Simple interpretation of the seemingly complicated X-ray spectral variation of NGC 5548

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ABSTRACT
NGC 5548 is a very well-studied Seyfert 1 galaxy in broad wavelengths. Previous multi-wavelength observation campaigns have indicated that its multiple absorbers are highly variable and complex. A previous study applied a two-zone partial covering model with different covering fractions to explain the complex X-ray spectral variation and reported a correlation between one of the covering fractions and the photon index of the power-law continuum. However, it is not straightforward to physically understand such a correlation. In this paper, we propose a model to avoid this unphysical situation; the central X-ray emission region is partially covered by clumpy absorbers composed of double layers. These “double partial coverings” have precisely the same covering fraction. Based on our model, we have conducted an extensive spectral study using the data taken by XMM-Newton, Suzaku, and NuSTAR in the range of 0.3–78 keV for 16 years. Consequently, we have found that the X-ray spectral variations are mainly explained by independent changes of the following three components; (1) the soft excess spectral component below ~1 keV, (2) the cut-off power-law normalization, and (3) the partial covering fraction of the clumpy absorbers. In particular, spectral variations above ~1 keV are mostly explained only by the changes of the partial covering fraction and the power-law normalization. In contrast, the photon index and all the other spectral parameters are not significantly variable.

Key words: accretion, accretion disks — galaxy: nucleus — galaxy: Seyfert — X-rays: individual: NGC 5548

1 INTRODUCTION
NGC 5548 is a typical well-studied Seyfert 1 galaxy, known to exhibit complicated X-ray spectral variations. It has complex and variable absorption features, and thus deep and multi-wavelength observation campaigns have been performed to reveal the surrounding structure around the central black hole. The “Anatomy of the AGN in NGC 5548” campaign covered the wide wavelength range from near-infrared to hard X-rays during 2013–2014 (e.g., Kaastra et al. 2014) and revealed the change of the absorbers’ structure and geometry. The “Space Telescope and Optical Reverberation Mapping Project” is a six-month-long reverberation-mapping experiment in 2014, which provided us with a deep insight into the broad line region (BLR) structure (e.g., De Rosa et al. 2015). In the “Anatomy” campaign, an outflowing stream of weakly ionized gas (called the “obscurer”), which had not been present until at least 2007, was recognized, causing the soft X-ray absorption and the broad UV absorption (Kaastra et al. 2014). Kaastra et al. (2014)

and Arav et al. (2015) also reported by spectral fitting of the Hubble Space Telescope UV data and XMM-Newton X-ray data that the warm absorber (WA) is composed of six-velocity components. Using the electron number densities and the ionization parameters, Arav et al. (2015) estimated locations of these components as a few pc to a few hundred pc from the central black hole.

NGC 5548 is one of the ideal sources to study gas structures around the AGN, thanks to its spectral variations and existence of the obscurer and the WA. For the “obscured” XMM-Newton and NuSTAR energy spectra during the Anatomy campaign, Cappi et al. (2016) applied a two-zone partial covering model with different covering fractions as well as other Anatomy campaign papers (e.g. Ursi et al. 2015, Di Gesu et al. 2015, and Mehdipour et al. 2016). Cappi et al. (2016) explained the spectral variation in 0.3–50 keV with the following nine free parameters; (1)–(6) column densities, partial covering fractions, and ionization parameters of the two partial absorbers, (7)–(8) power-law photon index and the normalization, and (9) the soft excess normalization. Interestingly, they reported a correlation between one of the covering fractions and the photon index of the power-law continuum, such that the power-law
we examine if the VDPC model can explain the seemingly com-
cal reasons. In Section 4, we discuss application of the VDPC model to other objects, the origin of the multi-component absorption.

slopes get steeper while the covering fraction increases. Since the covering fraction is determined by the geometry of the distant partial absorbers from the central black hole, this correlation may not be explained physically. Although Cappi et al. (2016) mentioned the possibility of a parameter degeneracy, they proposed a physical interpretation: Assuming a disk-corona geometry similar to the one expected for Mrk 509 (Petrucci et al. 2015), increase in the accretion rate might decrease the inner radius of the corona due to disk recondensation (e.g. Meyer-Hofmeister & Meyer 2006), raising the effective covering fraction. Meanwhile, the accretion rate increase produces more UV photons, causing more effective cooling in the corona and softer spectra. Thus, a correlation between the covering fraction and the spectral index might be reproduced. We suspect that the apparent correlation found by Cappi et al. (2016) is more likely due to parameter degeneracy between the photon index and the mildly-ionized partial absorber. In fact, when fitting a given CCD spectrum with increasing the partial covering fraction, the model soft X-ray photons are so decreased that the photon index has to get larger to compensate. To examine the possibility of parameter degeneracy, we need to constrain these parameters a priori in some manner. Here, we try the “variable double partial covering (VDPC) model” (Miyakawa et al. 2012; Mizumoto et al. 2014) expecting to solve this problem. In this model, the line of sight is partially covered by clumpy absorbers composed of double layers: a thick/cold core and a thin/warm layer. Even if the intrinsic photon index is invariable, change of the partial covering fraction causes apparent spectral variations below ~10 keV. In this paper, we examine if the VDPC model can explain the seemingly com-

Table 1. Observation logs with XMM-Newton (pn), Suzaku and NuSTAR.

| Obs. Name | Satellite | Obs. ID | Start–End date [UT] | Exposure time (ks) |
|-----------|-----------|---------|---------------------|-------------------|
| X1$^a$    | XMM-Newton | 0109960101 | 2000 Dec. 24–23 | 22.9 |
| X2        | XMM-Newton | 0089960301 | 2001 Jul. 09–10 | 83.0 |
| X3        | XMM-Newton | 0089960401 | 2001 Jul. 12–12 | 28.1 |
| S1        | Suzaku    | 702042010 | 2007 Jan. 18–19 | 31.1 |
| S2        | Suzaku    | 702042020 | 2007 Jun. 24–25 | 35.9 |
| S3        | Suzaku    | 702042040 | 2007 Jul. 08–08 | 30.7 |
| S4        | Suzaku    | 702042050 | 2007 Jul. 15–15 | 30.0 |
| S5        | Suzaku    | 702042060 | 2007 Jul. 22–22 | 28.9 |
| S6        | Suzaku    | 702042070 | 2007 Jul. 29–29 | 31.8 |
| S7        | Suzaku    | 702042080 | 2007 Aug. 05–05 | 38.8 |
| X4        | XMM-Newton | 0720110301 | 2013 Jun. 22–22 | 50.5 |
| X5        | XMM-Newton | 0720110401 | 2013 Jun. 30–30 | 55.1 |
| X6        | XMM-Newton | 0720110501 | 2013 Jul. 07–08 | 55.5 |
| X7        | XMM-Newton | 0720110601 | 2013 Jul. 11–12 | 55.4 |
| X7N$^b$   | NuSTAR    | 60002044002/3 | 2013 Jul. 11–12 | 55.2 |
| X8        | XMM-Newton | 0720110701 | 2013 Jul. 15–16 | 55.5 |
| X9        | XMM-Newton | 0720110801 | 2013 Jul. 19–20 | 56.5 |
| X10       | XMM-Newton | 0720110901 | 2013 Jul. 21–22 | 55.5 |
| X11       | XMM-Newton | 0720111001 | 2013 Jul. 23–24 | 55.5 |
| X11N$^b$  | NuSTAR    | 60002044005 | 2013 Jul. 23–24 | 53.1 |
| X12       | XMM-Newton | 0720111101 | 2013 Jul. 25–26 | 50.7 |
| X13       | XMM-Newton | 0720111201 | 2013 Jul. 27–28 | 55.5 |
| X14       | XMM-Newton | 0720111301 | 2013 Jul. 29–30 | 50.4 |
| X15       | XMM-Newton | 0720111401 | 2013 Jul. 31–Aug. 01 | 55.5 |
| X16       | XMM-Newton | 0720111501 | 2013 Dec. 20–21 | 55.3 |
| X16N$^b$  | NuSTAR    | 60002044008 | 2013 Dec. 20–21 | 53.8 |
| X17       | XMM-Newton | 0720111601 | 2014 Feb. 04–05 | 55.4 |
| X18       | XMM-Newton | 07710000101 | 2016 Jan. 14–14 | 35.2 |
| X19       | XMM-Newton | 07710002001 | 2016 Jan. 16–16 | 32.5 |

$^a$ Sum of all the good time intervals.
$^b$ Those marked with "*" are used in Cappi et al. (2016).
$^c$ Simultaneous observation by XMM-NuSTAR.

2 OBSERVATIONS AND DATA REDUCTION

We used all the available archival data taken by XMM-Newton (Jansen et al. 2001), NuSTAR (Harrison et al. 2013), and Suzaku (Mitsuda et al. 2007) during 2000–2016, including three simultaneous observations by XMM-Newton and NuSTAR (Table 1).

In the analysis of the XMM-Newton data, we used the European Photon Imaging Camera (EPIC)-pn (Struder et al. 2001) in 0.3–10.0 keV and the Reflection Grating Spectrometer (RGS; den Herder et al. 2001) in 0.4–2.0 keV. The EPIC-MOS data were not used because its effective area is lower than that of the pn detector. The pn and RGS data were reduced with SAS version 17.0.0 to obtain the filtered event files. Good time intervals were selected by removing the intervals dominated by flaring particle background when the count rate in 10–12 keV with PATTERN=0 is larger than...
0.4 counts s$^{-1}$ for EPIC-pn data. We used circular regions of 30$''$ radius and 45$''$ radius from the same CCD for extracting the source events and the background events, respectively. Following the “SAS Data Analysis Threads”\(^1\), we obtained the X-ray spectra and responses. The 1st-order spectra of RGS1 and RGS2 were combined.

To reduce the NuSTAR data, following the “NuSTAR Data Analysis Software Guide”\(^2\), we used the standard pipeline nupipeline for reprocessing the data. The source events were extracted from circular regions within a 1.64$''$ radius around the sources, and the background events were extracted from an annulus region of 2.87$''$–4.10$''$ around the source. The spectra were extracted from the cleaned event files using the standard tool addaspec for each of the two Focal Plane Modules (FPMA and FPMB). The FPMA and FPMB spectra were combined to provide better statistics using addaspec.

In the Suzaku data analysis, we used the X-ray Imaging Spectrometer (XIS; Koyama et al. 2007) 0, 1, and 3 in 0.3–10.0 keV and Hard X-ray Detector (HXD; Takahashi et al. 2007). The HXD consists of two types of detectors, PIN and GSO, achieving a combined sensitivity in 10–600 keV. We used only the PIN detector in this study (15–50 keV) because our target is not bright enough in the GSO energy band. In the reduction of the XIS data, the source events were extracted from circular regions within a 2.0$''$ radius of the sources, and the background regions were extracted from an annulus region of 3.0$''$–7.0$''$ around the source. Spectra of the front-illuminated (FI) camera (XIS0 and XIS3) were combined by addaspec. We adopted the “tuned background” as non X-ray background model of HXD-PIN\(^3\).

We grouped XMM-pn, Suzaku-XIS, and NuSTAR spectral bins so that each new bin holds more than 30 counts; similarly, 50 counts for XMM-RGS spectra and 500 counts for Suzaku-PIN spectra. Figure 1 shows the 0.3–78.0 keV spectra of all the currently available archival data with XMM-Newton, NuSTAR, and Suzaku. In this research, we used HEASOFT version 6.26 and XSPEC version 12.10.1f for spectral model fitting.

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\(^1\) https://www.cosmos.esa.int/web/xmm-newton/sas-thread-epic-filterbackground
\(^2\) https://heasarc.gsfc.nasa.gov/docs/nustar/analysis/nustar_swguide.pdf
\(^3\) https://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/pinbgd.html

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**Figure 1.** Left: All the archival spectra obtained by XMM-Newton pn in 0.3–10.0 keV and by NuSTAR in 3.0–78.0 keV. Right: All the archival spectra obtained by Suzaku XIS1 in 0.3–10.0 keV and by PIN in 15.0–50.0 keV. Detector responses are removed using the best-fit models.

**Figure 2.** Photon index versus one of the two covering fractions CF1. Blue/orange markers show the fitting results obtained when the two covering fractions are independent/tied.

### 3 DATA ANALYSIS & RESULTS

Our primary goal is to explain the apparently complex spectral variations of NGC 5548 by a simple model with a minimum number of free parameters without parameter degeneracy. In Section 3.1, we reproduce the correlation between the power-law index and one of the covering fractions using the same two-zone partial covering model by Cappi et al. (2016), and study whether the degeneracy disappears letting the two covering fractions tied. In Section 3.2, we explain our VDPC model used in this study. We first apply the VDPC model to the three XMM-NuSTAR simultaneous spectra and the dimmest XMM-Newton spectrum to constrain the major parameters to characterize the spectral shape. We find these parameters are not significantly variable throughout the 16 year observation period. In Section 3.3, we apply these invariant parameters to all the archival data and extract variations of other spectral parameters.

#### 3.1 Reproduction of the parameter correlation by Cappi et al. (2016)

First, we examine the XMM-Newton spectral dataset used by Cappi et al. (2016). Using the same two-zone partial covering model by
Capi et al. (2016), we fitted allowing the two covering fractions to vary independently. We used XSTAR version 2.2.1bn21 (Kallman et al. 2004) for the plasma simulation code, instead of the Cloudy code (Ferland et al. 2013) adopted by Capi et al. (2016). As expected, we confirmed the reported correlation between one of the partial covering fractions (CF1) and the photon index, where the correlation coefficient is 0.63 (Figure 2, blue crosses). Next, we fitted the same dataset forcing the two covering fractions to be identical, then the correlation coefficient decreased to 0.31 (Figure 2, orange crosses). If we ignore an outlier (X4), the coefficient further drops to 0.08. Consequently, we suggest that the reported correlation is most likely due to the parameter degeneracy, and reduction of the free parameters can explain the spectral variation without any unphysical correlations.

3.2 Spectral fitting to the simultaneous XMM-NuSTAR spectra

We apply our VDPC model to the spectral data. First, we select the XMM-NaSTAR simultaneous spectra (X7, X7N, X11, X11N, X16, X16N in Table 1) and the dimmest XMM-Newton spectrum (X4) to constrain the main spectral parameters. Since both the power-law and the reflection components (pexmon) are dominant above ~10 keV, and effect of the partial absorption is most prominent in the dimmest spectrum, we expect to effectively constrain the overall spectral shape by fitting these spectra simultaneously.

The VDPC model adopted in this work is represented by the following equation:

\[ F = \frac{(P + B)(1 - \alpha + a W_1)(1 - \alpha + a W_2) W_3 W_4 + R_{bc} + I_{gas}}{(P + B)(1 - \alpha + a W_1)(1 - \alpha + a W_2)} A \]

\[ = \frac{(P + B)(1 - \alpha + a W_1)(1 - \alpha + a W_2) W_3 W_4 + R_{bc} + I_{gas}}{(P + B)(1 - \alpha + a W_1)(1 - \alpha + a W_2) W_3 W_4 + R_{bc} + I_{gas}} A, \]

where meaning of the parameters are explained below. The XSPEC representation is written as:

\[ F = \frac{\text{cutoffPL}}{\text{diskbb}} \frac{1 - \text{constant} + \text{ne table1}}{\text{pexmon}}, \text{ ne table2} + \text{mt table3} + \text{ne table4}} \text{phabs}. \]

A cut-off power-law component from the hot corona and the diskbb component from the optically thick accretion disk are the direct X-ray continua (see Figure 3). We suppose that the clumpy absorber has an internal double-layer structure that consists of a warm layer (\( W_1 \)) and a cold core (\( W_2 \)). These clumpy absorbers partially obscure the intrinsic continuum, where changes of the partial covering fractions in the line of sight are causing the apparent spectral variations. Then X-rays are fully absorbed by the ionized absorbers (\( W_1 \) and \( W_4 \)) located farther from the center than the partial absorbers. Moreover, the power-law component is reflected by the outer accretion disk accompanying a narrow Fe emission line (\( \text{pexmon} \)). Besides these model components, there is a constant plasma thermal emission (\( \text{mekal} \)) that accounts for the emission lines in the soft X-ray band.

The cosmic redshift is 0.017 (Cappi et al. 2016), and we set the cosmic abundances to the \( \text{vima} \) values (Wilms et al. 2000). Since the spectral slopes above ~10 keV looks very similar (Figure 1, left), we adopt a simple cut-off power-law model where the index \( \Gamma \) and the cut-off energy are variable. Cross-normalization constants between the three instruments (XMM-pn, XMM-RGS, and NaSTAR-FPM) were determined by the simultaneous fitting, resulting in the consistent values with Madsen et al. (2017).

We have tried to fit the seven spectra of the four observations simultaneously with minimum free parameters. Consequently, we have found that these observations can be explained without varying the power-law index significantly, and the reflection component and the multiple absorber parameters at all (Table 1 and Figure 4).

The power-law photon-index can be the same at 1.54, besides the dimmest observation (X4), 1.39. In Table 2, we show the best-fit parameters common to the four observations. Other variable parameters are shown in Table 3. Figure 4 shows the results of the fitting in 0.3–78.0 keV, where the reduced chi-square value is 1.24 (d.o.f. = 9418).

The following is an explanation of the individual model components in equations (1) and (2):

(i) Interstellar absorption: \( \text{phabs} \) \( \exp(-N_H \sigma(E)) \)

\( N_H \) and \( \sigma(E) \) are the hydrogen column density along the line of sight and the photoelectric absorption cross section as a function of the X-ray energy, respectively. The column density was fixed at the Galactic value \( N_H = 1.55 \times 10^{20} \text{ cm}^{-2} \) (Bekhti et al. 2016).

(ii) Cut-off power-law: \( \text{pexoffPL}: KE^{-\Gamma} \exp(-E/E_{\text{cut}}) \)

\( K \) is the normalization in \( \text{photons/keV/cm}^2 \) at 1 keV, \( \Gamma \) is the photon index and \( E_{\text{cut}} \) is the cut-off energy. We assume that the power-law component is emitted from the hot corona around the central black hole (Figure 3).

(iii) Partial absorption by “cold clumps”: \( W_{1,2}\text{ne table1,2}: \exp(-\sigma(E, \xi)N_H) \)

These are the essential components in the VDPC model and correspond to the “obscurer” recognized in the “Anatomy” campaign observation (Kastra et al. 2014). The \( \text{ne table} \) models describe transmission by ionized absorbers as a function of the column density \( N_H \) and the ionization parameter \( \xi \), calculated with XSTAR. We adopt the 20×20 parameter grids in the range of \( 0.1 < \log (\xi / \text{erg cm s}^{-1}) < 5 \) and \( 20 < \log (N_H / \text{cm}^{-2}) < 25 \) in logarithmic steps. We fix the gas temperature at \( 10^5 \text{ K} \), the gas density at \( 1.1 \times 10^{12} \text{ cm}^{-3} \), and the turbulent velocity at \( 200 \text{ km s}^{-1} \). Abundances are fixed to the solar values except for those minor elements (Be, Ba, Na, Al, P, Cl, K, Sc, Ti, V, Cr, Mn, Co, Cu, and Zn) that are ignored to simplify the calculation. The incident spectrum is assumed to be a power-law with the photon index 2.0. Effects of changing the intrinsic spectra are estimated in the final paragraph of this section.

Combination of the fixed \( \text{ne table} \) and the variable covering fraction \( \alpha / \text{conat} \) represents the partial absorption. We need two different ionized partial absorbers, which have the same \( \alpha \). These partial absorbers are presumably due to double-layered cold clumps (Figure 3). We will discuss physical interpretation of these absorbers in detail in Section 4.1.

(iv) Full absorption by “ionized absorber”: \( W_{3,4}\text{ne table3,4}: \exp(-\sigma(E, \xi)N_H) \)

These two components cause the ionized full-covering absorption (Figure 3), which approximate several components of WAs. Cappi et al. (2016) noted that the six-component WAs reported in Kaasta et al. (2014) are approximated by two components during the unobscured period and that influence of the multi-components is weaker during the obscured period. We applied average values of the two WAs by Cappi et al. (2016) to the invariable components \( W_3 \) and \( W_4 \).

(v) Cold reflection with Fe line: \( R_{bc}/\text{pexmon} \)

This is a Compton reflection component from cold outer-part of the accretion disk, including the narrow fluorescence lines (\( \text{pexmon} \); Nandra et al. 2007). We fixed the disk inclination angle at \( i = 30^\circ \), which was suggested as \( i = 38.8^{+12.4}_{-11.4} \) (Pancoast et al. 2014) or \( 36 \pm 10^\circ \) (Starkey et al. 2017). We determined the redshift value by
the simultaneous fitting considering the line shift from the cosmic value due to an ionized disk or a kinetic Doppler shift. Since the observed fluorescent Fe Kα line strength does not vary significantly compared to the continuum variation, we have fixed the $\alpha$ value due to an ionized disk or a kinetic Doppler shift. Since the paper, we assume a black body accretion disk model for simplicity.

**(vi) Soft excess: $B/diskbb$**

Several interpretations exist for the soft excess component, e.g., the optically thick Comptonized disk model (Done et al. 2012). In this paper, we assume a black body accretion disk model for simplicity. The diskbb has two parameters, temperature at the inner edge of the accretion disk $kT_{disk}$ and normalization $= r_0^2 \cos(i) / d_i^{2.70,10}$, where $r_0$, $d_i^{10,kpc}$, and $i$ are the innermost radius of the disk, the distance in the unit of 10 kpc, and the disk inclination angle, respectively. In most cases of NGC 5548, only the soft excess tail is observed below ~1 keV, and the temperature and the normalization are hardly constrained simultaneously. Thus, we fixed the diskbb normalization, and varied only $kT_{disk}$.

**(vii) Thermal plasma emission: $I_{gas}$mekal**

The soft excess component has not only the continuum emission but also the emission lines. We modeled the emission-line component using the thermal plasma radiation model mekal. Since one-temperature mekal does not accurately describe the observed spectrum, we apply two-temperature mekal in this study. This component has been constant throughout the 16-year observation. The hot plasma is considered to originate either in the host galaxy or in the narrow line region (e.g., Whowell et al. 2015; Cappi et al. 2016).

In the actual multi-absorber scenario, we note that the first absorber would alter the input spectrum to the second one, and so does the second one to the input spectrum to the third one, and so on. Thus, it would be ideal to carry out such successive photoionization calculation that a preceding absorber’s output spectrum is incident to the following absorber. However, this is not so easy that we have adopted such a simple approximation that the incident spectrum to the absorbers is a static power-law function.

Below, we evaluate the validity of this approximation. We investigate whether the spectral fitting results are dependent on XSTAR table models (mtable) created with different incident spectra. Table 2 shows the best-fit parameters using the table model created with the photon index 2.0. We created new table models with the input photon indices 1.5 and 2.5, and repeated the same simultaneous fitting replacing the tables. Consequently, we found that the fitting results are almost identical (the reduced chi-square values are 1.26 and 1.22, respectively, as opposed to the original one, 1.24), and the residual patterns are not distinguishable. Best-fit parameter values are invariant within statistical uncertainty, besides those of the partial absorber parameters ($N_H$ and $\log \xi$ for $W_1$ and $N_H$ for $W_2$). The new best-fit values are the following (in the order of the photon-indices 1.5 and 2.5): For $W_1$, ($N_H / 10^{22} cm^{-2}$)=1.17 and 1.05, $\log \xi$ (erg $cm^{-2} s^{-1}$)=0.93 and 0.1. For $W_2$, ($N_H / 10^{22} cm^{-2}$)=2.46 and 3.04. These differences are minor, and we conclude that our approximation of the constant incident spectra to the multi-absorbers is valid to represent the picture depicted in Figure 3.

**3.3 Fitting of all the available spectra**

We have shown in the previous section that the four spectra in the 2013 campaign (X4, X7, X11, and X16) including the brightest (X7) and the dimmest (X4) ones are explained without varying the main spectral shape and the multiple absorber parameters (Table 2 and Figure 4). Most variable parameters are (1) the partial covering...
fraction, (2) the power-law normalization and (3) the $d\alpha k T$ temperature (Table 3). We examine if similar spectral fitting is possible for all the other observations with minimum numbers of the variable parameters.

We fit each of all the observations individually with minimum variable parameters in addition to the three free-parameters in the 2013 XMM-NuSTAR campaign. First, we found no significant variations in the iron emission line and the reflection component ($pexmon$). We also found that the spectra taken during the unobscured period (X1, X2, and X3 in 2000–2001) had clearly different characteristics from those taken in 2007 and afterward. These unobscured spectra were much brighter than others below ~2 keV (Figure 1), where the covering fraction was null. They required a higher photon index and a lower soft excess normalization than the best-fit model (see table 2). The lower panel shows residuals of the model fitting.

For all the other spectra in 2007 and afterward, the same index (1.54) as in the simultaneous fitting is valid beside the faintest spectrum X4 which requires a lower photon-index (1.39). The $d\alpha k T$ normalization was also fixed to the value determined from the XMM-NuSTAR simultaneous fitting. We show all the results of the model fitting in Figure A.1 (for Suzaku) and Figure A.2 (for XMM-Newton). The best-fit parameters are shown in Table 3. Some spectra (e.g., X5, X15 and X17) exhibit local residual feature below ~1 keV, which would suggest a minor variation of the absorbers. Besides, major variable parameters over the entire ~16 year period are (1) the covering fraction $\alpha$, (2) the cutoffPL normalization, and (3) the $d\alpha k T$ temperature $kT_{\text{in}}$, as in the 2013 XMM-NuSTAR campaign. We emphasize that all the model fits are reasonable with such a simple model with little changes in the intrinsic spectra and absorbers’ parameters.

We point out that the observation X4, which was the faintest in the XMM-Newton observations, returns a photon index of 1.39, that seems extremely hard. Such low photon-indices in extreme low states have been also reported in other Seyfert galaxies (e.g., Pounds et al. 2004). It is possible that the the AGN corona may have a tendency to get hotter and/or thicker when getting dimmer.

During the Suzaku observation period (June to August 2007), the covering fraction was tiny (< 0.05) or null, which may imply that the obscurer started to emerge at around that time. While previous studies (e.g., Liu et al. 2010; Kronold et al. 2010) analyzing the same Suzaku data have not reported the presence of the obscurer, Kaasra et al. (2014) argued that the obscuration may have started between August 2007 and February 2012, when Swift was not monitoring NGC 5548.

## 3.4 Reproduction of RMS spectra with the best-fit model

In this section, we try to explain the observed RMS spectra with the best-fit spectral model obtained in the previous section. The RMS spectra show fractional variations as a function of the X-ray energy, that intuitively informs us which components primarily contribute to the spectral variability.

Following Edelson et al. (2002), the RMS spectra were calculated from the observed and best-fit model spectra for each XMM-Newton observation with the 0.1 keV energy bins between 0.3–10.0 keV. Figure 5 shows the observed and model RMS spectra. The left one shows the RMS spectra from all the observations including the unobscured period (X1–X3), and the right is calculated from only X4–X19 in the obscured period.

In both figures, the dip around 6.4 keV indicates that the neutral Fe line from the outer-disk reflection is relatively constant compared to other spectral components. In the left figure, the variations are as large as ~200 % below 1 keV, which is due to the emergence of the obscurers after 2007. In the right figure, where most variations are due to change of the partial covering fraction, the RMS spectrum is characterized by a broad peak around ~1 keV. This is because the partial absorber is most opaque just below the Fe-L edge, thus variation of the partial covering fraction most affects the spectral variation at around ~1 keV (see also Figure 7). Similar ~1 keV peaks are recognized from RMS spectra of other Seyfert 1 galaxies, where partial covering is dominant (e.g., Yamasaki et al. 2016).

## 4 DISCUSSION

We have found that the VDPC model, where two partial absorbers have exactly the same covering fraction, can explain the long-term spectral variations and RMS spectra of NGC 5548. This model is shown to be also valid for other Seyfert galaxies in precedent works (Miyakawa et al. 2012; Mizumoto et al. 2014; Iso et al. 2016; Yamasaki et al. 2016). Below, we discuss physical origin and implication of the VDPC model.

### 4.1 Mathematical and Physical description of the VDPC model

The mathematical VDPC representation is described in Equation 1, which indicates a situation that the central X-ray emitting region is sequentially obscured by the partial absorbers $W_1$ and $W_2$ having the same covering fraction and fully covered by the full-absorbers $W_3$ and $W_4$. The upper diagram in Figure 6 literally illustrates this situation. The key point of the VDPC model is that the two partial absorbers $W_1$ and $W_2$ have exactly the same and variable covering fractions. However, it is very challenging to assume that the two independent absorbing layers accidentally have the same covering fraction and always vary in sync.
Table 3. Variable parameters determined by the spectral fitting with XMM-Newton (pn, RGS) and Suzaku (XIS0, 1, 3, PIN). Other parameters common to all the spectra are shown in Table 2. Those parameters without error values are the fixed ones.

| Obs. | fitting results (refer Section 3.3) | computed flux (refer Section 4.2) |
|------|-----------------------------------|----------------------------------|
|      | $\alpha$ diskbb $kT_a$ (eV) diskbb norm (10$^{-5}$) PL norm (10$^{-5}$) PL index $\chi^2$/dof | $\alpha$ diskbb flux$^a$ (10$^{-12}$ erg/cm$^2$/s) PL flux$^b$ (10$^{-12}$ erg/cm$^2$/s) |
| X1   | 0 162.3 1.21±0.09 8.4±0.1 1.70 | 0.9±0.1 11.1±0.5 |
| X2   | 0 176.1 0.83±0.03 10.5±0.1 1.70 | 1.0±0.1 16.1±0.5 |
| X3   | 0 186.2 1.04±0.05 13.8±0.1 1.70 | 1.1±0.1 21.1±0.5 |
| S1   | 0.02±0.01 5.7±3 44.0 1.8±0.1 1.54 | 27.8±3.9 24.1±3.5 |
| S2   | 0.02±0.01 50 44.0 2.8±0.1 1.54 | 16.4 43±1.5 |
| S3   | 0 72±1 44.0 6.0±0.1 1.54 | 70.7±3.9 92±1.5 |
| S4   | 0.04±0.01 62±2 44.0 3.7±0.1 1.54 | 39.7±7.5 57±1.5 |
| S5   | 0 71±1 44.0 7.4±0.1 1.54 | 66.8±3.8 113±1.5 |
| S6   | 0 55±5 44.0 4.7±0.1 1.54 | 24.1±8.8 72±1.5 |
| S7   | 0.05±0.01 55±5 44.0 2.5±0.1 1.54 | 24.1±3.5 38±1.5 |
| X4   | 0.96±0.01 137±1 44.0 2.4±0.1 1.39±0.01 1.13 | 926.6±27.1 37±1.5 |
| X5   | 0.71±0.01 50 44.0 7.5±0.1 1.54 | 16.4 115±1.5 |
| X6   | 0.76±0.01 74±1 44.0 5.2±0.1 1.54 | 78.9±4.3 80±1.5 |
| X7   | 0.73±0.01 50 44.0 8.2±0.1 1.54 | 16.4 125±1.5 |
| X8   | 0.78±0.01 78±1 44.0 6.7±0.1 1.54 | 97.4±5.0 103±1.5 |
| X9   | 0.81±0.01 84±1 44.0 6.4±0.1 1.54 | 131.0±6.2 98±1.5 |
| X10  | 0.77±0.01 77±1 44.0 5.5±0.1 1.54 | 92.5±4.8 80±1.5 |
| X11  | 0.95±0.01 146±1 44.0 6.2±0.1 1.54 | 1195±132.7 95±1.5 |
| X12  | 0.74±0.01 78±1 44.0 7.3±0.1 1.54 | 97.4±5.0 112±1.5 |
| X13  | 0.75±0.01 78±1 44.0 7.2±0.1 1.54 | 97.4±5.0 110±1.5 |
| X14  | 0.74±0.01 78±1 44.0 6.4±0.1 1.54 | 97.4±5.0 98±1.5 |
| X15  | 0.77±0.01 80±1 44.0 5.6±0.1 1.54 | 107.7±5.4 86±1.5 |
| X16  | 0.94±0.01 142±1 44.0 5.4±0.1 1.54 | 1069.4±30.1 83±1.5 |
| X17  | 0.59±0.01 69±1 44.0 6.1±0.1 1.54 | 59.6±3.5 93±1.5 |
| X18  | 0.63±0.01 64±1 44.0 5.0±0.1 1.54 | 44.1±2.8 77±1.5 |
| X19  | 0.62±0.01 66±1 44.0 5.4±0.1 1.54 | 49.9±3.0 83±1.5 |

$^a$ Bolometric fluxes of diskbb without any absorption.

$^b$ cutoffPL fluxes without any absorption in 0.3–50.0 keV assuming the best-fit parameters $\Gamma = 1.54$ and $E_{\text{cut}} = 72.8$ keV.

Figure 5. RMS spectra calculated from the observed spectra (black) and the best-fit model spectra (red). Observations used for RMS calculation are X1–X19 (left) and only X4–X19 (right), respectively.

Therefore, we suppose that “double-layer clumpy absorbers” are more plausible, as in the lower illustration of Figure 6. In this case, it is naturally understood that the two absorbers have the same covering fraction. The only difference is in those X-rays indicated with the blue lines in the figure; in the top panel, they are intervened only by the core of the clump ($W_2$), but they are necessarily intervened by the outer-layer of the clump ($W_1$) in the bottom panel. However, since $W_1$ is much optically thinner than $W_2$, the additional $W_1$ absorption is not very significant (see Figure 7). Thus, the double-layer absorbers in the bottom panel practically satisfy Equation 1.

4.2 Comparison with other objects

Previous studies suggest presence of the multi-layer/clumpy absorbers in other Seyfert galaxies besides NGC 5548. For example, NGC 3783 exhibits heavy eclipsing events, which can be naturally explained by two partially covering components with similar covering fractions (Mehdipour et al. 2017). In the case of NGC 1365,
produce the blue-shifted Fe-K absorption lines (e.g., Hagino et al. 2015) and/or scatter X-rays to produce P-Cygni like broad features (e.g., Hagino et al. 2016; Mizumoto et al. 2019a). On the other hand, such strong Fe-K features are not seen in the X-ray spectra of NGC 5548, presumably because the inner-wind may be fully ionized and/or optically thin. Here, we instead suggest a possibility of the thermal wind origin of the WA (e.g., Krolik & Kriss 2001; Mizumoto et al. 2019b). Materials in the outer-torus or accretion flow are heated by X-rays, and evaporated to produce thermally driven outflows (Figure 3). These ionized outflows with moderate velocities in the line-of-sight are presumably the WAs’ origin to produce the X-ray and UV absorption lines.

The unified AGN model assumes the BLR clouds obscured by the dust torus (e.g., Antonucci & Miller 1985; Urry & Padovani 1995). However, physical origin, geometry, and dynamics of the BLR clouds are still under discussion. Thus, relationship between the clumpy outer winds (obscures) of the VDPC model and the BLR clouds has not been fully elucidated. On one hand, Miyakawa et al. (2012) estimated the size and location of the partial absorbers and suggested that the partial covering clouds in the VDPC model are consistent with the BLR clouds. Similarly, Matthews et al. (2020) reproduced the BLR-like spectra assuming clumpy biconical disk winds illuminated by an AGN continuum. Maiolino et al. (2010) also claimed that the cometary clouds’ parameters are consistent with those of the BLR clouds. On the other hand, Kastra et al. (2014) argued that the obscurer in NGC 5548 should be farther away from the BLR because it partially absorbed the broad emission lines. According to the reverberation mapping observations of the STORM campaign (e.g., Williams et al. 2020), the radius of the NGC 5548 BLR is estimated to be several hundred times the Schwarzschild radius. Simulation by Kobayashi et al. (2018) predicted presence of the clumpy-outer winds farther than several hundred times the Schwarzschild radius, which corresponds to the position equal to or farther than the BLR. Therefore, we suppose the clumpy absorbers in NGC 5548 either correspond to the outer BLR clouds or are located beyond the BLR clouds.

### 4.3 Origin of the multiple absorbers

We have seen that X-ray spectral variation of NGC 5548 is naturally understood by introducing invariable ionized absorbers (W₁ and W₂) and variable double-layer clumpy absorbers (W₃ and W₄). The former corresponds to the “warm absorber” (WA; e.g., Kastra et al. 2000) and the latter corresponds to the “obscurer” (e.g., Kastra et al. 2014) in previous studies.

It is being recognized that “outflow” is a common phenomenon in accretion systems such as AGNs and X-ray binaries. In fact, global radiation-magnetohydrodynamic simulations (e.g., Takeuchi et al. 2013; Kobayashi et al. 2018) predict emergence of the clumpy outflow mostly due to the Rayleigh-Taylor instability. The disk wind outflow is hotter near the accretion disk, then cooled down as it moves farther away, transforming into the clumpy-outer wind at several hundred times the Schwarzschild radius. These clumpy-outer winds are likely origins of the double-layer obscurers.

The “hot-inner and clumpy-outer wind” picture successfully describes the characteristic broad Fe-K line shape and the time-lags commonly observed from narrow-line Seyfert galaxies such as 1H0707-495 (Mizumoto et al. 2019a). In the case of these high-mass accretion rate systems, the fast and thick hot-inner wind would
Figure 7. Spectral fitting results of a representative simultaneous observation by XMM-NuSTAR (X11; left) and by Suzaku XIS1-PIN (S4; right) within 0.3–50.0 keV. On the upper panel of both figures, black solid line is the best-fit model spectrum and the dotted-lines show individual continuum components. Those spectral components colored in light-blue, blue, green and red correspond to those with the same colors in the top-panel of Figure 6. Among all the four component going through the full absorbers (W₁ and W₄), the light-blue component is neither absorbed by the warm layer (W₁) nor the cold core (W₂). Blue and green components are absorbed only by the cold core and the warm layer, respectively. Red one is absorbed by both absorbers. Note that the red component and the blue component are hardly distinguishable in shape, since W₁ is much optically thinner than W₂. Orange and magenta dotted-lines describe the outer-disk reflection (pexmon) and the thermal plasma component (two-temperature mekal), respectively. The vertical axes show energy flux. The spectra are unfolded around the best-fit model using the XSPEC command xspec.

Figure 8 shows variations of the partial covering fraction and the total unobscured flux during 2000–2016. Relation between the two parameters is indicated in Figure 9. We can see that the unobscured flux and the partial covering fraction are independent, which is reasonable since the former is determined by the inner accretion rate, and the latter represents the geometrical configuration of the clumpy absorbers.

5 CONCLUSION

We carried out a broad-band (0.3–78 keV) X-ray spectral analysis of NGC 5548 using the data obtained by XMM-Newton, NuSTAR, and Suzaku in 26 observations from 2000 to 2016. We have found that the long-term spectral variations are explained by the “variable double partial covering” (VDPC) model, where variations of the partial covering fraction due to double-layer clumpy absorbers account for most of the spectral variations (Figure 3). We propose a simple spectral variation model with only three variable components; the soft excess spectral component, the cut-off power-law normalization, and the partial covering fraction of the clumpy absorbers. Above ~1 keV, the observed flux/spectral variation is explained by two essentially variable parameters; the partial covering fraction and the cut-off power-law normalization, where the former dictates change of the spectral shape. In contrast, the intrinsic photon index and all the other spectral parameters are not significantly variable for over 16 years.

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Figure 9. Partial covering fraction versus sum of the unobscured \( \text{disk}b \) and \( \text{cutoffPL} \) fluxes. The arrow indicates the time order.

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DATA AVAILABILITY
Observational data used in this paper are publicly available, and any additional data will be available on request.

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APPENDIX A: ENERGY SPECTRAL FITTING
As discussed in Section 3.3, we performed energy spectral fitting with all the available archival data. Figure A.1 and Figure A.2 show the results of the model fitting. The best-fit parameters are shown in Table 3.

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Figure A.1. Spectral fitting results of all the spectra taken by XMM-Newton. Black and red lines show the pn and RGS spectra, respectively. The vertical axes in both the panels are the same as those in Figure 4.
Figure A.1. Cont.
Figure A.1. Cont.
Figure A.2. Spectral fitting results of all the spectra taken by *Suzaku*. Black, red, and green lines show the XIS1, FI (XIS0&3), and PIN spectra, respectively. The vertical axes in both the panels are the same as those in Figure 4.