An X-Ray Spectral Study of the Origin of Reflection Features in Bare Seyfert 1 Galaxy ESO 511–G030

Ritesh Ghosh1 and Sibasish Laha2,3

1 Visva-Bharati University, Santiniketan, Bolpur 731235, West Bengal, India; ritesh.ghosh1987@gmail.com, riteshghosh.rs@visva-bharati.ac.in
2 Astroparticle Physics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
3 Center for Space Science and Technology, University of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA

Received 2020 August 25; revised 2020 November 27; accepted 2020 December 14; published 2021 February 24

Abstract

The reprocessed X-ray emission from active galactic nuclei is an important diagnostic tool to study the dynamics and geometry of the matter surrounding supermassive black holes (SMBHs). We present a broadband (optical-UV to hard X-ray) spectral study of the bare Seyfert 1 galaxy, ESO 511–G030, using multi-epoch Suzaku and XMM-Newton data from 2012 and 2007, respectively. The broadband spectra of ESO 511–G030 exhibit a UV bump, a prominent soft excess below 2 keV, a relatively broad (σ = 0.08–0.14 keV) Fe emission line at 6.4 keV, and a weak Compton hump at E > 10 keV. The soft X-ray excess in ESO 511–G030 can be described either as the thermal Comptonization of disk seed photons by a warm (0.40±0.02 keV), optically thick (τ = 12.7^{+0.4}_{-0.3}) and compact (r < 15r_g) corona or as the blurred reflection from an untruncated and moderate to highly ionized accretion disk. However, for the blurred reflection, the model requires some extreme configuration of the disk and corona. Both these models prefer a rapidly spinning black hole (a > 0.78) and a compact corona, indicating a relativistic origin of the broad Fe emission line. We found an inner disk temperature of ~2–3 eV that characterizes the UV bump and the SMBH accretes at a sub-Eddington rate (L_{Edd} = 0.004–0.008).

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); X-ray active galactic nuclei (2035)

1. Introduction

Active galactic nuclei (AGNs) are the most powerful emitters in the Universe. The accretion of matter onto supermassive black holes (SMBHs) is the main energy source of this huge emission (Zel'dovich 1964; Lynden-Bell 1969). The accreted matter loses angular momentum and forms a disk-like structure, the simplest theoretical description of which is an optically thick but geometrically thin accretion disk (Shakura & Sunyaev 1973). Thermal emission from this disk mostly emits in the ultraviolet (UV) band, extending to soft X-rays. The seed UV photons are Compton upscattered by an optically thin and hot corona (Shakura & Sunyaev 1973; Haardt & Maraschi 1993), around the central SMBH, and produces a power-law spectrum, that dominates the X-ray continuum in AGNs. A part of the coronal emission illuminates the accretion disk and produces reflection features, such as Fe Kα emission around 6.4 keV and the Compton hump above 10 keV. Depending on the ionization state of the accretion disk (Ross & Fabian 2005; García & Kallman 2010) and the proximity of the SMBH, the reflection component can be blurred and distorted by relativistic effects (Laor 1991; Crummy et al. 2006) if originated close to the SMBH; or it can be cold and neutral if reflected farther from the black hole in the outer part of the disk and the torus. The presence of a broad and/or narrow Fe emission line in the AGN X-ray spectra generally depicts this idea. In the case of Seyfert 1s, apart from the primary power-law component and the Fe emission line, a soft-excess component (Arnaud et al. 1985; Singh et al. 1985; Crummy et al. 2006; Done et al. 2012; Laha et al. 2014a; Ghosh & Laha 2020) is also observed below 2 keV. The origin of this excess is still debated. Current studies usually tend to favor either the blurred and ionized disk reflection or the intrinsic disk Comptonization of disk photons. These reflection features originate within a few gravitational radii from the SMBH and hence serve as an important probe of the inner extent of the accretion disk and the black hole spin (Wilkins & Fabian 2011).

However, in several cases, these spectral features are modified by the line-of-sight absorption due to neutral (Laha et al. 2020) or ionized (Laha et al. 2011, 2013, 2016, 2018b, 2021; Tombesi et al. 2013, 2015) clouds. Hence, “bare” AGNs, showing no signs of absorption, are crucial to study the emission from the spatially unresolved central region. Notable examples of such sources are Fairall 9 (Gondoin et al. 2001; Schmoll et al. 2009; Emmanoulopoulos et al. 2011), and Ark 120 (Vaughan et al. 2004; Nardini et al. 2011) and Mrk 509 (García et al. 2019). Previous studies of these sources reveal prominent reflection features in the observed X-ray spectra in the form of soft excess and Fe line complex along with the presence of an occasional Compton hump. A reflection-based analysis of a sample of 25 bare AGNs by Walton et al. (2013) suggests a general preference for rapidly rotating black holes of bare AGNs. In our work, we aim to study the broadband X-ray spectra of a bare AGN to rigorously test the reflection interpretation and subsequently unravel the disk, corona, and the central engine properties.

ESO 511–G030 is a bare AGN, as has been found by Tombesi et al. (2010), Winter et al. (2012), and Laha et al. (2014b), and a prime candidate for fulfilling this role due to its prominent reflection features. It is a nearby (z = 0.0224) Seyfert 1 galaxy and also one of the X-ray brightest bare Seyferts featured in the Swift 58 month BAT catalog (Winter et al. 2012). ESO 511–G030 was observed only once by the XMM-Newton in 2007 and previous studies revealed the presence of a soft excess and an Fe emission line around 6.4 keV (Tombesi et al. 2010; Winter et al. 2012; Laha et al. 2014b) in the source spectra. Tombesi et al. (2010) and Laha et al. (2014b) found the presence of a broad Fe K line emission at 6.4 keV with an equivalent width of σ = 100 ± 15 eV. Using the same observation, a similar study carried out by Winter et al. (2012), showed the presence of a narrow Fe emission line (σ = 39^{+8}_{-8} eV) in the source spectrum. Fukazawa et al. (2011)
studied the source using two Suzaku observations and found the presence of narrow Fe K emission lines. They studied the Fe line flux variability of a sample of sources including ESO 511–G030 and suggested that X-ray reflection by a torus is the main origin of this narrow Fe K emission. Previous studies of ESO 511-G030 mentioned here have primarily focused on understanding the details of the warm absorber and high-velocity outflows. In this work we address the following science questions: 1. The nature and origin of the Fe line emission in the source spectra 2. Detection or nondetection of the soft excess and the Compton hump, and finally 3. If we do detect a broad Fe line, can we constrain the black hole spin? We used the multi-epoch broadband (0.001–50 keV) spectra of ESO 511-G030 using the XMM-Newton and Suzaku observations. We have also used OM data from XMM-Newton to constrain the UV bump, necessary to investigate the accretion disk and black hole properties with physically motivated models. Throughout this paper, we assumed a cosmology with \( H_0 = 71 \text{ km s}^{-1} \text{Mpc}^{-1} \), \( \Omega_m = 0.73 \) and \( \Omega_k = 0.27 \). The paper is organized as follows: Section 2 describes the observation and data reduction techniques. The steps taken in the spectral analysis are discussed in Section 3. Section 4 discusses the results followed by conclusions in Section 5.

2. Observation and Data Reduction

ESO 511–G030 was observed only once by XMM-Newton in 2007 August 5 and twice by Suzaku in 2012 July 22 and in 2012 August 17. The details of the observations and the short notation of the observation IDs are mentioned in Table 1. We processed the EPIC-pn and OM data using V18.0.0 of the Science Analysis Software (SAS) (Gabriel et al. 2004) with the task epchain and omichain, respectively, and filtered them using the standard filtering criterion. We used the latest calibration database available at that time. The EPIC-pn data was preferred due to its higher signal-to-noise ratio compared to MOS. We checked the background rate above 10 keV for any flaring particle background and used a rate cutoff of <1 ct s\(^{-1}\) to create the good time intervals. To extract the source spectrum and light curve, we selected a circular region of 40 arcsec, centered on the centroid of the source. For the background spectrum and light curve, we chose nearby circular regions, located on the same CCD, that are free of any sources. The EVSELECT task was used to select single and double events for EPIC-pn (PATTERN = 4, FLAG = 0) source event lists. We created the time-averaged source + background, the background spectra and the corresponding response matrix function (RMF) and auxiliary response function (ARF) for each observation using the omniclamp task. The omichain command in SAS. We checked for pile-up in the XMM-Newton source spectra using the command epatplot and found that observation (obs1 from now on) is not piled up. The XMM-Newton spectra were grouped by a minimum of 50 counts per channel and a maximum of three resolution elements using the command specgroup. For the OM data, we obtained the count rates in four active filters (B, UVW1, UVM2, and UVW2) by specifying the R.A. and decl. of the source in the source list file obtained by the omichain task. The om2pha task was used to produce the necessary files for OM photometric data to be analyzed simultaneously with EPIC-pn in XSPEC.

ESO 511–G030 was observed twice by Suzaku on 2012 July 22 and 2012 August 17 (see Table 1). The three X-ray Imaging Spectrometers (XISs) (Koyama et al. 2007) along with the Hard X-ray Detector (HXD) (Takahashi et al. 2007) cover the broad energy band of 0.2–50 keV. In both observations (from now on obs2 and obs3, respectively), all the data were obtained in standard XIS (3 \( \times \) 3 and 5 \( \times \) 5) and HXD data modes. The data reduction technique of XIS and HXD-PIN is the same as Ghosh et al. (2018), following the standard Suzaku data reduction. We used HEASOFT(v6.27.2; HEASARC 2014), software and the recent calibration files to reprocess the Suzaku data. For the non-imaging HXD/PIN data, we used the appropriate tuned background files provided by the Suzaku team and available at the HEASARC website. The XIS front-illuminated spectra were coadded to enhance the signal-to-noise ratio. We grouped the XIS spectral data off to a minimum of 200 and 100 counts in each energy bin for obs1 and obs2, respectively. We also grouped the PIN data using the command grppha in the HEASOFT software to produce \( \sim 30 \) energy bins with more than 20 counts per bin in the source spectra.

3. Data Analysis and Spectral Fitting

We used XSPEC (Arnaud 1996) version 12.11.0 m to analyze all the data sets and all errors quoted on the fitted parameters reflect the 90% confidence interval corresponding to \( \Delta \chi^2 = 2.7 \) (Lampton et al. 1976). We excluded the XIS data in the 1.7–2.3 keV from our spectral analysis due to calibration uncertainties. We used the tbabs model to estimate the effect of Galactic absorption and set the scattering cross-section to Verns and abundances to Wilms values. In all our spectral fitting, we adopted the Galactic column density value of \( N_H = 4.34 \times 10^{20} \text{cm}^{-2} \) (Dickey & Lockman 1990).

We started our analysis with a preliminary look at the spectra of the source. We used an absorbed power-law model in the 4–5 keV energy band and when extrapolated to the rest of the X-ray band revealed a prominent soft excess (below 2 keV), a Fe line complex at 67 keV, with physically motivated models, will help us investigate the nature of accretion disk and black hole properties and the role they play in the origin of the soft excess. The latest XSPEC version used here provides us with the best-fit statistics of individual data sets during simultaneous model fitting. Hence, a simultaneous multi-epoch spectral fit of XMM-Newton and Suzaku spectra was carried out in all three cases.

### Table 1

The X-Ray Observations of ESO 511–G030

| X-Ray Satellite | Observation ID | Short ID | Date of obs | Net Exposure | Net Counts |
|-----------------|---------------|---------|-------------|--------------|------------|
| XMM-Newton      | 0502090201    | obs1    | 05-08-2007  | 76 ks        | 1.16E+06   |
| Suzaku          | 707023020     | obs2    | 22-07-2012  | 224 ks       | 3.18E+06   |
|                 | 707023030     | obs3    | 17-08-2012  | 52 ks        | 1.12E+06   |
3.1. Investigating the Fe Emission Line

To investigate the excess emission in 6–7 keV, we first introduced a narrow Gaussian to the absorbed power-law model. An energy-independent multiplicative factor was used to account for the relative normalization between different instruments of Suzaku. Assuming a bare nature of the source we did not include any neutral or partially ionized absorber model to the set of models used here. In XSPEC, the model reads as constant x tbabs x (pc+ zgauss). The best-fit model for this set of models is $\chi^2$/dof = 1587/1414. The line energy is consistent with 6.4 keV for all three observations and the equivalent width ranges between 62 eV to 94 eV. We found the line frame width $\sigma = 0.08–0.14$ keV between observations, which indicates the presence of a broad Fe emission line in the source spectra. The broad Gaussian if replaced with a narrow Gaussian line ($\sigma = 0.01$ keV) provides a relatively poor fit to the data sets ($\chi^2$/dof = 1603/1417). Next, we replaced the broad Gaussian line with a more realistic broad Fe line profile diskline, (Fabian et al. 1989), which resulted in a similar fit statistics ($\chi^2$/dof = 1587/1417). In the diskline model, the inner and outer radius of the disk was fixed at $r_{in} = 6r_g$ and $r_{out} = 400r_g$, respectively, for all three observations. The power-law dependence of emissivity ($\beta$), the line energy and the model normalizations are made free for obs 1 and obs 2. The inclination angle is tied between observations. The best-fit line energy is consistent between observations with a value of 6.42 keV. The high value of emissivity profile ($q = 0.9–9.1$) indicates a large amount of coronal radiation intercepts the disk.

Alternatively, a partial covering absorber model (neutral or ionized) may mimic the red wing of the broad Fe emission line in the broadband X-ray spectrum. The partial covering model with neutral or ionized absorption ($zpcfabs$ or $zxcfp$) when multiplied with the absorbed (galactic) power-law model resulted in a poor statistics for all the three data sets ($\chi^2$/dof = 1868/1421 and $\chi^2$/dof = 1873/1422 for $zpcfabs$ or $zxcfp$, respectively). See Table 2 for the comparison of a different set of models used to fit the Fe line emission. Our analysis indicates the presence of a broad Fe Kα emission line in the X-ray spectra of all three observations. Next, we study the full X-ray band to further characterize the reflection features.

Table 2

| Models Used |Obs-1|Obs-2|Obs-3| Simultaneous Fit |
|---|---|---|---|---|
|model 1 + zxcfp| 209/109 | 1091/883 | 567/457 | 1868/1420 |
|model 1 + narrow | 145/105 | 945/881 | 513/433 | 1603/1417 |
|Gaussian | model 1 + broad | 131/104 | 942/880 | 510/433 | 1587/1414 |
|Gaussian | model 1 + diskline | 133/104 | 943/879 | 512/433 | 1587/1414 |
|Gaussian | model 1 + relline | 137/105 | 946/880 | 516/433 | 1599/1411 |

Note. Notes: Model 1 is above 3 keV power-law fit modified by the Galactic absorption. The normalization parameter of all the models were made free for each observations.

3.2. The Full X-Ray Band

We initially analyzed the broadband X-ray data with a phenomenological set of models to test the presence and strength of reflection features in the source spectra. The baseline phenomenological model used here includes a neutral galactic absorption (tbabs), a multiple blackbody component to model the soft excess (diskbb, Mitsuda et al. 1984) and the coronal emission described by a power law. In addition, we used a diskline model to describe excess emission at around 6.4 keV. An energy-independent multiplicative factor was introduced to account for the relative normalization of different XIS and PIN instruments. In XSPEC notation, the phenomenological model reads as constant x tbabs x (powerlaw+diskbb+diskline). Addition of a ztbabs model did not improve the fit statistics and we conclude that all three observations are free from any intrinsic neutral absorption of the host galaxy. We included the pexrav model to check for the reflection component from the neutral medium which contributes to the Compton hump. The XMM-Newton EPIC-pn data (<10 keV) is insufficient to constrain the pexrav reflection parameters and hence tied with the Suzaku observation (obs2) with longer exposure. We found a significant improvement in the fit statistics upon the addition of pexrav.
Table 3
The Best-fit Parameters of the Baseline Phenomenological Models for the XMM-Newton and Suzaku Observations of ESO 511–G030

| Models       | Parameter | obs1       | obs2       | obs3       |
|--------------|-----------|------------|------------|------------|
| Gal. abs.    | \(N_\text{H} (\times 10^{20} \text{ cm}^{-2})\) | 4.34 (f)   | 4.34 (f)   | 4.34 (f)   |
| power law    | \(\Gamma\) | 1.77 +0.03 | 1.80 +0.01 | 1.96 +0.01 |
|              | \(\text{norm} (10^{-3})\) | 5.13 +0.01 | 5.21 +0.00 | 9.14 +0.46 |
| diskbb (1)   | \(T_\text{e} (\text{keV})\) | 0.36 +0.02 | 0.23 +0.01 | 0.23 (t) |
|              | \(\text{norm} (10^{7})\) | 16.7 +2 | 2 +1 | 2 (t) |
| diskbb (2)   | \(T_\text{e} (\text{keV})\) | 0.11 +0.01 | 0.07 +0.00 | 0.08 +0.01 |
|              | \(\text{norm} (10^{7})\) | 4.93 +0.04 | 97.5 +1.4 | 87.8 +2.6 |
| diskline     | \(E (\text{keV})\) | 6.31 +0.03 | 6.28 +0.02 | 6.28 +0.03 |
|              | \(\beta\) | -0.8 +0.7 | -0.3 +1.1 | -0.8 +0.7 |
|              | \(r_{\text{in}}(r_g)\) | 6 (f) | 6 (f) | 6 (f) |
|              | Incl \(\text{incl}^\circ\) | 10 +2 | 10 (t) | 10 (t) |
|              | \(\text{norm} (10^{-5})\) | 1.75 +0.48 | 1.54 +0.15 | 1.55 +0.33 |
| Pexrav B     | \(\Delta\chi^2/\text{dof}\) | 178/3 | 373/3 | 96/3 |
|              | \(R\) | -0.56 (t) | -0.56 [0.21 -0.12] | -0.74 [0.13 -0.15] |
|              | \(\Delta\chi^2/\text{dof}\) | 12/1 | 34/2 | 26/1 |
| reduced \(\chi^2/\text{dof}\) | 1.28/168 | 1.13/1699 | 1.11/1108 |

Note.
\(a\) The \(\Delta\chi^2\) improvement in statistics upon addition of the corresponding discrete component. (f) indicates a frozen parameter and (t) indicates parameters are tied between observations.

\((\Delta\chi^2 \sim 72 \text{ for 4 dof})\) indicating the presence of a neutral reflection component in the hard X-ray band above 10 keV. The phenomenological model provides a satisfactory description to the two Suzaku as well as XMM-Newton spectra. The best-fit parameter values obtained using the phenomenological models are marginally consistent between observations and quoted in Table 3. We also quoted the improvement in statistics \((\Delta\chi^2/\text{dof})\) for each spectrum upon the addition of different model components to determine the statistical significance of the model (see Table 3). The line energy of the Fe emission is consistent with 6.4 keV for all three observations. Our results indicate that a prominent soft excess and a broad Fe K\(_\alpha\) emission line is present in all the observations that are usually considered as signs of relativistic reflection from the disk.

However, the origin of soft excess is still debated and apart from the relativistic reflection from disk, intrinsic disk Comptonization has also been found to be a viable physical model in other Seyfert 1 galaxies. In our work, we used two sets of physical models to describe both the soft excess and the Fe emission line in the Suzuki and XMM-Newton X-ray spectra of ESO 511–G030. In XSPEC, our first set of physical models reads as \textit{constant} \(\times\) \textit{tbabs} \(\times\) \textit{relxill}+\textit{MYTorus}. Here, the \textit{relxill} model, version 1.3.7, (García et al. 2014) describes the soft X-ray excess, the power-law continuum, the broad Fe K\(_\alpha\) emission line and the reflection of primary hard X-ray photons off an ionized accretion disk; on the other hand, the Compton reflection of hard X-ray photons off cold, neutral material is modeled with \textit{MYTorus}. The \textit{MYTorus} model comprised three components: first, the torus-absorbed primary power law; second, the scattered emission (MYTorusS) due to the reflection of primary hard X-ray photons from the torus; and third, the iron FeK\(_\alpha\) and K\_\text{line} (MYTorusL), which are assumed to arise due to the reflection by the torus. ESO 511–G030 is a type-1 AGN, hence we do not expect any obscuration due to torus along the line of sight. We have used only MYTorusS and the MYTorusL component in our spectral fitting and tied their column densities together. The column density of \textit{MYTorus} gives a value in an equatorial direction of a dusty torus, so a Compton-thick value is expected even in type 1 sources (Yaqoob et al. 2016; Laha et al. 2019; Ghosh & Laha 2020). When made free, the \textit{MYTorus} column density pegged at \(10^{25} \text{ cm}^{-2}\) and we got a lower limit of \(2.9 \times 10^{24} \text{ cm}^{-2}\). Hence, we froze the \textit{MYTorus} column density to a value of \(10^{25} \text{ cm}^{-2}\), assuming that a Compton-thick torus is responsible for this emission. We also fixed the inclination angle between the torus polar axis and the observer’s line of sight to 45 degrees for both sets of physical models. The photon index of the \textit{MYTorus} model was tied with that of the photon index of the primary continuum of the \textit{realign} model. In the \textit{relxill} model, the primary hard X-ray emission from corona illuminates the accretion disk and produces fluorescence emission lines. These fluorescence lines get blurred and distorted due to extreme gravity near the central supermassive black hole and produce the soft excess. The transition between Newtonian and relativistic geometry is marked by a breaking radius \(r_{\text{br}}\). In our work, the emissivity index of reflection from the disk outside \(r_{\text{br}}\) \((q2)\) is fixed at 3, as in Newtonian geometry, for a point source, the emissivity at a large radius out from the source has a form \(r^{-3}\). The emissivity index inside \(r_{\text{br}}\) falls under the relativistic high-gravity regime and calculations (Dabrowski & Lasenby 2001; Miniutti et al. 2003; Wilkins & Fabian 2011) suggest a very steeply falling profile in the inner regions of the disk. Hence, we made the emissivity index of the inner part \((q1)\) of the accretion disk inside \(r_{\text{br}}\), free to vary in between \(3 < q1 < 10\).

During our simultaneous analysis of joint XMM-Newton and Suzaku data sets, the parameters that are unlikely to change within human timescale, e.g., the black hole spin and the inclination angle, were tied between all observations. Apart from the power-law photon index, normalization, and the reflection fraction \((R)\), all other parameters were tied between the two Suzaku observations. The \textit{MYTorus} model requires a hard X-ray spectrum to constrain its parameters. Due to the absence of >10 keV spectrum in XMM-Newton observation, the \textit{MYTorus} parameters were tied with best-fit parameter values of obs2. This set of physical models produced a satisfactory fit with fit statistics \(\chi^2/\text{dof} = 3431/2981\), however, we observed some excess in...
the residual at \( \sim 0.5 \) and 0.9 keV. Addition of two narrow Gaussian line profiles to the model yielded an improved fit \((\chi^2/\text{dof} = 3345/2976)\). We estimated the high-energy cutoff of the primary power-law component using the Suzaku observation with the longest exposure (obs1). We found a lower limit to the high-energy cutoff with \( E_c > 297 \) keV. We tied this value for all other observations. A rapidly spinning black hole (\( > 0.98 \)) is required by the model to fit the X-ray spectra. We carried out a test to find out if the black hole is indeed maximally spinning. First, we froze the spin parameter to zero and kept the inner radius \((r_{in})\) of the relxill model fixed to the inner circular stable orbit for a non-rotating black hole \((r_{in} = 6r_g)\) and fitted the data sets. Next, we froze spin to 0.998 and fixed the \( r_{in} \) value to that of a maximally spinning black hole \((r_{in} = 1.24r_g)\). We found that the maximally spinning scenario provides a significantly better fit statistics \((\Delta \chi^2 = 501)\). Following this result, we fixed the inner radius of the disk at \( r_{in} = 1.24r_g \) throughout the rest of the fit and allowed the spin parameter to vary freely. We found the iron abundance of the material in the accretion disk to be significantly lower than the solar value \((A_F < 0.7)\) for the two Suzaku observations. The best-fit reflection fraction \((R)\) ranges between \( R = 0.5-5.3 \) for the three observations. The best-fitting model parameters along with the best-fitting statistics for each observation are quoted in Table 4.

We have also tested other flavors of relxill, such as relxillD and relxillP. The model relxillD allows a higher density for the accretion disk (between \( \log N/\text{cm}^3 = 15.3 \) to \( \log N/\text{cm}^3 = 18 \)) and the model relxillP assumes a lamp post geometry and determines the variation in the position of the hard X-ray emitter. Both these models produced a relatively poor statistics \((\chi^2/\text{dof} = 3434/2973\) for relxillD and \( \chi^2/\text{dof} = 3469/2976 \) for relxillP, respectively) compared to relxill, for all the observations and no significant variation either in the disk density or in the position of the hard X-ray emitter was found.

For the second set of physical models, we use intrinsic thermal Comptonization from a warm corona (optxagnf). In the optxagnf model, thermal Comptonization of disk photons by a warm \((T \sim 0.5-1 \) keV) and optically thick \((\tau \sim 10-20)\) corona (Magdziarz et al. 1998; Done et al. 2012), that lies in the inner part \((10-20r_g)\) of the accretion disk, produces the soft excess. The gravitational energy released in the accretion process fuels the disk emission in UV, the soft X-ray excess and the power-law emission. The model normalization flux is determined by the source Eddington rate, the black hole mass, the black hole

| Component | Parameter | obs1 | obs2 | obs3 |
|-----------|-----------|------|------|------|
| Gal. abs. | \( N_{\text{H}}(10^{21}\text{cm}^{-2}) \) | 4.34 (f) | 4.34 (f) | 4.34 (f) |
|          | \( A_F \) | 0.7(0.1) | ... | ... |
|          | \( \log \xi (\text{erg cm s}^{-1}) \) | 2.29(0.08) | 3.20(0.01) | 3.20 (i) |
|          | \( \Gamma \) | 2.05(0.01) | 1.74(0.01) | 1.74(0.01) |
|          | \( E_{\text{cut}}(\text{keV}) \) | >297 | 388(i) | 388(i) |
|          | \( n_{\text{rel}}(10^{-5}\mu) \) | 8.72(0.15) | 11.24(0.16) | 2.69(0.12) |
|          | \( q \) | 7.3(0.3) | 4.6(1.3) | ... |
|          | \( a \) | >0.98 | 0.99 (i) | 0.99 (i) |
|          | \( R(\text{rest}) \) | 1.2(0.1) | 0.5(1.3) | 5.3(0.3) |
|          | \( R_{\text{in}}(r_g) \) | 1.24(f) | 1.24(f) | 1.24(f) |
|          | \( R_{\text{out}}(r_g) \) | 4.9(0.3) | 4.3(0.2) | 3.6(0.2) |
|          | \( i(\text{degree}) \) | 27(3) | 27(i) | 27(i) |
| MYTorusLI | \( M_\text{d} \) | ... | 4.57(f) | ... | 4.57(f) |
|          | \( d (\text{Mpc}) \) | ... | 95 (f) | ... | 95 (f) |
|          | \( L/\text{E} \) | ... | 0.004(0.001) | ... | 0.008(0.001) |
|          | \( K_{\text{E}}(\text{keV}) \) | ... | 0.39(0.02) | ... | 0.10(0.04) |
|          | \( \tau \) | ... | 12.9(1.4) | ... | >11.8 |
|          | \( i_{\text{cor}}(r_g) \) | ... | 11.8(3.3) | ... | 5.2(9.9) |
|          | \( a \) | ... | >0.78 | ... | 0.99(i) |
|          | \( f_{\text{rad}} \) | 0.56(0.03) | 0.41(0.04) | 0.59(0.07) |
| optxagnf | \( \Gamma \) | ... | 1.74(0.02) | ... | 1.79(0.02) |

| reduced \( \chi^2/\text{dof} \) | 1.37/170 | 1.18/171 | 1.13/1703 | 1.14/1706 | 1.05/1110 | 1.09/1112 |

Note. Model 1 = TBABS \times (RELXILL + MYTorusS); Model 2 = TBABS \times (OPTXAGNF + MYTorusS). The MYTorus parameters for obs1 and obs3 are tied with obs2, which is the longest Suzaku observation (see Table 1). (f) indicates a frozen parameter. (*) indicates parameters are not constrained. (n) \( n_{\text{rel}} \) represent normalization for the model relxill (b) in units of \( 10^{56}\).
Table 5
The Best-fitting Parameters When We Modeled the Optical-UV to Hard X-Ray Energy Band of XMM-Newton and Suzaku Observations of ESO 511–G030 with the Ionized Reflection Model, reflxill (Model 1), and the Thermal Comptonization Model, optxagnf (Model 2)

| Component | Parameter | obs1 | obs2 | obs3 |
|-----------|-----------|------|------|------|
|           |           | Model 1 | Model 2 | Model 1 | Model 2 | Model 1 | Model 2 | Model 1 | Model 2 |
| Gal. abs. | $N_{\text{H}}(10^{21}\text{cm}^{-2})$ | 4.34 (f) | 4.34 (f) | 4.34 (f) | 4.34 (f) | 4.34 (f) | 4.34 (f) | 4.34 (f) | 4.34 (f) |
| diskbb    | $T_{\text{disk}}$(keV) | 0.004$^{+0.001}_{-0.001}$ | ... | 0.004(t) | ... | 0.004(t) | ... | 0.004(t) | ... |
|          | $\text{norm}(10^{-3})$ | 2.54$^{+0.13}_{-0.18}$ | ... | 2.54(t) | ... | 2.54(t) | ... | 2.54(t) | ... |
| reflxill | $A_0$ | 0.7 (f) | ... | 0.5 (f) | ... | 0.5 (f) | ... | 0.5 (f) | ... |
|          | $\log \xi (\text{erg cm s}^{-1})$ | 2.29 (f) | ... | 3.20(f) | ... | 3.20 (f) | ... | 3.20 (f) | ... |
|          | $\Gamma$ | 2.05 (f) | ... | 1.74(f) | ... | 1.88 (f) | ... | 1.88 (f) | ... |
|          | $E_{\text{ad}}$(keV) | 388 (f) | ... | 388(t) | ... | 397(t) | ... | 397(t) | ... |
|          | $n_{\text{rel}}(10^{-5})$ | 8.27(f) | ... | 11.24 (f) | ... | 2.69(f) | ... | 2.69(f) | ... |
|          | $q_1$ | 7.3 (f) | ... | 4.6 (f) | ... | 8.2 (f) | ... | 8.2 (f) | ... |
|          | $a$ | 0.99(f) | ... | 0.99 (f) | ... | 0.99 (f) | ... | 0.99 (f) | ... |
|          | $R(\text{reffrac})$ | 1.2(f) | ... | 0.5 (f) | ... | 5.3 (f) | ... | 5.3 (f) | ... |
|          | $R_0(r_{\text{in}})$ | 1.24(f) | ... | 1.24(f) | ... | 1.24(f) | ... | 1.24(f) | ... |
|          | $R_0(r_{\text{out}})$ | 4.9 (f) | ... | 4.3 (f) | ... | 3.6 (f) | ... | 3.6 (f) | ... |
|          | $R_{\text{out}}(r_{\text{in}})$ | 400 (f) | ... | 400(f) | ... | 400(f) | ... | 400(f) | ... |
|          | $i(\text{degree})$ | 27 (f) | ... | 27(t) | ... | 27 (t) | ... | 27 (t) | ... |
| MYTorusL  | $i(\text{degree})$ | 45 (t) | 45 (t) | 45 (f) | 45 (f) | 45 (t) | 45 (t) | 45 (t) | 45 (t) |
|          | $\text{norm}(10^{-3})$ | 7.37(t) | 8.18(t) | 7.37(t) | 8.18(t) | 7.37 (t) | 8.18(t) | 7.37 (t) | 8.18(t) |
| MYTorusS  | $N(10^{21}\text{cm}^{-2})$ | 10.0 (t) | 10.0 (t) | 10.0(f) | 10.0(f) | 10.0(t) | 10.0(t) | 10.0(t) | 10.0(t) |
|          | $\text{norm}(10^{-3})$ | 3.20(t) | 6.05(t) | 3.20(f) | 6.05(f) | 3.20(t) | 6.05(t) | 3.20(t) | 6.05(t) |
| optxagnf  | $M_\text{BH}^2$ | ... | 4.57(t) | ... | 4.57(t) | ... | 4.57(t) | ... |
|          | $d$ (Mpc) | ... | 95 (f) | ... | 95(t) | ... | 95(t) | ... |
|          | $\text{M}_\odot$ | ... | 0.004$^{+0.001}_{-0.001}$ | ... | 0.007$^{+0.001}_{-0.001}$ | ... | 0.008$^{+0.001}_{-0.001}$ | ... |
|          | $kE_{\text{d}}$(keV) | ... | 0.40$^{+0.02}_{-0.02}$ | ... | 0.09$^{+0.03}_{-0.03}$ | ... | 0.53$^{+0.03}_{-0.03}$ | ... |
|          | $\tau$ | ... | 12.7$^{+0.5}_{-0.4}$ | ... | >11.9 | ... | 7.9$^{+0.5}_{-0.5}$ | ... |
|          | $r_{\text{in}}(r_{\text{out}})$ | ... | 11.8$^{+0.5}_{-1.8}$ | ... | 5.9$^{+0.5}_{-0.5}$ | ... | 5.9(t) | ... |
|          | $a$ | ... | >0.98 | ... | 0.99(t) | ... | 0.99(t) | ... |
|          | $f_{\text{pl}}$ | ... | 0.57$^{+0.02}_{-0.02}$ | ... | 0.41$^{+0.06}_{-0.08}$ | ... | 0.60$^{+0.06}_{-0.06}$ | ... |
|          | $\Gamma$ | ... | 1.74$^{+0.02}_{-0.02}$ | ... | 1.79$^{+0.01}_{-0.03}$ | ... | 1.86$^{+0.01}_{-0.01}$ | ... |
| reduced$\chi^2$/dof | 1.38/170 | 1.38/171 | 1.13/1704 | 1.14/1706 | 1.05/1108 | 1.09/1112 |

Note. Model 1 = TBABS $\times$ (DISKBB + RELXILL + MYTORUS); Model 2 = TBABS $\times$ (OPTXAGNF + MYTORUS). The MYTorus parameters for obs1 and obs3 are tied with obs2 which is the longest Suzaku observation (see Table 1). (f) indicates a frozen parameter. (*) indicates parameters are not constrained. (a) $n_{\text{rel}}$ represent normalization for the model reflxill (b) in units of $10^9M_\odot$.

spin and the luminosity distance. Hence in our analysis, we froze this value at unity. The hard excess emission, in this set of models, arises exclusively due to neutral Compton reflection from the torus. In XSPEC notation, the model reads as $(\text{constant} \times \text{tobs} \times \text{optxagnf} + \text{MYTORUS})$. We used a black hole mass of $\sim 4.57 \times 10^9M_\odot$, adopted from Ponti et al. (2012), who derived it using X-ray variability of the source. In our simultaneous fit of Suzaku and XMM-NEWTON, apart from the black hole spin, all other optxagnf model parameters were made free to vary. On the other hand, for the two Suzaku observations, except for the Eddington rate, photon index and the parameter $f_{\text{pl}}$, that determines the fraction of powerlaw emitted as soft excess, all other parameters were tied between observations. This set of physical models produced a poor fit statistics ($\chi^2$/dof = 3411/2992) compared to our first set of models, however, we observed similar excess emission in the residual at $\sim 0.5$ keV and $\sim 0.9$ keV. Addition of two Gaussian line profile to the set of models provided similar fit statistics ($\chi^2$/dof = 3351/2987) compared to the reflection model reflxill. All three observations show sub-Eddington accretion rate ($\sim 0.004$–$0.008$) and infer a maximally spinning black hole ($\sim 0.98$). Table 5 includes the best-fitting parameters obtained using this model. Figure 2 shows both the best-fitting physical models used here and their respective residuals. Next, we included the OM data from the XMM-Newton and tried to get a better constrain on the optxagnf model parameters.

3.3. The Joint UV and X-Ray Band

The thermal Comptonization model uses disk photons to produce the power-law spectra and the soft excess. Therefore, the UV bump is required to constrain the optxagnf parameters. In this section, we re-fit the X-ray data along with the simultaneously obtained UV spectra to constrain the model parameters.

We used the optical/UV fluxes in four bands (B, W1, W2, and M2) measured with the XMM-Newton to constrain the thermal emission from the disk. The galactic extinction correction was done following (Fitzpatrick 1999) reddening law with $R_V = 3.1$ and is taken into account by the REDDEN model. The parameter value used here is $E(B-V) = 0.056$ (Schlafly & Finkbeiner 2011). We have added 5% systematic error to the OM fluxes to account
Our results suggest the presence of a warm optically thick electron temperature, the radius, and the opacity get a better constraint on the warm corona properties, e.g., the warm corona and bulk black hole spin. We found a model-dependent high black hole spin and a strong soft X-ray excess that is present even for a small fraction (0.4%–0.8%) of $\lambda_{\text{Edd}}$. Our measured Eddington ratio is consistent with the value previously found by Laha et al. (2014b), indicating a steady accretion state in the source during 2007 and 2012. Using the reflection model we got a lower limit to the high-energy cutoff value ($E_c > 297$ keV) of the primary power-law component. Below we discuss the main results investigating the spectral features observed in this source.

4.1. The Fe $K_{\alpha}$ Line and the Compton Hump

Previous studies of the X-ray spectra of ESO 511–G030 have mostly revealed the presence of a relativistically broad Fe emission line. Tombesi et al. (2010); Laha et al. (2014b) studied the 2007 XMM-Newton data and found a broad Fe emission line at 6.4 keV with an equivalent width of $\sigma = 100 \pm 15$ eV. On the other hand, using the same observation, Winter et al. (2012) studied the X-ray broadband properties and detected the presence of a narrow Fe emission line ($\sigma = 39^{+5}_{-4}$) in the source spectrum. Fukazawa et al. (2011) studied the source using two Suzaku observations and found the presence of narrow Fe K lines. In our work, we have investigated the above 3 keV energy band with a set of models to unambiguously determine the nature of the Fe emission line. We found the presence of a broad Fe emission line at ~6.4 keV in all the spectra of ESO 511–G030. The best-fit Fe emission line $\sigma$ (0.08–0.14 keV) and equivalent width (62–94 eV) are significantly broader than the equivalent width of typical narrow Fe emission line found in nearby Seyfert 1...
galaxies. The broad Gaussian line profile and the diskline model provides a better description of the Fe line emission than other sets of models and indicates the presence of a relativistically-broadened Fe emission line from an accretion disk around a rotating black hole. Our broadband spectral modeling of ESO 511-G030 with both sets of physical models favors a rapidly spinning black hole and supports this idea. In all the observations, the Fe line centroid energy was consistent with 6.4 keV, which indicates that the iron is neutral or in low ionization state. The best-fit ionization parameter value of the XMM-Newton observation \((\log \xi = 2.3^{+0.1}_{-0.1})\) supports this idea. However, for the two Suzaku observations, we got a highly ionized accretion disk \((\log \xi = 3.2^{+0.1}_{-0.1})\) compared to obs1. From Figure 1 we note that the Compton hump above 10 keV is relatively weak but the addition of a\(\text{pexrav}\) model to the phenomenological set of models did improve the fit statistics \((\Delta \chi^2 \sim 72\) for 4 dof) significantly. From Figure 2 we find that both neutral and ionized reflection components provide a good description of the Compton hump. With the current data quality in Suzaku, we are unable to comprehensively detect or separate out the contributions of the ionized and neutral reflection components and further deep observations of Seyfert 1 s are required.

### 4.2. The Soft Excess

Our analysis of the full X-ray band of ESO 511–G030 revealed the presence of a prominent soft excess below 2 keV for all three observations. We investigated the broadband multi-epoch data in detail to identify the disk and black hole properties responsible for this excess emission. Recent studies suggest that both relativistic reflection from an ionized accretion disk and the intrinsic thermal Comptonization of disk photons can successfully describe the soft excess in Seyfert 1 s (Ghosh et al. 2016; Ghosh & Laha 2020; García et al. 2019; Waddell et al. 2019; Ehler et al. 2018). These two models assume two very different geometries and physical properties of the accretion disk and the corona (e.g., the position, temperature, and the opacity). However, it is not easy to distinguish them on statistical grounds alone and often extreme values of certain model parameters are used to favor one model over the other. In some nearby Seyfert 1 s, e.g., HE 1143-1810 (Ursini et al. 2020) and Zw 229.015 (Tripathi et al. 2019), the ionized disk reflection model was ruled out due to the relatively extreme values of the iron abundance, the inclination angle and reflection fraction, compared to other Seyfert 1 s. On the other hand, in Mrk 478 (Waddell et al. 2019), the flux variability between data sets was better described by ionized disk reflection, compared to the thermal Comptonization model.

In our work, we have studied the reflection features observed in the ESO 511–G030 spectra and got comparable fit statistics for both of these physical models. The soft excess is equally well described by both these models. The best-fit parameter values obtained for theoptxagnf model were in a range detected in typical Seyfert 1 galaxies (See Table 4) although, we were unable to constrain the optical depth in obs2 (see Table 5). Similarly, for the reflection model, some model parameters require extreme values to model the soft excess and the X-ray energy band. The best-fit photon index \(\Gamma\) of the modelrelxill ranges between 1.7 and 2.0 for all three observations. The best-fit ionization parameter value of the model \((\log \xi \sim 2\text{–}3\) erg\ cm\ s\(^{-1}\)) suggests a transition between moderate to highly ionized disk between obs1 and obs2, respectively. In the reflection model\(\text{relxill}\), the black hole spin and the inner radius are degenerate and hence fixing the inner radius to the ISCO provides a better constraint on the spin. Hence we fixed the inner radius to 1.24\(r_g\) and obtained a maximally spinning black hole \((a > 0.98)\). We were able to constrain the inclination angle parameter and found a best-fit value of 27°. The iron abundance of the reflecting medium \((A_{Fe})\) or the disk is marginally consistent with the solar abundance value for the XMM-Newton observation, however, when made free we got an upper limit of <0.6 for the two Suzaku observations. We also found a large variation in the best-fit value of reflection fraction \((R)\) between the three observations, ranging between 0.5 and 5.3, although consistent with other Seyfert 1 s. This value \(R\) determines the ratio of photons entering the disk to the ones escaping to infinity and indicates that most of the hard X-ray photons are entering the disk and this results in a highly ionized disk. These results
along with the high emissivity index ranging between 4.6–8.2 imply that a major part of the soft excess has originated from a region very close to the central supermassive black hole due to reflection of hard X-ray photons from a highly ionized untruncated accretion disk. Although very high values of black hole spin and the reflection fraction or lower iron abundances in the disk are occasionally reported for AGNs, a corona placed so close to the black hole implies a very extreme configuration of the accretion disk and the corona.

On the other hand, the intrinsic thermal Comptonization model optxagnf combined with the neutral reflection from the torus, modeled by MyTorus, provides a similar fit statistics compared to the ionized reflection. Most of the best-fit parameter values obtained from the fitting of the full X-ray band are well constrained and are typical of other Seyfert 1 galaxies (Ghosh & Laha 2020; Porquet et al. 2018; Ursini et al. 2020). In this model, the soft excess originates due to Comptonization of thermal disk photons by a warm and optically thick corona that covers roughly 5–12$R_g$ of the inner accretion disk (Petrucci et al. 2013). However, we note that the accretion rate in optxagnf is also determined by the outer accretion flow beyond $r_{\text{corona}}$ that contributes primarily in the optical-UV band. This explains our inability to constrain some of the model parameters e.g., the $r_{\text{corona}}$ and the black hole spin. Hence we discuss the best-fit parameter values obtained from the simultaneous analysis of the optical-UV to hard X-ray broadband data with optxagnf as they provide us with a more clear view of the accretion disk and the black hole properties.

### 4.3. The Optical-UV to Hard X-Ray Continuum

In the optxagnf model, the gravitational energy released in accretion, powers three distinct emission components—the UV bump, the soft excess, and the hard X-ray power law. As expected, optxagnf combined with neutral reflection from torus yielded better fit statistics (see Table 5) compared to the ionized reflection model. From the joint fits of all three observations, using the relxill+diskbb model, we find that the disk blackbody has a much colder temperature of $kT = 3.8^{+0.7}_{-0.2}$ eV. This value is comparable with the inner radius temperature, $\sim 2$ eV, of the accretion disk that is accreting at a rate of $\lambda_{\text{Edm}} = 0.004$, obtained for obs1, using optxagnf model. This best-fitting accretion rate is close to our estimated value ($\lambda_{\text{Edm}} = 0.002$) obtained using the bolometric luminosity of ESO 511–G030. The soft excess in XMM-Newton observation is well described as a warm ($kT = 0.4^{+0.02}_{-0.02}$ keV) and optically thick ($\tau = 12.7^{+0.5}_{-0.5}$) corona. These values are marginally consistent with that of obs3. In the case of obs2, we could not constrain the optical depth ($\tau$). The measured warm-corona radius ($r_{\text{corona}}$) remains nearly consistent between observations with values of $11.8^{+1.1}_{-1.0}R_g$ and $5.9^{+1.9}_{-0.5}R_g$ for XMM-Newton and Suzaku observations, respectively, and indicates a compact corona. We note that the optxagnf model, similar to the relxill, favors a maximally rotating black hole spin to describe the broadband spectra. We could not constrain the spin parameter in optxagnf and got a lower limit of $>0.98$. We argue that a highly rotating black hole is required to model the broadband data in both ionized reflection and thermal Comptonization scenarios, and the presence of a broad Fe emission line in the spectra further supports the idea of a highly spinning black hole at the center of the AGN. The $f_{\text{pl}}$ parameter in the optxagnf model determines the fraction of power below the coronal radius emitted in the hard Comptonization component. This parameter value is marginally consistent between the three observations with moderate values of $\sim 0.6$ and $\sim 0.4$ for XMM-Newton and Suzuki observations, respectively. This implies, in obs1, around 60% of the gravitational energy released below $12R_g$, is emitted as the primary power-law emission with a photon index $\sim 1.74$ and the rest would help produce the soft excess. These values are consistent with recent studies found in other local Seyfert 1s (Ghosh & Laha 2020; Porquet et al. 2019). Hence we conclude that for ESO 511–G030, highly ionized, relativistically blurred reflection from an untruncated accretion disk and the intrinsic thermal Comptonization of disk seed photons by a warm and optically thick compact corona, both combined with the neutral reflection from the torus, provide a good description to the multi-epoch optical-UV to hard X-ray spectra with parameter values consistent with other Seyfert 1s.

### 5. Conclusions

We have extensively studied the broadband optical-UV to hard X-ray spectra of the bare Seyfert 1 galaxy ESO 511–G030 using XMM-Newton and Suzuki multi-epoch observations and investigated the spectral features observed in the source with a physically motivated set of models. We list the main conclusions below.

1. The optical-UV to hard X-ray spectra of ESO 511–G030 is typical of local Seyfert galaxies and consists of four components. A UV bump with an inner radius temperature of $\sim 2–3$ eV, a power-law continuum with a photon index varying between $\Gamma = 1.7–2.0$, a prominent soft excess and a relatively broad Fe line emission at $\sim 6.4$ keV.

2. We found that the source is accreting at a sub-Eddington rate ($\lambda_{\text{Edm}}$ varies within $0.004–0.008$) between 2007 and 2012.

3. The soft X-ray excess in ESO 511–G030 can be described either as the thermal Comptonization of disk seed photons by a warm $(0.40^{+0.02}_{-0.02}$ keV), optically thick ($\tau = 12.7^{+0.5}_{-0.5}$) and compact $(<15R_g)$ corona or as the blurred reflection from an untruncated and moderate to highly ionized accretion disk. However, for the blurred reflection, the model requires some extreme configuration (e.g., $A_{\text{Fe}} < 0.7$ and $R = 5$) of the disk and corona.

4. We confirm the presence of a broad Fe emission line at $\sim 6.4$ keV in the source spectra with an equivalent width of 62–95 eV.

5. Our broadband spectral modeling of ESO 511–G030 with both sets of physical models favors a rapidly spinning black hole ($a > 0.78$) and a compact corona, indicating a relativistic origin of the Fe emission line.

R.G. acknowledges the financial support from Visva-Bharati University and IUCAA visitor program. The authors are grateful to the anonymous referee for insightful comments that improved the quality of the paper.

**Software:** HEASoft (v6.27.2; HEASARC 2014), SAS (v18.0.0; Gabriel et al. 2004), XSPEC (v12.11.0m; Arnaud 1996).

**Data Availability**

This research has made use of archival data of Suzuki and XMM-Newton observatories through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA Goddard Space Flight Center.
References

Arnaud, K. A. 1996, in ASP Conf. Ser., 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17

Arnaud, K. A., Branduardi-Raymont, G., Culhane, J. L., et al. 1985, MNRAS, 217, 105

Crummy, J., Fabian, A. C., Gallo, L., & Ross, R. R. 2006, MNRAS, 365, 1067

Dabrowski, Y., & Lasenby, A. N. 2001, MNRAS, 321, 605

Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215

Done, C., Davis, S. W., Jin, C., Blaes, O., & Ward, M. 2012, MNRAS, 420, 1848

Ehler, H. J. S., Gonzalez, A. G., & Gallo, L. C. 2018, MNRAS, 478, 4214

Ghosh, R., Dewangan, G. C., Mallick, L., & Raychaudhuri, B. 2018, MNRAS, 479, 2464

Ghosh, R., Dewangan, G. C., & Raychaudhuri, B. 2016, MNRAS, 456, 554

Gondoin, P., Lumb, D., Siddiqui, H., Guainazzi, M., & Schartel, N. 2001, A&A, 373, 805

Haardt, F., & Maraschi, L. 1993, ApJ, 413, 507

Koyama, K., Tsunemi, H., Dotani, T., et al. 2007, PASJ, 59, 23

Laha, S., Dewangan, G. C., Chakravorty, S., & Kembhavi, A. K. 2013, ApJ, 777, 2

Laha, S., Dewangan, G. C., & Kembhavi, A. K. 2011, ApJ, 734, 75

Laha, S., Dewangan, G. C., & Kembhavi, A. K. 2014a, MNRAS, 437, 2664

Laha, S., Ghosh, R., Guainazzi, M., & Markowitz, A. G. 2018a, MNRAS, 480, 1522

Laha, S., Ghosh, R., Tripathi, S., & Guainazzi, M. 2019, MNRAS, 486, 3124

Laha, S., Guainazzi, M., Chakravorty, S., Dewangan, G. C., & Kembhavi, A. K. 2016, MNRAS, 457, 3896

Laha, S., Guainazzi, M., Dewangan, G. C., Chakravorty, S., & Kembhavi, A. K. 2014b, MNRAS, 441, 2613

Laha, S., Guainazzi, M., & Piconcelli, E. 2018b, ApJ, 863, 10

Laha, S., Markowitz, A. G., Krumpe, M., et al. 2020, ApJ, 897, 66

Laha, S., Reynolds, C. S., & Reeves, J. 2021, NatAs, 5, 13

Lampton, M., Margon, B., & Bowyer, S. 1976, ApJ, 208, 177

Laor, A. 1991, ApJ, 376, 90

Lusso, E., Comastri, A., Vignali, C., Zamorani, G., & Brusa, M. 2010, A&A, 512, A34

Lynden-Bell, D. 1969, Natur, 223, 690

Magdziarz, P., Blaes, O. M., Zdziarski, A. A., Johnson, W. N., & Smith, D. A. 1998, MNRAS, 301, 179

Minniti, G., Fabian, A. C., Goyder, R., & Lasenby, A. N. 2003, MNRAS, 344, L22

Mitsuda, K., Inoue, H., Koyama, K., et al. 1984, PASJ, 36, 741

Nardini, E., Fabian, A. C., Reis, R. C., & Walton, D. J. 2011, MNRAS, 410, 1251

Noda, H., & Done, C. 2018, MNRAS, 480, 3998

Porquet, D., Done, C., Reeves, J. N., et al. 2019, A&A, 623, A11

Porquet, D., Reeves, J. N., Matt, G., et al. 2018, A&A, 609, A42

Ross, R. R., & Fabian, A. C. 2005, MNRAS, 358, 211

Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337

Singh, K. P., Garmire, G. P., & Nousek, J. A. 1985, ApJ, 297, 633

Takahashi, T., Abe, K., Endo, M., et al. 2007, PASJ, 59, 25

Tombesi, F., Cappi, M., Reeves, J. N., et al. 2010, A&A, 521, A57

Tombesi, F., Cappi, M., Reeves, J. N., et al. 2013, MNRAS, 430, 1102

Tripathi, S., Waddell, S. G. H., Gallo, L. C., Welsh, W. F., & Chiang, C. Y. 2019, MNRAS, 488, 4831

Ursini, F., Petrucci, P. O., Bianchi, S., et al. 2020, A&A, 634, A92

Vaughan, S., Fabian, A. C., Ballantyne, D. R., et al. 2004, MNRAS, 351, 193

Waddell, S. G. H., Gallo, L. C., Gonzalez, A. G., & Zoghbi, A. 2019, MNRAS, 489, 5398

Walton, D. J., Nardini, E., Fabian, A. C., Gallo, L. C., & Reis, R. C. 2013, MNRAS, 428, 2901

Wilkins, D. R., & Fabian, A. C. 2011, MNRAS, 414, 1269

Winter, L. M., Veilleux, S., McKernan, B., & Kallman, T. R. 2012, ApJ, 745, 107

Yaqoob, T., Turner, T. J., Tatum, M. M., Trevor, M., & Scholtes, A. 2016, MNRAS, 462, 4038

Zel’dovich, Y. B. 1964, PhD, 9, 195