XMM-Newton and Swift observations of the Seyfert 1 AGN NGC 5940

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Abstract
Probing the physics of the accretion flow around active galactic nuclei (AGN) is crucial to understanding their emission mechanisms as well as being able to constrain the geometrical and variability properties of the different regions around them. The soft X-ray excess – usually observed below ∼ 2 keV in excess of the dominant X-ray powerlaw continuum – is one prominent feature that is commonly seen in type 1 Seyfert AGN and therefore readily provides a useful diagnostic of the accretion flow mechanism around these systems. NGC 5940 is a Seyfert 1 AGN which reveals strong, prominent soft X-ray excess below ∼ 2 keV as seen in both its XMM-Newton and Swift observations. Model fit to the data revealed that this feature could be equally well explained by the ionised partial covering, the thermal Comptonisation and the blurred reflection models. Although the other models cannot be decisively ruled out with the data at hand, the lack of significant broad iron Kα as well as any significant emission/absorption line features in the reflection grating spectrometer (RGS) data tend to favour the thermal Comptonisation origin for the soft X-ray excess in NGC 5940.

Keywords Accretion, accretion discs · Galaxies: active · Galaxies: individual: NGC 5940 · Galaxies: nuclei · X-rays: galaxies

1 Introduction
Active galactic nuclei (AGN) have been known to be luminous in all bands of the electromagnetic spectrum. The optical/UV emission of AGN is believed to be produced in an optically thick standard accretion disc (Shakura and Sunyaev 1973; Novikov and Thorne 1973) due to viscous heating as material in the disc spiral down towards the central blackhole. The dominant X-ray powerlaw emission – which is a significant fraction of an AGN’s bolometric luminosity – is theorised to be produced from the Compton- upscattering of seed disc optical/UV photons in a compact (size ∼ 10–20 Rg, where Rg is the gravitational radius), hot (having electron temperature $K T_e \sim 100$ keV), optically thin (with optical depth $\tau < 1$) electron plasma, called the corona (Haardt and Maraschi 1993; Adegoke et al. 2019). Other complex features imprinted on the X-ray spectra of AGN include the soft X-ray excess emission below ∼ 2 keV, iron Kα emission complex at ∼ 6.4 keV and a Compton reflection “hump” which peaks normally at ∼ 20 keV.

The soft X-ray excess is a smooth emission component in the 0.3–2.0 keV energy range that is commonly observed in Seyfert 1 AGN. It was first reported over three decades ago and was thought at the time to be the Wien’s tail of the multi-temperature disc blackbody emission observed in the UV band (see e.g., Singh et al. 1985; Arnaud et al. 1985; Pounds et al. 1986; Walter and Fink 1993). However, it was soon shown that the predicted temperature (∼ 0.1–0.2 keV) is much higher than expected for a standard accretion disc around a supermassive blackhole. It was equally found that the temperature is fairly constant and not related to the luminosity and mass of the central blackhole as against expectations that disc temperatures should be correlated with blackhole masses (see e.g., Gierliński and Done 2004; Piconcelli et al. 2005; Miniutti et al. 2009). Gierliński and Done (2004) proposed that the soft excess could be an artefact of smeared absorption from partially ionised material, the model however requires unphysically large smearing velocity (∼ 0.5c, where c is the speed of light) for disc wind which has been shown to be difficult to generate from hydrodynamic simulations (Schurch and Done 2007). Thus, the origin of the soft excess is still being debated even today. Most recently, two competing models have tried to explain the origin of the soft X-ray excess – the thermal Comptonisation and the relativistically blurred reflection models. The thermal Compton-
isation model posits that the soft X-ray excess results from the inverse-Compton scattering of disc optical/UV photons in an optically thick ($\tau \sim 10$), warm ($K_T \sim 0.1-1$ keV) corona (e.g., Magdziarz et al. 1998; Done et al. 2012; Adegoke et al. 2017), different from the hot ($\sim 100$ keV) corona responsible for the dominant X-ray powerlaw. The relativistic reflection model on the other hand explains the soft X-ray excess to be the result of blurred reflection from partially ionised disc material in the vicinity of the blackhole due to its strong gravity and the high velocities of the accreting material (e.g., Crummy et al. 2006; García et al. 2014; Dauser et al. 2014). While both models tend to fit the data equally well in many cases, testing these models for a large number of sources and with data covering a wide range of the X-ray and other bands will be crucial to narrowing down on the actual origin of the soft X-ray excess as well as its possible dependence on the accretion flow properties of individual systems (see e.g., Jin et al. 2012; Petrucci et al. 2018; Gliozzi and Williams 2020). For such a large sample, a systematic search for the presence or absence of other features such as emission/absorption lines will help in identifying the preferred models. It is equally plausible that both thermal Comptonisation and X-ray reflection contribute simultaneously to the overall broadband X-ray spectra in AGN such that while the Compton reflection hump is due to relativistic reflection, thermal Comptonisation produces the soft X-ray excess, as was recently reported for the Seyfert 1 AGN Ton S180 (Matzeu et al. 2020).

NGC 5940 is a nearby Seyfert 1 AGN at a redshift of 0.034 and luminosity distance of 147 Mpc (Robinson et al. 2019). Its mass has been estimated to be $1.085^{+0.182}_{-0.167} \times 10^7 M_\odot$ in the reverberation mapping database\(^1\) of Bentz and Katz (2015). This is based on the 2011 Lick Observatory H$\beta$ and FeII lag measurements reported in Barth et al. (2013, 2015). Despite its relative proximity, its spectral properties have not been probed in detail until now, especially in the X-ray energy band.

This paper presents a detailed analysis of the \textit{XMM-Newton} X-ray data of NGC 5940 – supplemented with data from the \textit{Swift} X-ray Telescope. In Sect. 2, we describe the observation and data reduction procedure. In Sect. 3, we detail the data analysis approach used. We discuss the data analysis result in Sect. 4, and in Sect. 5, we draw conclusions and summarise our results.

## 2 Observations and data reduction

NGC 5940 was observed by \textit{XMM-Newton} (Jansen et al. 2001) on the 23rd of February, 2012 for a duration of $\sim 33$ ks (ObsID: 0670040601). All cameras onboard the telescope were used during the observation. The European Photon Imaging Cameras (EPIC) (Strüder et al. 2001; Turner et al. 2001) were operated in the full frame mode. While EPIC-pn was operated with thin filter, both MOS1 and MOS2 were operated with medium filters. The optical monitor (OM) (Mason et al. 2001) was operated in the image mode using the UVM2 and UWW1 filters.

The data was processed using the Science Analysis System (\texttt{sas v.17.0.0}) with updated Current Calibration Files (CCF). The sas task EVSELECT was employed to extract the event list. The data were subsequently screened and filtered for intervals of high particle background after which a good time interval (GTI) file was created. To check for possible pile-up in the data, a filtered event list was extracted from the raw event list – from a radius of 40 arcseconds centred on the source coordinates – using the GTI file after which the EPATPLOT command was applied. The check revealed the presence of significant pile-up in the pn data. To correct for the pile-up, X-ray loading was first corrected for, – since X-ray loading normally accompanies piled-up observations – after which the EVSELECT command was applied on the new event list using the GTI file to create a cleaned event file. Source photons were extracted from a region of radius 40 arcseconds centred on the source position while background was extracted from a circular source-free region of radius 80 arcseconds on the same CCD. The EVSELECT task was used to generate the X-ray source and background spectra. The SAS tasks ARFGEN and RMFGEN were subsequently used to compute the ancillary and photon redistribution matrices. Pile-up correction was implemented in the generation of the redistribution matrix which was calculated from the frequency and spectrum of the incoming photons. The resulting spectra were then grouped using the SPECGROUP command to have a minimum of 25 counts per bin to facilitate use of the $\chi^2$ minimisation technique.

The reduction of the reflection grating spectrometer (RGS) (den Herder et al. 2001) data followed standard procedure employing the SAS task RGSPROC. The accuracy of the source coordinates was checked from the source list and found to be in order. The data were subsequently checked against periods of high particle background by plotting the lightcurve of the pure background events. For improved signal-to-noise ratio, first order RGS1 and RGS2 spectra were combined using the task RGSCOMBINE and then grouped to have a minimum of 30 counts per bin for use with \texttt{XSPEC} $\chi^2$ statistics.

\textit{Swift} (Gehrels et al. 2004) has observed NGC 5940 a couple of times since 2008. Although none of the snapshots were simultaneous with the 2012 \textit{XMM-Newton} observation of the source, four observations carried out between 2010 and 2011 were combined into one spectra of total exposure $\sim 9.8$ ks and used for spectral analysis. This

\(^1\)http://www.astro.gsu.edu/AGNmass/
is based on the assumption that the spectral properties of the source had not changed significantly between the time of the 2012 XMM-Newton and the earlier 2010/2011 Swift observations. The Swift X-ray Telescope (XRT; Burrows et al. 2005) data reduction was carried out with the aid of the online Swift/XRT product generator hosted at the University of Leicester² (Evans et al. 2009).

### 3 Spectral analysis

We used the EPIC-pn X-ray data for our spectral analysis due to its higher signal-to-noise ratio compared to EPIC-MOS. We carried out the spectral analysis on NGC 5940 using XSPEC v.12.11.1 (Arnaud 1996). We used the $\chi^2$ statistics and for a single parameter of interest, errors were quoted at the 90% confidence level – corresponding to $\Delta \chi^2 = 2.706$ – unless otherwise stated. In all the fitting, we have added contributions from galactic absorption column of $N_H = 3.6 \times 10^{20}$ cm$^{-2}$ obtained from the recent HI21cm measurements (HI4PI Collaboration et al. 2016), modelled with tbabs (Wilms et al. 2000).

We began by fitting the 2–10 keV band with a baseline model consisting of a simple powerlaw modified by galactic absorption (i.e. tbabs*powerlaw). This provided a very good fit to the data with photon index $\Gamma = 1.78$ and $\chi^2$/dof of 91.7/93, where dof represents the degrees of freedom. Inclusion of a gaussian line to model possible iron $K_a$ features did not improve the fit, giving $\chi^2$/dof = 88.3/90. When extrapolated down to 0.3 keV, the data revealed strong soft X-ray emission in the source below $\sim 2$ keV in excess of the powerlaw as shown in the residual plot of Fig. 1, providing an unacceptable fit with $\chi^2$/dof of 223.6/140. To test existing models on the origin of this soft excess emission, we fitted the entire $0.3 - 10$ keV band with phenomenological and subsequently physically motivated models.

#### 3.1 Phenomenological model

To model the soft X-ray excess, we added the multicolour disc blackbody model diskbb (see e.g., Mitsuda et al. 1984; Makishima et al. 1986) to the baseline model (i.e. tbabs*(diskbb+powerlaw)). This provided an acceptable fit to the data with $\chi^2$/dof = 159.7/138. The inner disc temperature $T_{in} \sim 0.18$ keV is high for an accretion disc around a $10^7 M_\odot$ blackhole. The photon index $\Gamma$ is 1.89. Adding a gaussian line at 6.4 keV to the model slightly improved the fit with $\Delta \chi^2$/dof = −12/−3, giving $\chi^2$/dof = 147.4/135. However, in the subsequent models, addition of a gaussian line at $\sim 6.4$ keV did not improve the fits in any way and was therefore excluded.

#### 3.2 Physical models

##### 3.2.1 Ionised partial covering: zxipcf

The shape of the residual plot for the powerlaw fit to the 0.3 – 10 keV data seem to show features that may result from complex partial covering absorption along the line of sight (shown in Fig. 2 – top, leftmost plot). In this scenario, the intrinsic powerlaw continuum is obscured by an ionised absorber along the line of sight. The observed spectrum is then a combination of the obscured and the direct powerlaw components (see e.g., Reeves et al. 2008; Gallo et al. 2011; Tripathi et al. 2019). We tested this possibility by multiplying the absorbed powerlaw with the ionised partial covering absorption model zxipcf (i.e. tbabs*zxipcf*powerlaw). This provided a very good fit to the data with $\chi^2$/dof = 135.9/137, covering fraction $C_f = 0.42$ and line of sight column density $N_H \sim 1.6 \times 10^{23}$ cm$^{-2}$, the best-fit parameters are shown in Table 1.

##### 3.2.2 Warm corona model: optxagnf

The warm coronal model (Done et al. 2012) posits that the gravitational energy released at each annulus of the disc is radiated as thermal blackbody emission down to the radius of the corona $R_{cor}$. The gravitational potential energy within this radius is assumed to no longer be completely thermalised, giving rise to a warm ($kT_{SE} \sim 0.2$ keV), optically thick ($\tau > 1$) plasma responsible for the soft X-ray excess emission and a hot ($kT_e \sim 100$ keV), optically thin ($\tau < 1$) corona responsible for the dominant X-ray powerlaw continuum above $\sim 2$ keV. Important parameters of the

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²https://www.swift.ac.uk/index.php.
Table 1 The best-fit parameter values from fitting different models to the 0.3—10 keV XMM-Newton EPIC-pn data of NGC 5940

| Model/Parameter & Best-fit values | \( \chi^2/dof \) |
|----------------------------------|-----------------|
| Model \( \text{tbabs*(diskbb+powerlaw)} \) | 0.185 ± 0.02 |
| \( T_\text{in}(\text{keV}) \) | 0.185 ± 0.02 |
| Normalisation - diskbb | 51.28 ± 15.51 |
| Photon index \( \Gamma \) | 1.89 ± 0.03 |
| Normalisation \( (10^{-3}) \) - powerlaw | 1.35 ± 0.05 |
| \( \chi^2/dof \) | 159.7/138 |
| Model \( \text{tbabs*(zxipcf*powerlaw)} \) | |
| \( \text{Column density } N_h (10^{22}) - \text{zxipcf} \) | 15.74 ± 24.49 |
| \( \text{Ionisation parameter } \log(\xi) \) | −0.20 ± 0.41 |
| \( \text{Covering fraction } C_{\text{Frac}} \) | 0.42 ± 0.09 |
| Photon index \( \Gamma \) | 2.09 ± 0.02 |
| Normalisation \( (10^{-3}) \) - powerlaw | 2.62 ± 0.34 |
| \( \chi^2/dof \) | 135.9/137 |
| Model \( \text{tbabs*(optxagnf)} \) | |
| \( \text{Mass } (\times 10^7 M_\odot) \) | 1.1(\( f \)) |
| \( \text{Luminosity distance } (\text{Mpc}) \) | 147(\( f \)) |
| \( \log(\frac{L}{L_\text{edd}}) \) | −1.26 ± 0.60 |
| \( \text{spin } a^* \) | 0.998(\( f \)) |
| Corona radius \( R_{\text{cor}} \) | 18.12 ± 11.14 |
| \( \text{Warm corona } kT_{\text{SE}} (\text{keV}) \) | 0.40 ± 0.09 |
| Optical depth \( \tau \) | 12.92 ± 2.55 |
| Photon index \( \Gamma \) | 1.71 ± 0.09 |
| Powerlaw fraction \( f_{\text{pl}} \) | 0.77 ± 0.21 |
| \( \chi^2/dof \) | 135.6/136 |
| Model \( \text{tbabs*(relxillcp)} \) | |
| \( \text{spin } a^* \) | 0.998(\( f \)) |
| Inclination | 30deg(f) |
| Photon index \( \Gamma \) | 1.92 ± 0.02 |
| \( \text{Ionisation parameter } \log(\xi) \) | 3.00 ± 0.15 |
| Iron abundance \( A_{Fe} \) | 1.0(\( f \)) |
| Hot corona \( kT_e (\text{keV}) \) | 100(\( f \)) |
| Reflection frac | 0.55 ± 0.16 |
| Normalisation \( (10^{-5}) \) | 1.89 ± 0.14 |
| \( \chi^2/dof \) | 164/138 |
| Model \( \text{tbabs*(relxill+nthcomp)} \) | |
| \( \text{spin } a^* \) | 0.991 ± 0.418 |
| Inclination | 30deg(f) |
| Photon index \( \Gamma - \text{relxill} \) | 2.12 ± 0.04 |
| \( \text{Ionisation parameter } \log(\xi) \) | 0.02 ± 0.03 |
| Iron abundance \( A_{Fe} \) | 1.0(\( f \)) |
| High energy cutoff \( E_{\text{cut}} (\text{keV}) \) | 300(\( f \)) |
| Reflection frac \( R_{\text{frac}} \) | −1(\( f \)) |
| Normalisation \( (10^{-5}) \) - nthcomp | 5.65 ± 0.92 |
| Photon index \( \Gamma - \text{nthcomp} \) | 2.12(\( f \)) |
| Hot corona \( kT_e (\text{keV}) \) | 100(\( f \)) |
| Disk blackbody \( kT_{bb} (\text{keV}) \) | 0.1(\( f \)) |
| Normalisation \( (10^{-3}) \) - nthcomp | 1.49 ± 0.02 |
| \( \chi^2/dof \) | 134.1/138 |

Note: “\( f \)” implies that the value is frozen, “\( t \)” implies that the parameter value is tied to another parameter and “\( P \)” implies that the error value is pegged at the hard limit.
Fig. 2 Unfolded spectra of best fit for each of the models applied to the 0.3–10 keV XMM-Newton EPIC-pn data of NGC 5940. The upper panels in each plot show the model-data fit – the black solid lines represent the composite model in each of the plots. The lower panels in each plot show the residuals.

model include the blackhole mass $M_{BH}$, the dimensionless spin $a^*$, the electron temperature $kT_{SE}$ for the soft Comptonisation component and its optical depth $\tau$, the photon index of the powerlaw X-ray continuum $\Gamma$, the Eddington ratio in log scale $\log(L/L_{Edd})$ and the luminosity distance $D_L$ to the source. In fitting with this model, we fixed the blackhole mass at $\sim 1.1 \times 10^7 M_\odot$ (Robinson et al. 2019), the disc outer radius at its default value and $D_L$ at 147 Mpc. Following Crummy et al. (2005), we fixed and froze the spin parameter to the maximum allowed value of $a^* = 0.998$ as it was found to be unconstrained when freed. This model resulted in an excellent fit with $\chi^2/dof = 135.6/136$. The best-fit values of the Eddington ratio, $R_{cor}$, $kT_{SE}$, optical depth and the powerlaw photon index are 0.05, 18.08 $R_g$, 0.40 keV, 12.92 and 1.71 respectively. All the fit parameters are shown in Table 1.

### 3.2.3 Blurred reflection: relxill

To a good extent, reflection models have been successful in modelling some of the prominent features imprinted on the X-ray spectrum of AGN including the soft X-ray excess, the hard X-ray excess as well as line profiles like the iron $K_{\alpha}$ emission feature seen at $\sim 6.4$ keV (see e.g., Fabian et al. 2004; Walton et al. 2013; Jiang et al. 2019). To test whether blurred relativistic reflection in the immediate vicinity of the AGN can explain the origin of the prominent soft X-ray excess emission, we used the relxill model. This model combines the capabilities of the reflection code xillver (García et al. 2014) with the relativistic ray-tracing code relline (Dauser et al. 2014). It models the irradiation of the accretion disc by a broken powerlaw emissivity of the form $\epsilon \propto r^{-q_1}$ between $r_{in}$ and $r_{br}$ and $\epsilon \propto r^{-q_2}$ between $r_{br}$ and $r_{out}$; where $q_1$ and $q_2$ are the inner and outer emissivity indices, $r$ is the radius of the accretion disc while $r_{in}$, $r_{br}$ and $r_{out}$ are the inner, break and outer radii of the accretion disc respectively. More information about the model and its different flavours are available on its documentation webpage. We started by applying the relxillcp flavour of the model which is more physically consistent as the reflection fraction in this case is computed using the primary continuum implemented with the nthcomp Comptonisation model (Zdziarski et al. 1996; Zycki et al. 1999).

During fitting, the indices $q_1$ and $q_2$ were kept at their default values of 3. Also, $r_{br}$, inclination, $r_{in}$ and $r_{out}$ were left frozen at their default values. Iron abundance relative to solar abundance $A_{Fe}$ and the hot corona temperature were fixed at 1 and 100 keV respectively. The spin parameter $a^*$ was fixed at its maximum value of 0.998. The model provided an acceptable fit to the data with $\chi^2/dof = 164/138$ and a steeper photon index $\Gamma = 1.92$. Allowing the inner emissivity index $q_1$, break radius $r_{br}$, spin, inclination and the iron abundance $A_{Fe}$ parameters to be free improved

3http://www.sternwarte.uni-erlangen.de/~dauser/research/relxill/.
the fit significantly, with $\Delta \chi^2 / \Delta \text{dof} = -20 / -4$ giving $\chi^2 / \text{dof} = 144 / 133$. This configuration additionally gave $r_{br} \sim 4 \, R_g$, $q_1 \sim 9.8$, $a = 0.899$, $\Gamma = 1.96$, inclination $\sim 35$ deg and $A_{Fe} \sim 4$. As evident, the inner emissivity index is rather extreme in this case which may indicate strong inner disc reflection due to strong general relativistic effects in the immediate vicinity of the blackhole. The modelled iron abundance is also considerably super-solar.

We afterwards replaced the relxillcp with the relxill+nthcomp model where the illuminating powerlaw is modelled with nthcomp and the blurred reflection only with relxill. For this, the reflection fraction parameter $R_{frac}$ was set to $-1$. Most parameters of the relxill and relxillcp models are the same with the exception of the coronal electron temperature $kT_e$ in relxillcp which is replaced by the high energy cutoff $E_{cut}$ in relxill. The photon index of nthcomp was tied to that of the relxill model. This provided an excellent fit to the data with $\Delta \chi^2 = -10$ compared to the previous model for four additional degrees of freedom, giving $\chi^2 / \text{dof} = 134 / 137$ and a slightly steeper photon index value $\Gamma = 2.12$. Table 1 contains all the fitted parameter values of the model.

### 3.3 RGS spectral analysis

We analysed the RGS spectra of NGC 5940 to check for possible prominent emission and absorption line features in the $0.3 - 2$ keV energy range associated with the soft X-ray excess. This is because the RGS has a much higher energy resolution compared to both EPIC-pn and MOS and as such these reflection features should be evident in the RGS spectra of the source if blurred relativistic reflection is predominantly what produces the soft X-ray excess. We modelled the combined first order RGS spectra with a simple powerlaw modified by galactic absorption. This provided a very good fit with $\chi^2 / \text{dof} = 216.9 / 221$ and $\Gamma = 2.12$. Figure 3 shows the powerlaw modelled RGS $(1 + 2)$ stacked spectra of NGC 5940, with the residual shown in the lower panel of the plot. This spectral analysis result suggested that the soft X-ray spectra in NGC 5940 is largely featureless, consistent with a simple powerlaw. Following Matzeu et al. (2020), we systematically scanned blindly the $6.5 - 29$ Å wavelength band of the RGS spectra for absorption and emission line features. To do this, we included a Gaussian line profile in the absorbed powerlaw model, allowing for both positive and negative normalisations. The search did not result in the detection of any prominent features that is significant.

### 3.4 Swift XRT spectral analysis

We combined Swift XRT spectra from four observations (ObsIDs: 00037386002, 00037386003, 00037386004, 00037386005) of NGC 5940 carried out between 2010 and 2011 for improved statistics. We grouped the data to have a minimum of 5 counts per bin for use with XSPEC $\chi^2$ statistic. We started by fitting the $1.5 - 7.0$ keV Swift XRT spectrum (in red) of NGC 5940 extrapolated down to $0.3$ keV. The lower panel shows the residual plot.

![Fig. 3](image1.png)

**Fig. 3** The upper panel shows a powerlaw fit (in black) to the first order RGS1+2 spectrum (in red) of NGC 5940. The lower panel shows the residual plot.

![Fig. 4](image2.png)

**Fig. 4** The upper panel shows a powerlaw fit (in black) to the $1.5 - 7.0$ keV Swift XRT spectrum (in red) of NGC 5940 extrapolated down to $0.3$ keV. The lower panel shows the residual plot.

### 4 Discussion

We carried out spectral analysis on the 2012 XMM-Newton observation of the Seyfert 1 AGN NGC 5940. The data revealed the presence of strong soft X-ray emission in the
source below 2 keV in excess of the dominant X-ray power-law. Here, we investigated the possible origin of this emission component.

We started by fitting a phenomenological model to the data, namely; the multicolour disc blackbody, to model the soft X-ray excess with the addition of the powerlaw model for the X-ray emission above ~ 2 keV. As is the case with most fits using the blackbody model, the inferred temperature of ~ 0.18 keV is too high for an accretion disc around a blackhole mass of ~ 10^7 M⊙. Standard accretion disc theory predicts that the inner disc temperature of such a system is given by the relation

\[ T_{\text{eff}} \sim 6.3 \times 10^5 \left( \frac{M}{M_{\text{Edd}}} \right)^{1/4} \left( \frac{M}{10^8 M_\odot} \right)^{-1/4} \left( \frac{R}{R_s} \right)^{-3/4}, \]

where \( \dot{M}/M_{\text{Edd}} \) is the Eddington-scaled accretion rate, \( M \) is the blackhole mass, \( R \) and \( R_s \) are respectively the disc annular radius and the Schwarzschild radius. Thus, for a Schwarzschild blackhole of ~ 10^7 M⊙, at the inner edge \( T_{\text{eff}} \) should be of order 30 eV (e.g., Bhattacharyya et al. 2014; Adegoke et al. 2017). We subsequently modelled the lower X-ray energy features using the ionised partial covering model – multiplied by the powerlaw model. This model posits that the lower energy features may include contributions from partial covering of the X-ray source due to partially ionised material along the line of sight (e.g., Miller et al. 2006; Reeves et al. 2008). This model provided a very good fit to the data and has been employed to study the soft X-ray excess and the spectral variability in PG 0844+349 (Gallo et al. 2011) and Zw 229.015 (Tripathi et al. 2019) among others with similarly good fits. However, a compact absorber would imply the presence of a strong iron fluorescence line which is not observed in the data. It is plausible that the geometry of the absorber may be responsible for the non-detection of the line. Longer and possibly joint multi-wavelength observations of the source will throw more light on this.

We then applied two more physically motivated models – the warm Comptonisation and the blurred reflection models – that have been applied to model successfully the soft excess in several Seyfert 1 AGN e.g., 1H 0707-495 (Fabian et al. 2009), Mrk 509 (Mehdipour et al. 2011), ESO 113-G010 (Cackett et al. 2013), II Zw 177 (Pal et al. 2016), Ton S180 (Matzeu et al. 2020). Both the thermal Comptonisation and the blurred reflection models provided acceptable fit to the data implying they both explained the origin of the soft excess.

The warm Comptonisation model (optxagnf) considers the soft X-ray excess to originate due to repeated inverse-Compton scattering of seed disc photons in a warm, optically thick corona. The fitted optical depth \( \tau \) and temperature \( kT_{SE} \) of the warm corona were respectively ~ 13 and 0.4 keV with a moderately high accretion rate value of about 5% of Eddington. This inferred value of accretion rate supports earlier analysis carried out on the source (Castelló-Mor et al. 2016). The model favoured a maximally spinning blackhole with corona radius, photon index and power fraction of the powerlaw having values ~ 18 R_g, ~ 1.7 and 77% respectively. The modelled 0.3 – 10 keV flux and luminosity came out to be 8.2 x 10^{-12} erg cm^{-2} s^{-1} and 2.2 x 10^{43} erg s^{-1} respectively.

The blurred reflection model (relxill) on the other hand considers that strong X-ray reflection in the inner region of the accretion disc, blurred and smoothed due to strong general relativistic effects in this region is responsible for the soft X-ray excess emission. Fit with the relxill+nthcomp flavour of the model gave reflection fraction value of ~ 0.5 implying moderately strong X-ray reflection in the disc innermost region. The model equally favoured a maximally spinning blackhole having photon index ~ 1.9. The relxill+nthcomp version of the model provided a very good fit to the data with photon index value of ~ 2. The value of the ionisation parameter here is much smaller at \( \log \epsilon = 0.02 \). An additional evidence for blurred inner disc reflection origin for the soft X-ray excess is the expected presence of broad iron \( K_\alpha \) line at ~ 6.4 keV as this line is also believed to be produced due to strong X-ray reflection in the disc (Tanaka et al. 1995). The line is however not detectable in this observation – to any level of significance. Moreso, the RGS spectra with its higher resolution should normally reveal some of the prominent line features that blend to produce the soft excess, but the RGS data of this source appear to be largely featureless, fitted by a simple powerlaw. Longer focused observation in the X-rays and optical/UV bands may be required to probe this further.

## 5 Conclusion & summary

We studied the spectral properties of the nearby Seyfert 1 AGN NGC 5940 using predominantly its 2012 XMM-Newton observation supplemented with data from Swift. This source has been spared of scrutiny over the past years despite its proximity and availability of usable data. The data revealed strong soft X-ray excess emission below ~ 2 keV as is commonly seen in many unobscured AGN. Using state-of-the-art spectral models, we went ahead to probe the origin of the soft X-ray excess emission.

The phenomenological model applied provided acceptable fits to the XMM-Newton EPIC-pn data of the source. From the disc blackbody plus powerlaw model, the model-predicted temperature is much higher than expected for accretion discs around supermassive blackholes. The model for partial covering from partially ionised material tend to provide a very good fit to the data for the origin of the soft excess. However, longer duration, high resolution multi-wavelength observations will be required to probe further.
the possibility of partial covering in the source. Such observations will better probe additional emission/absorption and other signatures that should accompany an ionised partial covering scenario.

Two additional physically motivated models were also applied – The thermal Comptonisation and the blurred reflection models. We found that both models provided acceptable fits and thus can explain the origin of the soft X-ray excess emission well although with suggestive preference for the thermal Comptonisation model. This is because other features that should normally accompany strong reflection – like the broad iron Kα line as well as emission line features in the RGS spectra – were not observed in our analysis.

Timing analysis may provide useful insight into understanding the importance of thermal Comptonisation and/or blurred reflection in the accretion flow physics of the source. For example, if cross-correlation analysis reveals that optical/UV disc photons lead the X-rays in their variability, then thermal Comptonisation could play a dominant role in the origin of the soft excess (Adegoke et al. 2019). If on the contrary, X-rays lead, then reprocessing and therefore blurred reflection may play a more dominant role (Krolik et al. 1991; Cackett et al. 2007). It is equally possible that both thermal Comptonisation and relativistically blurred reflection play a role in the overall spectral energy distribution of the source such that while warm Comptonisation explains the origin of the soft X-ray excess, reflection may explain the line features as well as the hard X-ray excess. Simultaneous observations of the source at higher X-ray energies with instruments like the broad iron Kα line as well as emission line features in the RGS spectra – were not observed in our analysis.

Informed consent

None.

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None.

Data Availability

Details of all the data analysed in this study are included in the article.

Declarations

Conflict of Interest

The author has no competing interests to declare regarding the content of this article.

Informed consent

None.

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