AstroSat View of Spectral Transition in the Changing-look Active Galaxy NGC 1566 during the Declining Phase of the 2018 Outburst

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Abstract

NGC 1566 is a changing-look active galaxy that exhibited an outburst during 2017–2018 with a peak in 2018 June. We triggered AstroSat observations of NGC 1566 twice in 2018 August and October during its declining phase. Using the AstroSat observations, along with two XMM-Newton observations in 2015 (pre-outburst) and 2018 June (peak outburst), we found that the X-ray power law, the soft X-ray excess, and the disk components showed extreme variability during the outburst. Especially, the soft excess was negligible in 2015 before the outburst, increased to a maximum level by a factor of $>200$ in 2018 June, and reduced dramatically by a factor of $\sim 7.4$ in 2018 August and became undetectable in 2018 October. The Eddington fraction ($L/L_{\rm Edd}$) increased from $\sim 0.1\%$ (2015) to $\sim 5\%$ (2018 June) and then decreased to $\sim 1.5\%$ (2018 August) and 0.3% (2018 October). Thus, NGC 1566 made a spectral transition from a high soft-excess state to a negligible soft-excess state at a few percent of the Eddington rate. The soft excess is consistent with warm Comptonization in the inner disk that appears to have developed during the outburst and disappeared toward the end of the outburst over a timescale comparable to the sound-crossing time. The multiwavelength spectral evolution of NGC 1566 during the outburst is most likely caused by the radiation pressure instability in the inner regions of the accretion disk in NGC 1566.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16)

1. Introduction

Active galactic nuclei (AGNs) are luminous objects in the universe that vary across the entire electromagnetic band from radio to X-rays and $\gamma$-rays. A small number of AGNs exhibit large-amplitude variability or outbursts in their optical/UV and X-ray luminosity on timescales of months to a few years. These sources change their spectroscopic appearance owing to strongly variable broad Balmer emission lines and are classified as “changing-look” AGNs (CL-AGNs; Matt et al. 2003). Observationally, the number of CL-AGNs is growing (Ruan et al. 2016; Ross et al. 2018; Yang et al. 2018; Stern et al. 2018; MacLeod et al. 2019). The drastic variations in the optical/UV continuum, broad emission lines, and the X-ray spectrum of CL-AGNs result in a change in the formal classification of their Seyfert types (Bianchi et al. 2005; Shappee et al. 2014). The physical mechanism responsible for the multiwavelength variability in CL-AGNs is not well understood. The possible explanations are radiation pressure instabilities in the disk (Sniegowska et al. 2020), changing the inner-disk radius leading to state transition (Noda & Done 2018; Ruan et al. 2019), tidal disruptive events (TDEs; Ricci et al. 2020), variation in the accretion rate (Elitzur et al. 2014), and variable obscuration causing a switch from a Compton-thick to Compton-thin absorption in the X-ray band (Guainazzi 2002; Matt et al. 2003). For most of the sources, the changing-look behavior has been attributed intrinsic to the source (Sheng et al. 2017; Mathur et al. 2018; Stern et al. 2018; Hutsemékers et al. 2019). NGC 1566 is a nearby ($z = 0.00502$) Seyfert galaxy and the nearest CL-AGN that consists of a supermassive black hole (SMBH) at the center, with the black hole mass estimated using various techniques of $\log(M_{\text{BH}}/M_\odot) \sim 6.92$ (stellar velocity dispersion; Woo & Urry 2002), $7.11 \pm 0.32$ (spiral pitch angle; Davis et al. 2014), $6.83 \pm 0.3$ (molecular gas dynamics; Combes et al. 2019), and $6.48_{-0.11}^{+0.14}$ (Bry emission line; Smajić et al. 2015). This source exhibits recurrent outbursts. Based on spectrophotometric monitoring of the NGC 1566 nucleus during 1970–1985, Alloin et al. (1986) reported four periods of the outburst activities over the 15 yr long baseline. Each of them lasted for $\sim 1300$ days with a quiescent phase of a few months to years between two consecutive burst periods. The AGN remained at the highest flux state for less than a month. In the activity period from 1981 January to 1985 August, Alloin et al. (1986) found a series of rapid bursts, each with a typical rise time of $\sim 20$ days and a long exponential decay of $\sim 400$ days. Parker et al. (2019) noticed another single outburst in the 105-month-long Swift/BAT$^5$ light curve covering the period from 2004 December to 2013 August. During this outburst in 2010, the source attained an outburst peak of 4 mcrab from a low flux level of 0.8 mcrab in the 15–200 keV band in 2–3 months. Further, in 2018 an increase in the hard X-ray flux was observed byucci et al. (2018) and followed by Swift (Ferrigno et al. 2018). Oknyansky et al. (2019) mention that the beginning of this burst is uncertain owing to the lack of data during the rising period, but the light curves in ASAS-SN V band and NEOWISE mid-infrared showed that the flux started increasing around 2017 September (Cutri et al. 2018; Dai et al. 2018). After a rising period of $\sim 9$ months, the source reached the peak of the burst around 2018 June–July (Parker et al. 2019; Oknyansky et al. 2019, 2020).

Oknyansky et al. (2019, 2020) analyzed the UV and X-ray data of NGC 1566 acquired with Swift and the MASTER Global Robotic Network from 2007 to 2019. During this period, the source was in a low flux state until 2015, followed by an

https://swift.gsfc.nasa.gov/results/bst05mon/216
Table 1

AstroSat Observations of NGC 1566

| Date       | Obs. ID            | FUV-G1 | UVIT | F154W | SXT |
|------------|--------------------|--------|------|-------|-----|
| yyyy/mm/dd |                    | Exp    | Rate | Exp   | Rate | Exp | Rate |
|            |                    | (ks)   | (counts s⁻¹) | (ks) | (counts s⁻¹) | (counts s⁻¹) | (ks) | (counts s⁻¹) |
| 2018/11/08 | T02_08ST01_90000002296 | 2.5    | 4.69 ± 0.05 | 3.5  | 11.03 ± 0.07 | 0.27 ± 0.04 | 23.3 | 0.637 ± 0.006 |
| 2018/10/22 | T03_02OT01_90000002444 | 4.8    | 1.21 ± 0.03 | 1.5  | 3.56 ± 0.06 | 0.23 ± 0.06 | 19.1 | 0.186 ± 0.004 |

Notes. The net source and background count rates with 1σ errors are listed.

a Background-subtracted net source count rate derived from the first order of FUV-G1 in the 1225–1852 Å band.

b The mean background-subtracted net source count rate of the F154W filter extracted from a circular region of 7″ radius (shown with a green circle in Figure 2).

c The mean background count rate derived from three circular regions of 7″ radius each (shown with white circles in Figure 2).

d Background-subtracted net source count rate in the 0.5–6.5 keV band extracted from a circular region of 15′′ radius.

observational gap during 2015 to 2018. The flux of the source started rising, and a strong outburst was observed in 2018, peaking during the end of June to the beginning of July. A substantial increase in the X-ray flux by a ~1.5 order of magnitude was observed, followed by an increase in the UV flux. The maximum measured X-ray flux of 1.1 × 10⁻¹⁰ erg cm⁻² s⁻¹ on MJD 58,309 is ~50 times larger than the minimum recorded flux of 2.2 × 10⁻¹² erg cm⁻² s⁻¹ on MJD 56,936 (Oknyansky et al. 2019). Using the post-brightening observations, Oknyansky et al. (2020) reported three more rebrightening states of the source during the decline of the outburst on (i) 2018 November 17–2019 January 10 (MJD 58,440–58,494), (ii) 2019 April 29–2019 June 19 (MJD 58,603–58,654), and (iii) 2019 July 27–2019 August 6. They found the soft X-ray band (0.5–2 keV) to be more variable (by a factor of ~30) than the hard X-ray (2–10 keV) band (by a factor of ~20) during the 9 months after the maximum of the burst. Parker et al. (2019) investigated the X-ray spectral properties of the source using simultaneous XMM-Newton and NuSTAR observations performed on 2018 June 26, when the outburst was at the peak, and XMM-Newton data alone acquired on 2015 November 6, when the source was at a low flux state. The 2018 July X-ray spectrum showed a power-law component, soft X-ray excess emission, distant and relativistic reflection components, and two warm absorbing components with low column densities (N_H ~ 2.5 × 10²⁰ cm⁻²). The quiescent X-ray spectrum of the 2015 observation is dominated by AGNs with negligible contribution from extended emission. They estimated the Eddington ratios of 0.2% and ~5% for the 2015 and 2018 data, respectively, using the 2–10 keV X-ray flux, a bolometric correction factor of 20, and the black hole mass from Woo & Urry (2002). They found the black hole spin parameter to be a < 0.25.

Here we investigate the far-UV (FUV)/X-ray spectral evolution of the source during the decline period of the 2018 June–July outburst using observations performed with AstroSat (Singh et al. 2014). We also analyze the UV/X-ray XMM-Newton data from the 2015 and 2018 observations to find the evolution of different spectral components when compared with our AstroSat observations. While the XMM-Newton X-ray data are already analyzed by Parker et al. (2019), the joint UV/X-ray broadband study has not been performed using these observations. We organize the paper as follows. We describe the observation and data reduction methods in Section 2. We describe the spectral analyses in Section 3, followed by results and discussion in Section 4. Finally, we conclude our results in Section 5.

2. Observation and Data Reduction

We triggered Target of Opportunity (ToO) observations of NGC 1566 with the AstroSat (Singh et al. 2014) mission during the declining phase of the 2018 outburst. We observed the source on 2018 August 11 (MJD 58,340.46; ObsID: T02_08ST01_9000002296, hereafter obs1) and on 2018 October 22 (MJD 58,412.78; ObsID: T03_02OT01_9000002444, obs2). These observations were performed after ~30 days of the maximum of the 2018 burst (MJD 58,309) and a few days before the post-brightening bursts reported by Oknyansky et al. (2020). AstroSat carries four coaligned payloads—the Large Area X-ray Proportional Counter (LAXPC; Yadav et al. 2016; Agrawal et al. 2017; Antia et al. 2017), the Soft X-ray Telescope (SXT; Singh et al. 2016, 2017), the Ultra-Violet Imaging Telescope (UVIT; Tandon et al. 2017, 2020), and the Cadmium-Zinc-Telluride Imager (CZTI; Vadawale et al. 2016)—that observe simultaneously. We used the data observed with the SXT and UVIT. We did not use the LAXPC data, due to the high background, or the CZTI data, as the source was not detected there. Details of the observations are listed in Table 1.

2.1. The SXT Data

The SXT is a focusing X-ray telescope with a CCD camera operating in the photon-counting mode. It is capable of low-resolution imaging (FWHM ~ 2″, half-power diameter (HPD) ~ 11″) and medium-resolution spectroscopy (FWHM ~ 150 eV at 6 keV) in the 0.3–8 keV band. We processed the level-1 data using the SXT data processing software (AS1SXTLevel2-1.4b) available at the SXT payload operation center (POC) website,2 and we generated level-2 clean event files for individual orbits of each observation. We merged the clean event files for a given observation ID using the Julia SXT event merger tool (SXT_L2EVTLIST_MERGE) developed by us and made available at the SXT POC website. We obtained the processed and cleaned level-2 data for a net exposure time of ~23.3 ks (obs1) and ~19.1 ks (obs2). We used the XSELECT tool and extracted the source spectrum from the two merged level-2 event files using a circular region of 15′′ radius centered on the source position. The large HPD (~11′′) of the SXT and the calibration sources present at the corners of the CCD camera do not leave source-free regions. Therefore, we used the blank-sky spectrum (SkyBkg_comb_EL3p5_CI_Rd16p0_v01.pha) as the background spectrum as recommended by the SXT POC. We also

2 https://www.tifr.res.in/~astrosat_sxt/sxtpipeline.html
used the recommended redistribution matrix file (sxt_pc_mat_g0to12.rmf) and the ancillary response file (sxt_pc_excl00_v04_20190608.arf) for the SXT spectral analysis. We grouped the SXT spectral data to a minimum of 25 counts per bin using the GRPPHA tool. The background-corrected net source count rates are \(0.637 \pm 0.006\) counts s\(^{-1}\) and \(0.186 \pm 0.004\) counts s\(^{-1}\) for obs1 and obs2, respectively. Thus, the observed X-ray count rate decreased by a factor of \(\sim 3.4\) in \(\sim 70\) days.

### 2.2. The UVIT Data

The UVIT (Tandon et al. 2017, 2020) consists of two coaligned telescopes, one of which is sensitive in the FUV (1300–1800 Å) band and is referred to as the FUV channel. The light from the second telescope is split into the near-ultraviolet (NUV; 2000–3000 Å) and visible (3200–5500 Å) bands, thus forming the NUV and VIS channels, respectively. The FUV and NUV channels are equipped with a number of broadband filters and operate in the photon-counting mode, and they provide high-resolution (FWHM=1’’ – 1.5”) imaging capability. Additionally, the two FUV gratings and one NUV grating mounted in the filter wheels are useful for low-resolution slitless spectroscopy. The maximum efficiency is achieved in the −2 order of the FUV gratings and −1 order of the NUV grating. The peak effective area and the spectral resolution (FWHM) are, respectively, \(\sim 4.5\) cm\(^2\) and \(\sim 15\) Å for the FUV gratings and \(\sim 18.7\) cm\(^2\) and \(\sim 33\) Å for the NUV grating (Dewangan 2021). We observed NGC 1566 using both the FUV gratings in obs1 and only the FUV-Grating1 (FUV-G1) in obs2. We could not observe the source in the NUV band, as the NUV channel stopped functioning in 2018 March (Ghosh et al. 2021). We processed the level-1 FUV data using the UVIT pipeline CCDLAB (Postma & Leahy 2017) software, and we generated clean merged images for each grating/filter used in obs1 and obs2. We use the FUV-G1 data here, as the FUV-G2 data from obs2 are severely contaminated by other sources along the dispersion direction. The observational details are listed in Table 1.

![Image](https://nexus.gsfc.nasa.gov/fTOOLS/caldb/help/addspec.png)  
**Figure 1.** The AstroSat/UVIT FUV-G1 images from obs1 (ObsID T02_085T01_9000002296; left) and obs2 (ObsID T03_020T01_9000002444; right). The first and second orders are relatively cleaner in obs1 than those of obs2. In obs2, the second order is strongly contaminated, while the first order is relatively free of contamination. The green and white rectangles represent the source and background extraction regions, respectively. The images are shown at the same color scale, and the color bars are shown at the top of the images.

In Figure 1, we show the FUV-G1 images of obs1 and obs2 in the left and right panels, respectively. The two observations were performed at different roll angles. Therefore, the orientation of the galaxy in the detector plane is changed such that the spiral arms are rotated by \(\sim 80\)° counterclockwise in obs2 relative to obs1. A star present in the upper spiral arm in obs1 is rotated in obs2, which resulted in a stronger host-galaxy contamination in obs2. In the right panel of Figure 1, the −2 order spectrum of the NGC 1566 nucleus is strongly contaminated by the −1 and −2 orders of a strong UV source located in one of the spiral arms, whereas the −1 order spectrum of the NGC 1566 nucleus is relatively less contaminated (see Figure 1). Therefore, we extracted the source spectrum from the −1 order of FUV-G1 with a cross-dispersion width of 24 pixels (where 1 pixel \(\sim 0.741\)) and the background spectra from above and below the AGN region with a cross-dispersion width of 12 pixels for each region. We selected the background regions exactly in the same pixel range along the dispersion direction as for the AGN region, but above and below the dispersed image of the AGN. The source and background extraction regions are shown as the green and white rectangles, respectively, in Figure 1. We used the UVITTools package (Dewangan 2021) written in the Julia language to extract the OGIP compliant spectral files for a given grating order and cross-dispersion width (Dewangan 2021). We combined the two background spectra for a single observation using the ADDSPEC\(^3\) task. We used the instrument response file (fuv_grating1_m1_3oct19.rmf; Dewangan 2021) in the spectral analysis. We did not require grouping the data, as each energy bin of the spectrum has more than 20 counts. We list the net source count rates for FUV-G1 in Table 1. The FUV-G1 count rate varied by a factor of \(\sim 3.9\).

Figure 2 shows the broadband images of NGC 1566 in the F154W filter (mean wavelength \(\lambda_m = 1541\) Å, \(\Delta \lambda = 380\) Å). The central AGN is clearly separated from the nearby sources, as well as from the spiral arms of the galaxy, resulting in relatively less host-galaxy contamination compared to the FUV grating data. Therefore, we also used the broadband filter data to derive the relatively uncontaminated AGN emission, which we use to scale the slitless grating spectra. We extracted the source counts from a circular region of \(7''\) radius centered at the location of the nucleus (shown as green circles in Figure 2). The excellent spatial resolution of the UVIT allows us to choose such a small extraction region that includes almost all AGN emission but avoids significant contamination from the host-galaxy emission. To correct for the background and the host-galaxy emission, we extracted background counts from three local source-free, circular regions with \(7''\) radii (shown as white circles in Figure 2) and calculated the mean background contamination.

\(^3\) https://heasarc.gsfc.nasa.gov/fTOOLS/caldb/help/addspec.txt
level for each observation. We subtracted the mean background rate from the source count rate and derived the net source count rate for both observations. We have listed the net source count rates and the mean background rates in Table 1. The net source count rate decreases from 11.03 ± 0.07 counts s⁻¹ to 3.56 ± 0.06 counts s⁻¹ in ~70 days. We wrote the net source count rate in an XSPEC compatible spectral file using the FTFLX2XSP task for each observation and used the F154W filter response (F154W_effarea_Tandon_etal2020.rsp; Dewangan 2021) in our spectral analysis below.

3. Spectral Analysis

We performed spectral analysis using the XSPEC (Arnaud 1996) and SHERPA (Freeman et al. 2001) packages. We used the Galactic column density of \( N_H = 9.19 \times 10^{19} \) cm⁻² (Kalberla et al. 2005) and the abundance and the cross section of the interstellar medium according to Asplund et al. (2009) and Verner et al. (1996), respectively. We used the \( \chi^2 \)-minimization technique to obtain the best-fitting model. We quote the errors on the best-fit parameters at the 90% confidence level.

3.1. SXT Spectral Analysis

We begin our spectral analysis by fitting the two SXT data sets jointly in the 0.5 – 6.8 keV band. After the launch of AstroSat, gain of the SXT CCD has drifted slightly, which we handle using the GAIN command in XSPEC. We fixed the slope at 1.0 and varied the intercept. We used an absorbed power-law model (TBABS \times ZPOWERLAW in XSPEC terminology) to fit the data. We applied a 3% systematic error to account for uncertainties in the calibration and background. We varied photon index and normalization of the ZPOWERLAW model across the two data sets. The fit resulted in \( \chi^2 = 439.3 \) for 400 degrees of freedom (dof). We noticed the soft X-ray excess emission below 2 keV in the best-fit residuals. Therefore, we added a blackbody component ZBBODY to the model. Initially, we tied the temperature and the normalization of the ZBBODY between the two data sets. This resulted in a poor fit with \( \chi^2/\text{dof} = 433.9/398 \). We then varied the normalization of the ZBBODY component for the two data sets independently. The fit improved significantly with \( \Delta \chi^2 = -16.1 \) for one parameter (\( \chi^2/\text{dof} = 417.8/397 \)). An \( F \)-test in XSPEC resulted in the \( F \)-statistic of 15.3 and probability of \( \sim 10^{-4} \), suggesting that a variation in the blackbody normalization is statistically significant. The blackbody normalization for obs2 is not well constrained and is consistent with zero, implying the absence of the soft X-ray excess in this observation. We also varied the blackbody temperature between the two data sets, which did not improve the fit (\( \Delta \chi^2 = 0.5 \) for one parameter). The best-fit photon index and the 2–10 keV flux of the X-ray power-law component are, respectively, \( \Gamma = 1.65^{+0.06}_{-0.08} \) and \( f_{\text{PL}} = (3.2 \pm 0.2) \times 10^{-11} \) erg cm⁻² s⁻¹ for obs1 and \( \Gamma = 1.78^{+0.07}_{-0.13} \) and \( f_{\text{PL}} = (0.85 \pm 0.08) \times 10^{-11} \) erg cm⁻² s⁻¹ for obs2. The blackbody temperature and 0.5 – 2 keV flux are, respectively, \( kT_{\text{bb}} = 0.16 \pm 0.02 \) keV and \( f_{\text{bb}} = (2.56 \pm 1.03) \times 10^{-12} \) erg cm⁻² s⁻¹ for obs1 and \( 0.45 \times 10^{-12} \) erg cm⁻² s⁻¹ (90% upper limit) for obs2. The soft X-ray excess and the power-law flux varied by factors of \( >5.7 \) and \( \sim 3.8 \) in \( \sim 70 \) days. The SXT spectral data, the best-fit models, and the deviations of the data from the models are shown in Figure 3. We also calculated the observed flux in the 0.5 – 10 keV band to be \( 4.9 \times 10^{-11} \) erg cm⁻² s⁻¹ and \( 1.4 \times 10^{-11} \) erg cm⁻² s⁻¹ for obs1 and obs2, respectively, which are consistent for the intermediate states between the maximum and minimum of the outburst (Oknyansky et al. 2019).

The soft X-ray excess can be produced from thermal Comptonization of the disk seed photons in a warm and optically thick corona. We tested this scenario by modeling the soft X-ray excess emission with a thermal Comptonization model, NTHCOMP (Zdziarski et al. 1996; Życki et al. 1999). The main parameters of this model are the photon index of the Comptonized emission (\( \Gamma_{\text{warm}} \)), temperature of the warm corona (\( kT_{\text{warm}} \)), and temperature of the seed photons (\( kT_{\text{seed}} \)). We assume the blackbody seed photons (inp_type=0)
with a temperature of $kT_{\text{seed}} = 1 \text{ eV}$. We used this model for the first epoch only, where the soft X-ray excess is present. The model $\text{TBABS} \times (\text{POWERLAW} + \text{ZBBODY})$ resulted in a similar fit quality ($\chi^2$/dof = 417.7/397) as before. The best-fit $\Gamma_{\text{warm}}$, $kT_{\text{warm}}$, and normalization ($N_{\text{nthcomp}}$) of the NTHCOMP model are $\Gamma_{\text{warm}} \lesssim 3$ ($3\sigma$ upper limit), $kT_{\text{warm}} = 0.15^{+0.17}_{-0.07} \text{ keV}$, and $N_{\text{nthcomp}} = 1.2^{+1.3}_{-0.6} \times 10^{-3}$. The soft X-ray excess flux in the 0.5–2 keV band using the best-fit NTHCOMP component is $f_{\text{SXE}} = (3.4 \pm 1.8) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$.

3.2. UVIT/FUV Grating Spectral Analysis

We analyzed the two sets of FUV-G1 grating + F154W filter data from the two AstroSat observations jointly in XSPEC. Inspecting the grating data, we noticed strong contamination from the diffuse emission of the host galaxy at the low and high ends of the FUV band (1250–1800 Å). The contamination is stronger for obs2. We could use the data in the 1305–1771 Å (7.9–9.5 eV) range for obs1 and in the 1458–1698 Å (7.3–0.85 eV) range for obs2. The broadband F154W data are relatively clean from the host-galaxy contamination. Therefore, we analyzed the grating and the broadband data jointly, and our UV flux measurements refer to the F154W data.

We used a simple $\text{POWERLAW}$ model modified by the Galactic reddening with the REDDEN (Cardelli et al. 1989) component. We fixed the color excess parameter of the REDDEN component at $E(B - V) = 0.0134$ calculated from the Galactic column density of $N_H = 9.19 \times 10^{19} \text{ cm}^{-2}$ using the gas-to-dust ratio $N_H = E(B - V) \times 6.86 \times 10^{21}$ (Güver & Özel 2009). We also used a CONSTANT component to account for relative normalization between the grating and the filter data. We fixed the CONSTANT at 1 for the filter and varied it for the grating for each observation. This relative normalization is useful to account for any differences in the host-galaxy contamination and/or differences in the absolute flux calibration (Dewangan 2021). We kept tied the rest of the model parameters across the FUV-G1 and F154W data for each observation. We varied the photon index and the normalization of the $\text{POWERLAW}$ model for both observations. This resulted in a poor fit with $\chi^2$/dof = 1125.2/116. We noticed strong residuals near 1550 Å owing to the C IV $\lambda 1549$ emission line. We added a Gaussian line (ZGAUSS) to the model. We tied the energy and the width ($\sigma$) of the line across the two data sets and varied the normalization for each observation. The fit improved significantly with $\chi^2$/dof = 185.9/112. We further noticed an absorption feature near 1741 Å (7.15 eV) most likely associated with Ni II (Outram et al. 1999). Therefore, we added a Gaussian absorption line (GABS). The fit further improved to $\chi^2$/dof = 134/109. We also noticed a weak residual near 1402 Å (8.9 eV), most likely due to Si IV and O IV emission lines. We noticed this line in obs1 only, as the data below 1450 Å were excluded in obs2 owing to the host-galaxy contamination. Addition of another Gaussian line at 1402 Å improved the fit further to $\chi^2$/dof = 123.6/106. We also accounted for an emission feature near 1653 Å (7.5 eV) by adding a Gaussian line, which further improved the fit to $\chi^2$/dof = 114.4/102. This emission feature is most likely due to He II and O III] (Vanden Berk et al. 2001). We list the best-fit parameters in Table 2 and show the unfolded spectra, best-fit model, and deviations of the data from the model in Figure 4. The photon indices $\Gamma_{\text{FUV}} = 2.4^{+0.2}_{-0.6}$ (obs1) and $2.8^{+0.3}_{-2.2}$ (obs2) of the FUV

![Figure 3. The best-fit SXT (0.3–6.8 keV) spectra of obs1 (black) and obs2 (red) fitted with $\text{TBABS} \times (\text{POWERLAW} + \text{ZBBODY})$ models. The total (solid), $\text{ZPOWERLAW}$ (dashed), and $\text{ZBBODY}$ (dashed) models for a single observation are shown with the same colors. The $\text{ZBBODY}$ model is negligible for obs2. The bottom panel shows residuals in terms of (data − model)/error.](image-url)
power law \((N_E \propto E^{-\Gamma_{\text{FUV}}})\) correspond to the spectral indices \(\alpha_\lambda = 0.6^{+0.5}_{-0.6}\) (obs1) and \(0.2^{+0.3}_{-0.3}\) (obs2) since \(\Gamma_{\text{FUV}} = 3 - \alpha_\lambda \) with \(f_\lambda \propto \lambda^{-\gamma} \). These spectral indices are consistent with the population mean and the standard deviation \((\alpha_\lambda = 1.1 \pm 0.8)\) of the observed spectral indices for other AGNs listed in Table 4 of Kuraszkiewicz et al. (2002).

### 3.3. Joint FUV/SXT Spectral Analysis

We investigated the FUV/X-ray spectral variability of NGC 1566 by fitting the FUV and the X-ray data from the two AstroSat observations jointly. We fixed the parameters of FUV emission and absorption lines and the relative normalization constants between the grating and broadband filter data at their best-fit values obtained earlier (see Table 2). We removed the ZPOWERLAW model, which was used to fit the FUV continuum, and used the OPTXAGNF (Done et al. 2012) model to fit the FUV continuum, X-ray powers law, and soft X-ray excess component. The main parameters of the OPTXAGNF model are the mass of the black hole \(M_{\text{BH}}\), comoving distance to the source \(D\) (in Mpc), dimensionless accretion rate \((\log m = L/L_{\text{Edd}})\), dimensionless black hole spin \(a\), inner- and outer-disk radii \(r_{\text{cor}} \) and \(r_{\text{out}}\), temperature \(kT_{\text{n}}\) and optical depth \(\tau_{\text{n}}\) of the warm corona, X-ray power-law photon index \((\Gamma)\), and fraction of the power below \(r_{\text{cor}}\) that is emitted in the hard comptonization component \((f_{\text{fp}})\). We fixed the black hole mass at \(M_{\text{BH}} = 8.32 \times 10^6 M_\odot\) (Woo & Urry 2002) following the previous studies (see Parker et al. 2019; Oknyansky et al. 2020; Jana et al. 2021), the black hole spin \(a = 0\) for a slowly spinning black hole (Parker et al. 2019; Jana et al. 2021), and the outer-disk radius \(r_{\text{out}} = 10^5 R_\text{g}\), where \(R_\text{g} = G M_{\text{BH}} / c^2\) is the gravitational radius. The comoving distance of the source is uncertain, and the reported distance ranges from 5.5 Mpc (Sorce et al. 2014) to 21.3 Mpc (Elagali et al. 2019; Osmond & Ponman 2004). In our analysis, we adopt the comoving distance \(D = 21.3\) Mpc based on the Hubble constant \(H_0 = 70.3\) km s\(^{-1}\) Mpc\(^{-1}\), which is also consistent with the most recently reported Tully–Fisher distance of the source \(16.9^{+4.4}_{-3.1}\) Mpc (Elagali et al. 2019). We used the TBABS model for the Galactic absorption in the X-ray band only and the REDDEN model for the Galactic reddening in the FUV band only. We tied the parameters of OPTXAGNF for the SXT spectra with those of the FUV spectra for each observation. We varied the mass accretion rate, inner-disk radius, photon index, and fraction of the X-ray power-law component independently for each observation. We also fixed the warm corona temperature at the best-fit value derived from the SXT data using the NTHCOMP model earlier. We tied the optical depth across the two observations and allowed it to vary. As before, we applied a 3% systematic error and the gain correction. While fitting, we found that the \(f_{\text{fp}}\) parameter is 1 for obs1, as we did not detect the soft X-ray excess component in this observation. We therefore fixed this parameter at 1 for obs2. This did not change other parameters and resulted in an acceptable fit with \(\chi^2 / \text{dof} = 522.7 / 518\). We list the best-fit parameters in Table 3. We show the UV/X-ray spectral data, the best-fit model, and the deviations of the data from the model in Figure 5.

### 3.4. XMM-Newton UV/X-ray Spectroscopy

In order to investigate the broadband UV/X-ray spectral evolution of NGC 1566, we also analyzed two XMM-Newton observations on 2018 June 26 (Obs.ID: 0800840201), when the source was at the peak of the outburst, and 2015 November 5 (Obs.ID: 0763500201), when the source was at a low flux state before the outburst. We processed the EPIC-pn data in the same way as described in Parker et al. (2019), and we derived the source and background spectra. Additionally, we processed the OM data using the OMICHAIN task and generated images ready for the aperture photometry. The optical/UV data are contaminated by the host-galaxy emission; we therefore used the OM data below 3000 Å only to avoid stronger host-galaxy contamination. We performed the aperture photometry using the OM SOURCE task for UVW2 \((\lambda_{\text{eff}} = 2120 \text{ Å}, \Delta \lambda = 500 \text{ Å})\) and UVM2 \((\lambda_{\text{eff}} = 2310 \text{ Å}, \Delta \lambda = 480 \text{ Å})\) filters of two observations. Following Mehdipour & Costantini (2018), we extracted the source counts from a circular region with a radius of 13 pixels \((1 \text{ pixel} = 0^\prime 953)\) centered on the source and background counts from a similar size of annular region outside the source but inside the host galaxy. We calculated the net background-subtracted source count rates for the two filters. We corrected the net source count rates for the Galactic extinction using the CCM extinction law (Cardelli et al. 1989) with a color excess of \(E(B-V) = 0.0134\) and the ratio of total to selective extinction of \(R_V = A_V / E(B-V) = 3.1\), where \(A_V\) is the extinction in the \(V\) band. Further, the optical/UV data are also contaminated by the broad-line region (BLR)/narrow-line region (NLR) emissions, which cannot be corrected directly from the broadband filter data. We therefore used an HST spectrum of NGC 1566 in the 1250–4000 Å band to estimate the fractional contribution of the BLR/NLR emission to the total AGN flux. We used the G270H grating data of the HST Faint Object Spectrograph (FOS) observed on 1991 February 08 (ObsID: y0h70207t) with a total exposure time of 2 ks. We obtained the G270H grating/HST spectrum from the MAST portal.4 We

4 https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html
modeled the HST spectrum in SHERPA (Freeman et al. 2001). We used a POWERLAW modified by the Galactic reddening (CCM) model for the UV continuum, Gaussian line models for emission lines, and an Fe II template convolved with the Gaussian-smoothing model GSMOOTH. We fixed the $\tau_{Fe II}$ of the smoothing component at the $\sigma$ width of the broad emission lines corresponding to FWHM $\sim 2300$ km s$^{-1}$. Following Mehdipour et al. (2015), we also added the Balmer continuum function and a host-galaxy bulge template (Kinney et al. 1996), which did not change the fit. We therefore did not use these components further. The HST spectrum and models are shown in Figure 6. From the best-fit model of the HST spectrum, we removed the reddening component and derived the dereddened total model and POWERLAW model. We treated the dereddened POWERLAW model as the UV continuum. We used the effective area of each filter and calculated the count rates of the dereddened POWERLAW ($f_{\text{cont}}$) and total model ($f_{\text{total}}$) in the filter’s band. Using these contributions, we finally calculated the fractional contributions of the non continuum objects in the total spectrum (i.e., 1 - ($f_{\text{cont}}/f_{\text{total}}$)). We found these fractions to be $\sim 23\%$ for UVW2 and $\sim 26\%$ for UVM2. We subtracted these fractions from the extinction-corrected count rates and derived the intrinsic count rates of the source. We wrote these count rates in an OGIP-compliant spectral file generated using the OM2PHA task.

As before, we used the OPTXAGNF model to fit the X-ray power law, the soft X-ray excess, and the UV continuum simultaneously. We modeled the distant and blurred reflection features using XILLVER and RELXILL components, respectively. We fixed the parameters of the reflection models at their best-fit values derived by Parker et al. (2019) such that the emissivity index $q = 3$, iron abundance $A_{Fe} = 3$, inclination angle $\theta = 10^\circ$, ionization parameter log $\xi$ = 2.4, spin of the SMBH $a = 0$, and high-energy cutoff $E_{\text{cut}} = 167$ keV. We also fixed the reflection fraction $R = -1$ for both the reflection models. We also added the additional Gaussian line at 6.85 keV reported by Parker et al. (2019) and fixed its parameters. We added 1% systematic in the joint fitting. The best fit resulted in $\chi^2$/dof = 246.8/238 for 2018 data. Similarly, we also fitted the 2015 data using the OPTXAGNF and XILLVER models. We did not require the blurred reflection component for this data set. While fitting, we found that the $f_{\text{pl}}$ parameter of the OPTXAGNF model is close to 1, which is expected owing to the negligible soft X-ray excess at this epoch. We therefore fixed this parameter at 1, which did not change the fit. The fit resulted in $\chi^2$/dof = 243.9/221 for 2015 data. We list the best-fit parameters and the fluxes of the accretion disk, soft X-ray excess, and power-law components for both the XMM-Newton observations in Table 3. The best-fit UV/X-ray spectra and the residuals in terms of data-to-model ratios are shown in Figure 7. We separately calculated the soft X-ray excess flux for 2015 data using the ZBBODY model, which resulted in $kT_{bb} = 0.16 \pm 0.02$ keV and the $0.5 - 2$ keV flux $(8.5 \pm 3.5) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$.

### 3.5. Blurred Reflection and the Soft X-Ray Excess Emission

We investigated whether the strong soft X-ray excess emission present in the 2018 XMM-Newton data can be modeled with the blurred reflection from the accretion disk as a result of the coronal X-ray illumination onto the disk. We used a high-density blurred reflection model, RELXILL (García et al. 2016), to fit the soft X-ray excess emission, broad iron line, and power-law continuum. We allowed all the parameters to vary freely. We found a statistically good fit only for a highly spinning black hole ($a > 0.6$) and strong reflection ($R \sim 1.3$), which is inconsistent with the black hole spin of $a \leq 0.2$ and reflection fraction of $R < 0.2$ derived from the broad iron line alone (see Parker et al. 2019; Jana et al. 2021). Generally the smooth soft X-ray excess component when described as the blurred reflection model requires maximum black hole spin (see Mallick et al. 2018; Jiang et al. 2019). To further investigate, we also fitted 3–10 keV EPIC-pn data from the 2018 June observation with a ZPOWERLAW for the X-ray continuum, XILLVER for the distant reflection, and LAOR line

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|}
\hline
Model & Parameter & AstroSat 2018 August & 2018 October & XMM-Newton 2018 June, November 2015 \\
\hline
OPTXAGNF & $\log m_0$ & $-1.81^{+0.02}_{-0.07}$ & $-2.44^{+0.03}_{-0.04}$ & $-1.29^{+0.01}_{-0.01}$ & $-2.91^{+0.01}_{-0.01}$ \\
 & $a$ & 0 (f) & 0 (f) & 0 (f) & 0 (f) \\
 & $r_{\text{cor}}(R_g)$ & $52^{+3}_{-2}$ & $38.9^{+3.9}_{-13}$ & 45.5 & 25.9_{+0.3} \\
 & $kT_{\text{e}}$(keV) & 0.15 (f) & ... & 0.51^{+0.05}_{-0.05} & ... \\
 & $\tau_{\text{w}}$ & $\geq 25$ (3$\sigma$) & ... & 9.5^{+0.5}_{-0.5} & ... \\
 & $f_{\text{pl}}$ & $1.63^{+0.07}_{-0.03}$ & $1.78^{+0.07}_{-0.03}$ & 1.70^{+0.02}_{-0.02} & 1.86^{+0.01}_{-0.01} \\
 & & $0.979^{+0.003}_{-0.013}$ & 1 (f) & 0.49^{+0.03}_{-0.03} & 1 (f) \\
 & RELXILL & $N_{\text{e}}^{\text{surf}}(10^{-3})$ & ... & 4 \pm 1 & ... \\
 & XILLVER & $N_{\text{e}}^{\text{surf}}(10^{-3})$ & ... & 5.6 \pm 1 & 1.2 \pm 0.2 \\
 & FLUX & $f_{\text{abs}}$ & 10.63 & 3.01 & 40.46 & 1.35 \\
 & & $f_{\text{abs}}$ & ... & ... & 2.07 & ... \\
 & & $f_{\text{abs}}$ & 3.23 & 0.85 & 5.83 & 0.23 \\
 & \hline
\end{tabular}
\caption{Best-fit Parameters of NGC 1566 Derived from the Broadband UV/X-ray SED}
\end{table}

Notes.

- $^a$ The disk flux in $1 \mu m - 50$ eV band in $10^{-11}$ erg cm$^{-2}$ s$^{-1}$.
- $^b$ The soft X-ray excess flux in 0.5–2 keV band in $10^{-11}$ erg cm$^{-2}$ s$^{-1}$.
- $^c$ The power-law flux in 2–10 eV band in $10^{-11}$ erg cm$^{-2}$ s$^{-1}$.
for the broad iron line. We fixed the line energy at 6.4 keV, inclination angle at 10° as before, and normalization of the XILLVER at the best-fit value derived above. The fit resulted in $\chi^2$/dof = 155/165. The best-fit parameters of the LAOR line are the inner-disk radius $R_{in} = 15_{-10}^{+15} R_g$, emissivity index $q > 2.4$, and equivalent width EW = 45_{-10}^{+20} eV. Thus, the inner-disk radius is also consistent with a low spinning black hole, and a small equivalent width of the line suggests that the blurred reflection is not strong in this source. Therefore, the strong soft X-ray excess emission observed in 2018 June is unlikely to arise as a result of the blurred reflection.

4. Results and Discussion

We analyzed two observations of NGC 1566 in the FUV and X-ray bands performed by AstroSat in 2018 August and October during the declining phase of the 2018 outburst. We also analyzed two XMM-Newton observations performed before the outburst in 2015 and during the peak of the outburst in 2018 June. Using these four UV/X-ray observations, we investigated the changes in the primary spectral components—the accretion disk, the soft X-ray excess, and the X-ray power law during the 2018 outburst. The main results of our analysis are as follows.

1. The FUV spectra of NGC 1566 derived using the FUV-G1 and F154W data consist of the FUV continuum and the emission lines of CIV, SiIV, + O IV, and HeII + O III. The widths of these lines (FWHM ~ 4000 – 7000 km s^{-1}) are consistent with their origin in the BLR.

2. The observed fluxes in the FUV (1300–1800 Å) and X-ray (0.5–6.8keV) bands decrease by a factor of ~3 in ~70 days during the declining phase from 2018 August to October (see Table 1).

3. The reduction in the ionizing flux also led to reduced strengths of broad UV emission lines; the C IV λ1549 line varied by a factor of ~2.

4. The UV/X-ray broadband spectral energy distributions (SEDs) of NGC 1566 are well described by the accretion disk component superimposed with emission lines, warm Comptonization responsible for the soft X-ray excess, the X-ray power law, and distant and blurred reflection (see also Kawamuro et al. 2013; Parker et al. 2019; Oknyansky et al. 2019).
5. All the UV/X-ray spectral components strongly varied during the outburst. The accretion disk continuum emission increased by a factor of $\sim30$ from pre-outburst in 2015 to peak outburst in 2018 June and then declined by a factor of $\sim13$ in 4 months.

6. The soft X-ray excess component was extremely weak, almost undetectable in 2015. This component increased by a factor of $\sim243$ during the peak outburst and then decreased by a factor of $\sim7$ in 2018 August and again became undetectable in 2018 October.

7. The X-ray power-law component increased by a factor of 25 from 2015 to 2018 June and decreased by factors of $\sim1.8$ in 2018 August and $\sim6.8$ in 2018 October. The X-ray power law was steeper in the lowest flux states and appears to have flattened at high flux states.

8. The bolometric luminosity relative to the Eddington luminosity ($L/L_{\text{Edd}}$) increased from $\sim0.1\%$ (2015) to $\sim5\%$ (2018 June) and then decreased to $\sim1.5\%$ (2018 August) and $\sim0.3\%$ (2018 October).

We summarize the spectral evolution of NGC 1566 in Figure 8, which shows the best-fitting UV to X-ray broadband models derived from the observations in 2018 June (black), 2018 August (green), 2018 October (blue), and 2015 November (red). The spectral components—the accretion disk (short-dashed lines), soft X-ray excess (dotted–dashed lines), X-ray power law (long-dashed lines), and reflection components (dotted lines)—are also shown in Figure 8. Clearly, NGC 1566 has shown one of the most extreme variabilities in its primary spectral components. In particular, the soft-excess component dropped by a factor $>45$ during the declining phase, which is more than any other component. The broadband spectra of NGC 1566 are similar to those observed from other CL-AGNs such as Mrk 1018 (Noda & Done 2018), which also showed the most extreme variability in its soft X-ray excess emission in $\sim8$ yr. Another CL-AGN, Mrk 590, is also known to show a drop in its soft-excess emission by a factor of $\sim20–30$ in 7 yr, while the 2–10 keV continuum showed only a $\sim10\%$ change in flux (Rivers et al. 2012). Similarity of the observed spectral variability associated with the changing-look phenomena in these AGNs points toward a fundamental process that is not well understood.

### 4.1. Variation in the Accretion Disk Emission

The FUV continuum in the 1300–1800 Å band observed with the AstroSat/UVIT and the near-UV band observed with the XMM-Newton/OM are consistent with the standard accretion disk around a black hole with $M_{\text{BH}} = 8.32 \times 10^6 M_\odot$. The accretion disk is found to contribute $0.07\%$ (2015), $2.15\%$ (2018 June), $0.57\%$ (2018 August), and $0.16\%$ (2018 October) in the 1 $\mu$m to 50 eV band relative to the Eddington luminosity. The intrinsic disk Comptonization model OPT-XAGNF, which we used to fit the broadband spectra, suggests that the change in the disk flux is governed not only by the change in the accretion rate but also by the change in the size of the warm Comptonizing medium ($r_{\text{cor}}$) from $\sim26R_g$ in 2015 to $50R_g$ in 2018 June–August. The disk flux increased by a factor of $\sim30$ despite a possible decrease in the emitting area of the standard disk from 2015 to 2018. The inner part of the disk appears to have been converted in the warm Comptonizing medium, giving rise to the soft X-ray excess in the high flux states. As pointed out by a number of authors (e.g., Noda & Done 2018; Wang et al. 2019; Ricci et al. 2020), the viscos timescale for accretion disks in AGNs is much longer than the changing-look timescale in AGNs. To compare the disk variability timescale, we calculate the accretion disk timescales at the inner radius of the disk obtained from the best-fit broadband spectral model. The dynamical ($t_{\text{dyn}}$), thermal ($t_{\text{th}}$), and viscous ($t_{\text{vis}}$) timescales of the accretion disk are given by (Czerny 2006)

$$t_{\text{dyn}} = \left( \frac{r^3}{G M_{\text{BH}}} \right)^{1/2}$$

$$t_{\text{th}} = \frac{1}{\alpha} t_{\text{dyn}},$$

and

$$t_{\text{vis}} \approx \frac{1}{\alpha} \left( \frac{r}{h} \right)^2 t_{\text{dyn}},$$

where $r$ is the radial distance in the disk, $\alpha$ is the viscosity parameter, and $h$ is the height of the disk. We used the results from the 2018 August observation and calculated the accretion disk temperature of $\sim3.6$ eV for an inner-disk radius of $\sim50R_g$, accretion rate of $\dot{m} \sim 0.015$, and black hole mass of $8.32 \times 10^6 M_\odot$. We used this temperature to estimate the height-to-radius ratio of the disk $h/r = c_s/v_0 \sim 4.4 \times 10^{-4}$ (where $c_s = \sqrt{kT/m_p}$ is the sound speed and $v_0 = \sqrt{G M_{\text{BH}}/r}$ is the Keplerian velocity). Assuming $\alpha = 0.1$, we finally calculated the dynamical, thermal, and viscous timescales $t_{\text{dyn}} \sim 0.17$ days, $t_{\text{th}} \sim 1.7$ days, and $t_{\text{vis}} \sim 2.4 \times 10^4$ yr, respectively. The timescale for the observed outburst is much smaller than the viscous timescale but longer than the dynamical and thermal timescales at an inner radius of $50R_g$. On the other hand, the estimated sound-crossing time of $t_s \sim 50R_g/c_s \sim 1$ yr is comparable to the changing-look time of
NGC 1566. This suggests that the outburst is likely related to pressure instabilities in the disk.

4.2. Variations in the Soft X-Ray Excess Emission and Its Origin

The soft X-ray component exhibited the most extreme variations during the outburst. This component is well described by thermal Comptonization of the accretion disk photons in a warm and optically thick corona. The strongest soft excess observed during the peak of the outburst is described by warm plasma with $kT_w = 0.51 \pm 0.05$ keV, $\tau = 9.5 \pm 0.5$. After about 2 months, the soft excess weakened with increased optical depth and decreased temperature. The variability of the soft X-ray excess component is larger than the disk and the power-law components. Therefore, it cannot be produced by the warm Comptonization of the disk photons without an intrinsic change in the warm Comptonizing medium, nor by the illumination of the X-ray power-law component alone. The soft excess component was almost nonexistent before the outburst and toward the end of the outburst, and it was at its maximum during the outburst peak. The warm Comptonizing region emitting the soft X-ray excess is characterized by the transition radius $r_{\text{cor}}$ between the disk and the warm corona, and below this radius the warm corona is thought to exist. It appears that this inner region is formed during the outburst on a timescale comparable to the sound-crossing time at the inner radius of the standard disk. It also appears to have disappeared toward the end of the outburst on the sound-crossing time. The increasing optical depth and decreasing temperature of the warm Comptonizing medium during the declining phase and, finally, the disappearance of the soft excess toward the end of the outburst imply that the warm Comptonizing medium most likely converted back to the standard inner-disk material.

4.3. Variation in the X-Ray Power Law and Thermal Comptonization

We found that the X-ray power-law flux increases with the increasing disk and soft X-ray excess fluxes (see Table 3). Similar correlations have been found in other AGNs also—IC 4329A (Tripathi et al. 2021), PKS 0558–504 (Gliozzi et al. 2013), NGC 7469 (Nandra 2001)—and interpreted in terms of thermal Comptonization of the seed photons in the hot corona. The number of scattering in the hot corona increases with the number of increasing seed photons, which increases the Comptonized X-ray flux. It is possible that the accretion disk and the soft X-ray excess components both provide the seed photons for thermal Comptonization in the hot corona. The increasing seed photons cool the corona, which results in a steeper photon index (see Zdziarski et al. 1996; Życki et al.).
However, the X-ray power-law photon index is not correlated with the disk and/or soft X-ray excess flux in our case. This implies that the outburst also caused intrinsic change in the hot corona, affecting its optical depth and temperature. NuSTAR observations performed during the outburst should reveal possible intrinsic change in the hot corona.

### 4.4. Spectral Transition

The physical mechanisms used to explain such drastic variability include variable obscuration, TDE events, and disk instabilities. The variable obscuration due to changing clouds along the line of sight blocks the direct AGN emission, which causes a formal classification change of the source (Guainazzi 2002; Matt et al. 2003). In the case of NGC 1566, the variable obscuration mechanism is ruled out, as the low-flux X-ray spectra are free from intrinsic absorption. Oknyansky et al. (2019) proposed that increasing luminosity may be a result of sublimation of the dust in the line of sight, which previously obscured part of the BLR. The greater luminosity of the direct emission from the central regions can also increase the intensity of the Balmer lines. In our analysis, we found that fluxes of the broad emission lines are correlated with the X-ray power law and the FUV continuum flux, but we did not find additional reddening by the dust at the source redshift. Thus, the obscuration of the BLR due to the dust along the line of sight is unlikely to be responsible for the multiwavelength flux change.

TDEs are also thought to produce such events. For example, Ricci et al. (2020) used the TDE mechanism to explain the changing-look behavior of 1ES 1927+65. In the case of NGC 1566, outbursts are observed repeatedly (Alloin et al. 1986). Even during the declining period of the 2018 outburst, Oknyansky et al. (2020) observed three additional bursts in $\sim$1 yr. The theoretical rate of TDEs is too low ($\sim 10^{-4}$–$10^{-5}$ galaxy$^{-1}$ yr$^{-1}$; see Kawamuro et al. 2016; Komossa 2015, and references therein) to produce such repetitive events. Also, the X-ray spectra of NGC 1566 are harder than a typical X-ray spectrum of TDEs (Komossa 2015, 2017). Thus, the TDEs are unlikely to be responsible for the burst activities in NGC 1566.

NGC 1566 showed extreme-UV/X-ray flux and spectral variability during the 2018 outburst (see Figure 8). The emergence of the soft X-ray excess component during the outburst requires major structural changes in the innermost regions. Thus, the observed spectral changes are not merely due to minor changes in the physical conditions of the existing emitting regions, but the transition from a negligible soft-excess state to a strong soft-excess state and back to the negligible soft-excess state requires the formation and disappearance of the warm Comptonizing medium. The accretion rate is found to increase with the onset of the outburst, which results in the increased energy generation in the innermost disk. This increased energy generation most likely could not all be released in the form of radiation, and the trapping of photons raises the temperature and pressure and most likely decreases the density or the optical depth of the inner disk, thus transforming the innermost accretion disk to the warm Comptonization medium. This in turn gave rise to the observed soft X-ray excess emission via thermal Comptonization in the warm, optically thick innermost disk. The final configuration is likely the same as already hypothesized in the intrinsic disk Comptonized models (OPTXAGNF, Done et al. 2012; AGNSED, Kubota & Done 2018). Unlike the narrow-line Seyfert I galaxies, the soft X-ray excess from NGC 1566 does not seem to persist for a long time but lasted only during the outburst. During the declining phase, the soft-excess-emitting region appears to have disappeared, most likely transforming to the innermost disk. This transition appears to occur at a few percent of the Eddington rate, below which there is no soft-excess-emitting region, but only a standard disk and hot corona exist. It is thus likely that NGC 1566 makes transitions between a cold disk and a cold+warm disk.

The changing-look phenomenon appears to occur in a number of AGNs, including NGC 1566, at a few percent of the Eddington rate, e.g., Mrk 1018 (Noda & Done 2018), Mrk 590 (Denney et al. 2014), NGC 2617 (Shappee et al. 2014), and SDSS J0159 + 0033 (LaMassa et al. 2015). At an Eddington fraction of a few percent, black hole X-ray binaries (BHBs) are known to make a high/soft-to-low/hard spectral transition. Hence, similar spectral transition has been suggested for the changing-look events in Mrk 1018 (Noda & Done 2018) and in a sample of changing-look quasars (Ruan et al. 2019). However, there are subtle differences. In the high/soft-to-low/hard spectral transition of BHBs, the disk emission diminishes and the X-ray power-law component strengthens and flattens, while the disk emission, soft excess, and power-law component all vary in a correlated manner in CL-AGNs. The X-ray power law does not appear to flatten in the low flux states of CL-AGNs. There does not seem to be a spectral component in BHBs that can be identified with the soft excess in AGNs. Moreover, the spectral transition in BHBs takes place on a viscous timescale, while the changing-look phenomenon occurs on a much shorter timescale compared to the viscous timescale (Noda & Done 2018; Parker et al. 2019). These dissimilarities suggest that the changing-look phenomena of AGNs and the spectral transition in BHBs may not be caused by the same physical process.

Janiuk & Czerny (2011) have investigated different types of instabilities in accretion disks and argue that radiation pressure instability is likely to operate in AGNs above an Eddington ratio of 0.025. Parker et al. (2019) discussed the 2018 outburst of NGC 1566 in terms of the disk instability, where the dominating radiation pressure over the gas pressure enhances the flux coming from the inner disk. Sniegowska et al. (2020) explored the four bursts in NGC 1566 observed by Alloin et al. (1986) during 1970–1985 with the disk instability mechanism, such that the disk becomes unstable during such events at the transition radius between the outer standard disk and the inner advection-dominated accretion flow (ADAF) region. The rise time of the burst is expected to be comparable to the thermal timescale of the disk at the transition radius (Sniegowska et al. 2020). However, a timescale of $\sim$9 months has been claimed for the 2018 outburst, longer than the typical thermal timescale of $\sim$1.7 days at the inner-disk radius of $50R_g$. We found that the outburst timescale is comparable to the sound-crossing time $\sim$1 yr at $\sim 50R_g$ assuming gas pressure only. In the case of the radiation pressure dominating over the gas pressure in the inner regions, the sound-crossing time is expected to be even shorter but most likely still comparable to the outburst timescale. Janiuk & Czerny (2011) have studied the parameter space for the accretion disk instabilities and found the radiation pressure instability to be present in the inner region of AGN disks below $\sim 100R_g$ when the Eddington ratio is larger than 0.025. Interestingly, NGC 1566 seems to satisfy both these criteria, as the soft-excess emission observed during the
outburst arises below \( \sim 0.001 \) \( (\text{pre-outburst}) \) to \( \sim 0.05 \) \( \) \( \text{(outburst peak)} \) and then declined to \( \sim 0.003 \) when no soft excess is observed. Thus, we conclude that the 2018 outburst of NGC 1566 is most likely caused by the radiation pressure instability in the inner accretion disk. This conclusion is valid for the adopted source distance of 21.3 Mpc based on the Hubble parameter of \( H_0 = 70.3 \text{ km s}^{-1} \text{ Mpc}^{-1} \), as well as for the source distance \( 16.9^{+7.5}_{-1.1} \) Mpc estimated from the Tully–Fisher relation (Elagali et al. 2019). However, for the lower limit of the Tully–Fisher distance (12.8 Mpc), the Eddington ratio \( (L/L_{\text{Edd}} = 0.0126 \pm 0.0003) \) for the 2018 June data is somewhat lower than the threshold Eddington rate for the disk instability. The Eddington ratio will be even much lower \( (~15 \) times) for the shortest estimated distance of 5.5 Mpc (Sorce et al. 2014), and in this case the disk instability condition cannot be fulfilled. However, this distance is unlikely, as it is excluded by the distance measurement based on the Tully–Fisher relation (Elagali et al. 2019). Further, our conclusion is also based on the adopted values of the black hole spin parameter \( (a = 0) \) and the mass \( (\log M_{\text{BH}}/M_\odot = 6.92) \) for NGC 1566. We investigated the effect of the uncertainties in the estimation of black hole mass and spin parameter. We refitted the broadband UV/X-ray data of 2018 June using the lowest \( (\log M_{\text{BH}}/M_\odot = 6.48; \) Smaćić et al. 2015) and highest \( (\log M_{\text{BH}}/M_\odot = 7.11; \) Davis et al. 2014) estimated masses and two different values of spin parameter \( (a = 0 \) and \( 0.998) \). The best-fit Eddington ratios for the largest black hole mass are \( L/L_{\text{Edd}} \sim 2.4\% \) for \( a = 0 \) and \( \sim 3.5\% \) for \( a = 0.998 \). Similarly, the Eddington ratios for the smallest black hole mass are \( \sim 17\% \) for \( a = 0 \) and \( \sim 15\% \) for \( a = 0.998 \). Thus, for any combinations of the mass and spin our conclusion remains valid; however, for the largest black hole mass and the lowest spin the Eddington ratio is just below but very close to the threshold value for the disk instability.

5. Conclusion

We characterized evolution of the primary spectral components—the accretion disk, soft X-ray excess, and the X-ray power law—during the 2018 outburst of NGC 1566 by analyzing two FUV/X-ray data acquired by AstroSat during the decline phase of the outburst and two UV/X-ray data acquired by XMM-Newton before and at the peak of the outburst. We found that the accretion disk, soft X-ray excess, and X-ray power law exhibited large-amplitude variability during the outburst. The variability of the soft X-ray excess component is significantly larger than those of the disk and the X-ray power-law components. Thus, the variability of the soft X-ray excess cannot be produced by either thermal Comptonization of the disk photons in a steady warm corona or the disk-illuminating X-ray power-law component alone. Rather, it is intrinsic to a changing warm corona. We refer to this change in the warm corona as causing the spectral transition in NGC 1566 from a strong soft-excess state to a negligible soft-excess state. The outburst decline timescale is very different from the dynamical, thermal, or viscous timescales of the accretion disk at the inner edge. The outburst timescale is comparable to the sound-crossing timescale of the disk at the transition radius of \( \sim 50R_g \) between the standard disk and warm Comptonization region. We suggest that the transition of the source from a negligible soft X-ray excess state into the maximum soft X-ray excess state during the outburst is most likely caused by the radiation pressure instability in the inner regions of the disk.

The declining X-ray power-law flux with the UV and the soft X-ray excess fluxes is due to thermal Comptonization of the disk and soft-excess photons in the hot corona. However, the X-ray power law does not steepen with increasing seed flux, which suggests intrinsic changes in the hot corona during the outburst. Thus, all three regions—the accretion disk, the warm corona, and the hot corona—responsible for the primary continuum changed during the outburst.

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Facilities: AstroSat, XMM-Newton.

Software: CCDLAB (Postma & Leahy 2017), XSPEC (Arnaud 1996), Sherpa (Freeman et al 2001), SAOImageDS9 (Joye & Mandel 2003), Julia (Bezanson et al 2017), Astropy (Collaboration et al 2013) APLpy (Robitaille & Bressert 2012; Robitaille 2019).

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