X-RAY AND OPTICAL CORRELATION OF TYPE I SEYFERT NGC 3516 STUDIED WITH SUZAKU AND JAPANESE GROUND-BASED TELESCOPES

HIROFUMI NODA 1,2, TAKEO MINEZAKI 3, MAKOTO WATANABE 4,14, MITSURU KOKUBO 3,5, KENJI KAWAGUCHI 6, RYOSUKE ITOH 6, KUMIKO MORIHANA 7, YOSHIHiko Sato 8, HIKARU NAKAO 9, MASATAKA IMAI 4, YUKI MORITANI 9, KATSUTOSHI TAKARI 6, MIHO KAWABATA 8, TATSUMi NAKAOKA 6, MAKOTO UEUMURA 10, KOJI KAWABATA 10, MICHIYOSHI YOSHIDA 10, AKIRA Arai 7,15, YUHEI TAKAGI 7, TOMOKI MOROKUMA 3, MAMORU DOI 3, YOICHI ITOH 7, SHIN’YA YAMADA 11, KAZUHIRO NAKAZAWA 12, YASUSHI FUKAZAWA 9, and KAZUO MAKISHIMA 12,13

1 Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, 6-3 Aramaki-aono, Aoba-ku, Sendai, Miyagi 980-8578, Japan; hirofumi.noda@astr.tohoku.ac.jp, hirofumi.noda@riken.jp
2 Astronomical Institute, Tohoku University, 6-3 Aramaki-aono, Aoba-ku, Sendai, Miyagi 980-8578, Japan
3 Institute of Astronomy, Graduate School of Science, The University of Tokyo, Mitaka, Tokyo 181-0015, Japan
4 Department of Cosmosciences, Hokkaido University, Kita 10, Nishi 8, Sapporo, Hokkaido 060-0810, Japan
5 Department of Astronomy, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
6 Department of Physical Science, Hiroshima University, 1-3-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8526, Japan
7 Nishi-harima Astronomical Observatory, Center for Astronomy, University of Hyogo, 407-2 Nichigaichi, Sayo-cho, Sayo, Hyogo 670-5313, Japan
8 Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan
9 Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa 277-8583, Japan
10 Hiroshima Astrophysical Science Center, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
11 Department of Physics, Tokyo Metropolitan University, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397 Japan
12 Department of Physics, School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
13 MAXI Team, Global Research Cluster, RIKEN, Wako, Saitama 351-0198, Japan

Received 2016 February 6; revised 2016 May 11; accepted 2016 May 23; published 2016 September 6

ABSTRACT

From 2013 April to 2014 April, we performed X-ray and optical simultaneous monitoring of the type 1.5 Seyfert galaxy NGC 3516. We employed Suzaku and five Japanese ground-based telescopes—the Pirka, Kiso Schmidt, Nayuta, MITSuME, and the Kanata telescopes. The Suzaku observations were conducted seven times with various intervals ranging from days or weeks to months, with an exposure of ~50 ks each. The optical B-band observations not only covered those of Suzaku almost simultaneously, but also followed the source as frequently as possible. As a result, NGC 3516 was found in its faint phase with a 2–10 keV flux of 0.21–2.70 × 10−11 erg s−1 cm−2. The 2–45 keV X-ray spectra were composed of a dominant variable hard power-law (PL) continuum with a photon index of 1.7 and a non-relativistic reflection component with a prominent Fe–Kα emission line. Producing the B-band light curve by differential image photometry, we found that the B-band flux changed by ~2.7 × 10−14 erg s−1 cm−2, which is comparable to the X-ray variation, and we detected a significant flux correlation between the hard PL component in X-rays and the B-band radiation, for the first time in NGC 3516. By examining their correlation, we found that the X-ray flux preceded that in the B band by 2.0±0.6 days (1σ error). Although this result supports the X-ray reprocessing model, the derived lag is too large to be explained by the standard view, which assumes a “lamppost”-type X-ray illuminator located near a standard accretion disk. Our results are better explained by assuming a hot accretion flow and a truncated disk.

Key words: galaxies: active – galaxies: individual (NGC 3516) – galaxies: Seyfert – X-rays: galaxies

Supporting material: machine-readable table

1. INTRODUCTION

An active galactic nucleus (AGN) is known to generate multi-wavelength radiation by mass accretion onto a supermassive black hole (SMBH) in its central engine. An important element of the central engine is the standard accretion disk (e.g., Shakura & Sunyaev 1973; Balbus & Hawley 1991; Machida et al. 2000), which is expected to form at the Eddington ratio of $L_{\text{bol}}/L_{\text{Edd}} \sim 0.1$ (e.g., Abramowicz et al. 1995) and to convert an appreciable fraction of the gravitational energy released by the accreting matter into optically thick radiation. Part of the radiation has been observed as a “big blue bump” seen in optical spectra from AGNs that have disk radiation stronger than jet emission, such as Seyfert galaxies and quasars (e.g., Elvis et al. 1994).

The central engine requires another element that boosts these low-energy photons into the observed X-ray signals. This is usually attributed to some sort of hot Maxwellian electrons, or “corona,” which Compton-upscatter the seed photons into broadband X-ray photons. However, the configuration of such a corona is still under much debate, in contrast to the well-understood standard accretion disk. Some X-ray studies led to the argument that a compact corona is located on the rotation axis of the accretion disk like a “lamppost,” producing an extremely relativistically broadened reflection component by illuminating the inner accretion disk (e.g., Miniutti & Fabian 2004; Dausser et al. 2013). Others argue that an extended corona is present at the inner edge of an accretion disk, sometimes affected by a partial coverage of absorption by ionized matter (e.g., Miller et al. 2008; Miyakawa et al. 2012). To settle the
scenario of the Comptonizing corona, we need to focus on primary X-ray spectra and their flux variability.

According to X-ray studies of AGNs, several kinds of primary X-ray signals with distinct spectral and timing properties have been reported. A flat primary spectrum, which is reproduced by a single power-law (PL) continuum with a photon index of $\Gamma \lesssim 1.7$, dominates in X-rays from AGNs with relatively low Eddington ratio (e.g., Terashima et al. 2002). On the other hand, a steep primary continuum, which can be explained by a PL model with $\Gamma \gtrsim 2.3$, is dominant in X-rays from highly accreting AGNs such as narrow-line type 1 Seyferts (e.g., Laor et al. 1994; Boller et al. 1996). Recently, Noda et al. (2011a, 2013a, 2014) revealed that these primary continua, both flat and steep, are simultaneously present in the X-ray emission from multiple Seyfert galaxies. The presence of these different primary X-rays may represent the presence of several distinct types of coronae with different electron temperatures and optical depths. Furthermore, in order to explain a soft X-ray excess in a low energy band below $\sim 3$ keV, a soft thermal Comptonization continuum has been suggested, invoking yet another corona (e.g., Mehdipour et al. 2011; Noda et al. 2011b, 2013c, Jin et al. 2013). The reality of this third corona, however, needs further examination, because the soft excess may alternatively be modeled in terms of relativistically smeared ionized reflection (e.g., Fabian et al. 2004) or absorption by disk winds (e.g., Gierliński & Done 2004).

To clarify the geometry of materials around a SMBH, correlations and time lags between emissions in different energy bands are useful. Recently, studies of reverberation between different X-ray bands revealed that soft X-rays and Fe–K$\alpha$ emission lines have positive time lags, by hundreds of seconds, compared with hard X-rays, with an implication that some reprocessing materials are present near the hard X-ray emitters (e.g., Uttley et al. 2014). Likewise, X-ray and optical/ultraviolet (UV) correlations are useful to investigate coronal geometries around an accretion disk. Because seed photons for the inverse Comptonization process are presumably provided via the optical/UV disk blackbody, variations in these low-energy bands can precede that of X-rays with a lag of several days (e.g., Nandra et al. 2000). When fluctuations in the mass accretion rate propagate inward from the accretion disk to the corona, the optical emission is also expected to precede X-rays, but on a viscous or thermalizing timescale that may be much longer than days (e.g., Uttley & Casella 2014). On the other hand, the disk should be illuminated by the X-rays, so that X-ray variations can cause changes in optical flux, producing delays of several days in the opposite sense (e.g., Krolik et al. 1991). In order to distinguish these cases, and to better understand the geometry of the coronae and accretion disk, we need to measure the sign and length of the time lag between optical and X-rays, and to quantify the strength of their correlations.

So far, a large amount of effort has been invested in coordinated X-ray and optical/UV observations of a number of AGNs. However, we are far from achieving a unified view. For example, Seyfert galaxies including NGC 5548 (Uttley et al. 2003; Suganuma et al. 2006; McHardy et al. 2014), NGC 3783 (Arévalo et al. 2009), and Mrk 79 (Breedt et al. 2009) exhibited relatively strong correlations with optical lags of several days, while those including Ark 564 (Gaskell 2006) and NGC 3516 (Maoz et al. 2002) showed much poorer correlations. One possible cause of this variety, we speculate, is that the different X-ray primary continua have different correlations to the optical/UV signals, and the previous coordinated observations mixed up the effects from these multiple X-ray components. To overcome this difficulty, simultaneous observations of AGNs should be conducted, under conditions in which the different X-ray components can be clearly identified and separated.

To derive the geometrical information from the multi-wavelength correlations, we performed simultaneous X-ray and optical monitoring during 2013–2014, by utilizing Suzaku (Mitsuda et al. 2007) and five Japanese ground-based telescopes. The target of this campaign is the bright type 1.5 Seyfert galaxy NGC 3516. It has a redshift of $z = 0.00884$, which corresponds to a distance of $D = 41.3$ Mpc $= 1.3 \times 10^{26}$ cm. Its SMBH is estimated to have a mass of $M_{\text{BH}} = 3.2 \times 10^7 M_\odot$ (Denney et al. 2010), which yields a Schwarzschild radius of $R_\text{S} = 0.95 \times 10^{13}$ cm. The column density of the Galactic interstellar absorption toward NGC 3516 is $N_\text{H} = 4.08 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990), and the optical Galactic extinction is $A_\text{B} = 0.151$ mag (NASA/IPAC Extragalactic Database based on Schlafly & Finkbeiner 2011). Although NGC 3516 was previously reported, by Maoz et al. (2002), to exhibit a poor X-ray and optical correlation, the result will change if we properly decompose its X-ray continuum using the technique of Noda et al. (2011b, 2013c), because NGC 3516 is one of the prototypical objects to which this method has been successfully applied (Noda et al. 2013a). Unless otherwise stated, errors shown in tables and figures in the present paper refer to 1σ errors.

2. OBSERVATION AND DATA REDUCTION

2.1. X-Ray

The X-ray monitoring observations of NGC 3516 were performed in the Suzaku AO-8 cycle during 2013–2014. Specifically, NGC 3516 was observed with Suzaku five times from 2013 April 10 to May 29, with intervals of $\sim 1$–2 weeks (see Table 1). Another pointing was carried out on November 7, and the last one on 2014 April 4, making a total of seven observations, with various intervals from days to months. In the present paper, we call the first, second, ... and seventh observations epoch 1, epoch 2, ... and epoch 7, respectively. The exposure in each epoch was $\sim 50$ ks, except for epoch 2 which had an exposure of $\sim 20$ ks. In all these epochs, the XIS (Koyama et al. 2007) and HXD (Takahashi et al. 2007) were operated in their normal modes, and data from the XIS and HXD-PIN are utilized in the present paper, except for epoch 7, in which the HXD-PIN count rate was too low to significantly detect the signals.

The data of the XIS and HXD-PIN were processed via the software version 2.4. In the XIS analysis, we added the data of XIS0 and XIS3, and utilized these as FI data, while we did not use XIS1 due to their higher background. The XIS source events were extracted from a circle of radius 120″ with its center on the source. Background events were accumulated from a surrounding annular region with an inner radius of 180″ and outer radius of 270″. The response and ancillary-response files were prepared via software in HEASOFT 6.14 calledxisrmfgen andxisissrmfgen (Ishisaki et al. 2007), respectively. The HXD data were prepared in the same way as those from the XIS. In the HXD analysis, non-X-ray background and cosmic X-ray background were estimated using standard models described by Fukazawa et al. (2009) and Gruber...
et al. (1999), respectively. They were subtracted from the on-source data.

2.2. Optical

The optical photometric monitoring observations of NGC 3516 were performed by using the charge-coupled device (CCD) cameras installed at the Pirka, MITSuME, Kiso Schmidt, Nayuta, and Kanata telescopes, of which the major parameters are summarized in Table 2. Simultaneous monitoring observations were performed at the same seven epochs as the X-ray observations by Suzaku. In addition, from 2013 January to 2014 April, these telescopes densely monitored the source even without simultaneous X-ray coverage, with a typical intervals of ~1 day. In the present paper, we present the $B$-band and $g'$-band photometric data, because the optical continuum emission of AGNs is generally bluer than that of the host galaxy, thus ensuring better sensitivity to the AGN signals. The images were reduced using IRAF\(^\text{16}\) following the standard procedures of image reduction for CCD detectors.

### Table 1

| Epoch | Observation Start (UT) | End (UT) | Middle (MJD) | Exposure Time (ks) |
|-------|------------------------|----------|--------------|-------------------|
| 1     | 2013 Apr 9 23:13:20    | Apr 11 01:06:16 | 56392.51     | 51                |
| 2     | 2013 Apr 27 00:17:13   | Apr 27 10:42:22 | 56409.27     | 19                |
| 3     | 2013 May 12 00:22:24   | May 13 02:30:23 | 56424.58     | 50                |
| 4     | 2013 May 23 03:32:08   | May 24 07:05:07 | 56435.72     | 51                |
| 5     | 2013 May 29 11:02:50   | May 30 15:15:14 | 56442.05     | 54                |
| 6     | 2013 Nov 4 06:15:13    | Nov 5 05:10:17 | 56600.74     | 46                |
| 7*    | 2014 Apr 7 16:54:26    | Apr 8 12:00:24 | 56755.12     | 52                |

Note.
* Only the XIS data are utilized.

### Table 2

| Telescope | Mirror Diameter (m) | Instrument | Field of View (arcmin) | Pixel Scale (arcsec pixel\(^{-1}\)) | Observing Band | $n_{\text{obs}}$ |
|-----------|---------------------|------------|------------------------|-------------------------------------|----------------|-----------------|
| Pirka     | 1.6                 | MSI\(^b\)  | 3.3 × 3.3               | 0.39                                | $B, V$         | 86              |
| MITSuME   | 0.5                 | MITSuME\(^c\) | 28 × 28                | 1.64                                | $g', R_c, I_c$ | 6               |
| Kiso Schmidt | 1.5       | KWFC\(^d\) | 60 × 30"               | 0.95                                | $B, V$         | 32              |
| Nayuta    | 2.0                 | MINT\(^e\) | 11 × 11                 | 0.32                                | $B, V$         | 31              |
| Kanata    | 1.5                 | HOWPol\(^f\) | $\phi$ 15               | 0.29                                | $B, V$         | 31              |

Notes.
* The total number of observing nights.
* Multi-Spectral Imager (MSI; Watanabe et al. 2012).
* Multicolor Imaging Telescopes for Survey and Monstrous Explosions (MITSuME; Kotani et al. 2005).
* Kiso Wide Field Camera (KWFC; Sako et al. 2012).
* Only one of the eight CCDs installed in KWFC was used.
* Multiband Imager for Nayuta Telescope (MINT; Ozaki 2005).
* Hiroshima One-shot Wide-field Polarimeter (HOWPol; Kawabata et al. 2008).

et al. (1999), respectively. They were subtracted from the on-source data.

2.2. Optical

The optical photometric monitoring observations of NGC 3516 were performed by using the charge-coupled device (CCD) cameras installed at the Pirka, MITSuME, Kiso Schmidt, Nayuta, and Kanata telescopes, of which the major parameters are summarized in Table 2. Simultaneous monitoring observations were performed at the same seven epochs as the X-ray observations by Suzaku. In addition, from 2013 January to 2014 April, these telescopes densely monitored the source even without simultaneous X-ray coverage, with a typical intervals of ~1 day. In the present paper, we present the $B$-band and $g'$-band photometric data, because the optical continuum emission of AGNs is generally bluer than that of the host galaxy, thus ensuring better sensitivity to the AGN signals. The images were reduced using IRAF\(^{16}\) following the standard procedures of image reduction for CCD detectors.

### Table 1

| Epoch | Observation Start (UT) | End (UT) | Middle (MJD) | Exposure Time (ks) |
|-------|------------------------|----------|--------------|-------------------|
| 1     | 2013 Apr 9 23:13:20    | Apr 11 01:06:16 | 56392.51     | 51                |
| 2     | 2013 Apr 27 00:17:13   | Apr 27 10:42:22 | 56409.27     | 19                |
| 3     | 2013 May 12 00:22:24   | May 13 02:30:23 | 56424.58     | 50                |
| 4     | 2013 May 23 03:32:08   | May 24 07:05:07 | 56435.72     | 51                |
| 5     | 2013 May 29 11:02:50   | May 30 15:15:14 | 56442.05     | 54                |
| 6     | 2013 Nov 4 06:15:13    | Nov 5 05:10:17 | 56600.74     | 46                |
| 7*    | 2014 Apr 7 16:54:26    | Apr 8 12:00:24 | 56755.12     | 52                |

Note.
* Only the XIS data are utilized.

### Table 2

| Telescope | Mirror Diameter (m) | Instrument | Field of View (arcmin) | Pixel Scale (arcsec pixel\(^{-1}\)) | Observing Band | $n_{\text{obs}}$ |
|-----------|---------------------|------------|------------------------|-------------------------------------|----------------|-----------------|
| Pirka     | 1.6                 | MSI\(^b\)  | 3.3 × 3.3               | 0.39                                | $B, V$         | 86              |
| MITSuME   | 0.5                 | MITSuME\(^c\) | 28 × 28                | 1.64                                | $g', R_c, I_c$ | 6               |
| Kiso Schmidt | 1.5       | KWFC\(^d\) | 60 × 30"               | 0.95                                | $B, V$         | 32              |
| Nayuta    | 2.0                 | MINT\(^e\) | 11 × 11                 | 0.32                                | $B, V$         | 31              |
| Kanata    | 1.5                 | HOWPol\(^f\) | $\phi$ 15               | 0.29                                | $B, V$         | 31              |

Notes.
* The total number of observing nights.
* Multi-Spectral Imager (MSI; Watanabe et al. 2012).
* Multicolor Imaging Telescopes for Survey and Monstrous Explosions (MITSuME; Kotani et al. 2005).
* Kiso Wide Field Camera (KWFC; Sako et al. 2012).
* Only one of the eight CCDs installed in KWFC was used.
* Multiband Imager for Nayuta Telescope (MINT; Ozaki 2005).
* Hiroshima One-shot Wide-field Polarimeter (HOWPol; Kawabata et al. 2008).

The images were reduced using IRAF\(^{16}\) following the standard procedures of image reduction for CCD detectors.

### Data Analysis and Results

#### 3.1. X-Ray Light Curves and Spectra

Figure 1 shows light curves in the 2–3 and 3–10 keV bands in all seven epochs. While we can see gradual flux changes, the source did not show short-term variations, on timescales of several hours, that were observed by $XMM-Newton$ in 2006 (Mehdipour et al. 2010). The 2–3 keV light curves are clearly synchronized with those in the 3–10 keV band. The highest flux was obtained in epoch 4 and the lowest in epoch 7, with the amplitude of peak-to-peak variation reaching a factor of ~20. To quantify the flux variability, we made, in Figure 2, a count–count plot between count rates in the 2–3 and 3–3.5 keV bands, where these objects generally exhibit rather high variability (Noda et al. 2013a). The count–count plot of NGC 3516 derived in 2009 October (Noda et al. 2013b) is also shown for reference, after correcting the data for a difference in pointing position and long-term changes in the detector response. Surprisingly, all the data points in 2013–2014 line up with those in 2009, thus defining an almost linear correlation between the two bands. This means that the variable component in those energy bands observed in 2013–2014 has nearly the same spectral shape as that detected in 2009.

In energy bands higher than 3.5 keV, a reflection component with a prominent Fe–Kα emission line at ~6.4 keV is expected to become more dominant than in energies below 3.5 keV. Therefore, this variable component should be separated from the reflection via spectral fitting. Although the reflection component is considered to be almost stationary within a week (Noda et al. 2013a), it can vary on timescales of months, because a broad-line region and/or a dusty torus, where the reflection emission possibly originates, are known to be located at several tens to hundreds of light-days (e.g., Koshida et al. 2014). Accordingly, we treat the reflection signal as a variable component.

---

16 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
In the fitting, the photon index $\Gamma$ was tied among the epochs (because of Figure 2) and left free. The cutoff energy $E_{\text{cut}}$ was fixed at 150 keV based on the typical value reported by Malizia et al. (2014), while the normalization $N_{\text{wabs}}$ was left free in each epoch. For pexmon, $\Gamma$ and $E_{\text{cut}}$ of the incident PL were tied to those in cutoffpl, and the Fe abundance $A_{\text{Fe}}$, inclination angle $I$, and reflection fraction $f_{\text{ref}}$ were fixed at 1 $\text{Solar}$, 60°, and 1, respectively. The normalization $N_{\text{ref}}$ of the pexmon component was allowed to differ among the epochs. The $N_{\text{ref}}$ value is determined almost solely by the Fe–Kα line intensity, because the ratio between the Fe–Kα line intensity and the reflection continuum in pexmon does not change when $E_{\text{cut}}$, $A_{\text{Fe}}$, and $f$ are all fixed. As summarized in Figure 3 and Table 3, the simultaneous fitting was successful with $\chi^2$/dof = 1184.0/1113. As expected from Figure 2, all the spectra have been reproduced by a hard PL continuum having $\Gamma \sim 1.75$, which is consistent with that in 2009 $\Gamma = 1.72^{+0.08}_{-0.12}$, together with a reflection component accompanied by a prominent Fe–Kα emission line. Although $N_{\text{H}}$ varied slightly, the low-energy shapes of the time-averaged spectra were not so strongly affected (see Figure 3).

The highest and lowest 2–10 keV fluxes were $\sim 2.7 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ in epoch 4 and $\sim 0.3 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ in epoch 7, respectively. They are in a range of just 7%–70% of the 2–10 keV flux of $\sim 4.0 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ averaged over 1997–2002 (RXTE AGN Timing & Spectral Database; Maoz et al. 2002); thus NGC 3516 was in an X-ray-faint phase during the present observations. Table 3 further gives the 2–10 keV fluxes of the hard PL continuum and the reflection components, calculated separately, after removing the absorption. The 2–10 keV light curves of the two spectral components, derived in this way, are presented in Figure 4(top). The time of each data point refers to the middle epoch (in MJD) of that observation as given in Table 1. Interestingly, the flux of the reflection component changed significantly by a factor of 2 on a timescale of several months. However, the hard PL component varied by almost an order of magnitude or more in amplitude. Clearly, the large change in intensity in Figure 2 was mostly carried by the hard PL variation. The largest flux change in the hard PL emission in 2–10 keV is a difference of $\sim 2.4 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$, and a factor of $\sim 18$ between epochs 4 and 7.

To get further information about the AGN activity in NGC 3516, we also performed the spectral analysis including the energy band below 2 keV. For this purpose we selected epoch 7,
which describes a relativistically smeared re-

\[ \chi^2 / \text{dof} = 100.3 / 84 \] (Figure 5(a)), in which the soft excess, apparently involving emission lines, is reproduced by the plasma emission model. On the other hand, the fit with model (b) was unsuccessful with \( \chi^2 / \text{dof} = 355.9 / 82 \), mainly due to the lack of the emission lines at \( \sim 0.85 \) keV and a convex data shape in the 2–5 keV band (Figure 5(b)). Therefore, the spectrum below 2 keV is dominated by the host galaxy emission, at least in epoch 7. This justifies us in limiting the spectral studies to energies above \( \sim 2 \) keV. Of course, the AGN emission, when bright, probably dominates down to \( \sim 0.5 \) keV, but it is strongly affected by ionized-absorption features at \( \sim 0.8 \) keV, as shown in Figure 5(a).

\[ F_{\text{PL}} \]

3.2. Differential Imaging Photometry and Optical Light Curves

According to changes in atmospheric seeing during an observation, the flux of an AGN within an aperture changes differently from that of the host galaxy, leading to a significant

Table 3

Parameters Obtained by Simultaneous Fitting to all the 2–45 keV Time-averaged Spectra

| Component  | Parameter | Epoch 1       | Epoch 2       | Epoch 3       | Epoch 4       | Epoch 5       | Epoch 6       | Epoch 7       |
|------------|-----------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| wabs       | \( N_{\text{h}}^a \) | 1.93\( ^{+0.14}_{-0.15} \) | 1.86\( ^{+0.10}_{-0.11} \) | 1.21\( ^{+0.06}_{-0.07} \) | 0.94\( ^{+0.05}_{-0.06} \) | 1.16 \( \pm 0.07 \) | 1.52\( ^{+0.18}_{-0.17} \) | 2.10\( ^{+0.21}_{-0.25} \) |
| cutoffpl   | \( \Gamma_{\text{PL}} \) | 2.70           | 1.75\( ^{+0.02}_{-0.01} \) |           | 150 (fix)   |           | 4.10\( ^{+0.07}_{-0.09} \) | 0.69\( ^{+0.02}_{-0.03} \) | 0.39 \( \pm 0.02 \) |
| pexmon     |         |               |               |               |               |               |               |               |
| \( E_{\text{ref}} \) | 3.25                             | 3.25                             | 3.25                             | 3.25                             | 3.25                             | 3.25                             | 3.25                             | 3.25                             |
| \( N_{\text{ref}} \) | 3.88\( ^{+0.24}_{-0.26} \) | 4.24\( ^{+0.51}_{-0.50} \) | 5.17\( ^{+0.42}_{-0.44} \) | 5.88\( ^{+0.47}_{-0.49} \) | 5.60\( ^{+0.40}_{-0.41} \) | 2.73 \( \pm 0.21 \) | 2.51 \( \pm 0.18 \) |               |
| \( F_{\text{ref}} \) | 1.10 \( \pm 0.07 \) | 1.20\( ^{+0.15}_{-0.14} \) | 1.46 \( \pm 0.12 \) | 1.67 \( ^{+0.13}_{-0.14} \) | 1.59\( ^{+0.12}_{-0.12} \) | 0.78 \( \pm 0.06 \) | 0.71 \( \pm 0.05 \) |               |
| \( F_{\text{total}} \) | 0.48 \( \pm 0.04 \) | 1.56 \( \pm 0.07 \) | 2.14 \( ^{+0.06}_{-0.07} \) | 2.70 \( \pm 0.07 \) | 1.66 \( ^{+0.05}_{-0.06} \) | 0.33 \( \pm 0.03 \) | 0.21 \( \pm 0.02 \) |               |

Notes: Errors refer to 1\( \sigma \) confidence ranges.

\( ^a \) Equivalent hydrogen column density in units of 10\( ^{22} \) cm\(^{-2} \).

\( ^b \) The power-law normalization at 1 keV, in units of 10\(^{-5} \) photons keV\(^{-1} \) s\(^{-1} \) cm\(^{-2} \) at 1 keV.

\( ^c \) The 2–10 keV flux of the PL component without being absorbed, in units of 10\(^{-11} \) erg s\(^{-1} \) cm\(^{-2} \).

\( ^d \) The pexmon normalization at 1 keV, in units of 10\(^{-5} \) photons keV\(^{-1} \) s\(^{-1} \) cm\(^{-2} \) at 1 keV.

\( ^e \) The 2–10 keV flux of the reflection component without being absorbed, in units of 10\(^{-13} \) erg s\(^{-1} \) cm\(^{-2} \).

\( ^f \) The 2–10 keV total flux without being absorbed in units of 10\(^{-11} \) erg s\(^{-1} \) cm\(^{-2} \), calculated as a sum of \( F_{\text{PL}} \) and \( F_{\text{ref}} \).
uncertainty in measuring the flux variation of a faint AGN hosted by a bright galaxy. To minimize such uncertainty in the photometry of the nucleus of NGC 3516, we therefore performed Difference Image Photometry (DIP: Crotts 1992; Tomaney & Crotts 1996). As presented in Figure 6, for example, a reference image was created by stacking many images obtained on the same night with good seeing conditions. Then, we matched the position, the photometric intensity, and the point-spread function (PSF) of the reference image to those of each individual image and subtracted the former from the latter. Two nearby field stars, located at (R.A., decl.) = (11:06:28.51, +72:35:46.2) and (11:07:00.41, +72:33:33.3), were used as the reference to match the photometric intensity and the PSF. The IRAF <em>psfmatch</em> task was used for matching the PSFs. After that, for each individual image, the residual flux at the center of the galaxy was measured relative to the two nearby reference stars, with a circular aperture of \( \phi = 4 \times FWHM \) of the PSF in diameter. Finally, the residual flux data on the same observing night were averaged to obtain the flux difference of the nucleus of NGC 3516 at that epoch with respect to the reference image. The photometric error was estimated from the ensemble scatter of the DIP fluxes and the number of the images obtained on the same night. These procedures were applied to the data set from each telescope individually.

Because the observing epochs of the reference images used in the DIP analysis depend on the telescopes, there can be systematic offsets between them. Systematic differences in the scaling factor among them are also possible because of the differences in the filter color term. To match the offset and the scaling factor among the four telescopes, we therefore performed a linear regression analysis on their B-band flux data sets from the same observing nights. An example, between two telescopes, is presented in Figure 7. The reduced \( \chi^2 \) of the linear regression was much larger than unity only when the photometric errors were incorporated. This suggests the presence of some systematic errors, so we added an error \( \sigma_{\text{add}} \) to the photometric errors in quadrature, and regarded it as the systematic error of the photometry. By requiring the reduced \( \chi^2 \) to become unity, we obtained \( \sigma_{\text{add}} \sim 0.06 \text{ mJy} \).

The B- and V-band magnitudes of the two reference stars were calibrated relative to those of the more distant field stars whose magnitudes are presented in Sakata et al. (2010); these are based on the wide-field image data of the KWFC, in which both stars were observed simultaneously. The \( g' \)-band magnitudes of the reference stars were estimated from their B- and V-band magnitudes according to Jordi et al. (2006).

The light curves of the nucleus of NGC 3516, thus derived in the optical B and \( g' \) bands, are presented in the bottom panel of Figure 4, and the data are listed in Table 4, without correction for the Galactic extinction. They are both the differential fluxes with respect to the reference image obtained from the image data on 2014 April 8 (UTC), and the error bars of the data points do not include \( \sigma_{\text{add}} \). The total numbers of photometric data points are 180 and six for the B and \( g' \) bands, respectively. As shown in Figure 4, the B-band flux varied rather similarly to that of the hard PL component in the 2–10 keV band. Although the number of data points is small, the variation in \( g' \)-band flux also followed them. The larger relative scatters of the \( g' \)-band data points are caused by the small telescope size and the large pixel scale of the camera (MITSuME) with which the data were obtained. These results indicate that the optical continuum and the 2–10 keV PL component varied in a good correlation with each other. The B-band flux density varied by \( \sim 1.2 \text{ mJy} \) between the peak and bottom. After correcting for the Galactic extinction and the optical extinction of the nucleus of NGC 3516 (\( A_B \sim 1.3 \text{ mag} \) in total), this becomes \( \sim 4.0 \text{ mJy} \), corresponding to \( \sim 2.7 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \) in \( \nu F_\nu \) units.\(^{17}\)

To complete this DIP analysis, we estimated the AGN flux at the faintest phase during our observation. We applied an aperture photometry to the stacked B-band image obtained on

\(^{17}\) There are different estimates for the optical extinction of the nucleus of NGC 3516: Cackett et al. (2007) estimated it at \( E(B-V) = 0.15-0.16 \text{ mag} \), which can be converted to \( A_B = 0.62-0.66 \text{ mag} \), and Denney et al. estimated it at \( A_B = 1.68-1.72 \text{ mag} \). We adopted their average here. Although the \( N_H \sim 1-2 \times 10^{22} \text{ cm}^{-2} \) derived from the X-ray absorption suggests a much larger optical extinction of \( A_B \sim 10 \text{ mag} \), AGNs often show smaller optical extinction than that converted from the X-ray \( N_H \) (e.g., Burtscher et al. 2016).
2014 April 7 by the MINT attached on the Nayuta telescope (Figure 6), because on this day it achieved the best seeing among the four. Sakata et al. (2010) estimated the host-galaxy flux in the $B$ band as $8.38 \pm 0.18 \text{ mJy}$, within an aperture diameter of $\phi = 8.3 \text{ arcsec}$ with the sky reference of a $\phi = 11.1-13.9 \text{ arcsec}$ annulus. By applying the photometry with the same parameters, we obtained the $B$-band AGN flux of $0.1 \pm 0.2 \text{ mJy}$. Considering the various systematic errors in the photometry, the $B$-band AGN flux at the faintest phase during the observations is estimated to be about a few times $0.1 \text{ mJy}$, with a similar amount of flux error.

### 3.3. Time-series Analysis of the Flux Variations of the Hard PL X-Ray and Optical Continuum

As shown in Figure 4, the optical flux changed almost simultaneously with the 2–10 keV hard PL flux. In order to

---

18 Since Sakata et al. (2010) assumed the Galactic extinction of $A_B = 0.183 \text{ mag}$ according to Schlegel et al. (1998), we converted their host galaxy flux to that assuming $A_B = 0.151 \text{ mag}$ adopted in this paper.
Table 4  

| Observation Date (MJD) | Observatorya | Filter | Fluxb (mJy) | Flux Error (mJy) |
|------------------------|--------------|--------|-------------|-----------------|
| 56316.544              | P            | B      | 0.738       | 0.035           |
| 56334.674              | P            | B      | 0.519       | 0.003           |
| 56382.554              | N            | B      | 0.462       | 0.011           |
| 56382.588              | H            | B      | 0.133       | 0.144           |
| 56383.576              | P            | B      | 0.350       | 0.021           |
| 56384.454              | P            | B      | 0.274       | 0.008           |
| 56385.448              | K            | B      | 0.278       | 0.007           |
| 56385.611              | H            | B      | 0.103       | 0.115           |
| ...                    | ...          | ...    | ...         | ...             |
| 56392.487              | K            | B      | 0.303       | 0.011           |
| 56392.625              | M            | g′     | 0.541       | 0.029           |
| 56392.686              | N            | B      | 0.341       | 0.012           |
| ...                    | ...          | ...    | ...         | ...             |

Notes.  

a Observatory code: P—the MSI at the Pirka telescope, M—the MITSuME, K—the KWFC at the Kiso Schmidt telescope, N—the MINT at the Nayuta telescope, and H—the HOWPol at the Kanata telescope.
b The flux difference with respect to the reference image on 2014 April 8 (UTC).

(This table is available in its entirety in machine-readable form.)

examine possible time lags between them, we first focus on their expanded light curves from epochs 1 to 5, as presented in Figure 8(a). Clearly, the AGN became brightest in both bands at epoch 4. Also plotted in the same figure is the X-ray light curve shifted by +2 days and +4 days. Apparently, the X-ray light curve with a shift of a few days shows the closest agreement with the B-band light curve, suggesting that the variation of the X-rays preceded that of the B band by a few days. Figure 8(b) presents the correlation of the X-ray flux with temporal shifts of 0, +2, and +4 days, against the B-band flux at the delayed epochs. The latter was estimated by averaging the B-band fluxes in close observations within ±1 day. The correlation between those fluxes appears to be strongest when the X-ray light curve is shifted by +2 days. This reconfirms that the X-ray variations preceded those in the B band by a few days. Below, let us quantify the suggested time lag with two methods.

3.3.1. Cross-correlation Analysis

One method is the interpolated cross-correlation function (ICCF) method, which has been widely used (White & Peterson 1994; Peterson et al. 1998). This is the same as the ordinary cross-correlation function (CCF), but either or both sets of time-series data are interpolated, so that the CCF can be calculated even if the two data sets have different samplings, or when either or both are irregularly sampled. Since the monitoring cadence of the B-band data was much higher than that of the X-ray data, only the B-band light curve was interpolated, to make it nearly continuous. The interpolated B-band light curve was calculated using a fitting code developed by Zu et al. (2011), which assumes a damped random walk (DRW) model for the flux variation. The DRW model has been demonstrated to be a good statistical model of flux variations of the UV–optical continuum emission of AGNs (e.g., Kelly et al. 2009; Kozlowski et al. 2010; MacLeod et al. 2010, 2012; Zu et al. 2013). In this interpolation, the systematic error $\sigma_{\text{add}}$ of the photometry, either as determined in Section 3.2 or somewhat changed, was added in quadrature.

Figure 9 presents the observed B-band flux data and their interpolation. Thus, the interpolated light curve does not follow the observed data when we employ $\sigma_{\text{add}} = 0.06$ mJy as determined in Section 3.2: the peak flux of the interpolated light curve was lower and its decrease in flux after the peak was slower. We generally found that a larger value of $\sigma_{\text{add}}$ made the interpolated light curve smoother and less variable, probably because a larger $\sigma_{\text{add}}$ would work as if applying a stronger low-pass filter. Therefore, we performed the CCF analysis using the B-band data with $\sigma_{\text{add}} = 0$ mJy in addition to 0.06 mJy to examine the possible uncertainty in lag caused by $\sigma_{\text{add}}$. As shown in Figure 9, the interpolated light curves then follow the observed data much better when $\sigma_{\text{add}}$ is reduced.

The X-ray data of epochs 1–5 and the optical data of MJD = 56316–56511 were selected for the CCF analysis, because the most remarkable flux variations were present in those epochs and also because the B-band light curve data were sampled densely (Figures 4 and 8). The calculated CCFs, in which the B-band data were smoothed using $\sigma_{\text{add}} = 0$ and 0.06 mJy, are presented in Figure 10, in which the time lag $\tau$ is defined to be positive if the optical flux precedes the X-rays. As shown in Figure 10, the CCF is peaked at about $\tau = −2$ days. This reconfirms the inference from Figure 8 and implies that the optical variation is delayed from that in X-rays by ~2 days. The CCF value at the peak is very high, 0.98, as indicated by Figure 8(b).

For quantitative measurement of $\tau$, we use the centroid of the CCF peak, $\tau_{\text{cent}}$, which is computed from all neighboring points around the CCF peak where CCF values are >0.95 times that of the peak. The uncertainty of $\tau_{\text{cent}}$ is estimated using the model-independent Monte Carlo method of flux randomization and random subset sampling (FR/RSS) introduced by Peterson et al. (1998, 2004). The FR method modifies the observed fluxes in each realization randomly within the errors assigned to the individual data points, and the RSS method randomly extracts the same number of data points from the observed light curve allowing for multiple extraction. Then, the CCF and $\tau_{\text{cent}}$ are calculated for each realization in the same way to produce the cross-correlation centroid distribution (CCCD). The CCCDs calculated from 5000 realizations with the FR/RSS method are presented in Figure 10, and the derived $\tau_{\text{cent}}$ and its uncertainties are listed in Table 5. Thus, the results with $\sigma_{\text{add}} = 0$ mJy and 0.06 mJy agree well with each other. On average, the lag has been estimated as $\tau_{\text{cent}} = −2.02^{+0.55}_{−0.50}$ days (1σ error), and the time lag is significantly non-zero, because the 99% confidence limit is $\tau < −0.68$ days.

3.3.2. JAVELIN Analysis

The other method to estimate the lag is the JAVELIN software developed by Zu et al. (2011), which is widely employed not only in recent reverberation studies of the optical broad emission lines and the thermal dust emission of AGNs (e.g., Grier et al. 2012; Koshida et al. 2014; Peterson et al. 2014), but also in analysis of the lag between flux variations of their X-ray emission and the UV–optical continuum emission (McHardy et al. 2014; Shappee et al. 2014; Lira et al. 2015). It explicitly builds a model of a response light curve that is expressed as a convolution of a source light curve and a top-hat transfer function with a certain lag, and it fits the model to the
Figure 8. (a) Enlarged light curves of the $B$ band (gray) and the 2–10 keV hard PL component (red circles) from epochs 1 to 5. Green squares and blue open triangles show the X-ray light curves that are purposely delayed by +2 and +4 days, respectively. The X-ray flux amplitude was scaled to match that in the $B$ band. (b) A plot of the 2–10 keV hard PL flux against the $B$-band flux density, wherein an artificial time delay is applied to the X-ray data by 0 days (red circle), 2 days (green box), and 4 days (blue triangle).

Figure 9. Observed $B$-band light curve (filled dots) and its interpolations used for the time-series analysis. The solid, dotted–dashed, and dashed lines represent the best-fit light curves based on the DRW models with $\sigma_{\text{add}} = 0.00$ mJy, 0.03 mJy, and 0.06 mJy, respectively.

data on flux variations in different bands, one being the source light curve and the others the response light curves. The source light curve is modeled as a stochastic process using a DRW model, and the posterior distributions of the time lag as well as other model parameters are estimated using the Bayesian Markov chain Monte Carlo method.

We use the $B$-band light curve as the source but the X-ray data as the response, again with $\tau > 0$ meaning X-ray delays. The X-ray data of epochs 1–5 and the optical data of MJD 56316–56511 were selected for the JAVELIN analysis, and $\sigma_{\text{add}} = 0$ or 0.06 mJy was added to the $B$-band photometric errors in quadrature, just as in the CCF analysis. The posterior distribution of the time lag calculated from 250,000 realizations of the JAVELIN software is presented in Figure 11, and the resultant $\tau_{\text{JAV}}$ and its uncertainties are also listed in Table 5. The two values of $\sigma_{\text{add}}$ again gave very similar results. The time lags were estimated as $\tau_{\text{JAV}} = -2.12^{+0.59}_{-0.83}$ days (1σ error) with $\sigma_{\text{add}} = 0$ and 0.06, respectively. Again, we can exclude the case of $\tau = 0$, because the 99% confidence limit is $\tau < -0.78$ days on average. In summary, the two methods have given consistent results.

3.4. The X-Ray Reflection Component

As shown in Table 3 and Figure 4(top), we found a significant flux variation in the X-ray reflection component as well, on a timescale of several months, although its variation in amplitude is much smaller than that of the primary X-rays. This indicates that the source region of the reflection component has an extent on a scale of ~0.1 pc. Moreover, the flux variation of the reflection component lags slightly behind that of the hard PL component, on a scale of a week, or possibly longer because the X-ray sampling becomes very sparse after epoch 5.

According to the unified model of AGNs, the reflection component accompanied by the neutral Fe–Kα line is supposed to arise from a dust torus, but different origins such as outer accretion disks and the broad emission-line region have also been suggested (e.g., Awaki et al. 1991; Yaqoob & Padmanabhan 2004; Nandra 2006; Jiang et al. 2011; Gandhi et al. 2015; Minezaki & Matsushita 2015). Interestingly, the reverberation studies of NGC 3516 yielded a dust lag of ~50–70 days (Koshida et al. 2014) and a lag of broad Balmer emission lines of ~7–13 days (Peterson et al. 2004; Denney et al. 2010). These are comparable to the timescale of the variation of the X-ray reflection and its delay behind the hard PL component. In order to further examine the origin of the X-ray reflection component, a direct comparison of its variation with that of the dust emission and the broad Balmer emission lines would be necessary; this will be discussed in a forthcoming paper.

4. DISCUSSION AND CONCLUSION

4.1. Summary of the Results

In the present study, we performed simultaneous X-ray and optical monitoring of the type 1.5 Seyfert galaxy NGC 3516...
with Suzaku and Japanese ground-based telescopes—the Pirka, Kiso Schmidt, MITSuME, Nayuta, and Kanata telescopes. By applying spectral fitting to the X-ray data and differential image photometry to the B-band images, and quantitatively comparing the X-ray and optical flux variations, we have obtained the following results.

1. During our observations, NGC 3516 was in an X-ray-faint state. It was faintest in epoch 7, when the 2–10 keV flux became $\sim 0.21 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$, which is just 5% of the average flux recorded in 1997–2002 with RXTE. Even when brightest (epoch 4), the 2–10 keV flux was $\sim 2.70 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$, which is only 70% of the average in 1997–2002. The flux varied on timescales longer than a few days, without any intraday changes.

2. The 2–45 keV emission mainly consisted of two spectral components: a variable hard PL continuum with a photon index of $\sim 1.75$ and a reflection component with a prominent narrow Fe–Kα emission line. Throughout the monitoring, the hard X-ray component retained almost the same spectral shape and exhibited a peak-to-peak flux change of $\sim 2.5 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$, or about an order of magnitude.

3. The B-band flux density varied by $\sim 0.00$ mJy from peak to peak, which translates to a flux change of $\sim 2.7 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ in $\nu F_\nu$ units, after correcting for the optical extinction. The B-band flux varied on timescales longer than a few days, like that of the X-rays.

4. X-ray and B-band flux correlation was significantly detected for the first time in NGC 3516. The flux changes of the hard X-ray component significantly preceded those in the B band by $2.0^{+0.7}_{-0.6}$ days ($1\sigma$ error).

### 4.2. X-Ray–Optical Correlation Appearing Only in the Faint State

In previous monitoring of NGC 3516 conducted with RXTE and the Israeli WISE telescope in 1997–2002, no significant correlations were derived between X-ray and B-band flux variations, giving a cross-correlation coefficient (CCC) of $< 0.35$ (Maoz et al. 2002). In contrast, we succeeded in detecting a significant correlation between them with a high CCC of $> 0.95$. What is responsible for the clear difference? Maoz et al. (2002) argued that the lack of correlation might be due to changes in absorption that are independent of the primary variations in X-rays. However, the 2–10 keV flux varied during their monitoring by a factor of $\sim 4$ from peak to peak. Such a large change would be hardly explained by the variations recorded so far in the column density of optically thick neutral absorbers (Turner et al. 2011). We hence suggest alternatively that the dominant X-ray-variable component changed between the two monitoring campaigns.

Noda et al. (2013a) discovered that the X-ray emission of NGC 3516 comprises at least two different primary continua with distinct spectral shape and flux variability; a flat continuum ($\Gamma \sim 1.1–1.7$) and a steep one ($\Gamma \sim 2.3$), which we hereafter call the hard and gradually varying primary component (HGPC) and the soft and rapidly varying primary component (SRPC), respectively. Noda et al. (2013a) showed that the luminosities of the HGPC and SRPC were comparable in a bright state in 2005, when the absorption-corrected 2–10 keV total flux was $F_{\text{total}} \sim 3.5 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$. In contrast, the 2009 Suzaku observation caught NGC 3516 in a faint state with $F_{\text{total}} \sim$...
1.1 × 10⁻¹¹ erg s⁻¹ cm⁻², in which the variation was carried solely by a Γ = 1.7 PL, which can be identified with the HGPC. Thus, there is a certain threshold in between these two flux values, say, at \( F_{\text{th}} \sim 3 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \); the HGPC and SRPC coexist above \( F_{\text{th}} \), whereas only the HGPC remains below \( F_{\text{th}} \). These two primary continua have also been identified in another Seyfert, NGC 3227 (Noda et al. 2014)¹⁹: their luminosity-dependent behavior was found to be very similar to that observed from NGC 3516. Namely, the HGPC was always present, whereas the SRPC appeared when the source was brighter than a certain threshold, to then coexist with the other.

In the present Suzaku observations, the absorption-corrected 2–10 keV flux of NGC 3516 was in the range (0.2–2.7) × 10⁻¹¹ erg s⁻¹ cm⁻², i.e., always below the suggested \( F_{\text{th}} \). Furthermore, the 2–45 keV spectrum of the main variable PL was flat with \( \Gamma \sim 1.75 \), and the CCP distributions are smoothly connected to those in 2009 (Figure 2). Hence, we conclude that NGC 3516 was in the faint phase, with the HGPC dominating just as in the 2009 observation. On the other hand, during the 1997–2002 monitoring by Maoz et al. (2002), the averaged 2–10 keV flux was \( F_{\text{total}} \sim 4.0 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \), which is higher than \( F_{\text{th}} \) indicating that NGC 3516 was mostly in the bright phase. If the SRPC has a significantly poorer correlation with the optical than the HGPC does, the correlation between the total X-ray flux and the optical should become worse when NGC 3516 is in the bright phase. If the SRPC has a significantly poorer correlation with the optical than the HGPC does, the correlation between the total X-ray flux and the optical should become worse when NGC 3516 is in the bright phase. If the SRPC has a significantly poorer correlation with the optical than the HGPC does, the correlation between the total X-ray flux and the optical should become worse when NGC 3516 is in the bright phase. If the SRPC has a significantly poorer correlation with the optical than the HGPC does, the correlation between the total X-ray flux and the optical should become worse when NGC 3516 is in the bright phase. Therefore, we speculate that X-ray–optical correlation in Seyfert galaxies becomes commonly worse when the Eddington ratio increases, because the SRPC starts to dominate.

According to Figure 2(b) and related descriptions in Noda et al. (2014), the SRPC may originate from patchy coronae heated by a magnetic process on the surface of a disk (e.g., Reynolds & Nowak 2003). If the patchy coronae cover a small fraction of the disk, the SRPC generated in the corona can be related to just small areas of the disk, making X-ray and optical variations independent. Another possible origin of the SRPC is a faulty jet at the accretion axis of the SMBH (e.g., Ghisellini et al. 2004). If the region of jet emission is located far away from the accretion disk as suggested by Noda et al. (2014), the connection between the SRPC and the disk optical emission may become weaker, making their correlation poorer. In any case, the emergence and disappearance of these SRPC-generating regions are likely to be more localized effects than those responsible for the transitions from hard to soft state seen in black-hole binaries, because the changes in AGN state considered here take place on timescales of weeks to years, which are much shorter than would be expected (e.g., several tens of thousands of years) if the typical state-transition timescales of a few days are scaled to the mass ratios.

### 4.3. The Origin of X-Ray and Optical Correlation

#### 4.3.1. Application of the Standard X-Ray Reprocessing Model

The measured optical lag of 2.0⁺⁰⁻¹⁰.⁷ days strongly supports the X-ray reprocessing model (e.g., Krolik et al. 1991; Cackett et al. 2007); optical brightening occurred, at least in the present case, through irradiation by the increased hard X-ray intensity. This process is energetically feasible, because the increase in

![Figure 11](image-url)
2–10 keV X-ray flux by $2.5 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ is comparable to the increase in $B$-band flux by $\sim 2.7 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$. The optical time lag in NGC 3516 obtained here is similar to those of a few days observed in other Seyfert galaxies, including NGC 5548 (e.g., Suganuma et al. 2006; McHardy et al. 2014; Edelson et al. 2015), NGC 3783 (Áñóálo et al. 2009), NGC 4051 (Breidt et al. 2010), and NGC 6418 (Troyer et al. 2016). Therefore, the suggested mechanism, i.e., X-ray reprocessing, can be operating commonly among these Seyfert galaxies.

Let us, then, investigate whether or not the derived optical lag can be explained by the most commonly adopted X-ray reprocessing model (e.g., Cackett et al. 2007), which assumes that an optically thick, geometrically thin, standard accretion disk continues down to the innermost last stable circular orbit (ISCO), located at $3R_s$, where $R_s = 2GM_{BH}/c^2$ is the Schwarzschild radius and $M_{BH}$ the black-hole mass, and is illuminated by a lamp-post-type X-ray source proximate to the black hole. At radii $R \gg R_s$, the radial temperature profile of the disk is given as (Shakura & Sunyaev 1973)

$$T(R) = \left(\frac{3GM_{BH}M}{8\pi\sigma}\right)^{1/4} R^{-\frac{3}{2}},$$

where $M$ is the mass accretion rate, $G$ is the gravitational constant, and $\sigma$ is the Stefan–Boltzmann constant.

After a delay time $\tau$, the X-ray flux variation that arose close to the black hole will propagate to a radius $R = c\tau$, and will increase the emissivity there. Let us define a wavelength $\lambda = hc/kT(c\tau)X$ in such a way that the continuum emission at this radius is peaked at $\lambda$, where $X$ is a numerical factor of order unity. Although Wien’s displacement law for blackbody radiation in $\nu B_\nu$ gives $X = 3.92$, we here set $X \sim 3.2$, according to the detailed calculations of the disk response to continuum emission by Cackett et al. (2007) and Collier et al. (1999). Substituting $c\tau$ for $R$, and expressing $T(c\tau)$ with $\lambda$, Equation (1) can be rewritten as

$$T(R) = \left(\frac{hc}{k\lambda X}\right)^{1/2} \frac{R}{c\tau}.$$  

By eliminating $T(R)R^{3/4}$ from Equations (1) and (2), we obtain $\dot{M} \propto M^{-1.7/3}\lambda^{-4}$. Further expressing $\dot{M}$ as the bolometric luminosity of the accretion disk, $L_{bol} \sim 0.1Mc^2$ (assuming that the disk extends to the ISCO), and normalizing it to the Eddington luminosity ($\propto M_{BH}$), the Eddington ratio of the source $\eta$ is estimated as

$$\eta \equiv \frac{L_{bol}}{L_{Edd}} \sim 3.8 \left(\frac{M_{BH}}{3.2 \times 10^8 M_\odot}\right)^{-2} \times \left(\frac{\tau}{2.0 \text{ day}}\right)^3 \left(\frac{\lambda}{0.44 \mu m}\right)^{-4}.$$  

Equation (3), in fact, implies a serious problem. First of all, it indicates an unrealistic “super-Eddington” condition. Even putting aside this issue, it means a discrepancy of a factor of $\sim 500$ from the likely value of $\eta = 0.006–0.01$ (Section 4.2), which characterizes the nucleus of NGC 3516 during the present observations. This difficulty can be stated more directly: by summing up the blackbody contributions from various disk annuli, the continuum spectrum from the accretion disk under consideration can be calculated as

$$f_\nu \sim 550 \text{ mJy} \left(\frac{\tau}{2.0 \text{ days}}\right)^2 \left(\frac{D}{41.3 \text{ Mpc}}\right)^{-2} \times \left(\frac{\lambda}{0.44 \mu m}\right)^{-3} \cos i,$$

where $i$ is the disk inclination (Collier et al. 1999; Cackett et al. 2007). Thus, the measured delay predicts very bright optical emission, arising from the inner part of the accretion disk. In other words, the SMBH would have to be accreting at a very high rate in order for its accretion disk to emit the $B$-band light from such a large distance as $\sim 2$ lt-day. Equation (4) means a contradiction by two orders of magnitude with the present optical data, in which the peak-to-peak flux variation in the $B$-band was $\sim 4.0$ mJy, and the minimum $B$-band flux during the observation would be less than that. Conversely, if we started from the assumption of $\eta = 0.006–0.01$, the $B$-band lag predicted by Equation (3) would become $\sim 8$ times smaller than was measured. It is thus extremely difficult to reconcile the measured clear optical delay of $\sim 2$ days with the observed optical faintness, as long as we assume a standard disk extending down to the ISCO and an illuminating X-ray source close to the SMBH.

4.3.2. Consideration of the X-Ray Irradiation

In the X-ray reprocessing model, we should consider not only the viscous heating but also the heating by the X-ray irradiation. The former, which underlies Equation (1), is written...
as

\[ D_{\text{vis}} = \frac{3GM_{\text{BH}}M}{8\pi R^3}, \]  

whereas the latter is given as

\[ D_{\text{irr}} = \frac{(1 - A)L_X \cos \theta}{4\pi R^2}, \]  

where \( L_X \) is the X-ray luminosity, \( A \) is the disk albedo, \( R_X \) is the distance from the disk to the X-ray illuminator, and \( \theta \) is the angle of incidence of X-rays onto the disk. Collier et al. (1999) and Cackett et al. (2007) assumed that the X-ray emitter is located on the rotating axis of the SMBH like a “lamppost” (Figure 12(a)) and its height \( H_X \) from the SMBH is much smaller than \( R \) (\( H_X \ll R \)). Under these assumptions, we obtain\( R_X \sim R \) and \( \cos \theta = H_X/\sqrt{R^2 + H_X^2} \sim H_X/R \). Then, \( D_{\text{vis}} \) and \( D_{\text{irr}} \) have just the same \( R \)-profile, and the total heating per unit face area of the disk, \( D_{\text{tot}} = D_{\text{vis}} + D_{\text{irr}} \), is expressed as

\[ D_{\text{tot}} = \frac{3GM_{\text{BH}}M}{8\pi R^3} + \frac{(1 - A)L_XH_X}{4\pi R^3}. \]  

As a result, the radial temperature profile of the disk is now given by

\[ T(R) = \left[ \frac{3GM_{\text{BH}}}{8\pi \sigma} \left\{ M + \frac{2(1 - A)L_XH_X}{3GM_{\text{BH}}} \right\} \right]^{\frac{1}{4}} R^{-\frac{3}{4}}. \]  

This exhibits the same \( R \)-dependence as the standard viscous disk, namely, \( T \propto R^{-3/4} \). Furthermore, because of the proportionality \( L_X \propto M \), we should use \( M + 2(1 - A)L_XH_X/3GM_{\text{BH}} \) in place of \( M \) when converting this expression into that of \( \eta \) according to Equation (3). Consequently, the Eddington ratio \( \eta \) and the \( B \)-band flux density can be given by the same Equations (3) and (4), respectively.\(^{20}\) Thus, we encounter just the same problem as before, even when the X-ray irradiation is taken into account.

According to, e.g., Cackett et al. (2007), McHardy et al. (2014), and Edelson et al. (2015), typical Seyfert galaxies including NGC 5548, NGC 4051, and Mrk 335 yielded values of \( \tau \) that are a few times larger than those expected from their estimated \( \eta \). According to Morgan et al. (2010), the accretion disks of gravitationally lensed quasars are larger, by a factor of \( \sim 4 \), than those expected from \( \eta \), just like in the Seyfert galaxies. These subtle but systematic contradictions between the disk size and \( \eta \) have also been well known in the X-ray reprocessing scenario (e.g., Collier et al. 1999; Cackett et al. 2007). Recently, Troyer et al. (2016) reported that NGC 6814 exhibited a value of \( \tau \) that is \( \sim 40 \) times larger than that predicted from the estimated \( \eta \). In the present case of NGC 3516, the difference in the measured versus predicted optical delay amounts to a factor of \( \sim 10 \), which is considerably larger than those of NGC 5548, NGC 4051, and Mrk 335. These systematic discrepancies imply that the lamppost-type geometry of X-ray irradiation shown in Figure 12(a) has a common problem, which is considered to become more prominent toward lower luminosities, considering that NGC 3516 and NGC 6814 have both relatively low values of \( \eta \). Thus, we need to revise the geometrical assumptions in order to make \( \tau \) and \( \eta \) consistent in Seyfert galaxies with low Eddington ratio.

4.3.3. Possible Geometry of Accretion Flows in Seyferts with Low Eddington Ratio

What kind of geometry of the corona and the accretion disk can reconcile \( \eta \) and \( \tau \) from the present study? The contradiction in the lamppost-type X-ray reprocessing model, revealed in Section 4.3.1, arises mainly because the observed luminosity is too low for the size of the accretion disk determined by the observed time lag. Conversely, the measured \( \tau \sim 2 \) days is too large to be explained by the standard scenario, given the very low luminosity. In this respect, it has been very important that the present observations caught the object in a very faint state, not only in X-rays but also in the optical band (see the final paragraph in Section 3.2). This indicates that the inconsistency between \( \eta \) and \( \tau \) cannot be solved even if one considers an anisotropically irradiating lamppost corona (Dabrowski et al. 1997) that would make the X-ray flux we observe much lower than that illuminating the accretion disk. Hence, we need to consider other geometries of the corona and the accretion disk that can reconcile \( \eta \) and \( \tau \) from the present study.

One possible variant of the lamppost-type scenario is to place the X-ray source at a large height above the SMBH, to achieve \( H_X \sim 2 \) lt-day. In this geometry, variations in the X-ray flux can still precede those in the optical. Furthermore, the inner part of the accretion disk can be made rather cool, because \( M \) can be reduced and \( F_{\text{irr}} \) becomes much smaller than that with the assumption of \( H_X \ll R \). These would make the blackbody flux low enough to be consistent with the observed optical faintness. Such a lamppost-type corona with \( H_X \lesssim R \) was suggested to form at the base of a jet moving away from an SMBH with relativistic speeds (e.g., Lohfink et al. 2013; Wilkins & Gallo 2015). However, the value of \( H_X \sim 2 \) lt-day, or \( \sim 500 R_{\odot} \), which is required to explain the present results, is orders of magnitude larger than that invoked in the previous studies. It would be highly unrealistic to assume that such an emission region forms at a height of \( \sim 500 R_{\odot} \) in this radio-quiet object, and that the region radiates essentially the entire primary X-ray emission (Section 3.1). In addition, the mechanism of X-ray emission from such a region is problematic. As observed from BL-Lac objects, synchrotron radiation would give an X-ray spectral slope of \( \Gamma \sim 2.5 \) (e.g., Tanihata et al. 2004), which is much steeper than we observed (\( \Gamma \sim 1.75 \)). Comptonization of soft photons from the accretion disk would produce X-ray delays, contrary to the observed optical delay. In short, this variant scenario fails to explain the present results.

As we noted repeatedly, the X-ray reprocessing model that has been considered so far (Figure 12(a)) assumes the optically thick accretion disk to extend down to near the ISCO. However, it has long been known theoretically (e.g., Abramowicz et al. 1995) that a decreased luminosity, e.g., to \( \eta \lesssim 0.01 \), causes the inner regions of such a disk to make a transition into an optically thin and geometrically thick hot flow. This will lead to a configuration shown in Figure 12(b): the disk is truncated at a radius much larger than the ISCO, and the accretion flow inside that radius may form a radiatively inefficient accretion flow, or RIAF (e.g., Yuan & Narayan 2014). Such bimodal behavior of accretion disks has been firmly verified through extensive observations of black-hole binaries (e.g., Done et al. 2007). The truncated disk picture has also been investigated by many authors, both observationally.

\(^{20}\) The Eddington ratio would differ by a factor of order unity because the radial profile of the temperature of the irradiated disk would be somewhat different from that of the standard viscous disk at small radii.
and theoretically, to explain low-luminosity AGNs (e.g., Ho 2008; Taam et al. 2012; Nemmen et al. 2014; and references therein). It is hence much more natural to try to explain the present results based on the geometry of Figure 12(b).

Referring to Figure 12(b), let us then consider an accretion disk that is truncated at a radius \( R \geq 2 \) lt-day (or \( \sim 500 \) times the Schwarzschild radii) from the SMBH. Let us also assume that the accreting matter inside this radius forms a RIAF region, where the illuminating hard X-ray photons are produced via Comptonization (Makishima et al. 2008; Noda et al. 2013a, 2014; Yamada et al. 2013). In such a hot RIAF region, the electron density and temperature are theoretically predicted to increase inward toward the SMBH (e.g., Esin et al. 1997), whereas the seed photon flux for inverse Comptonization obviously increases toward positions closer to the disk. Hence, the X-ray emissivity is considered to become maximum at a location in between the SMBH and the inner disk edge. Then, the optical delay of \( \tau \sim 2 \) days can be explained simply as the light travel time from the X-ray-brightest regions to the inner disk edge. Of course, this scenario requires a relatively low inclination in order not to produce large differences in the light travel time to us from the near side and far side of the disk; NGC 3516 may satisfy this condition because it has a relatively low inclination of \( i \sim 38^\circ \) (Wu & Han 2001).

The truncated-disk picture can naturally explain, at the same time, the optical faintness, because the large amount of continuum radiation originating in the inner part of the accretion disk is no longer present. The B-band to X-ray flux ratio of NGC 3516 in these epochs is \( \nu F_\nu(B)/F_\nu(2\text{--}10 \text{ keV}) \approx 1 \). It is much lower than that of the composite spectrum for radio-quiet quasars (\( \sim 6 \); Shang et al. 2011), but is consistent with those of the composite and model spectra for low-luminosity AGNs (Ho 2008; Nemmen et al. 2014). To be quantitative, let us assume, in Equation (6), \( L_X = 5.2 \times 10^{42} \) erg \( s^{-1} \), \( \lambda = 0 \), \( R_X = 2 \) lt-day, and \( \theta = \pi/4 \). Then, the illuminating X-ray flux at a distance of 2.0 lt-day from the X-ray-bright region is calculated as \( D_{\text{app}} \sim 1.6 \times 10^{10} \) erg \( s^{-1} \text{cm}^{-2} \) during the peak of the flux variation. This predicts the disk temperature at the inner radius to be \( \sim 4000 \) K, wherein B-band photons can be produced on the Wien side, even when the viscous heating is ignored in Equation (8). Incidentally, the disk temperature would increase by a factor of \( (3/500)^{3/4} \sim 45 \) if the disk extended down to the ISCO.

As another merit of the truncated-disk scenario, the gradual X-ray variations without any intraday changes can be explained as well by the large volume of the RIAF region. In addition, the observed hard X-ray spectrum with \( \Gamma \sim 1.7 \) can be naturally explained as arising from the hot RIAF region via thermal Comptonization, as theoretically predicted (Esin et al. 1997), and observed in black-hole binaries (e.g., Makishima et al. 2008). Moreover, as shown in Figure 5, the soft X-ray band at epoch 7 was dominated by the galactic thin thermal plasma emission, and no relativistically smeared spectral components were required, also supporting the idea that the standard accretion disk did not continue down to the ISCO. This scenario may be able to solve the conflict between \( \tau \) and \( \eta \) in the other low-\( \eta \) Seyferts as well, including NGC 6814 in particular (Troyer et al. 2016). We hence prefer the picture of the truncated disk and RIAF shown in Figure 12(b).

How does our model compare with other attempts on the same subject? Recently, Gardner & Done (2016) proposed a model in which a geometrically thick region, called the soft-excess region, is present at the inner edge of an accretion disk and completely hides the hard X-ray corona. Far-UV photons, arising from the soft-excess region as a result of the X-ray illumination, are reprocessed by optically thick clouds distributed above the accretion disk and produce optical variations. This model is different from ours in that X-rays from the corona cannot directly reach the accretion disk, and the optical variation is due mainly to the clouds rather than the disk. Presumably, our results on NGC 3516 cannot be explained by the model of Gardner & Done (2016), because the 0.5--2 keV spectrum at epoch 7 is explained adequately by the galactic emission without any strong soft excess resulting from the AGN activity. Therefore, we prefer our model (Figure 12(b)) to theirs.

For some quasars, it is claimed that the accretion disks, as measured by the UV--optical microlensing observations, are generally several times larger than those predicted by the standard accretion disk model (e.g., Morgan et al. 2010). These measurements are thought to be observing an unexpectedly large disk size like those revealed by the reverberation mapping of the X-ray to optical continuum for nearby Seyfert galaxies (e.g., Edelson et al. 2015; McHardy et al. 2016). Dexter & Agol (2011) suggested that the large disk size of quasars from microlensing is due to stochastic and strong local fluctuations in the effective temperature profile of the standard accretion disk. Their inhomogeneous disk model is designed to enhance the flux contribution from outer disk radii and thus make the half-light radius of the disk larger than the predictions for the standard accretion disk. However, their model, which does not consider the X-ray emission and attributes all UV--optical variability to the assumed temperature fluctuations, cannot explain the strong X-ray versus optical correlations observed in NGC 3516 and other Seyfert galaxies. Furthermore, Kokubo (2015) showed that the disk model in Dexter & Agol (2011) cannot explain, either, the tight interband correlations often observed in the optical light curves of quasars. Therefore, we do not discuss that model any further.

For further refinement of the truncated-disk model, and its demarcation from the large-\( H_X \) model, correlations and time lags among different optical bands, including \( U, V, \) and \( R \) bands, become important (e.g., Kokubo et al. 2014; Edelson et al. 2015; Fausnaugh et al. 2016; Kokubo 2015). These will be discussed elsewhere.

### 4.4. Conclusion

The present coordinated X-ray and optical observations of NGC 3516 found the object in a very faint state at both wavelengths. A tightly correlated change in intensity lasting for \( \sim 60 \) days was detected, wherein the optical B-band variation showed a clear delay by \( \sim 2 \) days behind that of the X-ray continuum, which is described by a PL model with \( \Gamma \sim 1.7 \). This optical lag indicates the effect of X-ray reprocessing, but the delay cannot be reconciled with the B-band faintness as long as we consider the standard reprocessing scenario, which invokes a standard accretion disk irradiated by a lamp-post-type X-ray source. Instead, the observed results can be consistently explained by assuming that the disk is truncated at \( \sim 500 \) \( R_\odot \) and turns into a RIAF where the illuminating hard X-rays are produced via thermal Comptonization.

We thank the referee for his/her valuable comments and suggestions. This work was partly supported by the Grants-in-
