Absorption Variability of the Highly Obscured Active Galactic Nucleus NGC 4507

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ABSTRACT

We present a detailed study of the highly obscured active galaxy NGC 4507, performed using four Nuclear Spectroscopic Telescope Array (NuSTAR) observations carried out between May and August in 2015 (~ 130 ks in total). Using various phenomenological and physically motivated torus models, we explore the properties of the X-ray source and those of the obscuring material. The primary X-ray emission is found to be non-variable, indicating a stable accretion during the period of the observations. We find the equatorial column density of the obscuring materials to be ~ 2 × 10^{24} cm^{-2} while the line of sight column density to be ~ 7 × 10^{23} cm^{-2}. The source is found to be deeply buried with the torus covering factor ~ 0.85. We observe variability in the line-of-sight column density on a timescale of < 35 days. The covering factor of the Compton-Thick material is found to be ~ 0.35, in agreement with the results of recent X-ray surveys. From the variability of the line-of-sight column density, we estimate that the variable absorbing material is likely located either in the BLR or in the torus.

Key words: galaxies: active – galaxies: nuclei – galaxies: Seyfert – X-rays: galaxies – accretion: accretion discs – X-rays: individual: NGC 4507

1 INTRODUCTION

Active galactic nuclei (AGNs) are classified as Type-1 and Type-2, based on the presence or absence of broad optical/UV emission lines. The simplified unification model of AGNs can explain different types of AGN based on different inclination angles with respect to an obscuring torus (Antonucci 1993). In this framework, the Type-2 AGNs are seen edge-on (i.e. through the obscuring torus), while the Type-1 AGNs are observed face-on. Work carried out in the infrared has shown that the molecular torus is likely clumpy, rather than uniform (e.g., Nenkova et al. 2008a,b). The level of obscuration toward the X-ray source is typically parametrized with the hydrogen column density (N_H). Over the years, many AGNs are observed to show variable N_H in a timescale of hours to years (Risaliti et al. 2002). The short-term variations (on timescales of ~ days) are believed to be associated with the broad line emitting region (BLR), while the long-term variability (on timescales of months to years) are believed to be caused by the clumpy molecular torus (Markowitz et al. 2014). A growing number of AGNs, e.g., UGC 4203 (Risaliti et al. 2010), NGC 4151 (Puccetti et al. 2007), NGC 2992 (Weaver et al. 1996; Murphy et al. 2007), IC 751 (Ricci et al. 2016), NGC 6300 (Guainazzi 2002; Jana et al. 2020), have shown variable N_H by repeated X-ray observations. In recent years, a new sub-class of AGNs, known as changing-look AGN has emerged. In these objects, the line of sight column density can go from a Compton-thin (N_H < 10^{24} cm^{-2}) to a Compton-thick state (CT; N_H > 10^{24} cm^{-2}) level, or vice-versa. These events can lead to a dramatic change in the observed X-ray spectrum, which can go from being reflection dominated (in the Compton-thick state) to transmission dominated (in the Compton-thin state), or vice versa (Guainazzi 2002; Matt et al. 2003). These events are believed to be an important confirmation of the clumpiness of the BLR or torus (Guainazzi 2002; Elitzur 2012; Yaqoob et al. 2015; Jana et al. 2020).

NGC 4507 is a nearby (z = 0.0118) barred spiral galaxy, classified as SAB(s)ab (Tueller et al. 2008; Winter et al. 2009). NGC 4507 is reported to be one of the brightest (F_{2−10keV}^{wh} ~ 10^{-11} erg cm^{-2} s^{-1}) Seyfert 2 galaxies in the hard X-ray band (> 10 keV; Braito et al. 2013), and was detected by INTEGRAL/ISGRI, Swift/BAT and CGRO/OSS (Bassani et al. 1995; Ricci et al. 2017a). Over the years, several X-ray studies have revealed a variable N_H in the range of ~ 1 × 10^{23} cm^{-2} based on the observations by Ginga, ASCA, BeppoSAX, XMM-Newton and Chandra (Awaki et al. 1991; Comastri et al. 1998; Risaliti 2002; Matt et al. 2004; Marinucci et al. 2013).

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Table 1. Log of the NuSTAR observations of NGC 4507 studied here.

| ID  | UT Date       | Observation ID | Exp (s)     | Count s⁻¹ |
|-----|---------------|----------------|-------------|-----------|
| N1  | 2015-05-03    | 60102051002    | 30133       | 0.736 ± 0.005 |
| N2  | 2015-06-10    | 60102051004    | 34464       | 0.773 ± 0.005 |
| N3  | 2015-07-15    | 60102051006    | 32225       | 0.743 ± 0.005 |
| N4  | 2015-08-22    | 60102051008    | 30924       | 0.720 ± 0.005 |

Figure 1. Light curves of NGC 4507 in 3 – 60 keV energy ranges for the observation N1, N2, N3 and N4. Each points represent 500 s.

In this paper, we present a detailed X-ray spectral analysis of NGC 4507, obtained with four NuSTAR observations carried out between May and August 2015, with a total exposure time of ~130 ks. We aim to probe the variability of the obscuration from these broad-band X-ray observations. The paper is structured as follows. In §2, we present the data extraction procedure. The timing analysis is reported in §3. In §4, we report our detailed spectral analysis and our results. In §5, we discuss our findings, and compare them to previous studies. Finally, in §6, we summarize our findings.

2 OBSERVATION AND DATA REDUCTION

NuSTAR observed NGC 4507 four times between May and August 2015 with an interval of about five weeks between the different observations. In the present work, we studied all NuSTAR observations in a energy range of 3 – 60 keV (see Table 1). NuSTAR is a hard X-ray focusing telescope, consisting of two identical modules: FPMA and FPMB (Harrison et al. 2013). Data were reprocessed with the NuSTAR Data Analysis Software (NuSTARDAS, version 1.4.1). Cleaned event files were generated and calibrated by using the standard filtering criteria in the nupipeLine task, and the latest calibration data files available in the NuSTAR calibration database¹. The source and background products were extracted by considering circular regions with 90 arcsec radii, centred at the source coordinates and away from the source, respectively. The spectra and light curves were extracted using the nuproduct task. We re-binned the spectra to ensure that they had at least 20 counts per bin by using the grppha task.

3 TIMING ANALYSIS

We generated lightcurves in different energy ranges to study the variability in NGC 4507. Figure 1 shows the lightcurves in 3 – 60 keV energy range for observations N1, N2, N3 and N4. We calculated the fractional rms variability for the Galactic absorption in the direction of NGC 4507. Figure 1 shows the lightcurves in 3 – 60 keV energy range for observations N1, N2, N3 and N4. We calculated the fractional rms variability (Fvar) to study the variability of the source (Nandra et al. 1997; Edelson et al. 2002; Vaughan et al. 2003). During the observation N1, we obtained Fvar < 5% in 3 – 10 keV energy range. We did not observe any variability in 3 – 10 keV energy range in other observations. No variability was observed in 10 – 60 keV and 3 – 60 keV energy ranges. We also calculated the fractional rms variability in ~ 35 days timescale. We found the fractional rms variability, Fvar < 3% in 35 days timescale.

4 SPECTRAL ANALYSIS

We carry out the spectral analysis in the 3 – 60 keV energy range in XSPEC v12.10.2 (Arnaud 1996). For the spectral analysis, we used various spectral models, based on slab and torus geometries. In all models, we included phabs component for the Galactic absorption with abundances set to those of Anders & Grevesse (1989) and considered the photoelectric absorption cross-section of Verner et al. (1996). We fixed the Galactic column density to N_H = 6.8 × 10²⁰ cm⁻² (HI4PI Collaboration et al. 2016). We set the cosmological parameters to H₀ = 70 km s⁻¹ Mpc⁻¹, Ω M = 0.27 (Bennett et al. 2003). We calculated uncertainties of all spectral parameter at the 90% confidence level (1.6 σ).

4.1 Slab Model

We started our spectral analysis with a simple absorbed power-law model with exponential cutoff (zphabs*fabs*zcutofffpl1). Here, zphabs1 and fabs represent the line-of-sight absorption due to the hydrogen column density of zphabs1 and fabs were tied to have the same value. The zcutofffpl1 represents the primary continuum emission. This model did not provide an acceptable fit (χ² = 921 for 598 degrees of freedom or dof). We, therefore, added four components, representing the reprocessed emission (modelled with pekraV Magdziarz et al. 1998) and three Gaussian lines, representing Fe Kα, Fe Kβ, and Ni Kα lines. The pekraV model describes the reprocessed X-ray emission from a cold, neutral, semi-infinite slab. We set the reflection fraction (R_ref) to have a negative value, so that pekraV would only represent the reflection component. We linked the photon index, cutoff energy and normalization of pekraV to the values of the primary continuum. We set the iron abundance to one and the inclination angle to i = 60°. Along with this, a scattered component is also observed in obscured AGNs (Turner et al. 1997; Ueda et al. 2007; Gupta et al. 2021). Hence, we included one additional power-law component multiplied by a constant (const*zcutofffpl2). We linked the photon index (Γ) and normalization of this power-law component (zcutofffpl2) to the values of the primary continuum (zcutofffpl1). The 'constant' represents the scattering fraction (S_{Scat}). The line width of the Gaussian components were fixed to 50 eV, 10 eV, and 10 eV for Fe Kα, Fe Kβ, and Ni Kα, respectively. The final model reads in XSPEC as

phabs1 * (zphabs2*fabs*zcutofffpl1 + 3*gauss + pekraV + const*zcutofffpl2).

Here, phabs1 represent the Galactic absorption in the direction of

¹ http://heasarc.gsfc.nasa.gov/FTP/caldb/data/nustar/fpm/
² https://heasarc.gsfc.nasa.gov/xanadu/xspec/
the source. This model (hereafter the slab model) provided a good fit for all observations. The results show that the X-ray source is highly obscured during all observations, with \( N_H \) varying in the range \( 6.3 \pm 0.4 - 7.6 \pm 0.6 \times 10^{23} \) cm\(^{-2}\). The photon index was found to be roughly constant (\( \Gamma \sim 1.6 - 1.7 \)). The cutoff energy (\( E_{\text{cut}} \)) was obtained to be constant (\( E_{\text{cut}} \sim 121^{+107}_{-41} - 135^{+58}_{-23} \) keV) within the uncertainty. We detected strong Fe K\( \alpha \) line emission in all four epochs, with an equivalent width (EW) of \( 237 \pm 7 \) eV, \( 203 \pm 7 \) eV, \( 235 \pm 8 \) eV, and \( 233 \pm 8 \) eV in observations N1, N2, N3, and N4, respectively (see Table 1). The reflection was found to be moderate \( (R_{\text{eff}} \sim 0.4) \). The results obtained with this model are reported in Table 2. To test if the variability of \( N_H \) is real and not associated to a degeneracy with the continuum parameters (\( \Gamma \) and \( E_{\text{cut}} \)), we fitted all the spectra simultaneously with \( \Gamma \) and \( E_{\text{cut}} \) tied together. Using this approach, we found a similar variability of \( N_H \). We show the best-fitted unfolded spectra obtained with the slab model in the left panel of Figure 2, while the corresponding residuals are shown in the right panel of Figure 2. In the left panel of Fig 2, the black, red, green and blue solid lines represent the best-fitted slab model for N1, N2, N3 and N4, respectively, while the black, red, green and blue point represent the data for the observation N1, N2, N3 and N4, respectively. Figure 3 shows the confidence contour between the photon index (\( \Gamma \)) and line of sight column density (\( N_H \)).

### 4.2 MYTORUS

The PEXRAV model considers reflection from a semi-infinite slab. Hence, it might not provide an accurate representation of the reprocessed radiation in obscured AGN. Thus, to probe the complex absorber, one should consider a more physical torus model. For our spectral analysis, we used the physically-motivated torus model MYTORUS\(^3\) (Murphy & Yaqoob 2009; Yaqoob 2012). This model consists of an absorbing torus, surrounding the X-ray source, with a fixed opening angle of \( 60^\circ \) (i.e., a covering factor of 0.5). MYTORUS has three spectral components: the zeroth ordered component (MYTZ), a scattered/reprocessed component (MYTS), and a line component (MYTL). The MYTZ component describes the absorbed transmitted continuum emission in the line-of-sight. The MYTS component describes the reprocessed emission from the surrounding torus. The relative normalization (\( A_S \)) of the MYTS component is estimated using a `CONSTANT` in XSPEC. The MYTL component describes the Fe K\( \alpha \) and Fe K\( \beta \) line emission. The relative normalization of this component (\( A_L \)) is set to be the same as the relative normalization (\( A_S \)) of the MYTS component. Any deviation of \( A_S \) from unity could indicate a time-delay between MYTZ and MYTS components, or indicate

\(^3\) http://www.mytorus.com/
Table 2. The Slab model fitted spectral analysis result.

|   | N1       | N2       | N3       | N4       |
|---|----------|----------|----------|----------|
| (1) | $N_{\text{H}_\text{II}}^\text{ns}$ (10$^{23}$ cm$^{-2}$) | 7.6$^{+0.5}_{-0.6}$ | 6.3$^{+0.5}_{-0.4}$ | 7.4$^{+0.5}_{-0.4}$ | 6.7$^{+0.3}_{-0.5}$ |
| (2) | $\Gamma$ | 1.65$^{+0.06}_{-0.05}$ | 1.62$^{+0.05}_{-0.04}$ | 1.61$^{+0.05}_{-0.04}$ | 1.64$^{+0.07}_{-0.06}$ |
| (3) | $E_{\text{cut}}$ (keV) | 121$^{+107}_{-41}$ | 126$^{+61}_{-37}$ | 114$^{+62}_{-21}$ | 135$^{+58}_{-73}$ |
| (4) | $N_{\text{pl}}$ (10$^{-2}$ ph cm$^{-2}$ s$^{-1}$) | 2.26$^{+0.06}_{-0.04}$ | 1.76$^{+0.07}_{-0.08}$ | 1.88$^{+0.10}_{-0.09}$ | 1.82$^{+0.07}_{-0.06}$ |
| (5) | $R_{\text{ref}}$ | 0.38$^{+0.03}_{-0.12}$ | 0.46$^{+0.14}_{-0.23}$ | 0.29$^{+0.10}_{-0.14}$ | 0.41$^{+0.13}_{-0.24}$ |
| (6) | $f_{\text{scat}}$ (10$^{-2}$) | 0.97$^{+0.04}_{-0.03}$ | 0.97$^{+0.02}_{-0.02}$ | 1.21$^{+0.02}_{-0.02}$ | 0.81$^{+0.02}_{-0.02}$ |
| (7) | Fe K$\alpha$ | 6.38$^{+0.04}_{-0.04}$ | 6.35$^{+0.04}_{-0.04}$ | 6.37$^{+0.04}_{-0.03}$ | 6.33$^{+0.06}_{-0.05}$ |
| (8) | EW (eV) | 237$^{+34}_{-23}$ | 203$^{+35}_{-23}$ | 253$^{+56}_{-6}$ | 233$^{+8}_{-7}$ |
| (9) | Norm (10$^{-4}$ ph cm$^{-2}$ s$^{-1}$) | 3.15$^{+0.93}_{-0.68}$ | 2.15$^{+0.42}_{-0.61}$ | 2.93$^{+0.45}_{-0.62}$ | 2.61$^{+0.45}_{-0.68}$ |
| (10) | Fe K$\beta$ | 6.99$^{+0.07}_{-0.06}$ | 7.08$^{+0.05}_{-0.06}$ | 6.98$^{+0.09}_{-0.07}$ | 7.04$^{+0.07}_{-0.08}$ |
| (11) | EW (eV) | $< 24$ | $< 26$ | $< 31$ | $< 23$ |
| (12) | Norm (10$^{-6}$ ph cm$^{-2}$ s$^{-1}$) | 2.06$^{+0.04}_{-0.12}$ | 1.91$^{+0.02}_{-0.38}$ | 4.34$^{+0.10}_{-0.97}$ | 3.87$^{+1.53}_{-2.13}$ |
| (13) | Ni K$\alpha$ | 7.47$^{+0.10}_{-0.07}$ | 7.45$^{+0.17}_{-0.13}$ | 7.45$^{+0.11}_{-0.16}$ | 7.62$^{+0.07}_{-0.10}$ |
| (14) | EW (eV) | $< 48$ | $< 35$ | $< 32$ | $< 105$ |
| (15) | Norm (10$^{-5}$ ph cm$^{-2}$ s$^{-1}$) | 8.77$^{+1.34}_{-1.53}$ | 2.38$^{+1.35}_{-1.43}$ | 1.83$^{+0.71}_{-0.88}$ | 10.01$^{+1.45}_{-1.85}$ |
| (16) | $\chi^2$/dof | 632/590 | 620/625 | 615/613 | 567/586 |

(1) Line of sight hydrogen column density ($N_{\text{H}_\text{II}}^\text{ns}$) in 10$^{23}$ cm$^{-2}$, (2) photon index ($\Gamma$) of the primary emission, (3) cut-off energy ($E_{\text{cut}}$) in keV, (4) power-law normalization ($N_{\text{pl}}$) in 10$^{-2}$ ph cm$^{-2}$ s$^{-1}$, (5) reflection fraction ($R_{\text{ref}}$), (6) fraction of scattered primary emission ($f_{\text{scat}}$), (7) Fe K$\alpha$ line energy in keV, (8) equivalent width of the Fe K$\alpha$ line in eV, (9) normalization of the Fe K$\alpha$ line in 10$^{-4}$ ph cm$^{-2}$ s$^{-1}$, (10) Fe K$\beta$ line energy in keV, (11) equivalent width of the Fe K$\beta$ line in eV, (12) normalization of the Fe K$\beta$ line in 10$^{-6}$ ph cm$^{-2}$ s$^{-1}$, (13) Ni K$\alpha$ line energy in keV, (14) equivalent width of the Ni K$\alpha$ line in eV, (15) normalization of the Ni K$\alpha$ line in 10$^{-5}$ ph cm$^{-2}$ s$^{-1}$, (16) $\chi^2$ value for degrees of freedom (dof), (17) 2 – 10 keV observed flux $F_{\text{obs}}^{2-10}$ in 10$^{-11}$ erg cm$^{-2}$ s$^{-1}$, (18) 2 – 10 keV intrinsic luminosity $L_{\text{int}}^{2-10}$ in 10$^{43}$ erg s$^{-1}$, (19) 0.1 – 100 keV intrinsic luminosity ($L_{\text{int}}^{0.1-100}$) in 10$^{44}$ erg s$^{-1}$, (20) Fe K$\alpha$ line luminosity ($L_{\text{K}\alpha}$) in 2 – 10 keV energy ranges in 10$^{42}$ erg cm$^{-2}$ s$^{-1}$.

Different geometries of the material with different $N_{\text{H}_\text{II}}$, or a torus covering factor different than 0.5 (Yaqoob 2012). The MYTORS model can be used in two configurations: coupled (MYTC) and decoupled (MYTD). The coupled configuration describes an uniform torus, while the decoupled configuration could be used to describe a clumpy torus (Yaqoob 2012).

4.2.1 Coupled configuration

We started our analysis with MYTORS model using the coupled configuration. In XSPEC the model reads as:

```
PHABS * (ZPOWERLAW1*MYTC + CONST1*MYTS + CONST2*GSMOOTH*MYTL + CONST3*ZPOWERLAW2 + ZGAUSS).
```

In this model, the photon index ($\Gamma$), equatorial hydrogen column density ($N_{\text{H}_\text{II}}^\text{Eq}$), inclination angle ($i$) and normalization of MYTS and MYTL components are tied to those of the MYTZ component. As recommended, the relative normalization of MYTS and MYTL components are tied, i.e. $A_S = A_L$. The photon index and normalization of the scattered component (ZPOWERLAW2) are tied to those of the primary continuum (ZPOWERLAW1). We also added a Gaussian com-

![Figure 3](image-url)
ponent for Ni Kα line emission, and used a Gaussian convolution model gsmooth to convolve the MYTL component.

We fitted all the four spectra simultaneously, setting the inclination angle (θ_incl) to be the same. We found that θ = 61.8° ± 3.7 degrees, in agreement with the Seyfert 2 classification of the source (e.g., Beckmann & Shrader 2012). The equatorial column density was obtained to be $N_H^{\text{eq}} = 2.3_{-0.9}^{+0.6} \times 10^{24} \text{ cm}^{-2}$ for N1, N2, N3, and N4 observations, respectively. Here, we must note that the variation of equatorial column density ($N_H^{\text{eq}}$) is not plausible on timescales of months, and one may need to include an extra varying absorber to address this (e.g., Ricci et al. 2016). The line-of-sight column density is defined as (Murphy & Yaqoob 2009),

$$N_{\text{los}} = N_H^{\text{eq}} \left[ 1 - 4 \cos \theta \right]^{1/2}.$$  

The line-of-sight column density ($N_{\text{los}}$) is found to be $7.5^{+4.2}_{-2.2} \times 10^{23} \text{ cm}^{-2}$ for N1, N2, N3, and N4 observation, respectively. The photon index was obtained to be roughly constant ($\Gamma \sim 1.7$). The relative normalization ($A_s$) was observed to deviate from unity in all four observations, indicating delayed reprocessed emission or different geometries of the absorbing material with different $N_H$, or a different geometry from that assumed by mytorus. The parameters obtained by using this model are reported in Table A1. Figure B1 shows the best-fit spectrum obtained with the MYTC model. The confidence contour between $N_H^{\text{eq}}$ and $\Gamma$ are shown in Figure C1.

4.2.2 Decoupled configuration

MYTC considers an uniform obscuring torus, however, the torus is likely to be clumpy, and the MYTC model does not have the flexibility to accurately capture the variations in the line-of-sight column density. Thus, we used the decoupled configuration of MYTORUS (MYTD), which mimics a clumpy torus. This can be achieved by decoupling the column density of the MYTS component from that of the MYTZ component. In this configuration, we set the inclination angle of MYTS and MYTL components to 0° to mimic the backside reflection from the far side material. Thus, the column density represents the global averaged column density of the obscured material ($N_H^{\text{tor}}$). The inclination angle of the MYTZ component is instead set to 90°. MYTZ represents the direct component, and its column density is the line of sight column density ($N_{\text{los}}^{\text{tor}}$) (Yaqoob 2012). The model reads in XSPEC as:

$$\text{PHABS} \times \text{zpowerlaw} \times \text{MYTZ(90)} + \text{const1} \times \text{MYTS(0)} + \text{const2} \times \text{gsmooth} \times \text{MYTL(0)} + \text{const3} \times \text{zpowerlaw} + \text{zgauss}.$$

The spectral analysis, performed with the MYTD model, provided a good fit for all observations. We found, however, that the averaged column density of the obscured materials ($N_H^{\text{tor}}$) varied in the range of $\sim 1.9 - 2.4 \times 10^{23} \text{ cm}^{-2}$. Within the observation period of ~4 months, the global obscuration properties is unlikely to change. Thus, we fitted all four spectra simultaneously with $N_H^{\text{tor}}$ tied together, and obtained $N_H^{\text{tor}} = 2.7^{+0.6}_{-0.5} \times 10^{23} \text{ cm}^{-2}$. The line of sight column density varied in the range of $7.0 \pm 1.4 - 8.2 \pm 1.3 \times 10^{23} \text{ cm}^{-2}$. The detailed spectral analysis result using MYTD model is given in Table A2. MYTD model fitted unfolded spectra are shown in Figure B2. Figure C2 shows the confidence contour between $N_H^{\text{tor}}$ and $N_H^{\text{los}}$ for all observations, fitted with MYTD.

4.3 Borus02

The borus02 model consists of a spherical homogeneous torus with two polar cutouts in conical shape (Baloković et al. 2018). Unlike the MYTORUS model, the opening angle of the torus is a free parameter in borus02. The borus02 model also allows to separate the line of sight column density ($N_{\text{los}}^{\text{tor}}$) from the torus/obscuring material column density ($N_H^{\text{tor}}$). The model setup with borus02 model reads in XSPEC as,

$$\text{PHABS} \times (\text{zphabs2} \times \text{cabs} \times \text{zcutoffpl}) + \text{const1} \times \text{borus02} + \text{const2} \times \text{zcutoffpl}).$$

$\text{zphabs2} \times \text{cabs} \times \text{zcutoffpl}$ represents the absorbed direct primary emission. ‘const1’ represents the relative normalization ($A_s$) of the reprocessed component. const2$\times$zcutoffpl represents the scattered primary emission while const2 is the scattering fraction ($f_{\text{scat}}$). The photon index ($\Gamma$), cutoff energy ($E_{\text{cut}}$), normalization of cut-offpl1, zcutoffpl2, and borus02 model are linked together. The column densities of cabs and zphabs2 models are tied together, and represents the line of sight column density obscuration.

We simultaneously fitted all four spectra with borus02 model with $N_{\text{los}}^{\text{tor}}$, inclination angle ($\theta$), iron abundance ($A_{\text{Fe}}$) and torus covering factor ($C_{\text{tor}}$) tied together. First, we fitted the spectra with a fixed cutoff energy at $E_{\text{cut}} = 400 \text{ keV}$ and iron abundance at Solar value ($A_{\text{Fe}} = 1$). We allowed the cutoff energy to vary, and the fit improved by $\Delta \chi^2 = 8$ for 1 dof. The fit improved significantly ($\Delta \chi^2 = 34$ for 1 dof) when we allowed the Fe abundance ($A_{\text{Fe}}$) to vary, which resulted in a sub-Solar value in all four observations, with $A_{\text{Fe}} \sim 0.47 \pm 0.07$. We found a column density of the obscuring material of $N_H^{\text{tor}} = 2.6^{+0.7}_{-0.6} \times 10^{23} \text{ cm}^{-2}$. The line of sight column density was found to be $9.4^{+0.6}_{-0.5} \times 10^{23}, 8.3_{-0.7}^{+0.6} \times 10^{23}, 9.8_{-0.6}^{+0.5} \times 10^{23}$, and $8.4^{+0.5}_{-0.5} \times 10^{23} \text{ cm}^{-2}$, for N1, N2, N3 and N4, respectively. We obtained the inclination angle to be $i = 64.5^{+5.2}_{-6.3}$°. The torus covering factor is found to be $C_{\text{tor}} = 0.58 \pm 0.10$ with the torus opening angle to be obtained in the range of $47^{\circ} - 60^{\circ}$. The results obtained with this fit are reported in Table A3. borus02 model fitted unfolded spectra are shown in Figure B3. The confidence contour between $N_H^{\text{los}}$ and $N_H^{\text{tor}}$ is shown in Figure C3 for all observations, fitted with borus02.

4.4 XCLUMPY

Next, we used the xclumpy model (Tanimoto et al. 2019, 2020) to fit the NuSTAR spectra of NGC 4507. The model geometry is based on the CLUMPY infrared model developed by Nenkova et al. (2008a,b). This model assumes a power-law distribution of clumps in the radial direction between inner and outer radii, and a normal distribution in the elevation direction. The free parameters of this model are the equatorial column density ($N_H^{\text{eq}}$), the torus angular width ($\sigma_{\text{tor}}$), and the inclination angle ($\theta$). From the equatorial column density, one can easily calculate the line-of-sight column density using the following equation (Tanimoto et al. 2019),

$$N_{\text{los}} = N_{\text{eq}} \times \exp\left(-\frac{(i - \pi/2)^2}{\sigma_{\text{tor}}^2}\right).$$  

The xclumpy model has two components, xclumpy_R and xclumpy_L, representing the reprocessed and line emission, respectively. The full model reads in XSPEC as,

4 https://sites.astro.caltech.edu/~mislabv/download/
5 https://github.com/AtsushiTanimoto/XClumpy
The first term is the direct primary emission. The second and third terms represent the reprocessed and line emission, respectively. The last term represents the scattered primary emission. The parameters of xclumpy_R and xclumpy_L models are linked. The photon index ($\Gamma$), cutoff energy ($E_{\text{cut}}$) and normalization of xclumpy_R model are linked with the xclumpy1. The const1 and const2 represent the relative normalization of the line emission ($A_L$) and scattering fraction ($f_{\text{Scat}}$).

We fitted all the four spectra simultaneously using the xclumpy model, with $N_H^{\text{eq}}$ and $i$ tied together. We fitted the spectra with cutoff energy fixed at $E_{\text{cut}} = 370$ keV, since the xclumpy table consider a fixed cut-off energy at 370 keV. We found that the inclination angle is $i = 64.1^{\circ}$, while the equatorial column density is $N_H^{\text{eq}} = 2.1^{+0.6}_{-0.5} \times 10^{24}$ cm$^{-2}$. The line of sight density was obtained to be, $N_H^{\text{los}} = 8.1^{+2.4}_{-1.5} \times 10^{23}$, $7.0^{+1.5}_{-1.2} \times 10^{23}$, $8.2^{+1.5}_{-2.5} \times 10^{23}$ and $7.1^{+1.5}_{-1.1} \times 10^{23}$, for N1, N2, N3, and N4, respectively. The torus angular width we obtained is roughly constant with $\sigma_{\text{tor}} \sim 25-26^\circ$. The results of this spectral analysis are reported in Table A4. Figure B4 shows the xclumpy model fitted unfolded spectra. Figure C4 shows the confidence contour between the $N_H^{\text{eq}}$ and $\sigma_{\text{tor}}$, fitted with the xclumpy model.

### 4.5 RXTORUS

Next, we used RXTORUS model (Paltani & Ricci 2017) for the spectral analysis. RXTORUS is based on the ray-tracing code for X-ray reprocessing code REFLEX. This model includes absorption and reflection from the torus with varying torus covering factor. The covering factor is defined as the ratio of minor to major axis of the torus ($i/R$). The RXTORUS model has three components: absorbed primary emission (xclumpy_cont), scattered emission (xclumpy_scat) and line emission (xclumpy LocalDateTime). The scattered emission and line emission are merged into a reprocessed component (xclumpy_rprc). The model reads in XSPEC as,

\[
\text{PHABS(xclumpy_cont*cut-off*1 + xclumpy*cut-off*2 + xclumpy_rprc + xclumpy_scat)}
\]

Here, const1 represents the relative normalization. ‘const*cut-off’ is the scattered primary emission. The line of sight column density is given by,

\[
N_H^{\text{los}} = N_H^{\text{eq}} \sqrt{1 - \frac{\cos i}{1/R^2}}.
\]

We fitted all the spectra simultaneously with the inclination angle and equatorial column density tied together. The normalization of the primary emission and xclumpy_rprc components are tied together. The equatorial column density is found to be $N_H^{\text{eq}} = 2.1^{+0.6}_{-0.5} \times 10^{24}$ cm$^{-2}$, while the line of sight column density varied between $-6.0^{+1.9}_{-1.1} \times 7.0^{+1.6}_{-1.8} \times 10^{23}$ cm$^{-2}$. The covering factor ($i/R$) was obtained to be $\sim 0.41 - 0.42$. The results of the spectral analysis are presented in Table A5. Figure B5 shows the RXTORUS model fitted unfolded spectra. The confidence contour between the $N_H^{\text{eq}}$ and $\sigma_{\text{tor}}$ is shown in Figure C5.

\[\text{Table 3. Variation of line of sight column density ($N_H^{\text{los}}$), obtained from different models}\]

| ID   | Slab | MYTC | MYTD | borus02 | xclumpy | RXTORUS |
|------|------|------|------|---------|---------|---------|
| N1   | 7.6^{+0.5}_{-0.4} | 7.5^{+0.2}_{-0.2} | 8.2^{+0.3}_{-0.3} | 9.4^{+0.6}_{-0.6} | 8.1^{+0.4}_{-0.4} | 6.9^{+0.4}_{-0.4} |
| N2   | 6.3^{+0.5}_{-0.4} | 6.5^{+0.2}_{-0.2} | 7.0^{+0.3}_{-0.3} | 8.3^{+0.6}_{-0.6} | 7.0^{+0.4}_{-0.4} | 6.0^{+0.4}_{-0.4} |
| N3   | 7.4^{+0.5}_{-0.4} | 8.1^{+0.2}_{-0.2} | 8.1^{+0.3}_{-0.3} | 9.8^{+0.6}_{-0.6} | 8.2^{+0.4}_{-0.4} | 7.0^{+0.4}_{-0.4} |
| N4   | 6.7^{+0.5}_{-0.4} | 6.5^{+0.2}_{-0.2} | 7.1^{+0.3}_{-0.3} | 8.4^{+0.6}_{-0.6} | 7.1^{+0.4}_{-0.4} | 6.1^{+0.4}_{-0.4} |

$N_H^{\text{los}}$ is in unit of $10^{23}$ cm$^{-2}$.

### 5 DISCUSSION

We presented the detailed spectral analysis result of NGC 4507 using NuSTAR observations in 3–60 keV energy range. We carried out the spectral analysis with the slab model, MYTORUS, borus02, xclumpy and RXTORUS models.

#### 5.1 Comparison among different Spectral Models

Using the results obtained by our X-ray spectral analysis, we explore the nuclear and obscuration properties of NGC 4507. The main difference among different spectral models is how they treat the reprocessed emission. While PEXRAV assumed reflection from a cold, semi-infinite slab, physically motivated torus-based model assumed different torus structures and geometries. Therefore, the fits performed using the different models return slightly different results. As the absorber is likely not uniform, given the column density variability found here and in previous works (e.g., Braito et al. 2013), we do not discuss the results obtained considering the MYTC model.

The spectral analysis carried out using different models resulted in different values of $\Gamma$. The slab model, MYTC, xclumpy and RXTORUS models returned with $\Gamma \sim 1.6 - 1.7$, while the borus02 model indicated slightly flatter spectra with $\Gamma \sim 1.5$. For all models, the photon index was roughly constant across the different observations.

The variation of $N_H^{\text{los}}$ was observed to be similar as obtained from different spectral models. The slab model showed that $N_H^{\text{los}}$ varied in the range of $6 - 8 \times 10^{23}$ cm$^{-2}$, while MYTC and xclumpy showed that $N_H^{\text{los}}$ varied in the range of $7 - 9 \times 10^{23}$ cm$^{-2}$. The RXTORUS, borus02 and xclumpy models also returned with similar value of $N_H^{\text{los}}$, varying in the range of $6 - 9 \times 10^{23}$ cm$^{-2}$. The $N_H^{\text{los}}$ variation, obtained from different spectral model, is listed in Table 3.

### 5.2 Nuclear Properties

Our spectral analysis indicated very little variation of the photon index during the observations, and the parameter can be considered constant within the uncertainties. The cutoff energy is found to be in the range of $E_{\text{cut}} \sim 121^{+47}_{-38}$ keV - $135^{+58}_{-73}$ keV from the slab model and $75^{+29}_{-15} - 97^{+46}_{-18}$ keV from borus02 model. This is consistent with typical values found for nearby AGN (e.g., Ricci et al. 2018; Baloković et al. 2020). Both models indicate a constant cutoff energy within our observations. The intrinsic luminosity in the 2–10 keV energy band is found to be in the range of $L_{\text{bol}} \sim 3.0 \pm 0.2 - 3.6 \pm 0.3 \times 10^{43}$ erg s$^{-1}$. Vasudevan & Fabian (2009) estimated the bolometric correction factor $\kappa_{\text{bol}}$, $2-10$ keV $\approx 15 - 30$ for $J_{\text{edd}} > 0.1$, and $\kappa_{\text{bol}, 2-10}$ keV $\approx 10$ for $J_{\text{edd}} \leq 0.1$. Considering the bolometric correction factor $\kappa_{\text{bol}, 2-10}$ keV $\approx 20$, we obtained, the bolometric luminosity in the range of $L_{\text{bol}} = (5.9 \pm 0.4 - 7.2 \pm 0.5) \times 10^{44}$ erg s$^{-1}$.
The Eddington ratio would be $\lambda_{\text{Edd}} = L_{\text{bol}}/L_{\text{Edd}} \sim 0.1$, considering the black hole mass, $M_{\text{BH}} = 4.5 \times 10^7 M_\odot$ (Marinucci et al. 2012). However, Winter et al. (2009) reported of a higher mass ($M_{\text{BH}} \sim 10^{8.4} M_\odot$), which would lead to $\lambda_{\text{Edd}} \sim 10^{-1.7}$. Even if we consider $\lambda_{\text{bol}} \sim 10$, $\lambda_{\text{Edd}}$ would be $10^{-2}$. Regardless the assumption of mass or bolometric factor, the Eddington ratios of the source is consistent with that of nearby Seyfert galaxies (Wu & Liu 2004; Koss et al. 2017).

5.3 Obscuration properties

From the spectral analysis, we obtained several torus parameters, such as the line of sight column density ($N_{\text{H}}^{\text{los}}$), from the slab model, MYTC, MYTD, borus02 & xclumpy), the averaged column density of the obscuring materials ($N_{\text{H}}^{\text{E}}, \text{from MYTD \& borus02}$), the equatorial column density ($N_{\text{H}}^{\text{Ed}}$, from MYTC, xclumpy & RXTorus), and the torus covering factor ($C_{\text{tor}}$ or $\theta_{\text{tor}}$; from borus02, xclumpy & RXTorus). We obtained similar variations of $N_{\text{H}}^{\text{los}}$ from different spectral models (see Section 5.1). The equatorial column density ($N_{\text{H}}^{\text{Eq}}$) was found to be $\sim 2.1 \pm 0.6 \times 10^{24}$ cm$^{-2}$, whereas the line of sight column density was found to be $\sim 6 \times 8 \times 10^{23}$ cm$^{-2}$.

The observed column density of the obscuring material was obtained to be $N_{\text{tor}}^{\text{los}} = 2.2^{+0.6}_{-0.5} \times 10^{24}$ cm$^{-2}$ from the MYTD and borus02 model, respectively. Braito et al. (2013) applied the MYTD model to the XMM-Newton, Suzaku, and BeppoSAX observations obtained between 1997 and 2007, and obtained $N_{\text{tor}}^{\text{los}}$ in the range of $\sim (2.4 - 3.5) \times 10^{23}$ cm$^{-2}$, which is consistent with our findings. In our analysis, the angular dispersion of the torus is obtained as $\sigma_{\text{tor}} \sim 24^\circ - 26^\circ$. One can easily estimate the torus covering factor ($C_{\text{tor}}$) using Equation (2) (Yamaeda et al. 2020). Using $\theta = \pi/2 - i$, as the elevation angle, we can write Equation 2 as,

$$N_{\text{H}}^{\text{los}} = N_{\text{H}}^{\text{Eq}} \left[ \exp \left( -\frac{\theta}{\sigma_{\text{tor}}} \right)^2 \right].$$

For $N_{\text{H}}^{\text{los}} \sim 10^{22}$ cm$^{-2}$, we obtained corresponding elevation angle $\theta \sim 56^\circ - 61^\circ$. This transforms to the torus covering factor $C_{\text{tor}} = \sin \theta \sim 0.83 - 0.87$. Considering Compton-thick obscuration, i.e. setting $N_{\text{H}}^{\text{los}} = 10^{24}$ cm$^{-2}$ in Equation (4), we obtained a covering factor $C_{\text{tor}} \sim 0.34 - 0.37$. Our X-ray spectral analysis with the borus02 & RXTorus models returned $C_{\text{tor}} \sim 0.6$ and $\sim 0.4$.

Ricci et al. (2017b) showed that the radiation pressure from the AGN could efficiently expel dusty gas when $\lambda_{\text{Edd}} \geq 10^{-1.5}$. They showed for the Compton thin material ($N_{\text{H}}^{\text{los}} = 10^{22-24}$ cm$^{-2}$), a high covering factor is observed ($C_{\text{tor}} \sim 0.85$) for $4 \times 10^{-4} \leq \lambda_{\text{Edd}} \leq 10^{-1.5}$, while a much lower covering factor ($C_{\text{tor}} \sim 0.4$) is observed for $\lambda_{\text{Edd}} \geq 10^{-1.5}$. On the other hand, for the Compton-thick material ($N_{\text{H}}^{\text{los}} > 10^{24}$ cm$^{-2}$), the covering factor is predicted to be $C_{\text{tor}} \sim 0.2 - 0.3$ (see also, Ricci et al. 2015). We obtained an Eddington ratio of $\lambda_{\text{Edd}} \sim 0.1$ for $M_{\text{BH}} \sim 10^{7.65} M_\odot$ (Marinucci et al. 2012). Our estimated torus covering factor is $C_{\text{tor}} \sim 0.85$ which is higher than the predicted value for $\lambda_{\text{Edd}} \sim 0.1$. However, if we consider a higher mass, $M_{\text{BH}} = 10^{8.4} M_\odot$ (Winter et al. 2009), the Eddington ratio is $\lambda_{\text{Edd}} \sim 10^{-2}$. For this Eddington ratio, the covering factor predicted by Ricci et al. (2017b) ($C_{\text{tor}} \sim 0.85$) is consistent with the results we obtained from the fit with the xclumpy model. This seems to suggest a higher mass of the SMBH. However, the study of Ricci et al. (2017b) was conducted using a large sample, that show a variation of covering factor and/or $\lambda_{\text{Edd}}$ in a wide range. Hence, it will not be correct to prefer the higher mass for the SMBH solely from this. On the other hand, the covering factors for the Compton-thick material is obtained to be $C_{\text{tor}}^{\text{Edd}} \sim 0.35 - 0.37$, which is slightly higher than the value predicted by Ricci et al. (2017b).

The AGN absorber is complex and there may exist multiple absorbers along the line of sight. In a similar scenario with two absorbers, one absorber can be considered as varying while the other absorber is non-varying. In IC 751, Ricci et al. (2016) were able to disentangle the column density of the varying clouds from the non-varying absorbers. In NGC 4507, $N_{\text{H}}^{\text{los}}$ changed about $\sim 15 - 20\%$ in $\sim 35$ days timescale. This implies that $\sim 80 - 85\%$ $N_{\text{H}}^{\text{los}}$ did not change and there may exist a non-varying absorber. We tried to disentangle the non-varying absorber from the varying one by adding an additional absorber during the spectral analysis. We allowed one absorber to vary and kept the other absorber tied across the observations. However, we were not able to disentangle two absorbers as we could not constraint the column density of two absorbers.

5.4 Location of the Reprocessing Clouds

One can easily estimate the distance of the absorbing cloud from the central SMBH from the $N_{\text{H}}^{\text{los}}$ variability (for details, see Risaliti et al. 2007; Marinucci et al. 2013; Ricci et al. 2016). Assuming that the X-ray source size ($D_S$) and cloud size ($D_C$) are similar ($D_S \sim D_C$), one can easily calculate the transverse velocity of the cloud as $V_K = D_S/C_{\text{tor}}$, where $C_{\text{tor}}$ is light-crossing time. Considering Keplerian motion of the cloud, the distance of the absorbing cloud from the central SMBH is given by,

$$R_C = \frac{GM_{\text{BH}}T_C^2}{D_S}.$$  

(5)

The source size could be set to $D_S \approx 10 R_g$ (Marinucci et al. 2013), where $R_g = GM_{\text{BH}}/c^2$ is gravitational radius. We, therefore, obtain

$$R_C \approx 0.07 R_g^2 M_7 T_{10}^2 \text{pc}.$$  

(6)

Here, $R_g = D_S/10 R_g$, $M_7$ is in unit of $10^7 M_\odot$ and $T_{10}$ is the crossing time in unit of 10 light-days. The total time span of each NuSTAR observation was $\sim 70$ ks, and no significant variability is observed on that timescale. Thus, the location of the obscuring material must be, $R_{\text{min}} > 0.002$ pc ($\sim 2.4$ light-days). Marinucci et al. (2013) did not observe variability in $N_{\text{H}}^{\text{los}}$ in timescale of $\sim 1.5$ months, although they observed variability on timescales of $\sim 4$ months. From that, they concluded the location of the absorbing material to be $\sim 7 - 40$ pc, i.e. farther from the SMBH than the BLR. In this work, we observed $N_{\text{H}}^{\text{los}}$ variability on timescales of $\sim 35$ days which implies that the location of the absorbing clouds is $R_{\text{max}} \leq 4$ pc, considering $M_{\text{BH}} = 10^{7.65} M_\odot$. The different result for the location of the obscuring material could be due to different absorbers. Considering a mass of $M_{\text{BH}} = 10^{8.4} M_\odot$ (Winter et al. 2009), the absorbing cloud location would be $R_C \sim 0.01 - 0.21$ pc.

Optical reverberation mapping studies have shown that the radius of the BLR scales with the squared root of X-ray luminosity. Considering the H$\beta$ lag, Kaspi et al. (2005) obtained

$$R_{\text{BLR}}^{10 \text{~hr}} \sim 0.86 \times \left( \frac{L_2 - 10}{10^{43} \text{ergs/s}} \right)^{0.53}.$$  

(7)

Considering the average intrinsic luminosity of the source as $L_X \sim 3.2 \times 10^{43}$ erg s$^{-1}$, we obtained, $R_{\text{BLR}} \approx 16$ lt-days ($\sim 0.013$ pc). This indicates that the absorbing cloud is located beyond the BLR. From infrared studies, the near and mid-IR emitting regions are
found to scale as the squared root of the X-ray luminosity. From the reverberation mapping in the K-band, the inner edge of the torus ($R_{\text{NIR}}$) is estimated to be (Tristram & Schartmann 2011)

$$\log \frac{R_{\text{NIR}}}{1\text{pc}} = -23.10 + 0.5 \log (L_{14-195}).$$  \hspace{1cm} (8)

where $L_{14-195}$ is the intrinsic X-ray luminosity in the 14–195 keV energy band. One can also estimate the radius of the mid-IR emitting region ($R_{\text{MIR}}$; Tristram & Schartmann 2011):

$$\log \frac{R_{\text{MIR}}}{1\text{pc}} = -21.62 + 0.5 \log (L_{14-195}).$$  \hspace{1cm} (9)

The 70-months averaged luminosity of NGC 4507 is $\log (L_{14-195}) = 43.96$ (Rici et al. 2017a). Using this, we obtained $R_{\text{NIR}} \approx 0.08$ pc $\approx 95$ light-days, and $R_{\text{MIR}} \approx 2.32$ pc $\approx 2760$ light-days.

From the above calculations, we estimated that $R_{\text{BLR}} \approx 0.013$ pc, $R_{\text{NIR}} \approx 0.08$ pc and $R_{\text{MIR}} \approx 2.3$ pc. The location of the repocessed material is estimated to be $R_C \approx 0.01 - 21$ pc (for $M_{\text{BH}} \sim 10^{8.4} M_\odot$) or $R_C \approx 0.002 - 4$ pc (for $M_{\text{BH}} \sim 10^{7.65} M_\odot$). These results indicate that the material responsible for the $N_H$ variability could be associated either to the BLR or to the torus.

5.5 Comparison with Previous X-ray Observation

NGC 4507 was extensively observed in the X-ray wavebands over the years. Figure 4 shows the evolution of the line of sight column density ($N_H^{\text{los}}$). The blue points are taken from the literature. The red points in the inset figures are from the current work. Figure 5 shows the variation of (a) the $2 - 10$ keV observed flux, (b) the $2 - 10$ keV intrinsic luminosity and (c) photon index ($\Gamma$) between 1990 and 2015. The blue points are taken from the literature. The inset figures in each panel show the variation of the spectral parameters from this work.

Figure 4. Evolution of the line of sight column density ($N_H^{\text{los}}$) in $10^{23}$ cm$^{-2}$ between 1990 and 2015. The blue points are taken from the work of Awaki et al. (1991); Comastri et al. (1998); Risaliti et al. (2002); Matt et al. (2004); Marinucci et al. (2013); Braito et al. (2013). The inset figure shows the variation of the spectral parameters for this work.

Figure 5. Evolution of (a) the line of sight column density ($N_H^{\text{los}}$) in $10^{23}$ cm$^{-2}$, (b) the $2 - 10$ keV observed flux ($F_{\text{2-10}}$) in $10^{-11}$ erg cm$^{-2}$ s$^{-1}$, (c) the $2 - 10$ keV intrinsic luminosity ($L^{\text{int}}_{2-10}$) in $10^{39}$ erg s$^{-1}$, (d) the photon index ($\Gamma$) between 1990 and 2015. The blue points are taken from the literature. The inset figures in each panel show the variation of the spectral parameters from this work.

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6 SUMMARY

We studied NGC 4507 using NuSTAR observations obtained between May 2015 and August 2015. Using the phenomenological slab model and several physically motivated torus-based models, we studied the properties of the X-ray emission and of the obscuring gas. We also estimated various properties of the obscuring material, e.g., the line-of-sight column density, the average density of the obscuring material, and its covering factor. From the variability of the absorption, we also provided some refined constraints on the location of the obscuring materials. Our key findings are given below.

(i) We found that the equatorial column density of the torus is Compton-thick ($N_H^{eq} \sim 2 \times 10^{24} \text{ cm}^{-2}$).

(ii) During the period of the observations analyzed here, the line of sight column density of the torus was found to vary in the range of $N_H^{los} \sim 6 - 9 \times 10^{23} \text{ cm}^{-2}$. The variability of $N_H^{los}$ is observed on timescales of $\lesssim 35$ days.

(iii) No variability is observed in the primary emission during the observation period.

(iv) The source was found to be buried in the obscuring medium, with the torus having a high covering factor $C_{cov} \sim 0.83 - 0.85$. For the Compton-thick material, the torus covering factor was found to be $C_{tor} \sim 0.34 - 0.37$ which is in good agreement with average covering factors of the obscuring materials for nearby AGN (e.g., Ricci et al. 2015).

(v) The reprocessing material is found to be located either at the BLR or in the torus.

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DATA AVAILABILITY

We used archival data of NuSTAR observatories for this work. All the models used in this work, are publicly available. Appropriate links are given in the text.

REFERENCES

Anders E., Grevesse N., 1989, Geochimica Cosmochimica Acta, 53, 197
Antonucci R., 1993, ARA&A, 31, 473
Arnaud K. A., 1996, in Jacoby G. H., Barnes J., eds, Astronomical Society of the Pacific Conference Series Vol. 101, Astronomical Data Analysis Software and Systems V, p. 17
Awaki H., Kunieda H., Tawara Y., Koyama K., 1991, PASJ, 43, L37
Baloković M., et al., 2018, ApJ, 854, 42
Baloković M., et al., 2020, ApJ, 905, 41
Bassani L., Malaguti G., Jourdain E., Roques J. P., Johnson W. N., 1995, ApJ, 444, L73
Beckmann V., Shrader C. R., 2012, Active Galactic Nuclei
Bennett C. L., et al., 2003, ApJS, 148, 1
Braito V., Ballo L., Reeves J. N., Risaliti G., Ptak A., Turner T. J., 2013, MNRAS, 428, 2516
Comastri A., Vignali C., Cappi M., Matt G., Audano R., Awaki H., Ueno S., 1998, MNRAS, 295, 443
Edelson R., Turner T. J., Pounds K., Vaughan S., Markowitz A., Marshall H., Dobbie P., Warwick R., 2002, ApJ, 568, 610
Elitzur M., 2012, ApJ, 747, L33
Fiore F., Laor A., Elvis M., Nardini E., Risaliti G., Maraschi L., 2003, ApJ, 596, 539
Fiore F., Laor A., Elvis M., Nardini E., Risaliti G., 2007, MNRAS, 382, 17
Fiore F., Laor A., 2013, ApJ, 770, 103
Gupta K. K., et al., 2021, MNRAS, 504, 428
HI4PI Collaboration et al., 2016, A&A, 594, A116
Harrison F. A., et al., 2013, ApJ, 770, 130
Jana A., Chatterjee A., Kumari N., Nandi P., Naik S., Patra D., 2020, MNRAS, 499, 5396
Kaspi S., Maoz D., Netzer H., Peterson B. M., Vestergaard M., Jannuzi B. T., 2005, ApJ, 629, 61
Koss M., et al., 2017, ApJ, 850, 74
Magdziarz P., Blass O., Zdziarski A. A., Johnson W. N., Smith D. A., 1998, MNRAS, 301, 179
Marinucci A., Bianchi S., Nardini E., Matt G., 2003, ApJ, 578, 130
Marinucci A., Bianchi S., Nardini E., Matt G., 2004, MNRAS, 349, 1549
Markowitz A. G., 2017, ApJ, 840, 1403
Matt G., 2018, A&A, 594, 116
Matt G., Bianchi S., D’Abedetto F., Martocchia A., 2004, A&A, 421, 473
Murphy K. D., 2009, MNRAS, 397, 1549
Murphy K. D., 2010, MNRAS, 401, 1520
Nandra K., Gehrels N., 2001, ApJ, 552, 1549
Nandra K., George I. M., Mushotzky R. F., Turner T. J., 2007, ApJ, 670, 103
Orosz J. A., Markwardt C. B., 2005, ApJ, 622, 103
Page L., et al., 2014, MNRAS, 439, 1403
APPENDIX A: TABLES

APPENDIX B: SPECTRA

APPENDIX C: CONTOUR

This paper has been typeset from a TeX/LaTeX file prepared by the author.
Table A1. MYTORUS model fitted spectral analysis result for coupled configuration.

| ID | \(N_{H}^{\text{Eq}}\) (10\(^{24}\) cm\(^{-2}\)) | \(N_{H}^{\text{obs}}\) (10\(^{23}\) cm\(^{-2}\)) | \(\Gamma\) | \(N_{\text{PL}}\) (10\(^{-2}\) ph cm\(^{-2}\) s\(^{-1}\)) | \(\theta\) (degree) | \(A_{S}\) | \(f_{\text{Scat}}\) (10\(^{-2}\)) | \(\chi^2/\text{dof}\) |
|----|---------------------------------|---------------------------------|-----|-------------------------------|--------------|------|----------------|------------------|
| N1 | \(2.3^{+0.6}_{-0.9}\)          | \(7.5^{+2.2}_{-2.2}\)          | 1.75^{+0.06}_{-0.05} | 3.01^{+0.24}_{-0.17} | 61.8^{+3.7}_{-9.9} | 0.79^{+0.11}_{-0.16} | 1.49^{+0.02}_{-0.03} | 664/592       |
| N2 | \(2.0^{+0.7}_{-0.8}\)          | \(6.5^{+2.7}_{-1.6}\)          | 1.71^{+0.04}_{-0.05} | 2.15^{+0.12}_{-0.22} | "          | 0.71^{+0.08}_{-0.15} | 1.96^{+0.02}_{-0.03} | 620/627       |
| N3 | \(2.5^{+0.7}_{-0.7}\)          | \(8.1^{+2.9}_{-1.9}\)          | 1.70^{+0.03}_{-0.05} | 2.89^{+0.12}_{-0.23} | "          | 0.78^{+0.15}_{-0.24} | 1.04^{+0.02}_{-0.03} | 634/611       |
| N4 | \(2.0^{+0.6}_{-0.8}\)          | \(6.5^{+2.4}_{-1.4}\)          | 1.75^{+0.06}_{-0.05} | 2.09^{+0.18}_{-0.13} | "          | 0.73^{+0.12}_{-0.15} | 1.84^{+0.03}_{-0.08} | 584/588       |

(1) ID of the observation, (2) equatorial hydrogen column density \(N_{H}^{\text{Eq}}\) in 10\(^{24}\) cm\(^{-2}\), (3) line of sight hydrogen column density \(N_{H}^{\text{obs}}\) in 10\(^{23}\) cm\(^{-2}\), (4) photon index \(\Gamma\) of the primary emission, (5) power-law normalization \(N_{\text{PL}}\) in 10\(^{-2}\) ph cm\(^{-2}\) s\(^{-1}\), (6) inclination angle \(\theta\) in degree, (7) relative normalization of the line emission \(A_{S}\), (8) fraction of scattered primary emission \(f_{\text{Scat}}\).

Table A2. MYTORUS model fitted spectral analysis result for decoupled configuration.

| ID | \(N_{H}^{\text{obs}}\) (10\(^{23}\) cm\(^{-2}\)) | \(N_{H}^{\text{tor}}\) (10\(^{23}\) cm\(^{-2}\)) | \(\Gamma\) | \(N_{\text{PL}}\) (10\(^{-2}\) ph cm\(^{-2}\) s\(^{-1}\)) | \(A_{S}\) | \(f_{\text{Scat}}\) (10\(^{-2}\)) | \(\chi^2/\text{dof}\) |
|----|---------------------------------|---------------------------------|-----|-------------------------------|------|----------------|------------------|
| N1 | \(8.2^{+1.3}_{-1.3}\)          | \(2.2^{+0.6}_{-0.5}\)          | 1.67^{+0.04}_{-0.05} | 3.00^{+0.18}_{-0.31} | 0.71^{+0.03}_{-0.05} | 0.70^{+0.03}_{-0.02} | 663/592     |
| N2 | \(7.0^{+1.4}_{-1.3}\)          | "                               | 1.65^{+0.08}_{-0.09} | 2.15^{+0.09}_{-0.14} | 0.70^{+0.02}_{-0.04} | 1.40^{+0.01}_{-0.03} | 624/625     |
| N3 | \(8.1^{+1.5}_{-1.5}\)          | "                               | 1.60^{+0.06}_{-0.06} | 2.69^{+0.05}_{-0.12} | 0.60^{+0.06}_{-0.08} | 0.96^{+0.06}_{-0.02} | 633/610     |
| N4 | \(7.1^{+1.3}_{-1.4}\)          | "                               | 1.64^{+0.06}_{-0.09} | 1.98^{+0.06}_{-0.07} | 0.71^{+0.05}_{-0.04} | 1.30^{+0.05}_{-0.03} | 589/588     |

(1) ID of the observation, (2) line of sight hydrogen column density \(N_{H}^{\text{obs}}\) in 10\(^{23}\) cm\(^{-2}\), (3) global averaged hydrogen column density of the obscured materials \(N_{H}^{\text{tor}}\) in 10\(^{23}\) cm\(^{-2}\), (4) photon index \(\Gamma\) of the primary emission, (5) power-law normalization \(N_{\text{PL}}\) in 10\(^{-2}\) ph cm\(^{-2}\) s\(^{-1}\), (6) relative normalization of the line emission \(A_{S}\), (7) fraction of scattered primary emission \(f_{\text{Scat}}\).

Parameter (3) are tied across the observations.

Table A3. borus02 model fitted spectral analysis result.

| ID | \(N_{H}^{\text{obs}}\) (10\(^{23}\)) | \(N_{H}^{\text{tor}}\) (10\(^{23}\)) | \(\Gamma\) | \(E_{\text{cut}}\) (keV) | \(N_{\text{PL}}\) (10\(^{-2}\) ph cm\(^{-2}\) s\(^{-1}\)) | \(C_{\text{tor}}\) | \(\theta\) (degree) | \(A_{\text{Fe}}\) (A\(_{\odot}\)) | \(f_{\text{Scat}}\) (10\(^{-2}\)) | \(\chi^2/\text{dof}\) |
|----|----------------------------|----------------------------|------|----------------|----------------------------|-------|--------------|----------------|----------------|----------------|------------------|
| N1 | \(9.3^{+0.6}_{-0.6}\)      | \(2.6^{+0.7}_{-0.6}\)     | 1.48^{+0.06}_{-0.05} | 75^{+29}_{-15}     | 1.57^{+0.08}_{-0.11}     | 0.58^{+0.10}_{-0.08} | 64.5^{+52.2}_{-6.3} | 0.47^{+0.07}_{-0.06} | 1.02^{+0.11}_{-0.13} | 656/592     |
| N2 | \(8.3^{+0.7}_{-0.6}\)      | "                        | 1.50^{+0.02}_{-0.04} | 97^{+46}_{-18}     | 1.39^{+0.12}_{-0.10}     | "          | "            | "            | "            | 1.74^{+0.04}_{-0.03} | 620/629   |
| N3 | \(9.8^{+0.6}_{-0.6}\)      | "                        | 1.47^{+0.04}_{-0.04} | 91^{+30}_{-23}     | 1.51^{+0.16}_{-0.08}     | "          | "            | "            | "            | 1.14^{+0.08}_{-0.12} | 631/613   |
| N4 | \(8.4^{+0.5}_{-0.5}\)      | "                        | 1.46^{+0.04}_{-0.04} | 89^{+43}_{-12}     | 1.31^{+0.11}_{-0.13}     | "          | "            | "            | "            | 1.61^{+0.09}_{-0.12} | 577/592   |

(1) ID of the observation, (2) line of sight hydrogen column density \(N_{H}^{\text{obs}}\) in 10\(^{23}\) cm\(^{-2}\), (3) averaged hydrogen column density of the obscured materials \(N_{H}^{\text{tor}}\) in 10\(^{23}\) cm\(^{-2}\), (4) cut-off energy \(E_{\text{cut}}\) in keV, (5) photon index \(\Gamma\) of the primary emission, (6) power-law normalization \(N_{\text{PL}}\) in 10\(^{-2}\) ph cm\(^{-2}\) s\(^{-1}\), (7) covering factor the obscured materials, (8) inclination angle \(\theta\) in degree, (9) iron abundances \(A_{\text{Fe}}\) in solar value \(A_{\odot}\), (10) fraction of scattered primary emission \(f_{\text{Scat}}\).

Parameter (3) and (8) are tied across the observations.
### Table A4. XCLUMPY model fitted spectral analysis result.

| ID | $t_{\text{Eq}}^{\text{NH}_2}$ (10$^{-24}$) | $N_{\text{H}_2}^{\text{los}}$ (10$^{23}$) | $\Gamma$ | $N_{\text{PL}}$ (10$^{-2}$ ph cm$^{-2}$ s$^{-1}$) | $\sigma_{\text{tor}}$ (degree) | $i$ (degree) | $A_t$ | $f_{\text{scat}}$ (10$^{-2}$) | $\chi^2$/dof |
|---|---|---|---|---|---|---|---|---|---|
| N1 | 2.1$^{+0.6}_{-0.3}$ | 8.1$^{+2.4}_{-1.5}$ | 1.67$^{+0.06}_{-0.12}$ | 1.78$^{+0.10}_{-0.18}$ | 26.3$^{+8.4}_{-5.3}$ | 64.1$^{+7.4}_{-4.9}$ | 0.78$^{+0.10}_{-0.08}$ | 1.78$^{+0.42}_{-0.65}$ | 652/595 |
| N2 | " | 7.0$^{+1.6}_{-1.1}$ | 1.66$^{+0.12}_{-0.07}$ | 0.88$^{+0.14}_{-0.18}$ | 24.9$^{+4.6}_{-7.1}$ | * | 0.84$^{+0.07}_{-0.11}$ | 4.30$^{+0.53}_{-0.86}$ | 616/628 |
| N3 | " | 8.2$^{+1.6}_{-2.3}$ | 1.63$^{+0.09}_{-0.12}$ | 1.63$^{+0.18}_{-0.25}$ | 25.7$^{+5.2}_{-5.8}$ | * | 0.76$^{+0.08}_{-0.11}$ | 2.15$^{+0.34}_{-0.29}$ | 629/613 |
| N4 | " | 7.1$^{+1.5}_{-2.2}$ | 1.59$^{+0.12}_{-0.15}$ | 1.31$^{+0.18}_{-0.12}$ | 25.2$^{+4.6}_{-4.9}$ | * | 0.88$^{+0.10}_{-0.09}$ | 2.57$^{+0.27}_{-0.38}$ | 579/590 |

1. ID of the observation, 2. equatorial hydrogen column density ($N_{\text{H}_2}^{\text{eq}}$) in 10$^{24}$ cm$^{-2}$, 3. line of sight hydrogen column density ($N_{\text{H}_2}^{\text{los}}$) in 10$^{23}$ cm$^{-2}$, 4. photon index ($\Gamma$) of the primary emission, 5. power-law normalization ($N_{\text{PL}}$) in 10$^{-2}$ ph cm$^{-2}$ s$^{-1}$, 6. torus covering factor ($r/R$), 7. inclination angle ($i$) in degree, 8. relative normalization of the line emission ($A_t$), 9. fraction of scattered primary emission ($f_{\text{scat}}$).  

\* parameter (2) and (7) are tied across the observations.

### Table A5. RXTORUS model fitted spectral analysis result.

| ID | $t_{\text{Eq}}^{\text{NH}_2}$ (10$^{-24}$) | $N_{\text{H}_2}^{\text{los}}$ (10$^{23}$) | $\Gamma$ | $i/R$ | $N_{\text{PL}}$ (10$^{-2}$ ph cm$^{-2}$ s$^{-1}$) | $A_{\text{tor}}$ | $f_{\text{scat}}$ (10$^{-2}$) | $\chi^2$/dof |
|---|---|---|---|---|---|---|---|---|
| N1 | 2.1$^{+0.6}_{-0.5}$ | 6.9$^{+2.4}_{-1.6}$ | 1.63$^{+0.07}_{-0.06}$ | 66.7$^{+4.5}_{-7.2}$ | 0.42$^{+0.07}_{-0.09}$ | 1.75$^{+0.08}_{-0.07}$ | 1.04$^{+0.15}_{-0.11}$ | 1.58$^{+0.45}_{-0.75}$ | 652/596 |
| N2 | " | 6.9$^{+0.9}_{-1.1}$ | 1.58$^{+0.10}_{-0.08}$ | " | 0.41$^{+0.09}_{-0.07}$ | 1.46$^{+0.12}_{-0.16}$ | 1.03$^{+0.14}_{-0.19}$ | 2.14$^{+0.09}_{-0.12}$ | 615/629 |
| N3 | " | 7.0$^{+1.6}_{-1.8}$ | 1.60$^{+0.06}_{-0.07}$ | " | 0.42$^{+0.08}_{-0.07}$ | 1.70$^{+0.08}_{-0.12}$ | 0.97$^{+0.06}_{-0.12}$ | 1.74$^{+0.08}_{-0.11}$ | 625/615 |
| N4 | " | 6.1$^{+1.5}_{-2.1}$ | 1.57$^{+0.06}_{-0.07}$ | " | 0.41$^{+0.08}_{-0.08}$ | 1.36$^{+0.10}_{-0.11}$ | 1.06$^{+0.16}_{-0.21}$ | 2.11$^{+0.18}_{-0.22}$ | 578/592 |

1. ID of the observation, 2. equatorial hydrogen column density ($N_{\text{H}_2}^{\text{eq}}$) in 10$^{24}$ cm$^{-2}$, 3. line of sight hydrogen column density ($N_{\text{H}_2}^{\text{los}}$) in 10$^{23}$ cm$^{-2}$, 4. photon index ($\Gamma$) of the primary emission, 5. inclination angle ($i$) in degree, 6. torus covering factor ($r/R$), 7. power-law normalization ($N_{\text{PL}}$) in 10$^{-2}$ ph cm$^{-2}$ s$^{-1}$, 8. relative normalization of the reprocessed emission ($A_{\text{tor}}$), 9. fraction of scattered primary emission ($f_{\text{scat}}$).  

\* parameter (2) and (7) are tied across the observations.

Line of sight hydrogen column density is calculated using Equation 3.
Table A6. Variation of line-of-sight column density ($N_H^{\text{los}}$)

| Date (YYYY-MM-DD) | $N_H^{\text{los}}$ ($10^{23}$ cm$^{-2}$) | $F_{2-10\,	ext{keV}}$ ($10^{-11}$ erg cm$^{-2}$ s$^{-1}$) | Observatories | Ref. |
|-------------------|------------------------------------------|-------------------------------------------------|----------------|------|
| 1990-07-07         | 4.9 ± 0.7                                | 1.6*                                            | Ginga          | Awaki et al. (1991) |
| 1994-02-12         | 3.26 ± 0.7                               | 2.1*                                            | ASCA           | Comastri et al. (1998) |
| 1996-03-05         | 3.41 ± 0.11                              | 1.8 ± 0.2                                       | RXTE           | Guainazzi et al. (1997) |
| 1997-12-26         | 7.00 ± 0.45                              | 1.8*                                            | BeppoSAX       | Braito et al. (2013) |
| 1998-07-02         | 6.20 ± 0.50                              | 1.6*                                            | BeppoSAX       | Braito et al. (2013) |
| 1999-01-13         | 6.40 ± 0.95                              | 0.87*                                           | BeppoSAX       | Risaliti (2002) |
| 2001-01-04         | 5.0 ± 0.25                               | 1.2*                                            | XMM-Newton     | Braito et al. (2013) |
| 2001-03-15         | 4.0*                                     | 2.37*                                           | Chandra        | Matt et al. (2004) |
| 2007-12-20         | 8.2 ± 0.6                                | 0.6*                                            | Suzaku         | Braito et al. (2013) |
| 2010-06-24         | 8.7 ± 0.7                                | 7.7 ± 0.3                                       | XMM-Newton     | Marinucci et al. (2013) |
| 2010-07-03         | 9.7 ± 0.9                                | 8.0 ± 0.3                                       | XMM-Newton     | Marinucci et al. (2013) |
| 2010-07-13         | 7.6 ± 1.1                                | 8.4 ± 0.2                                       | XMM-Newton     | Marinucci et al. (2013) |
| 2010-07-23         | 9.4 ± 1.1                                | 8.0 ± 0.3                                       | XMM-Newton     | Marinucci et al. (2013) |
| 2010-08-03         | 8.0 ± 0.7                                | 7.5 ± 0.7                                       | XMM-Newton     | Marinucci et al. (2013) |
| 2010-12-02         | 6.5 ± 0.7                                | 10.0 ± 0.4                                      | Chandra        | Marinucci et al. (2013) |
| 2015-05-03         | 0.79 ± 0.03                              | 0.98 ± 0.07                                     | NuSTAR         | This work |
| 2015-06-10         | 0.69 ± 0.02                              | 1.07 ± 0.08                                     | NuSTAR         | This work |
| 2015-07-15         | 0.78 ± 0.03                              | 0.94 ± 0.06                                     | NuSTAR         | This work |
| 2015-08-22         | 0.73 ± 0.02                              | 1.01 ± 0.04                                     | NuSTAR         | This work |

* no error is quoted.
Figure B1. Unfolded spectra fitted with MYTC model for observation N1 (top left), N2 (top right), N3 (bottom left) and N4 (bottom right). Upper panel: Green points represent the data. The black, blue, red, magenta and brown lines represent the total emission, primary emission, reprocessed emission, line emission (Fe Kα, Fe Kβ and Ni Kα), and scattered primary emission. Bottom panel: Corresponding residual.
Figure B2. Unfolded spectra fitted with MYTD model for observation N1 (top left), N2 (top right), N3 (bottom left) and N4 (bottom right). Upper panel: Green points represent the data. The black, blue, red, magenta and brown lines represent the total emission, primary emission, reprocessed emission, line emission (Fe \( K\alpha \), Fe \( K\beta \) and Ni \( K\alpha \)), and scattered primary emission. Bottom panel: Corresponding residual.
Figure B3. Unfolded spectra fitted with borus02 model for observation N1 (top left), N2 (top right), N3 (bottom left) and N4 (bottom right). Upper panel: Green points represent the data. The black, blue, red, magenta and brown lines represent the total emission, primary emission, reprocessed emission, line emission (Fe Kα, Fe Kβ and Ni Kα), and scattered primary emission. Bottom panel: Corresponding residual.
Figure B4. Unfolded spectra fitted with xclumpy model for observation N1 (top left), N2 (top right), N3 (bottom left) and N4 (bottom right). Upper panel: Green points represent the data. The black, blue, red, magenta and brown lines represent the total emission, primary emission, reprocessed emission, line emission (Fe K\(\alpha\), Fe K\(\beta\) and Ni K\(\alpha\)), and scattered primary emission. Bottom panel: Corresponding residual.
Figure B5. Unfolded spectra fitted with RXTorus model for observation N1 (top left), N2 (top right), N3 (bottom left) and N4 (bottom right). Upper panel: Green points represent the data. The black, blue, red, magenta and brown lines represent the total emission, primary emission, reprocessed emission, line emission (Fe Kα, Fe Kβ and Ni Kα), and scattered primary emission. Bottom panel: Corresponding residual.
**Figure C1.** Confidence contour between the photon index ($\Gamma$) and equatorial column density ($N_{\text{HI}}$) in $10^{22}$ cm$^{-2}$, fitted with the MYTC model. The red, blue, magenta and orange lines represent the observation from N1, N2, N3 and N4, respectively. The solid and dashed line represent the contour at 1 $\sigma$ and 2 $\sigma$ level, respectively.

**Figure C2.** Confidence contour between the line of sight column density ($N_{\text{H}}$) and averaged torus column density in $10^{22}$ cm$^{-2}$, fitted with the MYTD model. The red, blue, magenta and orange lines represent the observation from N1, N2, N3 and N4, respectively. The solid and dashed line represent the contour at 1 $\sigma$ and 2 $\sigma$ level, respectively.

**Figure C3.** Confidence contour between the equatorial column density ($N_{\text{HI}}^{\text{Eq}}$) and averaged torus column density in $10^{22}$ cm$^{-2}$, fitted with the xclumpy model. The red, blue, magenta and orange lines represent the observation from N1, N2, N3 and N4, respectively. The solid and dashed line represent the contour at 1 $\sigma$ and 2 $\sigma$ level, respectively.

**Figure C4.** Confidence contour between the line of sight column density ($N_{\text{HI}}$) and torus angular width, fitted with the xclumpy model. The red, blue, magenta and orange lines represent the observation from N1, N2, N3 and N4, respectively. The solid and dashed line represent the contour at 1 $\sigma$ and 2 $\sigma$ level, respectively.
Figure C5. Confidence contour between the equatorial column density ($N_{\text{H}}^{\text{eq}}$) and covering factor, fitted with the RXTorus model. The red, blue, magenta and orange lines represent the observation from N1, N2, N3 and N4, respectively. The solid and dashed line represent the contour at 1 $\sigma$ and 2 $\sigma$ level, respectively.