variation was not clearly seen in the K band.

Apparently, the intraday variations in the V, J, and H bands are almost synchronized. In order to estimate the possible lag between the optical and near-infrared intraday variations, we applied a cross-correlation analysis. First, to increase the number of data points, the J-band and H-band light curves were combined according to the linear regressions of the J- and H-band fluxes to the V-band flux obtained simultaneously during the one-night monitoring observation. Then a cross-correlation function (CCF) was computed based on the linear interpolation method (Gaskell & Peterson 1987; White &

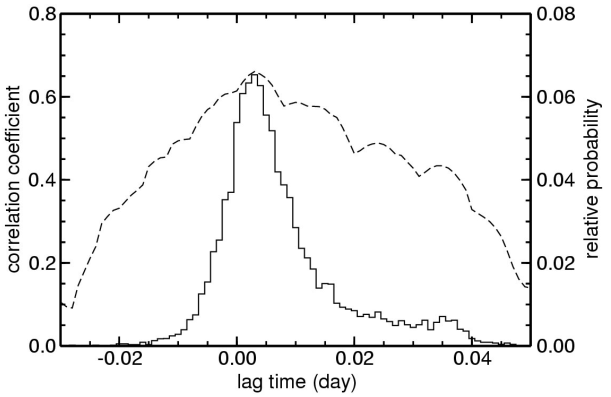

Fig. 2. CCF (dashed line) and CCCD (solid line) between the V-band light curve and the $J + H$ combined light curve on 2004 May 1 (UTC). The CCF peaks at 0.003 days, and the CCF centroid is estimated as $\tau_{\rm cent} = 0.005^{+0.011}_{-0.006}$ days, or $7.2^{+15.8}_{-8.6}$ minutes from the CCCD.

Peterson 1994). Since the number of V-band data points is larger and their photometric accuracy is better, the V-band light curve was interpolated. The lag of the CCF centroid $\tau_{\rm cent}$ was adopted to represent the lag between two light curves. The error of $\tau_{\rm cent}$ was estimated by a model-independent Monte Carlo simulation called the flux randomization/random subset selection (FR/RSS) method (Peterson et al. 2004). A cross-correlation centroid distribution (CCCD) was made based on the simulation of 10,000 realizations. Figure 2 shows the CCF and the CCCD between the V-band light curve and the combined near-infrared light curve on 2004 May 1 (UTC). The near-infrared lag time behind V is estimated from the CCCD as $\tau_{\rm cent} = 0.005^{+0.011}_{-0.006}$ days, or $7.2^{+15.8}_{-8.6}$ minutes. The intraday variations in the near-infrared (J, H) are almost synchronized with that in the optical within an accuracy of $\sim$ 10 minutes. The short timescale of variation (a few hours) and the synchronization with the optical variation ($\sim$ 10 minutes) suggest that the intraday-variable component in near-infrared is an extension of the UV-optical power-law continuum emission that originates in the accretion disk, and these results can be explained by the X-ray reprocessing model, that is, the X-ray flux variation propagates with light velocity and drives the flux variation in optical and near-infrared wavelengths.

2.4. Discussion

The X-ray reprocessing model for the short timescale flux variations of NGC 4395 is indicated by the simultaneous monitoring observation in X-ray, UV, and optical wavebands more directly. Desroches et al. (2006) found that the optical flux variation lagged behind the X-ray flux variation by 44 ± 13 minutes, and lagged behind the UV flux variation by 24^{+7}_{-9} minutes, which is consistent with the X-ray reprocessing model. O'Neill et al. (2006) found that the X-ray and UV flux variations were simultaneous within ±1 hour with a significance of $\sim$ 95 %, which is consistent with the view of the disk-corona model that the X-ray and UV fluxes are closely connected by reprocessing and/or Comptonization.

If the reprocessing model can be applied to the flux variation of the UV, optical, and near-infrared continuum emission, the lags between the variations at different wavelengths would be a direct measure of the extent of the accretion disk. In particular, the near-infrared emission from the accretion disk is expected to originate in its outermost region. Thus, the outer radius of the accretion disk would be indicated by the possible lag between the V-band and near-infrared intraday variations, and it is worthwhile to compare it with the size of the broad emission-line region (BLR).

Our measurement of the near-infrared lag time behind V is $\tau_{\rm cent} = 7.2^{+15.8}_{-8.6}$ minutes (2004 May 1). If we add the lag times of the V-band flux variations behind the UV or X-ray flux variations (2004 April 11) obtained by Desroches et al. (2006), the near-infrared lag time behind the UV continuum or X-ray flux that are considered to originate in the central part of the accretion disk would be $\tau_{\rm NIR} \sim 30 - 50$ minutes. Peterson et al. (2005) reported that the C IV emission-line lagged behind the UV continuum (λ = 1350 Å) by $\tau_{\rm CIV} = 48^{+24}_{-19}$ minutes (2004 April 10) and $\tau_{\rm CIV} = 66^{+24}_{-19}$ minutes (2004 July 3). A comparison of $\tau_{\rm NIR}$ and $\tau_{\rm CIV}$ indicates that the accretion disk is extended to just inside the BLR.

Next, we discuss the result that intraday flux variations in the K-band were not detected. Although a part of the K-band emission is contributed by power-law continuum emission from the accretion disk (Tomita et al. 2006; Kishimoto et al. 2008), it is usually dominated by thermal radiation from the dust torus. Thus, even if there was an intraday flux variation of the power-law continuum component in the K band, it would be veiled by the large amount of thermal radiation from the dust torus, because the dust torus is extended considerably so that short timescale variation of the incident flux is smeared out. The inner radius of the dust torus of NGC 4395 is estimated as $\sim$ 1 lt-day based on the correlation between the optical luminosity and the dust lag of AGNs (Minezaki et al. 2004), which is certainly much larger than the extent of the accretion disk.

3. Lag Between X-ray and Optical Flux Variations in NGC 5548

3.1. The correlation between X-ray and UV/optical flux variations in NGC 5548

Clavel et al. (1992) reported a UV lag of $\Delta t = 0 \pm 6$ days behind the X-rays by comparing the light curves in hard X-rays (2 − 10 keV) and UV (1350 Å) for NGC 5548. It

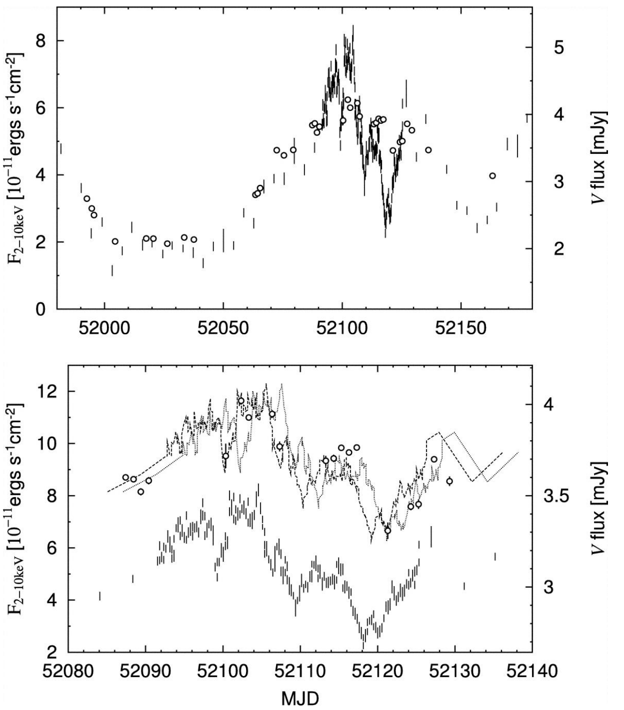

Fig. 3. Top: Observed light curves of NGC 5548 in the V band (open circles) and in the X-ray energy range of $2 - 10$ keV reported by Uttley et al. (2003). Bottom: Same as the top panel, but only for the active phase in 2001 (MJD $= 52,085{-}52,130$) when intensive X-ray satellite (RXTE) observations were done. The dashed line is the RXTE light curve shifted arbitrarily in the vertical direction and by $+1$ day in the horizontal direction; the dotted line is shifted by $+3$ days. Note that the scale for the optical flux is expanded in this panel.

is not easy to detect a clear correlation between X-ray and UV/optical variations on short timescales or the lag time between them because generally, the amplitude of UV/optical variation on a short timescale is small and difficult to observe.

From monitoring observations in the optical (5100 Å) and hard X-rays ($2 - 10$ keV) spanning for 6 years for NGC 5548, Uttley et al. (2003) reported a strong correlation in their long-timescale variations while only weakly restricting $\Delta t = 0 \pm 15$ days. Since the amplitude of such optical variation is found to exceed that of the hard X-rays, they argued that the X-ray reprocessing model is not the main driver of the long-timescale optical variation, at least for NGC 5548.

Thus, the problem yet to be answered is whether there is a clear correlation between X-ray and optical variations on short timescales.

3.2. Results and discussion

A long-term monitoring observation of NGC 5548 in optical and near-infrared wavebands was carried out by the MAGNUM project (Suganuma et al. 2006). It started in 2001 with a median sampling interval of ~ 3 days, and covered the period of the X-ray monitoring observation by the RXTE (Uttley et al. 2003). Then, the correlation and possible lag between the X-ray and optical flux variations were be examined.

The top panel of Figure 3 shows our V-band light curve and the X-ray $(2 - 10$ keV) light curve. These two light curves strongly correlate with each other, but the amplitude of the optical variation is much smaller than that of the X-rays. The bottom panel shows a portion of the light curves for a period of MJD $\approx 52,085 - 52,130$ with an expanded vertical scale for the optical flux. Although the optical data were not sampled as often as the RXTE data, we found that the optical flux variation clearly lagged behind the X-ray flux variation. The lag time is estimated as $\Delta t = 1.6^{+1.0}_{-0.5}$ days from the cross-correlation analysis of the two light curves.

The size of the X-ray–emitting region in AGNs is considered to be as small as a light-travel distance of hours, since a significant fraction of the X-ray flux varies on this timescale (Fig. 3). The observed correlated variability indicates that the optical emitting region in NGC 5548 is located at a light-travel distance of $1 - 2$ days from the X-ray–emitting region and favors the thermal reprocessing of X-rays by the optically thick accretion disk, rather than a nonthermal process that emits both X-ray and UV/optical fluxes from almost the same region. On the other hand, the long-timescale X-ray and optical variations might be generated by some other mechanisms, such as instabilities of the accretion disk itself.

Our result also shows a geometrical relationship between the accretion disk and the BLR. Korista et al. (1995) and Peterson & Wandel (1999) reported that the broad emission line of highest ionization in NGC 5548 gives the shortest lag of a few days. Therefore, the optical lag of $1 - 2$ days behind the X-ray indicates that the accretion disk is located just inside the BLR in NGC 5548.

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