Revealing Thermal Comptonization of Accretion Disk Photons in IC 4329A with AstroSat

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Abstract
We present five simultaneous UV/X-ray observations of IC 4329A by AstroSat performed over a 5 month period. We utilize the excellent spatial resolution of the Ultra-Violet Imaging Telescope on board AstroSat to reliably separate the intrinsic active galactic nucleus (AGN) flux from the host galaxy emission and correct for the Galactic and internal reddening, as well as the contribution from the narrow- and broad-line regions. We detect large-amplitude UV variability, which is unusual for a large black hole mass AGN like IC 4329A, over such a small period. In fact, the fractional variability amplitude is larger in the UV band than in the X-ray band. This demonstrates that the observed UV variability is intrinsic to the disk and not due to X-ray illumination. The joint X-ray spectral analyses of five sets of Soft X-ray Telescope and Large Area X-ray Proportional Counter spectral data reveal a soft X-ray excess component, a narrow iron line (with no indication of a significant Compton hump), and a steepening power law (ΔT ∼ 0.21) with increasing X-ray flux. The soft excess component could arise due to thermal Comptonization of the inner disk photons in a warm corona with kT_e ∼ 0.26 keV. The UV emission we detect acts as the primary seed photons for the hot corona, which produces the broadband X-ray continuum. The X-ray spectral variability is well described by the cooling of this corona from kT_e ∼ 42 to ∼32 keV with increasing UV flux, while the optical depth remains constant at τ ∼ 2.3.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16)

1. Introduction

The primary emission from type 1 active galactic nuclei (AGN) consists of the big blue bump (BBB) in the 1 μm to 1000 Å range, a soft X-ray excess component below ∼2 keV, and a broadband X-ray power-law continuum with a high-energy cutoff at a few hundred keV (Fabian et al. 2015; Lubinski et al. 2016; Ricci et al. 2017; Tortosa et al. 2018). Additional spectral components such as the infrared bump, the optical/UV emission lines, the X-ray reflection (consisting of the iron Kα line and the Compton reflection hump in the 20–40 keV band), and at least a fraction of the soft excess emission can arise due to the reprocessing of the primary emission.

The central engine in AGN responsible for the primary emission is thought to consist of an accretion disk surrounding a supermassive black hole and a compact hot corona (kT_e ∼ 100 keV) in the innermost regions. The BBB component is believed to be the direct signature of the accretion flow and is interpreted as thermal emission from the accretion disk. This component is thought to interact with the hot corona. Photons emitted by the disk undergo repeated Compton upscattering by energetic electrons in the corona, thus giving rise to the broadband primary X-ray power-law-like emission (Haardt & Maraschi 1993). The X-ray power law, in turn, illuminates the accretion disk that can absorb and reflect the X-rays, giving rise to the broad iron line, reflection hump, and at least some fraction of the soft X-ray excess emission. The soft excess emission can also be produced by thermal Comptonization of the optical/UV disk photons by a warm (kT_e ∼ 0.3 keV) and optically thick layer of the inner disk below a few tens of gravitational radii (Dewangan et al. 2007; Done et al. 2012; Mehdirpour et al. 2015; Kubota & Done 2018; Petrucci et al. 2018, 2020), though it is not clear if such a warm corona can be produced in the inner disk.

Observations of the broadband X-ray power-law emission cutting off at high energies in a number of AGN provide strong support to the thermal Comptonization model. However, the nature of the seed photons still remains to be explored. If the variability of the Comptonized X-rays were to be dominated by the variations in the seed flux, it would have been easier to identify the seed photons. But this is not usually the case. In most cases, the X-ray variability amplitude is significantly larger than the variability amplitude we observe in the optical/UV bands. In addition, observations of time lags in the optical/UV variations relative to those in the X-rays imply that it is the X-ray emission that drives the optical/UV variability. Such optical/UV lags are found to be wavelength-dependent and easily explained as arising due to the X-ray reprocessing by the accretion disk (Sergeev et al. 2005; Cackett et al. 2007; Cameron et al. 2012; Troyer et al. 2016; McHardy et al. 2018; Edelson et al. 2019; Cackett et al. 2020). To date, there are only a few observations of optical/UV emission leading X-rays that are consistent with Comptonization delays (Adegoke et al. 2019).

In the thermal Comptonization model, variations in the seed flux are expected to affect both the X-ray flux and spectral variability in AGN. A number of Seyfert 1 AGN show X-ray spectral steepening with increasing X-ray flux. Such spectral variability can be caused by cooling of the corona due to increased irradiating seed flux. For example, based on a monthlong monitoring observation of NGC 7469 simultaneously with the IUE and Rossi X-Ray Timing Explorer...
(RXTE), Nandra et al. (2000) found that the X-ray photon index is correlated with the intrinsic UV flux and suggested thermal Comptonization of UV photons as the origin of the X-ray continuum. Zdziarski & Grandi (2001) showed that the observed softening of X-ray emission in 3C 120 from $\Gamma \sim 1.7$ to $\sim 2$ with increasing soft X-ray flux could be explained in terms of thermal Comptonization by requiring the irradiating optical/UV flux to increase by a factor of $\sim 2$. However, this model could not be tested fully in the absence of simultaneous optical/UV observations. Gliozzi et al. (2013) reported a correlation between the photon index of the power-law component and the soft X-ray ($0.1$–$1$ keV) flux in X-ray-bright radio-loud NLS1 galaxy PKS 0558–504. Here we use AstroSat’s multiwavelength capability for simultaneous observations in the near- (NUV) and far-UV (FUV) and soft and hard X-rays and investigate the UV/X-ray connections in IC 4329A.

The nearby AGN IC 4329A is at a redshift of $z = 0.016054$ (Willmer et al. 1991) and the second-brightest type 1 AGN in the Swift/BAT catalog (Baumgartner et al. 2013). The AGN has been classified as a Seyfert 1.2 (Véron-Cetty & Véron 2006) residing at the center of an edge-on host galaxy with a dust lane passing through the nucleus. It has been studied with all major X-ray satellites, including ASCA/RXTE (Done et al. 2000), BeppoSAX (Perola et al. 2002), Chandra (McKerman & Yaqoob 2004), XMM-Newton (Nandra et al. 2007), and Suzaku (Mantovani et al. 2016) and jointly with Suzaku and NuSTAR (Brenneman et al. 2014). These observations suggest a modest or weak broad iron line that does not require X-ray reflection from the inner disk. Mehdipour & Costantini (2018) derived the broadband spectral energy distribution of IC 4329A using UV and optical observations with Swift, high-resolution XMM-Newton and Chandra X-ray data, and mid-IR spectroscopy and estimated an accretion rate of 10$\%$–20$\%$ of the Eddington limit for a given black hole mass in the range of $1$–$2 \times 10^8 M_\odot$.

We observed IC 4329A five times with the Indian multi-wavelength astronomy satellite AstroSat (Agrawal 2006; Singh et al. 2014) in the period between 2017 February and June. In a companion paper, Dewangan et al. (2021) studied in detail the Ultra-Violet Imaging Telescope (UVIT) data from these observations. They computed the mean source flux in the FUV ($F154W$, $\lambda_{\text{mean}} = 1541$ Å, $\Delta \lambda = 380$ Å) and NUV ($N245M$, $\lambda_{\text{mean}} = 2447$ Å, $\Delta \lambda = 280$ Å) filters and found that the source is not detected in the FUV band. Using the UVIT and archival Hubble Space Telescope data, they found that the intrinsic UV continuum of the active nucleus is fully consistent with standard accretion disk models, but only if the disk emits from distances larger than 80–150 gravitational radii (depending on the assumed extinction law). In this work, we focus on the analysis of the X-ray data from the same observations and the study of the relation between the observed UV and X-ray variations.

This paper is organized as follows. We first describe the observations and data reduction in Section 2. We describe in detail the UVIT data analysis in Section 3. We present the results from the spectral analysis in Section 4. We discuss the implications of our results in Section 5, and we conclude in Section 6.

2. AstroSat Observations and Data Reduction

The details of the AstroSat observations are listed in Table 1. AstroSat carries four coaligned instruments: UVIT (Tandon et al. 2017, 2020), the Soft X-ray Telescope (SXT; Singh et al. 2016, 2017), the Large Area X-ray Proportional Counter (LAXPC; Yadav et al. 2016; Agrawal et al. 2017; Antia et al. 2017), and the Cadmium-Zinc-Telluride Imager (CZTI; Vadhawal et al. 2016). We used the data acquired with the UVIT, SXT, and LAXPC. We did not use the CZTI data, as the source was not detected.

2.1. The SXT Data

The SXT is a focusing X-ray telescope with a CCD camera similar to those employed by the Swift/XRT and XMM-Newton/MOS. It operates in the photon-counting mode and is capable of low-resolution imaging (FWHM $\sim 2''$, half-power diameter (HPD) $\sim 11''$) and medium energy resolution spectroscopy (FWHM $\sim 150$ eV at 6 keV) in the 0.3–8 keV band. We processed the level 1 SXT data with the latest pipeline software ASISXTlevel2-1.4b, which is available at the SXT payload operation center (POC) webpage. We merged the clean event files corresponding to a given observation ID using the Julia SXT event merger tool sxt_l2evtlst_merge. This tool was developed by us and is available at the SXT POC website. It identifies common intervals in the event files and retains only unique events.

The SXT image of IC 4329A from observation 9000001048 is shown in the left panel of Figure 1. We used the xselect tool available within HEASoft version 6.26.1 to extract the source spectrum. For each observation, we extracted the spectrum from the merged event list using a circular region of 15$''$ radius centered on the source (indicated by the green circle in Figure 1, left). The large HPD and four corner calibration sources leave the SXT CCD camera with virtually no source-free regions. Hence, we used the blank-sky background spectrum (SkyBkg_comb_EL3p5_CL_Rd16p0_v01.pha) provided by the SXT instrument team. We also used the most recent spectral redistribution matrix file (RMF; sxt_pc_mat_g0to12.rmf) and ancillary response file (ARF; sxt_pc_excl00_v04_20190608.arf) available on the SXT POC webpage. We grouped each spectral data set using HEASoft task grppha to have a minimum of 30 counts bin$^{-1}$. The net 0.3–7.4 keV count rates are listed in the fourth column of Table 1. The count rate varies by more than a factor of 2, from 0.74 to 1.67 counts s$^{-1}$ during the five observations.

2.2. The LAXPC Data

The LAXPC consists of three identical and coaligned X-ray proportional counter units (LX10, LX20, and LX30) operating in the 3–80 keV band. The LAXPC operates in the normal mode, which is the combination of the broadband counting and event analysis modes. We did not use the data acquired with the LX10 and LX30. The LX10 is not suitable for faint sources such as AGN due to its unstable nature, while LX30 suffered with a continuous gain shift caused by gas leakage (Antia et al. 2017). We processed the LX20 data using the pipeline

https://www.tifr.res.in/~astrosat_sxt/sxtpipeline.html

https://heasarc.gsfc.nasa.gov/docs/software/lheasoft/
LAXPCSOFT V3.0\(^8\) provided by the instrument team. We considered only the layer 1 data to reduce the background and generated the spectrum. The LAXPCSOFT also generates a suitable background spectrum using the blank-sky observations performed close to the source observation. We used the response file 1x20L1v1.0.rmf for our spectral analysis. We grouped the spectrum using the GRPPHA task to have a minimum of 20 counts per energy bin. The net count rates in the LX20 energy band of 4–20 keV are listed in the sixth column in Table 1. The source count rate varied by almost a factor of 2, from 8.2 to 15.4 counts s\(^{-1}\) between the five observations.

2.3. The UVIT Data

The UVIT has two telescopes—one for the FUV (1300–1800 Å) and the other for the NUV (2000–3000 Å) and visible (VIS; 3200–5500 Å) channels. The UVIT is primarily an imaging telescope with excellent spatial resolution (FWHM $\sim$1"–1.75"). Each channel has a number of broadband filters with limited bandpass. The FUV and NUV channels operate in the photon-counting mode and are well calibrated for photometric studies. The VIS channel is operated in the integration mode, and it is used for tracking purposes only. We used the F154W (FUV BaF\(_2\)) and N245M (NUV B13) filters for all five observations. We processed the UVIT data of each observation using CCDLAB (Postma & Leahy 2017) and generated cleaned images for each observation. The AGN in IC 4329A is not detected in the FUV band due to a dust lane passing through the nucleus (Dewangan et al. 2021); therefore, we use only the NUV data here. The central part (2/4 × 2/5) of the NUV image of IC 4329A is shown in the right panel of Figure 1. The bright active nucleus, the diffuse emission from the edge-on host galaxy, and a dust lane passing through the central regions are clearly seen in this figure.

3. The UVIT Data Analysis

As a first test to examine possible variations in the NUV emission from the AGN, we performed aperture photometry of the central region of IC 4329A and a pointlike source (WISEA J134854.55–302140.7, which is classified as an ultraviolet source in the NED\(^9\), and its flux is relatively constant). A comparison between the light curves of IC 4329A

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\(^8\) https://www.tifr.res.in/~antia/laxpc.html

\(^9\) https://ned.ipac.caltech.edu/
and this source will directly indicate the presence of intrinsic variations in the active nucleus. We extracted source counts from a circular region with a radius of 25 pixels (∼10″) centered on IC 4329A (indicated by the green circle in the right panel of Figure 1). Background counts were extracted from 15 source-free regions of the same circular size around IC 4329A (two of them are shown with cyan circles in the right panel of Figure 1). We averaged the background counts from the 15 source-free regions and calculated the net source counts by subtracting the averaged background counts from the source counts. We list the net source count rates for IC 4329A and the averaged background count rates in the last columns of Table 1. For the point source, we used a circular region with a radius of 10 pixels (∼4″) centered on the source and a similar size of a nearby source-free region to calculate the background.

We plot the light curves of IC 4329A, the background, and the point source derived from the aperture photometry in Figure 2 (left panel). We fitted the light curves with a constant model that resulted in a reduced χ^2 of 9.3, 0.6, and 0.8 for IC 4329A (AGN plus galaxy), the background, and the point source, respectively. The best-fit constants are shown by the horizontal green dashed lines in Figure 2. Clearly, the NUV emission from the active nucleus in IC 4329A is highly variable. The constant emission from the point source and the steady background level demonstrate that the NUV variability of IC 4329A is real.

The UV emission from nearby AGN observed with broadband filters is contaminated by the host galaxy emission and numerous emission lines from the broad- and narrow-line regions, including the Fe II and Balmer continuum emission. It is also reddened due to the internal and Galactic absorption. Therefore, following Dewangan et al. (2021), first we separated the emission from the AGN and the host galaxy, then we corrected for the Galactic and internal extinction, and we subtracted the emission line emission. We describe the steps below.

3.1. Radial Profile Analysis

We utilized the excellent spatial resolution of the UVIT to reliably separate the host galaxy and AGN emission by constructing and fitting radial profiles of the source. We first determined the point-spread function (PSF) of the instrument. For this purpose, we extracted the radial profile of WISEA J134854.55−3021407.3, and we fitted it with a Moffat function

\[
M(x) = M_0 \left[ 1 + \left( \frac{x}{a} \right)^2 \right]^{-b}, \quad \text{FWHM} = 2\alpha \sqrt{2^{b/d} - 1}
\]

plus a constant for the background. We treated the best-fitting Moffat profile as the PSF. Analysis of the radial profile of other point sources in the field provided similar best-fit results when fitted by the same function. Tracking correction due to pointing jitter may lead to slightly different PSFs for different observations. We therefore repeated the above exercise for all five observations and determined the PSF for each observation. The FWHM of the best-fitting Moffat function is 1″06, 1″24, 1″34, 1″10, and 1″29 in the sequence of observation IDs, as listed in Table 1.

For each observation, we fitted the radial profile of IC 4329A with the corresponding PSF to account for the AGN emission, plus an exponential profile (i.e., \(I = I_0 \exp(-r/r_d)\)) for the host galaxy emission and a constant component for the background.\(^{10}\) The best fit resulted in \(\chi^2 = 1.18, 0.97, 1.02, 1.29,\) and 1.2 in the sequence of observation IDs. The radial profiles of IC 4329A extracted from the five observations and the corresponding best-fit models along with the individual components are shown in Figure 3. We integrated the best-fit Moffat function, the exponential profile, and the constant component over a radius of 60 pixels (∼24″), and we calculated the model count rates for the AGN, host galaxy, and background, respectively. The count rates thus derived are listed in Table 2 (first, second, and third rows).

3.2. Extinction Correction

We used the extinction curve of Cardelli et al. (1989) for the Galactic extinction with a color excess of \(E(B−V) = 0.052\) and the ratio of total to selective extinction \(R_V = A_V/E(B−V) = 3.1\), where \(A_V\) is the extinction in the V-
The AGN count rates corrected for the Galactic extinction are listed in the fourth row of Table 2. Following Mehdipour & Costantini (2018), we used the extinction curve of Czerny et al. (2004) with a color excess of $E(B - V) = 1$ for the intrinsic extinction. The AGN count rates corrected for the internal reddening are also listed in Table 2 (fifth row).

3.3. Correction for the Contributions from the Broad-/Narrow-line Regions

Finally, we used the composite quasar spectrum of Vanden Berk et al. (2001) and calculated the contribution of emission lines including the Fe II features and the Balmer continuum to the NUV emission from the AGN. We first determined the continuum of the composite quasar spectrum by fitting the 1350–1365 and 4200–4230 Å regions with a power-law model. We then used the effective area of the N245M filter and estimated the NUV count rates of the continuum and the total spectrum. We found that the fractional contribution of the noncontinuum components is ~17.7% for this filter. Assuming the presence of a similar fraction of the noncontinuum components in IC 4329A, we subtracted this contribution from the extinction-corrected AGN count rates to compute the intrinsic disk emission (results are listed in the sixth row of Table 2). We then converted the intrinsic source count rates to flux density (in erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$) using the flux conversion factor for the N245M filter (Tandon et al. 2017, 2020). The intrinsic fluxes of the source are given in the last row of Table 2.

Figure 2 (right panel) shows the AGN, background, host galaxy, and point-source light curves in the NUV/N245M band (from top to bottom, respectively) using the values listed in Table 2. The light curves are normalized to the respective minimum count rate. Clearly, the most variable light curve is that of the AGN. The background, host galaxy, and point-source emission are almost constant over the same period. This is consistent with the results plotted in the left panel of Figure 2 and shows that the variations detected in the central region of IC 4329A with the simple aperture photometry are due to the AGN. It also shows that the variations we detect in the AGN

![Figure 3](image_url)

*Figure 3.* Radial profiles of IC 4329A in all observations and the best-fit Moffat function (green), exponential (magenta), and constant (cyan) components (purple lines indicate the Gaussian component used to account for an emission feature located further away from the galaxy). Red lines show the overall model fits.

| Component | 90000001006 | 90000001048 | 90000001118 | 90000001286 | 90000001340 |
|-----------|-------------|-------------|-------------|-------------|-------------|
| Background | 1.091 ± 0.009 | 1.048 ± 0.011 | 1.081 ± 0.013 | 1.056 ± 0.012 | 1.074 ± 0.009 |
| Galaxy    | 0.692 ± 0.056 | 0.721 ± 0.063 | 0.691 ± 0.072 | 0.691 ± 0.058 | 0.713 ± 0.063 |
| AGN       | 0.057 ± 0.0035 | 0.075 ± 0.0034 | 0.054 ± 0.0037 | 0.077 ± 0.0036 | 0.103 ± 0.0045 |
| Galactic extinction -corrected | 0.082 ± 0.0050 | 0.108 ± 0.0049 | 0.077 ± 0.0053 | 0.110 ± 0.0052 | 0.147 ± 0.0057 |
| Intrinsic extinction -corrected | 35.26 ± 2.16 | 46.49 ± 2.11 | 33.30 ± 2.29 | 47.65 ± 2.25 | 63.49 ± 2.46 |
| Non-continuum-subtracted | 29.02 ± 1.78 | 38.25 ± 1.74 | 27.40 ± 1.88 | 39.21 ± 1.85 | 52.25 ± 2.03 |
| Intrinsic flux ($f_{NUV}$) | 21.04 ± 1.29 | 27.74 ± 1.27 | 19.87 ± 1.37 | 28.43 ± 1.35 | 37.88 ± 1.48 |

Notes.

* In counts per second.
* In units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$.

Table 2

Intrinsic Count Rates and Flux of IC 4329A in the N245M/UVIT Filter (We List 1σ Errors)
emission are genuine, rather than an artifact of our radial profile analysis. We observe significant variations with a factor of ~2 over a period of just 6 months. This large-amplitude variability in the NUV band on such a short timescale is rather remarkable for an AGN with a black hole mass larger than $10^8 M_\odot$.

4. Spectral Analysis

We performed the spectral analysis using XSPEC (version 12.10.1f; Arnaud 1996), and we quote the 1 – $\sigma$ errors on the best-fit spectral parameters. We consider the best-fit models as statistically acceptable when $p_{\text{null}} \geq 0.01$.

4.1. X-Ray Spectral Analysis

We used the SXT data in the 0.3–7.4 keV band and the LX20 data in the 4–20 keV band to ensure a good signal-to-noise ratio. First, we fitted the five sets of SXT and LX20 spectral data jointly in the 4–5 and 8–12 keV bands only. These bands are dominated by the intrinsic continuum emission. We used a simple POWERLAW model, where we varied the photon index and normalization for each data set. This fit resulted in $\chi^2 = 214.79$ for 240 degrees of freedom (dof) with $\Gamma \sim 1.7$–1.9 and a normalization in the range of $\sim(1.9$–5.0) $\times 10^{-2}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at 1 keV. The left panel in Figure 4 shows the ratio of the SXT and LX20 data over the best-fit POWERLAW model for each of the five observations. The spectra are clearly affected by significant absorption. We can also see the iron line and the reflection hump at higher energies (which may even be variable). Then we refitted the data in the same energy bands, but this time we kept $\Gamma$ and the normalization tied across the five data sets. The right panel in Figure 4 shows the data/model ratio for this case. This plot clearly shows the significant flux variability of the source during the AstroSat observations. We detect a significantly smaller flux during ObsID 9000001118. The spectral slope during this observation is clearly flatter than in the other four observations. The flux (and spectral) variations during the other observations are of smaller amplitude. We discuss below the results from the joint spectral analysis of the five SXT+LX20 spectral data sets.

We note that after the launch of AstroSat, the SXT gain was found to shift slightly. We handled this gain change by shifting the energies in the SXT RMF and ARF with the help of the XSPEC command GAIN. We fixed the gain slope to 1.0 and varied the intercept parameter. For each observation, we tied all the parameters of the spectral models for the LX20 and SXT spectra. We also used a constant to account for any difference in the relative normalization of the SXT and LAXPC spectra, and we applied 3% systematic errors in the spectral models to account for any residual calibration uncertainties.

Model fitting the 2–20 keV band. We begin our spectral analysis by fitting the 2–20 keV band with an absorbed power-law model (TBABS $\times$ POWERLAW in XSPEC terminology), with the absorption column density fixed at the Galactic value ($N_H = 4.61 \times 10^{20}$ cm$^{-2}$; Kalberla et al. 2005). We used the absorption cross section and abundances from Verner et al. (1996) and Asplund et al. (2009), respectively. We varied both the normalization and photon index of the power-law model for each observation. The model resulted in a poor fit with $\chi^2 = 1750.3$ for 1331 dof. We added an intrinsic neutral absorption model (ZTBABS) at the source redshift, and we kept the absorption column tied among all five data sets. The fit improved significantly ($\Delta \chi^2 = 212.7$ for one extra dof). We investigated whether the neutral absorbing component is variable and therefore untied the column density across the five data sets, which did not improve the fit significantly ($\Delta \chi^2 = 7.6$ for four extra parameters; $p_{\text{null}} = 0.16$). Therefore, we kept this parameter tied.

We then used the reflection model XILLVER (Garcia et al. 2014) to account for the iron line and related reflection emission. We tied the photon index of the reflection component with those of the power-law component for each observation, and we kept the normalization of the XILLVER model tied across five data sets. We fixed the iron abundance at $A_{Fe} = 1$, the inclination angle at $\theta = 60^\circ$, the ionization parameter at $\log \xi = 0$, the cutoff energy at $E_{\text{cut}} = 186$ keV (Brenneman et al. 2014), and the reflection fraction at $R_f = -1$. This resulted in a better fit with $\chi^2$/dof = 1457.2/1329. We investigated whether the XILLVER component is variable, and we untied its normalization. We found that the normalization was almost constant in four observations and increased by a factor of ~2 in

Figure 4. The SXT (0.3–7.4 keV) and LAXPC (4–20 keV) spectral data (open circles and filled squares, respectively) from five observations. The spectral data are divided by the best-fitting POWERLAW model fitted jointly to the 4–5 and 8–12 keV bands when the photon index and normalization are allowed to vary for each observation (left panel) and when they are tied across the five data sets (right panel). Green, red, black, blue, and orange points mark ObsIDs 9000001006, 9000001048, 9000001118, 9000001286, and 9000001340, respectively (the same color code and point symbols are used in all relevant figures in this work).
one of them (ObsID 9000001048). Therefore, we tied the normalization in four observations and allowed it to vary freely in the other one, which resulted in an improved fit with $\chi^2$/dof = 1446.4/1328. We note that this variation cannot be in response to the observed X-ray continuum variation between the first and second observations, since the power-law component did not vary. If we assume that the X-ray reflection originates in the obscuring torus, which may be located $\sim 10^3 R_s$ away from the central source (at least), then for an $\sim 10^6 M_\odot$ black hole, we expect to see correlated variations on a timescale of more than a year, which is much longer than this campaign. The best-fit results for the fit to the 2–20 keV band are listed in Table 3.

Model fitting the full X-ray band. We noticed the 0.3–2 keV band in all SXT data sets in order to study the spectrum in the soft X-ray band. First, we fitted the 0.3–20 keV band with the best-fit model that we derived from the fits to the 2–20 keV band. This resulted in a poor fit ($\chi^2$/dof = 4138.8/2176). Inspection of the best-fit residuals indicated the presence of a soft X-ray excess emission. We therefore added a blackbody component BBODY to the model, and we repeated the fit, keeping the power-law photon index fixed at the best-fit values we derived when fitting the hard-band spectra. Initially, we tied the BBODY temperature ($kT_{BB}$) and normalization across the five data sets. This resulted in an improved but still statistically poor fit with $\chi^2$/dof = 2663.3/2174. The fit improved to $\chi^2$/dof = 2530.7/2170 when we allowed the BBODY normalization to vary freely. We also investigated whether $kT_{BB}$ varies as well. We found that the blackbody temperature is similar within the errors for all but one observation (ObsID 9000001118), while the best-fit temperature is different. We unity $kT_{BB}$ for this observation, and this further improved the fit ($\Delta \chi^2 = 17.1$ for one dof).

The best-fit residuals indicated the presence of further absorption due to “warm” material this time. We therefore added a warm absorption component, ZXIPCF, to the model. We tied all of the parameters of the absorption component across five data sets, and the resulting fit improved significantly, to $\chi^2$/dof = 2207.21/2166, which is a statistically acceptable solution ($p_{null} = 0.26$). We investigated whether the parameters of the warm absorbing component vary across the five data sets. First, we checked whether the ionization parameter, log(ξ), is variable across the five data sets. We kept the column density, $N_{HW}$, and the covering factor (CF) tied and let the ionization parameter vary during the fit. This did not improve the quality of the fit significantly ($\Delta \chi^2 = 1.69$ for four extra dof). Then, we kept $N_{HW}$ and log(ξ) tied, and we let the CF vary during the fit. This did not improve the fit either ($\Delta \chi^2 = 5.45$ for four parameters). Then, we kept the CF and log(ξ) constant and let $N_{HW}$ be variable. We noticed that the column density is similar for four observations but different for ObsID 9000001118. We therefore tied the column density for the four observations, and we repeated the fit. The resulting $\chi^2$ of 2190.8/2165 dof indicates that the quality of the fit improved significantly in this case (we find an F-statistic of 16.2 and $p_{null} \sim 6 \times 10^{-5}$ when we apply the F-test). At the same time, we also found that the blackbody temperature for ObsID 9000001118 is now consistent with those for the four other observations. Hence, we tied $kT_{BB}$ among all five observations, and we repeated the fit. This resulted in a $\chi^2$ of 2190.8 for 2166 dof, which indicates a very good fit ($p_{null} = 0.35$). We accept this as our final fit of the broadband X-ray spectrum of the source during the five AstroSat observations. The best-fit parameters are listed in Table 3, together with the intrinsic power-law flux in the 2–10 keV band and the blackbody flux in the 0.3–2 keV band, which we consider indicative of the soft excess flux. Figure 5 shows the

Table 3

The Best-fit Parameters from the Joint SXT + LX20 Spectral Fit with the Model CONST × TBABS × ZXIPCF × (ZPOWERLAW+XILLVER+BBODY)

| Model | Component | Parametera | ObsID |
|-------|-----------|------------|-------|
|       |           | 9000001006 | 9000001048 | 9000001118 | 9000001286 | 9000001304 |
| CONST |           | 0.82±0.01  | 0.82±0.01  | 0.82±0.01  | 0.82±0.01  | 0.82±0.01  |
| ZTBABS | $N_H (10^{22} \text{ cm}^{-2})$ | 0.17±0.01 | 0.17±0.01 | 0.17±0.01 | 0.17±0.01 | 0.17±0.01 |
| ZTBABS | $N_{HW} (10^{22} \text{ cm}^{-2})$ | 2.35±0.09 | 2.35±0.08 | 2.93±0.18 | 2.35±0.18 | 2.35±0.18 |
| ZTBABS | log(ξb) | 0.46±0.05 | 0.46±0.05 | 0.46±0.05 | 0.46±0.05 | 0.46±0.05 |
| ZTBABS | CF | 0.88±0.01 | 0.88±0.01 | 0.88±0.01 | 0.88±0.01 | 0.88±0.01 |
| ZPOWERLAW | $\Gamma$ | 1.89±0.02 | 1.85±0.03 | 1.77±0.03 | 1.95±0.02 | 1.98±0.02 |
| ZPOWERLAW | $N_{x}(10^{-2})$ | 4.85±0.06 | 4.49±0.07 | 2.27±0.03 | 5.62±0.07 | 6.07±0.07 |
| ZPOWERLAW | $f_{x}(2 – 10 \text{ keV})$ | 1.15±0.02 | 1.44±0.02 | 0.83±0.01 | 1.54±0.02 | 1.59±0.02 |
| ZPOWERLAW | $N_{x}(10^{-4})$ | 3.07±0.30 | 6.44±0.52 | 3.07±0.30 | 3.07±0.30 | 3.07±0.30 |
| XILLVER | $kT_{BB}$ ( keV) | 0.258±0.005 | 0.258±0.005 | 0.258±0.005 | 0.258±0.005 | 0.258±0.005 |
| BBODY | $f_{BB} (0.3 – 2 \text{ keV})$ | 1.31±0.18 | 1.46±0.18 | 1.10±0.14 | 1.66±0.22 | 1.65±0.22 |

Notes.

a The notation “±” indicate tied parameters.

b Power-law normalization in units of photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV.

c Intrinsic X-ray flux in units of $10^{-9}$ ergs cm$^{-2}$ s$^{-1}$.

d Normalization of the XILLVER model.

i Normalization of the BBODY model in units of $10^{39}$ erg s$^{-1}$ and $D_{10}$ is the distance to the source in units of 10 kpc.

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spectra, the overall best-fit model, and the individual components. The bottom panel shows the model residuals in terms of sigmas with error bars of size one.

Our results show that the power-law photon index varied from $\sim 1.8$ to $\sim 2$ during the AstroSat monitoring of the source. The power law and the soft X-ray excess fluxes are also variable by a factor of $\sim 2$ and $\sim 1.5$, respectively, though the errors on the soft X-ray excess fluxes are relatively larger (see Table 3). The fractional rms variability amplitude (Vaughan et al. 2003) of the X-ray power law and soft excess fluxes using the PL and BB values listed in Table 3 are 22.46% ± 0.60% and 9.87% ± 5.93%, respectively. Interestingly, the X-ray continuum variability amplitude is slightly smaller than the NUV rms, which is 26.20% ± 2.24% (using the intrinsic AGN count rates listed in Table 2), although the difference is not statistically significant. Nevertheless, this is rather unusual for AGN.

4.2. Broadband UV/X-Ray Spectral Analysis

We investigated the UV/X-ray broadband spectral variability of IC 4329A by constructing and fitting the broadband SEDs using the intrinsic UV and X-ray spectral data acquired simultaneously with AstroSat. We converted the intrinsic UV flux into XSPEC-compatible spectral files for each observation (Table 2) using the FTLX2XSP tool.

We added an accretion disk component to the model (OPTXAGNF; Done et al. 2012) in order to fit the UV/X-ray data. The main parameters of OPTXAGNF are the black hole mass ($M_{\text{BH}}$), the comoving/proper distance ($D$ in Mpc), the Eddington ratio ($\dot{m} = \log(L/\dot{L}_{\text{Edd}})$), the dimensionless black hole spin ($a$), and the inner disk radius ($R_{\text{in}} = G M_{\text{BH}} / c^2$). We forced the OPTXAGNF model to produce the accretion disk spectrum only by setting $R_{\text{in}}$ to be negative.

Dewangan et al. (2021) studied in detail the optical/UV spectrum of IC 4329A using the same AstroSat observations

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**Figure 5.** The SXT (0.3–7.4 keV) and LAXPC (4–20 keV) spectra of the five observations. The first five panels show the data and best-fit models for individual observations (the observation IDs are shown), and the bottom panel shows $\chi$ residuals in terms of (data−model)/error. Solid and dashed lines in each panel show the overall best-fit models and the individual spectral components, respectively (see Section 4.1 for details).
that we also consider in this work. They corrected the optical/UV data for the intrinsic extinction using multiple extinction curves, and they modeled the intrinsic optical/UV data with the OPTXAGNF disk model for both a maximally spinning Kerr and a Schwarzschild black hole. They showed that the disk must be truncated in both cases. Here we assume their best-fit results derived by fitting the Kerr disk model to the intrinsic extinction-corrected data using the extinction curve of Czerny et al. (2004) with a color excess of $E(B-V)=1.0$. We therefore fixed the inner disk radius at $R_{\text{cor}}=80\,R_g$, and we fitted the data assuming $M_{\bullet}\text{BH}=2\times10^8\,M_\odot$, $D=69.61\,\text{Mpc}$, and $a=0.998$, like Dewangan et al. (2021). We note that the best-fit inner radius is the same irrespective of whether we assume a nonrotating or maximally rotating black hole (what changes in these cases is the best-fit accretion rate value). This is because the differences between the spectrum of an accretion disk around a spinning Kerr and Schwarzschild black hole differ at wavelengths shorter than $\sim1000\,\text{Å}$, where the intrinsic emission of IC 4329A is absorbed.

Furthermore, we replaced the ZPOWERLAW component with THCOMP, which is a convolution model that can be used to Comptonize any seed photon spectrum (Zdziarski et al. 2020). The main parameters of this component are (1) the X-ray power-law photon index $\Gamma$ or the Thomson optical depth $\tau$, (2) the electron temperature $kT_e$, and (3) the scattering fraction $f_{\text{sc}}$ (where $0 \leq f_{\text{sc}} \leq 1$; $f_{\text{sc}}=1$ implies that all seed photons will be Comptonized). We convolved the disk spectrum produced with OPTXAGNF with the THCOMP model. We also replaced the TBABS and ZTBABS components with PHABS and ZPHABS, respectively, as the former components also account for UV absorption. Thus, the final model is $\text{CONST} \times \text{PHABS} \times \text{ZPHABS} \times \text{ZXIPCF} \times (\text{THCOMP}+\text{OPTXAGNF}+\text{BBODY}+\text{XILLVER})$. We used this model to fit all five NUV and the broadband X-ray spectra of the source. We fixed the parameters of BBODY, XILLVER, ZXIPCF, and ZPHABS at the best-fit values that we derived from the X-ray spectral fits and allowed the accretion rate and the parameters of the Comptonization component to be variable during the fit. Our objective is to investigate whether this model, with the more physical model components, can fit the NUV/X-ray spectra of the source.

However, it is difficult to determine both the electron temperature and the Thomson optical depth of the corona due to the lack of X-ray data at high energies, where the energy cutoff could be observed. For that reason, we fitted the data twice. In the first case, we fixed $kT_e$ at 50 keV (Brenneman et al. 2014) assuming a spherical geometry of the corona, tied $f_{\text{sc}}$, and let $\tau$ and the accretion rate be variable during the fit. The best-fitting model resulted in $\chi^2/\text{dof}=2413.18/2179$. We tested the possibility of variable $f_{\text{sc}}$, and we found that the fit improves significantly ($\Delta \chi^2=114.15$ for an additional parameter) when we allow $f_{\text{sc}}$ to vary freely in one observation (ObsID 9000001118). The fit improves further ($\Delta \chi^2=77.27$ for an extra parameter) if we allow $f_{\text{sc}}$ to vary for a second observation (ObsID 9000001048). We did not notice any further improvement if we allow $f_{\text{sc}}$ to vary in the other observations. The final model resulted in a $\chi^2/\text{dof}=2221.76$ for 2177 dof. The best-fit results are listed in Table 4. Next, we fixed the optical depth at $\tau=2.34$ (Brenneman et al. 2014), and we allowed the accretion rate and electron temperature, $kT_e$, to vary during the fit. The model again resulted in a good fit with $\chi^2/\text{dof}=2221.80/2177$ dof. As with the fit above, the model fits the data best when we allow $f_{\text{sc}}$ to vary freely for the first and second observations. The variable $kT_e$ variant of the model fits the data as well as when we let $\tau$ vary. The best-fit parameters are listed in Table 4. In order to demonstrate the quality of the model fits in these cases, we show the best-fit UV/X-ray SED when $\tau$ was kept fixed in Figure 6.

### 4.3. The Soft X-Ray Excess and the Disk Emission

We also investigated whether the soft excess component can be explained as thermal Comptonization of the disk photons in a “warm” corona. For this, we revisited the joint X-ray spectral analysis. We removed the BBODY model and used the NTHCOMP model instead (Zdziarski et al. 1996; Ziolk et al. 1999) to fit the soft X-ray excess emission. Thus, our model now becomes $\text{CONST} \times \text{TBABS} \times \text{ZTBABS} \times \text{ZXIPCF} \times (\text{ZPOWERLAW}+\text{XILLVER}+\text{NTHCOMP})$. The main parameters of the NTHCOMP model are the photon index ($\Gamma_{\text{warm}}$) of the Comptonized spectrum, electron temperature ($kT_{\text{warm}}$), and seed photon temperature ($kT_{\text{seed}}$). We assumed blackbody seed photons (int_type=0) with the surface temperature profile of the disk given in Equation (4), and we calculated the seed photon temperature at $R_m=80\,R_g$ for each observation using the mass accretion rate given in Table 4 and a black hole mass of $2\times10^8\,M_\odot$. The seed photon temperatures ($kT_{\text{seed}}$) are 0.85, 1.03, 0.91, and 1.01 eV in the sequence of the observation IDs.

We kept $\Gamma_{\text{warm}}$, $kT_{\text{warm}}$, and the normalization of the NTHCOMP model ($N_{\text{nthcomp}}$) tied during the model fit. This resulted in $\chi^2/\text{dof}=2289.46/2169$. The quality of the fit improved considerably when we allowed the normalization to vary freely during the fit, resulting in $\chi^2/\text{dof}=2189.45/2165$. The quality of this fit is almost identical to the quality of the model fit when we used the BBODY model to account for the soft excess. The best-fit values of the NTHCOMP parameters are $\Gamma_{\text{warm}}<2.54$ (3$\sigma$ upper limit), $kT_{\text{warm}}=0.263^{+0.005}_{-0.003}$ keV, and $N_{\text{nthcomp}}=6.12^{+0.95}_{-0.81} \times 10^{-2}$, $6.81^{+0.98}_{-0.87} \times 10^{-2}$, $5.36^{+0.65}_{-0.63} \times 10^{-2}$, $7.78^{+1.15}_{-1.03} \times 10^{-2}$, and $7.75^{+1.05}_{-1.03} \times 10^{-2}$ ($N_{\text{nthcomp}}$ is unity at 1 keV for a norm of 1) in the sequence of the observation IDs. Other parameters remain unchanged.

Lastly, we also tried to simultaneously fit the NUV, soft X-ray excess, and power-law components of the five data sets using the OPTXAGNF model. In XSPEC terminology, the model is now $\text{CONST} \times \text{PHABS} \times \text{ZPHABS} \times \text{ZXIPCF} \times (\text{OPTXAGNF}+\text{XILLVER})$. We fixed the photon index ($\Gamma$) of the OPTXAGNF model at the best-fit values listed in Table 3. We allow the temperature and optical depth of the warm corona, the power-law fraction ($f_{\text{pl}}$), and the mass accretion rate for each observation to vary freely in the fit in order to take into account the variations we saw in the BBODY component, the power law, and the NUV flux (see Sections 4.1 and 3). We tied the inner disk radius ($R_{\text{cor}}$) across the five data sets, and we also allowed it to vary when we fitted the data. The best-fit results show that the power-law fraction is in the range 0.48–0.69, the temperature of the warm corona is of the order of $\sim0.24$ keV, and the optical depth varies between ~20 and 40. We found an inner disk radius of $\geq195\,R_g$. The best-fit model resulted in $\chi^2/\text{dof}=2253.16/2165$. This is a good fit ($p_{\text{null}}=0.09$), although it is not as good as the fit to the combined NUV/X-ray spectra we presented in Section 4.2. The best-fit inner disk radius is larger than the value we assumed in that section (which was based on the modeling of the UV/optical SED of the source of Dewangan et al. 2021). But this could be due to
The NUV data are shown by open triangles. The bottom panels show the same: a truncated disk and a warm corona, which vary in the fact that we may be reaching the accuracy of the models allowed us to reliably separate the AGN from the host galaxy. The excellent spatial resolution of UVIT allowed us to reliably separate the AGN from the host galaxy. The excellent spatial resolution of UVIT allowed us to reliably separate the AGN from the host galaxy.

### 5. Results and Discussion

We analyzed five simultaneous UV/X-ray observations of IC 4329A obtained using AstroSat during 2017 June, and we investigated the broadband X-ray spectral variability and its connection with the NUV emission from the AGN. The excellent spatial resolution of UVIT (∼1″5) allowed us to reliably separate the AGN from the host galaxy emission by fitting the radial profile of IC 4329A for each observation separately. We corrected the AGN emission for Galactic and internal reddening using the most suitable extinction law derived for IC 4329A. We also corrected for the contribution of the broad- and narrow-line regions and derived the intrinsic continuum emission from the AGN in the NUV band (see Section 3 and Table 2). Light curves generated from simple aperture photometry, as well as from the radial profile analysis, show similar variability patterns and demonstrate that the disk emission from IC 4329A varied genuinely by a factor of ∼2 during the 5 month period of monitoring observations.

We found that X-ray emission from IC 4329A consists of a continuum power-law–like component with a variable slope (Γ ∼ 1.8–2), a soft X-ray excess component described by a simple blackbody (kTBB ∼ 0.26 keV), and X-ray reflection. The measured temperature of the blackbody component is consistent with the values generally observed for type 1 AGN (Kubota & Done 2018). We also found that the nuclear emission suffers from both neutral and warm absorption, thus confirming earlier studies (McKernan & Yaqoob 2004; Mantovani et al. 2016; Mehdipour & Costantini 2018). We converted the column density of the neutral absorbing component (N_H = 1.7 × 10^{21} cm^{-2}) to optical extinction A_V = 0.77 using the relation N_H = 2.21 × 10^{21} A_V (Güver & Özel 2009). For R_V = 3.1, this corresponds to a color excess of E(B−V) = 0.25. This is smaller than the color excess of E(B−V) = 1.0 ± 0.1 reported by Mehdipour & Costantini (2018), who also pointed out that the neutral gas alone is not sufficient to produce all of the observed UV/optical extinction in the source, and dust can also be associated with the low-ionized absorbing components. This discrepancy could also be explained if the dust-to-gas ratio in IC 4329A is larger than that in our Galaxy.

#### 5.1. The Variable Disk Emission

The NUV flux of IC 4329A is highly variable. We found that the variability amplitude of the disk emission is actually higher than the amplitude of the X-ray variations (F_var,NUV/F_var,X ∼ 1.2). Figure 7 shows the intrinsic flux in the NUV band (f_{NUV}), the 0.3–2 keV band flux of the blackbody component (f_{BB}), and the 2–10 keV band power-law flux (f_{PL}) as a function of time (fluxes are those listed in Tables 2 and 3). Each light curve is normalized to its mean to facilitate the comparison of their amplitude. First, it is clear that the AGN is significantly variable in these bands, and the variations are highly correlated. This is not the result of any model fitting degeneracy. The NUV flux is determined from the radial profile analysis of the source in the NUV images, the f_{BB} determined by the best-fit power-law model in the 2–10 keV band, and the f_{PL} is calculated using the best-fit blackbody component while the power-law component is kept fixed. Second, the power-law flux is variable by a factor of ∼20% between the observations, except for the third observation, where we observe a large-amplitude flux decrease. The NUV light curve, on the other hand, appears to be even more variable than the X-ray continuum flux from one observation to the observation.
next. This explains the larger variability amplitude in the NUV band (see Section 4.1). This result is not statistically significant (the variability amplitudes are consistent within the errors), and it is based on just five observations spread over a 5 month period. Nevertheless, it is very interesting, as it is opposite to what we observe in other nearby AGN.

Recent results from intensive, multiwavelength monitoring of a few bright AGN over a period of a few months have shown that the variability amplitude of the Swift W1 band (which has a central wavelength similar to the AstroSat NUV filter) is always smaller than the X-ray variability amplitude. For example, the $F_{\text{var,NUV}}/F_{\text{var,X}}$ ratio is of the order of 0.35 in NGC 5548 (Fausnaugh et al. 2016), 0.25 in NGC 4593 (McHardy et al. 2018), 0.4 in NGC 2617 (Fausnaugh et al. 2018), 0.15 in NGC 4151, and 0.8 in Mrk 509 (Edelson et al. 2019). Except for NGC 5548, the $F_{\text{rms,NUV}}$ amplitudes may not be corrected for the host galaxy contribution, but, at these wavelengths, the host galaxy may not contribute significantly. The large NUV variability amplitude in IC 4329A is even more remarkable, if one considers that this is a high-mass AGN.

Since $F_{\text{var,NUV}} > F_{\text{var,X}}$ in IC 4329A, it is not possible to explain the variable disk emission as the result of X-ray thermal reverberation. Most of the observed NUV variations must be due to intrinsic physical processes in the disk. The dynamical ($t_{\text{dy}}$), thermal ($t_{\text{th}}$), and viscous ($t_{\text{vis}}$) timescales are given by (Czerny 2006)

$$t_{\text{dy}} = \left(\frac{r^{3}}{GM_{\text{BH}}}\right)^{1/2} \approx 500 \left(\frac{M_{\text{BH}}}{10^{8}M_{\odot}}\right) \left(\frac{r}{R_{g}}\right)^{3/2},$$

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

and

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

where $\alpha$ is the viscosity parameter, $r$ is the radial distance, and $h$ is the height of the disk (in units of $R_{g}$). We first estimated $h/r = c_{s}/v_{\phi} \sim 2.9 \times 10^{-2}$ (where $c_{s} = \sqrt{\Gamma \frac{K}{m_{p}}}$ is the sound speed and $v_{\phi} = \sqrt{GM_{\text{BH}}/r}$ is the Keplerian velocity) for a disk temperature of $\sim 11,300$ K (calculated below) and a black hole mass of $M_{\text{BH}} = 2 \times 10^{8} M_{\odot}$. Then, assuming $\alpha = 0.1$, we calculated the dynamical, thermal, and viscous timescales of the disk at $R_{g} = 80R_{e}$ to be $t_{\text{dy}} \sim 8.3$ days, $t_{\text{th}} \sim 83$ days, and $t_{\text{vis}} \sim 2.7 \times 10^{6}$ yr. We find variations by a factor of $\sim 2$ on timescales as short as $\sim 80$ days (see Figure 7).

Therefore, they could be due to some disk variation that develops on the thermal timescale. If the warm corona does exist on top of the inner disk (at radii smaller than $\sim 80R_{e}$), then perhaps a disk instability at this transition radius, which develops on the thermal timescale, may explain the observed variability. If that is the case, we would expect to see similar-amplitude UV variations in other sources, where a warm corona above the disk has been suggested. Perhaps this instability operates over a narrow annulus around the transition radius, and the resulting emission dominates in a narrow spectral range, which in IC 4329A just happens to be within the NUV filter. If a thermal instability develops at the transition radius, we would expect the maximum amplitude variations to appear at the wavelength where the maximum flux from this region is emitted. We investigated whether the emission from an annulus around the transition radius at $80R_{e}$ could contribute to the NUV in IC 4329A by assuming the accretion disk emits as a multicolor blackbody. The surface temperature radial profile ($T_{s}(r)$) of the disk is given by Krollik (1999),

$$T_{s}(r) = \left(\frac{3GM_{\text{BH}}}{8\pi\sigma r^{3}}\right)^{1/4},$$

where $M$ and $M_{\text{BH}}$ are the black hole mass and accretion rate in physical units, and $R_{g}(r)$ is the general relativistic reduction factor as a function of the radial distance, $r$. We calculated $M$ by the equation $M = \dot{m}M_{\text{Edd}}$, where $\dot{m}$ is the mean of the dimensionless accretion rates listed in Table 4 (which is equal to $\sim 0.06$), and $M_{\text{Edd}} = L_{\text{Edd}}/\eta c^{2}$, where $\eta$ is the accretion efficiency and $L_{\text{Edd}}$ is the Eddington luminosity. We assumed $\eta = 0.321$ for a spin parameter of 0.998. The Eddington luminosity for a mass of $M_{\text{BH}} = 1 - 2 \times 10^{8} M_{\odot}$ is $\sim 1.3 - 2.5 \times 10^{46}$ ergs s$^{-1}$. Further, the general relativistic reduction factor is $\sim 0.8$ at $r = 80R_{e}$ (see Figure 7.3 of Krollik 1999). Using these values, we found that the surface disk temperature at the transition radius is expected to be $\sim 11,300 - 13,500$ K. Using Wien’s displacement law ($\lambda_{\text{peak}} T_{s} = b$, where $b = 2.898 \times 10^{-3}$ mK and $\lambda_{\text{peak}}$ is the peak wavelength of the blackbody spectrum), we estimated that $\lambda_{\text{peak}} \sim 2150 - 2550$ Å, which, after accounting for the source redshift, is well within the bandpass of the NUV/N245M filter (Tandon et al. 2020). This simple calculation shows that, if a thermal instability develops at the transition region in IC 4329A, then its variability timescale is compatible with what we observe, and the maximum variability amplitude should appear in the NUV band. Perhaps this can also explain the fact that, while the NUV flux is highly variable, the visible flux is almost constant (Mehdipour & Costantini 2018).

5.2. The X-Ray Spectral Variability

Our analysis has revealed a variable X-ray spectrum, with the power-law slope becoming steeper ($\Gamma \sim 1.8 - 2$) with

![Figure 7. The 2–10 keV power-law flux (red), the soft X-ray excess flux in the 0.3–2 keV band (blue), and the NUV band (green) light curves, normalized to the mean flux of the respective bands.](image-url)
increasing X-ray flux \((f_{\text{PL}} \sim 8.3 - 15.9 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1})\); see Table 3). Figure 8 shows a plot of the best-fit \(\Gamma\) versus the continuum flux, where the “softer-when-brighter” trend is apparent. Such spectral variability has been found in a number of Seyfert galaxies (Dewangan et al. 2002; Zdziarski et al. 2003; Sobolewska & Papadakis 2009; Emmanoulopoulos et al. 2011; Yang et al. 2014) and is generally interpreted in terms of thermal Comptonization of seed optical/UV photons when the spectral steepening results from cooling of the coronal plasma as a result of increased seed flux (Zdziarski & Grandi 2001; Petrucci et al. 2004).

Using the simultaneous UV/X-ray monitoring observations with AstroSat, we found that the X-ray spectral slope is positively correlated with the NUV flux as well. This is clearly seen in the left panel of Figure 9. The solid line in this plot indicates the best linear fit to the data (estimated by taking into account the error on both variables). The best-fit slope is \(8.9 \pm 3.9 \times 10^{12}\), which implies that the correlation is significant at more than the 2\(\sigma\) level.

Consequently, the steepening of the X-ray photon index with increasing NUV emission supports the hypothesis of thermal Comptonization for the X-ray emission in AGN. This is further supported by the plot in the middle panel of Figure 9. This plot shows the best-fit coronal temperature, \(kT_e\), as a function of the NUV intrinsic flux in log-log space (the corona temperature values are those listed in Table 4, when the combined NUV/X-ray spectra were fitted with the thermal Comptonization model at a constant optical depth). The solid line shows the best-fit linear fit to the data (in log-log space; best-fitting slope of 0.5 \pm 0.2). The decreasing temperature with increasing NUV flux clearly supports the scenario of seed photons cooling the hot corona. Of course, the scenario of a constant corona with a variable optical depth can also fit the data, as we already discussed in Section 4.2. But in this case, the \(\tau\) variability anticorrelates with the NUV variations. We cannot think of a possible physical explanation for such a trend.

If the variable seed flux from the accretion disk is the main driver of the X-ray spectral variability via thermal Comptonization, we would also expect a strong correlation between the NUV and X-ray power-law flux, as the photon number must be conserved in the Comptonization process. This is already apparent from the normalized NUV and \(f_{\text{PL}}\) light curves plotted in Figure 7. To investigate this issue further, we also calculated the X-ray power-law photon flux in the 5 eV–500 keV band. To do so, we assumed a power-law model with an exponential cutoff. We used the best-fit power-law parameters listed in Table 3 and the best-fit temperature values in Table 4 to compute the cutoff energy, \(E_c\) (assuming \(E_c = 3kT_e\)). The right panel of Figure 9 shows the X-ray power-law photon flux \((f_{\text{PL}})\) plotted against the intrinsic NUV photon flux. The solid line again shows the best-fit linear relation (best-fit slope = 1.6 \pm 0.5). It is clear that the accretion disk emission and the X-ray power-law photon flux are strongly correlated, thus further supporting the idea that the accretion disk is providing the seed photons for thermal Comptonization. The scatter seen in all plots in Figure 9 (right) could arise due to the effects of the intrinsic variability of the hot corona emission.

### 5.3. The Origin of the Soft Excess

We detected a soft X-ray excess component below \(\sim 2\) keV, consistent with previous results (Mehdipour & Costantini 2018). We did not detect an iron line in our spectra, as the effective area of the SXT is small above 6 keV and the spectral resolution of the LAXPC is poor. Also, the broad iron line is weak, with an equivalent width of \(\sim 65\) eV (Nandra et al. 2007). Therefore, the nondetection of a broad iron line in our analysis is consistent with the earlier detection of a weak, moderately broad iron line (McKernan & Yaqoob 2004; Markowitz et al. 2006; Ogawa et al. 2019). These results indicate that X-ray reflection from the inner disk is weak in this source. Ogawa et al. (2019) fitted the \(\sim 0.7–70\) keV broadband Suzaku+NuSTAR spectral data with a relativistic reflection model and inferred a low reflection fraction \((R < 3.2 \times 10^{-3})\) from a truncated accretion disk \((R_{\text{in}} \sim 87 R_g)\). This result suggests that at least some part of the soft excess observed in
IC 4329A could be due to X-ray reflection from the disk at large radii. However, we did not fit the data with a relativistic disk reflection component to investigate this issue in detail.

On the other hand, thermal Comptonization of the disk seed photons in a warm corona that is located above the inner disk could also produce the soft X-ray excess emission that we observe in many AGN (Mehdipour et al. 2015; Petrucci et al. 2018, 2020). We actually found that the soft excess component in this object can be fitted well by the thermal Comptonization model NTHCOMP, with the best-fit warm corona temperature and spectral photon index being $\sim0.26$ keV and $\leq 2.54$ ($\sigma$ upper limit). Both of these values are consistent with the values generally observed for type 1 AGN (Kubota & Done 2018).

6. Conclusion

We analyzed high-resolution NUV images of IC 4329A and simultaneous X-ray data acquired with AstroSat and found that the intrinsic UV emission from the AGN varied more than the X-ray emission. The intrinsically variable UV emission is correlated with both the X-ray continuum spectral slope and the flux. Our observations are consistent with the accretion disk providing the seed photons for the thermal Comptonization process in the hot corona, and the observed X-ray spectral variability can be explained as the increasing UV emission cooling the hot corona at a constant optical depth. Future simultaneous broadband UV and X-ray spectroscopic monitoring observations with AstroSat and NuSTAR could determine both the temperature and optical depth of the corona and the effect of the changing seed flux on these characteristic coronal properties. Finally, we also detect a soft excess, which is well fitted by a blackbody component with a temperature of 0.26 keV, similar to what has been observed in other AGN as well. This component could be the result of a “warm” corona, located above the inner disk, that is upscattering the disk photons emitted by the inner disk radius at $\sim100 R_g$. Perhaps some of the soft excess flux may also be due to the X-ray reflection from the inner disk, which in this source is either far from the center or filled with a warm, optically thick medium (Dewangan et al. 2021).

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Facility: AstroSat.

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

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