

X-ray analysis of SDSS J165202.60+172852.4, an obscured quasar with outflows at peak galaxy formation epoch

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ABSTRACT

We report on deep *XMM-Newton* and *NuSTAR* observations of the high redshift, $z = 2.94$, extremely red quasar (ERQ), SDSS J165202.60+172852.4, with known galactic ionized outflows detected via spatially resolved [O III] emission lines. X-ray observations allow us to directly probe the accretion disc luminosity and the geometry and scale of the circumnuclear obscuration. We fit the spectra from the *XMM-Newton*/EPIC and *NuSTAR* detectors with a physically motivated torus model and constrain the source to exhibit a near Compton-thick column density of $N_{\text{H}} = (1.02^{+0.76}_{-0.41}) \times 10^{24} \text{ cm}^{-2}$, a near edge-on geometry with the line-of-sight inclination angle of $\theta_i = 85^\circ$, and a scattering fraction of $f_{\text{sc}} \sim 3$ per cent. The absorption-corrected, intrinsic 2–10 keV X-ray luminosity of $L_{2-10} = (1.4^{+1}_{-1}) \times 10^{45} \text{ erg s}^{-1}$ reveals a powerful quasar that is not intrinsically X-ray weak, consistent with observed trends in other ERQs. We also estimate the physical properties of the obscuration, although highly uncertain: the warm ionized scattering density of $n_e \sim 7.5 \times (10^2\text{--}10^3) \text{ cm}^{-3}$ and the obscuration mass of $M_{\text{obs}} \sim 1.7 \times (10^4\text{--}10^6) M_\odot$. As previously suggested with shallower X-ray observations, optical and infrared selection of ERQ has proved effective in finding obscured quasars with powerful outflow signatures. Our observations provide an in-depth view into the X-ray properties of ERQs and support the conclusions of severely photon-limited studies of obscured quasar populations at high redshifts.

Key words: galaxies: active – galaxies: evolution – quasars: general – X-rays: galaxies.

1 INTRODUCTION

Accreting supermassive black holes with $L_{\text{bol}} > 10^{45} \text{ erg s}^{-1}$ – quasars – are of major importance to galaxy formation. It is believed that part of the energy output is in the form of galaxy-wide outflows, impacting the host galaxy and the surrounding environment (Silk & Rees 1998; Kormendy & Ho 2013). On small scales, these outflows can be driven by the radiation pressure of quasar emission (Murray et al. 1995; Proga, Stone & Kallman 2000) or by jets (Fabian 2012). The interactions between the quasar and its environments are known as quasar feedback, which is likely important in quenching star formation, regulating central supermassive black hole growth, and limiting galaxy masses (Croton et al. 2006; Fabian 2012).

Theoretical models suggest quasar feedback occurs at a critical phase in galaxy evolution. Quasar activity can result from accretion on to the central black hole, which can be triggered by major mergers (Barnes & Hernquist 1992; Sanders & Mirabel 1996) or more commonly through secular processes (Hopkins & Hernquist 2009). These active galaxies then enter a dusty, obscured phase enshrouded by gas and dust. Finally, the energy and momentum is released by the accreting black hole through a ‘blow-out’ of galaxy-

wide outflows, revealing an unobscured quasar (Sanders et al. 1988; Hopkins et al. 2006). This makes the $z \sim 2\text{--}3$ epoch of high interest in galaxy formation since it marks the peak of both star formation and quasar activity (Boyle & Terlevich 1998; Hopkins et al. 2006). However, constraining the power, the mechanisms, and the impact of quasar feedback remain unresolved in galaxy formation theory (Harrison et al. 2018).

Thus, Type II (Antonucci 1993) quasars with powerful outflow signatures may be instrumental for probing the blow-out feedback phase. Of particular interest is the population of high-redshift extremely red quasars (ERQs; Ross et al. 2015; Hamann et al. 2017), which are associated with extreme-velocity ionized gas outflow activity, showing strong indications of active quasar feedback in the blow-out phase (Zakamska et al. 2016; Perrotta et al. 2019). Spatially resolved kinematic maps of [O III] $\lambda 5007 \text{ \AA}$ emission in some of the ERQs reveal powerful galactic winds (Vayner et al., in preparation).

To better constrain the intrinsic power and wind-driving mechanisms of the quasar’s central engine, a direct measurement of the accretion luminosity of quasars with powerful outflows is needed. However, this is often complicated by the obscuration from the optically-thick material (the torus and gas) in Type II quasars that prevent direct optical observations of the accretion disc (Hickox & Alexander 2018). Since powerful X-ray emission is directly associated with the corona above the quasar accretion disc, X-ray

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observations provide a reliable method in probing the quasar. In addition, by revealing photoelectric absorption and Compton scattering, X-ray measurements can provide insights into the geometry and scale of the circumnuclear obscuring material: key parameters that constrain the wind-driving mechanisms. Understanding the nature of the obscuring material (scale, densities, composition, and kinematics) and the physical processes that produce the obscuration will allow us to calculate the intrinsic X-ray luminosity associated with the accretion and to probe the connection between the outflows and obscuration emerging in studies of broad absorption-line (BAL) quasars (Luo et al. 2013).

Uncovering and characterizing obscured quasar populations at high redshift, especially the near-Compton-thick populations, remain among the most important goals of X-ray astronomy. There is an ongoing debate in which early studies suggested that the fraction of obscured active galactic nuclei was a strongly declining function of luminosity (Ueda et al. 2003). Whether this decline is real or is due to selection effects remain controversial (Lusso et al. 2013). Lawrence & Elvis (2010) found no observed luminosity dependence of the obscured fraction in the radio- and mid-infrared-selected samples, and in volume-limited samples, hinting that X-ray studies may have missed Compton-thick targets. Assef et al. (2015) suggest that at high luminosities and redshifts, there may be as many obscured and unobscured quasars. Lambrides et al. (2020) recently showed that obscured populations may be misclassified as low-luminosity objects. Therefore, it is of high interest to obtain high-quality X-ray data and to build an accurate model of the accretion properties of these unique quasars.

In this paper, we report on the joint *NuSTAR*+*XMM-Newton* X-ray follow-up study of the high-redshift $z = 2.94$ ERQ, SDSS J165202.60+172852.4 (SDSSJ1652 henceforth, see Table 1). It was identified by the Sloan Digital Sky Survey (SDSS; Eisenstein et al. 2011; Ross et al. 2015) and the *Wide-field Infrared Survey Explorer* (*WISE*; Wright et al. 2010), and its optical and infrared properties have been well studied by our collaboration. Extreme velocities ($v > 3000 \text{ km s}^{-1}$) with strong blueshifted wings of [O III] $\lambda\lambda 4959, 5007 \text{ \AA}$ emission lines indicate powerful quasar-driven wind (Alexandroff et al. 2018; Perrotta et al. 2019); polarized UV continuum suggests dust scattering and equatorial circumnuclear outflow (Alexandroff et al. 2018); and *HST* imaging reveals multiple components and a kpc-scale tidal tail that suggests possible galaxy interaction (Zakamska et al. 2019). Spatially resolved mapping of [O III] $\lambda 5007 \text{ \AA}$ emission is required to prove that [O III] winds are extended on galactic scales (Greene, Zakamska & Smith 2012; Liu et al. 2013a,b; Fischer et al. 2018). We now have direct observations that several ERQs, including SDSSJ1652, have [O III] $\lambda 5007 \text{ \AA}$ winds on galactic scales from integral-field unit observations (Vayner et al., in preparation). Finally, SDSSJ1652 has been approved for the *James Webb Space Telescope* (*JWST*) Early Release Science program to obtain spatially resolved spectra (ID 1335; Wylezalek et al. 2017), so we wish to conduct an in-depth X-ray study in preparation for *JWST*.

X-ray studies of high-redshift obscured quasars are often severely limited by photon statistics and rely on stacking techniques (Goulding et al. 2018; Vito et al. 2018). Here we present a deep X-ray study of SDSSJ1652 with *XMM-Newton* and *NuSTAR* conducted both to improve the knowledge of this particular object and to test the statistical techniques used in the photon-limited X-ray studies of the obscured high-redshift quasar population. We measure the photon index, Γ , of the X-ray power-law continuum ($dN/dE \propto E^{-\Gamma}$) and the absorbing column density, N_{H} , to constrain the intrinsic accretion luminosity and the geometry and scale of the obscuration.

Table 1. Summary of known SDSSJ1652 properties.

Parameter		Value	Ref.
RA	(J2000)	16:52:02.60	(Gaia Collaboration 2018)
Dec.	(J2000)	+ 17:28:52.4	
z		2.94	(Ahn et al. 2012)
$\log L_{6\mu\text{m}}$	(erg s^{-1})	47.19	(Goulding et al. 2018)
$\log L_{\text{Bol}}$	(erg s^{-1})	47.73	(Perrotta et al. 2019)

Note. The rest-frame $L_{6\mu\text{m}}$ is derived from *WISE* photometry.

In Section 2, we describe the observations and data reduction. In Section 3, we describe the spectral analysis. We discuss the physics of the observations in Section 4 and summarize our results in Section 5. We adopt the $h = 0.7$, $\Omega_{\text{M}} = 0.3$, and $\Omega_{\Lambda} = 0.7$ cosmology. The stated uncertainties represent the 90 percent confidence interval.

2 OBSERVATION AND DATA REDUCTION

2.1 XMM-Newton

SDSSJ1652 was observed with *XMM-Newton* (Jansen et al. 2001) on 2019 March 5–6 for an exposure of 130 ks (ObsID: 0830520101). Exposures were taken with the European Photon Imaging Camera (EPIC), which carries a set of three X-ray CCD cameras: MOS-1, MOS-2, and PN (Strüder et al. 2001; Turner et al. 2001). The EPIC CCDs are sensitive from 0.15 to 15 keV with moderate spectral energy resolution ($E/\Delta E \sim 20\text{--}50$) and point spread function with 6-arcsec full width at half-maximum (FWHM).

Each EPIC image was reduced with the *XMM-Newton* Science Analysis Software (XMMSAS; Gabriel et al. 2004) v18.0.0 and the Current Calibration Files (CCF) v3.12. The calibrated events were produced using the *EPPROC* task. A rate filter was applied to remove minor background flares, such that the effective exposure time was cut to approximately 50 ks.

We extracted the source spectra from 15-arcsec radius apertures. Background spectra were extracted from the same chip as the source; however, the aperture was treated differently depending on the source's location on the chip. For the EPIC-PN, we took a circular 110-arcsec radius aperture near the source aperture. For the EPIC-MOS, we took a 60–200 arcsec annular aperture centred on the source. Since the background regions also overlapped with neighboring point-source detections, we excluded 15-arcsec radii apertures for each contaminant. Images of the source with the 15-arcsec extraction apertures for the PN detector at three energy bands are shown in Fig. 1. The redistribution matrix file (RMF) and auxiliary response file (AMF) were generated with the *RMFGEN* and *ARFGEN*, respectively. The final background-subtracted spectra were grouped at 1 photon per bin using *GRPPHA*. Photometry results are summarized in Table 2.

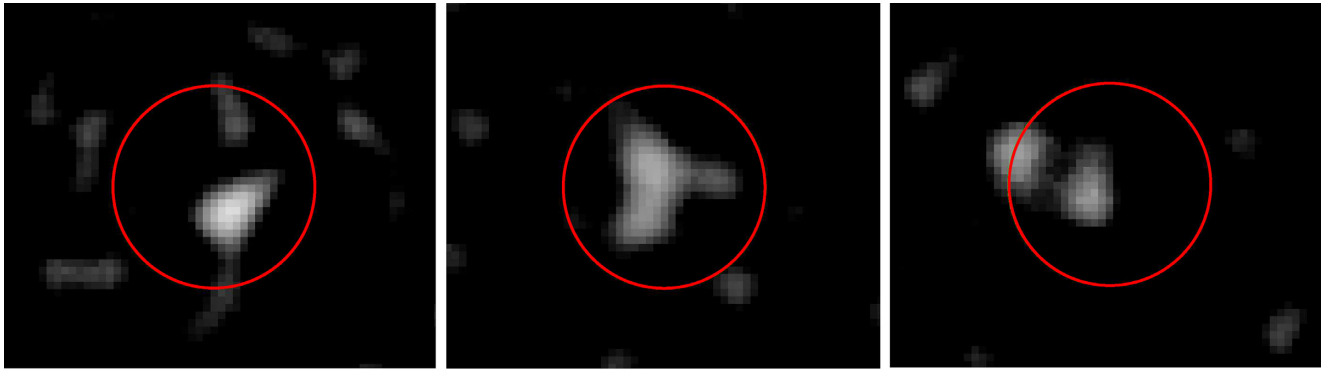
2.2 NuSTAR

The *NuSTAR* (Harrison et al. 2013) observatory is the first focusing satellite with sensitivity over a broad high-energy 3–79 keV energy band. It consists of two focal-plane modules (FPMA and FPMB) with a $12 \times 12 \text{ arcmin}^2$ field of view. Since we expected low-photon detections due the predicted Compton-thick nature of the SDSSJ1652, a much longer 218-ks observation was performed with *NuSTAR* on 2019 February 23 (obsID: 60401028002). The *NuSTAR* data were reduced with the *NuSTAR* Data Analysis Software (NUSTARDAS)

Table 2. Aperture photometry results of the *XMM–Newton* and *NuSTAR* observations in different energy bands.

Detector	GTI exposure time	Net counts	Count rate	Net counts	Count rate	Net counts	Count rate
<i>XMM–Newton</i>		(0.5–2 keV)		(2–5 keV)		(5–10 keV)	
EPIC MOS-1	52020	10 ± 5	1.8×10^{-4}	<10	$<2 \times 10^{-4}$	<10	$<2 \times 10^{-4}$
EPIC MOS-2	46400	6 ± 5	1.3×10^{-4}	7 ± 4	1.6×10^{-4}	<11	$<2 \times 10^{-4}$
EPIC PN	48870	15 ± 10	3.1×10^{-4}	33 ± 9	6.8×10^{-4}	<24	$<5 \times 10^{-4}$
<i>NuSTAR</i>		(6–10 keV)		(10–40 keV)		(40–79 keV)	
FPMA	218600	22 ± 9	1×10^{-4}	25 ± 18	1×10^{-4}	<48	$<2 \times 10^{-4}$
FPMB	218600	<31	$<1 \times 10^{-4}$	<54	$<3 \times 10^{-4}$	<45	$<2 \times 10^{-4}$

Notes. *XMM–Newton* source counts were extracted from 15-arcsec apertures; and the *NuSTAR* source counts were extracted from 30-arcsec apertures. The EPIC detectors showed lower signal-to-noise ratio towards the harder bands compared to that of the PN detector. Of the two *NuSTAR* detectors, only FPMA showed real detections, so we show 3σ upper limits for FPMB. The 3σ upper limits are also shown for other bands with low counts. Only data from the EPIC and FPMA detectors were used for the spectral analysis. The Good Time Interval (GTI) exposure time is in seconds.

**Figure 1.** The *XMM–Newton* EPIC PN images, smoothed with a 5-pixel FWHM 2D Gaussian, are shown in the 0.5–2, 2–5, and 5–10 keV bands. SDSSJ1652 is centred with the circular 15-arcsec extraction region indicated. The photometry is shown in Table 2.

v20160502 and the NuSTAR Calibration Database (CALDB), using the `nupipeline` tasks. The spectra and light curves were extracted with the `nuproducts` task.

Photometry results in Table 2 were extracted from a 30-arcsec radius circular region centred on the target coordinates from both detectors. Despite the long exposure, the FPMB detector did not detect any significant signal from the source. Thus, we only use data from the FPMA detector for spectral analysis. We calculate the 3σ upper limit for FPMB in three bands: 6–10, 10–40, and 40–79 keV. The *NuSTAR* photometry results are shown in Table 2. The non-detection can be attributed to a few reasons: high attenuation of X-ray signals due to the obscuring material, limited exposure time, and stray light, which complicated background subtraction.

3 X-RAY SPECTRAL ANALYSIS

We perform spectral analysis on SDSSJ1652 with XSPEC v12.10 (Arnaud 1996) for photon-limited Cash statistics (Cash 1979). We adopt the Galactic absorption column density of $N_{\text{H,Gal}} = 5.03 \times 10^{20} \text{ cm}^{-2}$ (HI4PI Collaboration et al. 2016), which is modelled by the `phabs` XSPEC model. We perform simultaneous spectral analysis on the *XMM–Newton* EPIC (MOS and PN) between 0.5 and 10 keV and the *NuSTAR* FPMA data between 6 and 79 keV, excluding the FPMB data due to low signal. The objectives are to constrain the power-law photon index Γ associated with the intrinsic luminosity and the column density N_{H} to understand the geometry and scale of the obscuration. All fits are performed in the rest frame assuming $z = 2.94$.

3.1 Absorbed power-law model

We first fit the SDSSJ1652 spectra with a power-law. The initial fit produces a small photon index $\Gamma \sim 0.8$. Since the typical value of the power-law slopes measured in active galactic nuclei is $\Gamma \approx 2$ (Nandra & Pounds 1994; Reeves & Turner 2000; Page et al. 2005; Piconcelli et al. 2005), the flat spectral slope of $\Gamma \sim 0.8$ is unlikely to reflect the intrinsic properties of the source, but rather indicates the presence of significant absorption (Alexander et al. 2001). The resulting observed spectrum is harder than the intrinsic spectrum of an unobscured quasar (Nandra & Pounds 1994; Goulding et al. 2018).

Next, we model the spectra using a power-law with photoelectric absorption in the rest frame. We refer to this as the absorbed power-law model, and the corresponding XSPEC model is listed in Table 3. When all model parameters (column density N_{H} , normalization K_{norm} , and the photon index Γ) are set as free parameters, the best-fitting model also produce a low power-law index $\Gamma \sim 0.8$, which is likely due to the high soft-energy excess, hinting complex attenuation mechanism. Instead, we adopt the approach taken by Goulding et al. (2018), among others, and force a more physically motivated model. We fix the photon index at a typical slope of $\Gamma = 1.9$ and freely fit for the column density N_{H} and energy normalization K_{norm} . The observed spectra with the best-fitting model are shown in Fig. 2. The best-fitting parameters are $N_{\text{H}} = (9^{+4}_{-3}) \times 10^{23} \text{ cm}^{-2}$ and $K_{\text{norm}} = (6 \pm 2) \times 10^{-5} \text{ photon keV cm}^{-2} \text{ s}^{-1}$ at 1 keV with an improved $C_{\text{stat}} = 633$ for 693 degrees of freedom (d.o.f.). The confidence ranges of the calculated N_{H} and K_{norm} are produced with the XSPEC `steppar` routine. The confidence contours of N_{H} and K_{norm} fits are shown in Fig. 2. The power-law model with $\Gamma = 1.9$ yields the same

Table 3. The XSPEC commands for each model considered.

Model	XSPEC commands
Absorbed power-law	phabs*zphabs*zpowerlw
MYTorus	const ₁ *phabs(zpowerlw*MYTZ + const ₂ *MYTS + const ₃ *gsmooth*MYTL + const ₄ *zpowerlw)

Notes. A constant Galactic absorption (phabs) is assumed for both models. The MYTorus model describes a reprocessed spectrum (MYTZ, MYTS, and MYTL) and an optically thin scattered continuum, assuming a terminal energy of 500 keV. Normalization for the Compton scattered emission (const₂) and fluorescent line emission (const₃) are tied together for a self-consistent model. The scattering fraction f_{sc} is given by const₄, which is linked to the power-law model of the source zpowerlw.

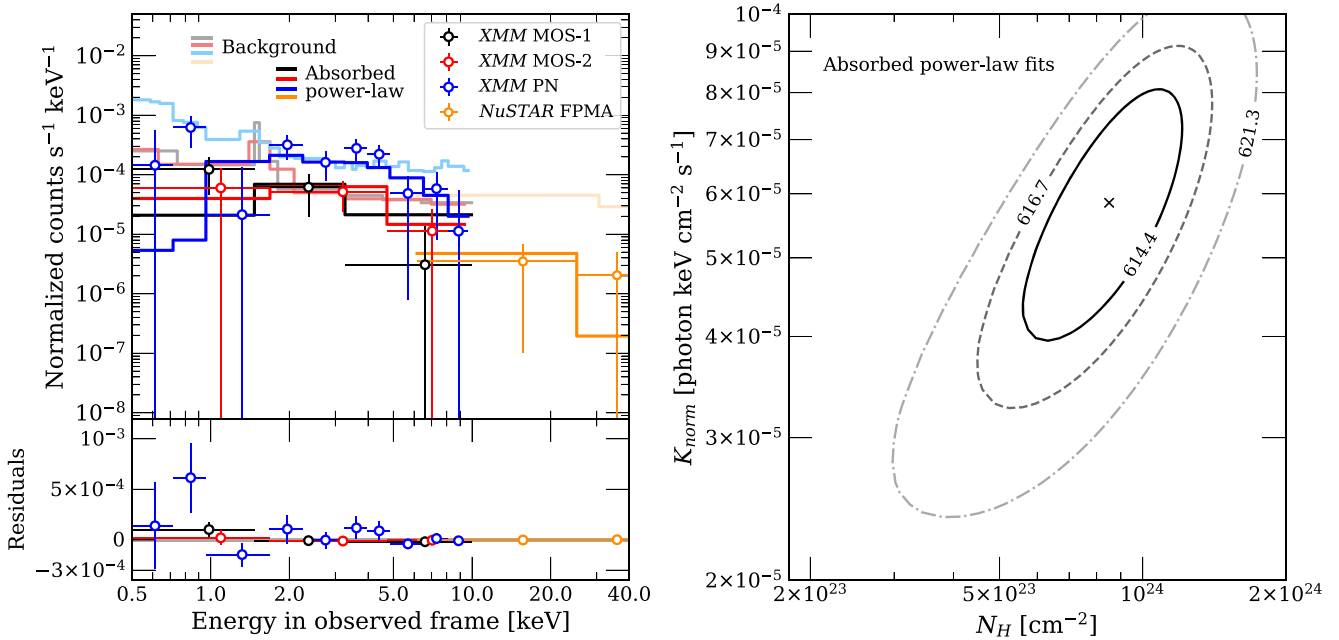


Figure 2. Top left-hand panel: The *XMM-Newton* and *NuSTAR* spectra and the folded absorbed power-law model fits are shown. The spectra have been rebinned for plotting purposes. The binned data points are indicated with circles, and the models are shown as solid lines: MOS-1 (black), MOS-2 (red), PN (blue), and FPMA (orange). The extracted background spectrum for each detector is also shown as faded lines in the same colour scheme. Bottom left-hand panel: The data-model residuals show increased deviations in the <1.5 keV soft-energy region, which indicates the need for a more complex model. While it is possible that the soft-energy features may be background driven, it is unlikely that features around 3–5 keV are affected by the background. Right-hand panel: The confidence contours for the best-fitting K_{norm} and N_{H} for the absorbed power-law model. The contour lines represent the 68 (solid), 90 (dashed), and 99 per cent (dash-dotted) C_{stat} confidence levels for 693 degrees of freedom. We see that the model indicates a near-Compton thick absorption of $N_{\text{H}} \sim 10^{24} \text{ cm}^{-2}$.

results for the intrinsic luminosity whether it is applied to just the *NuSTAR* data or to the combined *XMM-Newton*+*NuSTAR* data set. Spectral fit results are summarized in Table 4.

The best-fitting model spectrum in Fig. 2 displays a noticeable inversion around the observed frame 1.5 keV. Examining the data-model residual, we see that this absorbed power-law model does not capture this observed-frame soft-energy excess in the 0.5–1 keV range. Although the Fe K α emission line (1.6 keV in the observed frame) is present (Piconcelli et al. 2015), due to the low counts observed, we cannot find an appropriate binning that comfortably shows both the line and the continuum. These observed spectral features combined with the initial column density estimate approaching $N_{\text{H}} \sim 10^{24} \text{ cm}^{-2}$ suggest significant Compton-thick obscuration with a more complex absorption structure.

3.2 MYTorus model

We adopt the physically motivated MYTorus spectral model (Murphy & Yaqoob 2009; Yaqoob 2012), which is a Monte Carlo model based on a toroidal circumnuclear reprocessor that also accounts for geometry. The increased soft X-ray component seen in Fig. 2 suggests

a Compton scattering continuum, which MYTorus can also model self-consistently. We fit a model that uses pre-calculated MYTorus tables that include: (a) the zeroth-order reprocessed power-law continuum – MYTZ, (b) the Compton-scattered continuum – MYTS, (c) the scattered fluorescent line emission due to Fe K at ~ 6.4 -keV rest frame – MYTL, and (d) the optically-thin scattered power-law continuum, separate from the MYTorus tables, to account for electron scattering in a warm/hot ionized region surrounding the central engine. This added optically-thin scattering region is larger than the obscuring structure. For simplicity, we refer to this model set as the MYTorus model throughout this paper. This spectral shape is motivated by the stacked analysis in Goulding et al. (2018). The XSPEC implementation of this model is shown in Table 3. All models considered assume that the intrinsic power-law continuum terminates at 500 keV, referred to as the terminal energy.

Similar to the absorbed power-law model treatment, we fix $\Gamma = 1.9$ and tie it to each MYTorus model components. We also fix the MYTorus normalization constants at unity and link each of their column densities N_{H} . Previous UV spectropolarimetry analysis suggested a broad-line region scattering, in which the likely line-of-sight inclination angle θ_i to the central engine is near edge-on;

Table 4. Best-fitting parameters for the unabsorbed power-law, absorbed power-law model, and the MYTORUS models at varying θ_i .

Parameter		Power-law	Absorbed power-law	MYTORUS $\theta_i = 45^\circ$	60°	75°	85°
Γ	–	0.8 ± 0.3	(1.9)	(1.9)	(1.9)	(1.9)	(1.9)
K_{norm}	$(10^{-5} \text{ photons keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1})$	$0.1^{+0.2}_{-0.1}$	6 ± 2	$0.3^{+0.3}_{-0.9}$	$0.9^{+0.3}_{-0.9}$	8^{+7}_{-4}	9^{+7}_{-4}
N_{H}	$(10^{24} \text{ cm}^{-2})$	–	$0.9^{+0.4}_{-0.3}$	2 ± 52	2 ± 27	$1.2^{+1}_{-0.5}$	$1.02^{+0.76}_{-0.41}$
f_{sc}	(10^{-2})	–	–	3 ± 20	1 ± 4	3.5 ± 2.8	3.6 ± 2.7
$C\text{-stat}$	(d.o.f.)	617 (665)	633 (693)	656 (692)	655 (692)	610 (664)	610 (667)
$L_{2-10, \text{obs}}$	$(10^{44} \text{ erg s}^{-1})$	–	$0.7^{+0.2}_{-0.2}$	$1^{+2}_{-0.9}$	$1^{+4}_{-0.9}$	$0.9^{+0.3}_{-0.2}$	$0.9^{+0.2}_{-0.3}$
$L_{2-10, \text{int}}$	$(10^{45} \text{ erg s}^{-1})$	$0.11^{+0.01}_{-0.05}$	$0.6^{+0.4}_{-0.2}$	2.5^{+2}_{-1}	0.9 ± 0.9	1.2 ± 1	1.4^{+1}_{-1}

Notes. The power-law index is fixed at $\Gamma = 1.9$ for all models with absorption. For the detailed error bounds, refer to the confidence contours in Figs 2 and 3 for the absorbed power-law and the MYTORUS models, respectively. $L_{2-10, \text{obs}}$ indicate observed luminosity, and $L_{2-10, \text{int}}$ indicate absorption-corrected luminosity, both in rest frame. All parameters have been redshift corrected. Stated uncertainties represent the 90 per cent confidence interval.

however, θ_i was not constrained at the time (Alexandroff et al. 2018). Rather than treating θ_i as another free parameter, we fix at a particular value, and freely fit for K_{norm} , N_{H} , and the scattering fraction f_{sc} corresponding to the optically-thin scattered continuum. We repeat this fitting process over four angles: $\theta_i = 45^\circ$, 60° , 75° , and 85° (edge-on is defined as 90°). In each iteration of the fit, we initially fix $f_{\text{sc}} = 1$ per cent to localize N_{H} , then free the f_{sc} parameter for simultaneous K_{norm} , N_{H} , and f_{sc} fitting.

The best-fitting parameters for the four MYTORUS models are listed in Table 4, and the corresponding confidence contour maps of the N_{H} and f_{sc} fits are shown in Fig. 3. We find a strong dependence on θ_i , in which greater inclination angles are preferred. In fact, the uncertainties for the $\theta_i = 45^\circ$ and 60° could not be constrained, reaching extreme estimates for N_{H} and f_{sc} as indicated by the 68 per cent contour. From the fit values and the contour maps, we conclude that the $\theta_i = 75^\circ$ and 85° geometries fit the data better. Since the estimated values for N_{H} and f_{sc} at these two angles are nearly identical with overlapping error bounds, it is difficult to conclusively pick one model over the other. Neither were we able to constrain a lower limit for f_{sc} to high confidence. However, the confidence contour maps in Fig. 3 suggest that the model parameters are better constrained at $\theta_i = 85^\circ$ with $N_{\text{H}} = (1.02^{+0.76}_{-0.41}) \times 10^{24} \text{ cm}^{-2}$ and $f_{\text{sc}} = (3 \pm 2)$ per cent at 90 per cent confidence with $C_{\text{stat}} = 610$ for 667 degrees of freedom.

The unfolded energy spectrum with the best-fitting $\theta_i = 85^\circ$ MYTORUS model is shown in Fig. 4. We compare the different best-fitting unfolded MYTORUS θ_i models with the observed data. We also plot the models and their respective components in Fig. 4. Despite the differences in fits, all of the MYTORUS model fit results suggest that SDSSJ1652 is a highly obscured, Compton-thick quasar. The calculated model (redshift and absorption-corrected) rest-frame luminosity for the $\theta_i = 85^\circ$ model is $L_{2-10} = (1.4^{+1}_{-1}) \times 10^{45} \text{ erg s}^{-1}$.

3.3 Comparing the models

The $C\text{-stat}$ values of the best fitting the absorbed power-law and MYTORUS models both indicate similar goodness-of-fits. Here we focus on the data-model residuals in Figs 2 and 4. In general, the MYTORUS model fits capture the spectral features across all energies better than absorbed power-law model (Fig. 2 left-hand panel versus Fig. 4 top left-hand panel). We argue that the MYTORUS model fit is mostly driven by the spectral shape in $E > 2 \text{ keV}$ observed frame. In fact, according to just the $C\text{-stat}$ values, the $\theta_i = 45^\circ$ and 60°

MYTORUS models would be preferred over the $\theta_i = 75^\circ$ and 85° models, which is not supported by the parameter confidence contours. An obscuring structure with a more inclined geometry is preferred to explain the medium/hard energies.

However, there are some uncertainties within the MYTORUS model fits that do not fully model the spectral features at $<1.5 \text{ keV}$ and $3\text{--}5 \text{ keV}$, which are more pronounced in the XMM–Newton/PN data (blue data points). The background spectrum in Fig. 2 does not show any significant features at $3\text{--}5 \text{ keV}$, suggesting that the unmodelled features are not likely to be background driven. Unmodelled components in $3\text{--}5 \text{ keV}$ may suggest that we are not fully modelling the peak of the X-ray emission, implying underestimated N_{H} , L_{2-10} , and f_{sc} .

To understand the soft-energy fits, we also considered MYTORUS models without the warm electron scattering, which produce similar best-fitting θ_i , N_{H} , K_{norm} , and $C\text{-stat}$ values. With this modification, the best-fitting spectrum displays deviations in the soft-energies similar to that of the absorbed power-law model, suggesting the need for a soft-energy scattering component. Therefore, we argue that the inclined MYTORUS geometry with the scattering region is the preferred model. A possible explanation for the systematic model residuals in our best-fitting MYTORUS model is a presence of a more complex thermal structure, not captured by MYTORUS or the electron scattering components. However, adding a thermal component did not change the parameters nor improve the fit quality, so we cannot preferentially constrain the model. Another possibility is a presence of a more complex obscuring torus that can be described with a variable opening angle model like boros (Baloković et al. 2018) as explored in LaMassa et al. (2019), but this would require higher signal data. Finally, the remaining uncertainties may reflect the poor data quality from severely photon-limited studies.

4 DISCUSSION

4.1 Power of central engine

There is an ongoing debate about the relationship between outflows and accretion in luminous quasars: whether near-Eddington accretion is associated with disrupting the X-ray-emitting corona or whether the corona must be compact and shielded to enable radiative driving (Luo et al. 2013). The X-ray luminosity is one of the key determinants of the wind launching mechanism.

X-ray emission and mid-infrared emission are both tracers of black hole accretion activities. X-rays originate from the corona over the

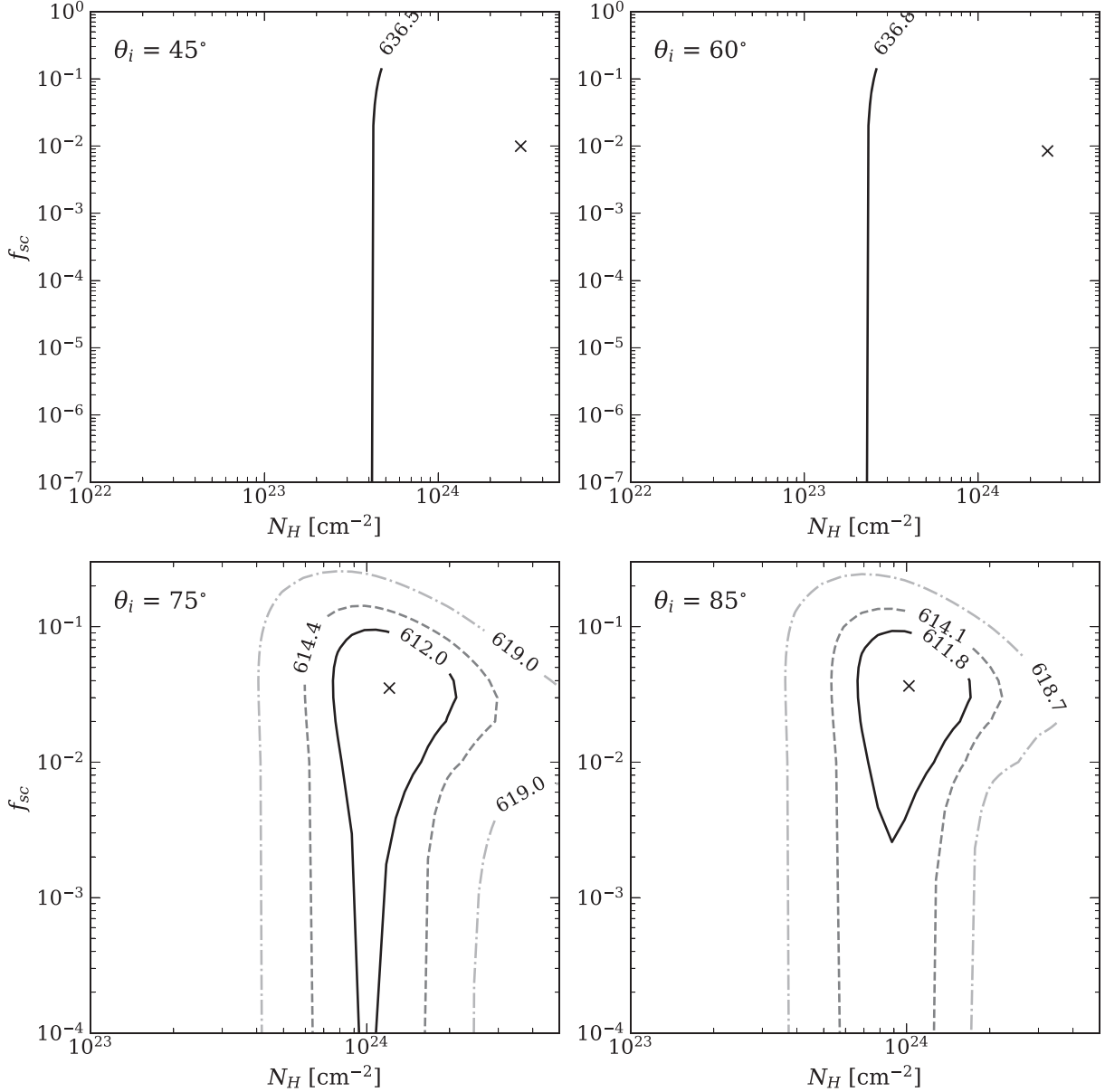


Figure 3. The confidence contours for the best-fitting MYTORUS parameters N_H and f_{sc} for $\theta_i = 45^\circ$ (top left-hand panel), 60° (top right-hand panel), $\theta_i = 75^\circ$ (bottom left-hand panel), and 85° (bottom right-hand panel) at 68 (solid), 90 (dashed), and 99 per cent (dash-dotted) C_{stat} confidence levels. It was not possible to constrain the confidence contours better than 68 per cent for $\theta_i = 45^\circ$ (left-hand panels) and 60° . Comparing the contours, we find that larger inclinations are preferred; and the $\theta_i = 85^\circ$ model appear to better constrain N_H and f_{sc} over $\theta_i = 75^\circ$.

inner accretion flow and the mid-infrared emission is re-radiated by the obscuring dust on larger scales. A common analysis is to compare the intrinsic 2–10 keV X-ray luminosity, L_{2-10} , against the mid-infrared rest-frame 6- μm luminosity, $L_{6\mu\text{m}}$. Stern (2015) and Chen et al. (2017) showed an empirically derived sub-linear $L_{6\mu\text{m}} - L_{2-10}$ relationship for luminous Type I quasars with $L_{6\mu\text{m}} \gtrsim 10^{45} \text{ erg s}^{-1}$, in which the measured L_{2-10} at fixed $L_{6\mu\text{m}}$ is an order of magnitude below the extrapolations expected from the linear Gandhi et al. (2009) relationship, as shown in Fig. 5. The origin of this sub-linear relationship remain unresolved.

One possibility is that luminous quasars with strong X-rays would overly ionize the circumnuclear gas and suppress the production of radiatively-driven winds (Luo et al. 2013). The physical connection would then lead to the observed Stern (2015) and Chen et al. (2017)

relations through the coronal quenching phenomenon (Luo et al. 2013), in which X-ray emission is suppressed by a massive accretion flow such as a failed disc wind that falls into the accretion disc (Proga 2005; Leighly et al. 2007; Lusso et al. 2010; Jin, Ward & Done 2012). This would suggest that high accretion efficiency leads to a decrease in radiative efficiency.

Interestingly, there is evidence for other luminous quasars with even weaker observed X-ray luminosities, falling below the Stern (2015) and Chen et al. (2017) relations even after accounting for absorption (Lansbury et al. 2020). Examples of quasars with a very weak X-ray emission include a Type I quasar with emission-line outflows (Leighly et al. 2007), BAL quasars (Luo et al. 2013), ultra-luminous infrared galaxies (ULIRGs; Teng et al. 2014, 2015), and HotDOGs (Ricci et al. 2017). Either these quasars are intrinsically

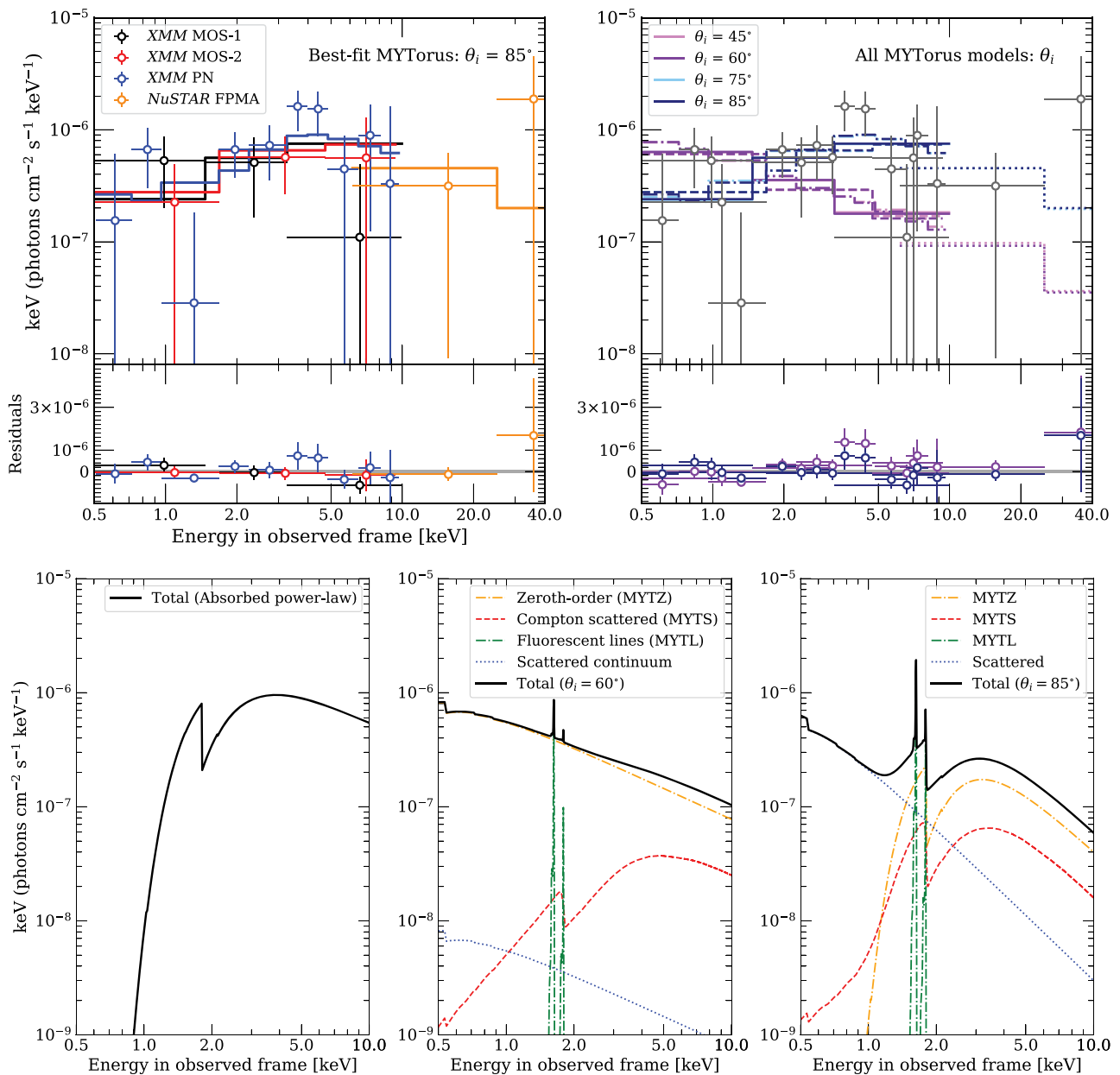


Figure 4. Top left-hand panel: the observed-frame, unfolded energy spectrum with the best-fitting $\theta_i = 85^\circ$ MYTorus model. The spectra have been re-binned for plotting purpose. The binned data points are shown in circles, and the black, red, blue, and orange solid lines represent the best-fitting MYTorus model at $\theta_i = 85^\circ$. Top right-hand panel: all of the MYTorus models for the various θ_i considered are plotted against the binned data points (in grey). The data-model residuals in units of keV are also shown and show that models at larger θ_i (light/dark blue) capture both the soft- and hard-energy data better than at smaller θ_i (light/dark purple). Bottom panel: comparison of the observed frame absorbed power-law (left-hand panel) and MYTorus models, $\theta_i = 60^\circ$ (centre panel) and 85° (right-hand panel), with the power-law parameter fixed at $\Gamma = 1.9$. The solid black line indicates the total model spectrum, while the coloured dashed/dotted lines indicate the individual model components. We note that a pure absorbed power-law does not capture the soft-energy components, while the less inclined MYTorus $\theta_i = 60^\circ$ spectrum predicts a smoother profile without a prominent hard Compton-scattered continuum past the Fe K α fluorescent line, suggesting a highly inclined geometry such as the $\theta_i = 85^\circ$ model. Refer to Table 4 for the best-fitting parameters of each model.

X-ray weak or they have a complex inner geometrical structure with multiple absorbers that cannot be identified in a single low-quality spectrum.

Combining the *WISE* photometry data and the X-ray analysis from this paper, we can perform a similar analysis to probe the outflow mechanisms of SDSSJ1652. In Fig. 5, we compare the results for SDSSJ1652 against the Stern (2015) and Chen et al. (2017) relationships and the stacked *Chandra* measurements of

ERQs, which includes SDSSJ1652, by Goulding et al. (2018). Given the uncertainties of individual sources using the stacking technique, the stacking estimate and our estimate of the intrinsic luminosity of SDSSJ1652 are consistent, while deeper observations of SDSSJ1652 places a better constraint on the absorption-corrected luminosity. This result supports the Goulding et al. (2018) observation that there is no strong evidence that ERQs are intrinsically X-ray weak. They appear to be consistent with Type I quasars once the intervening

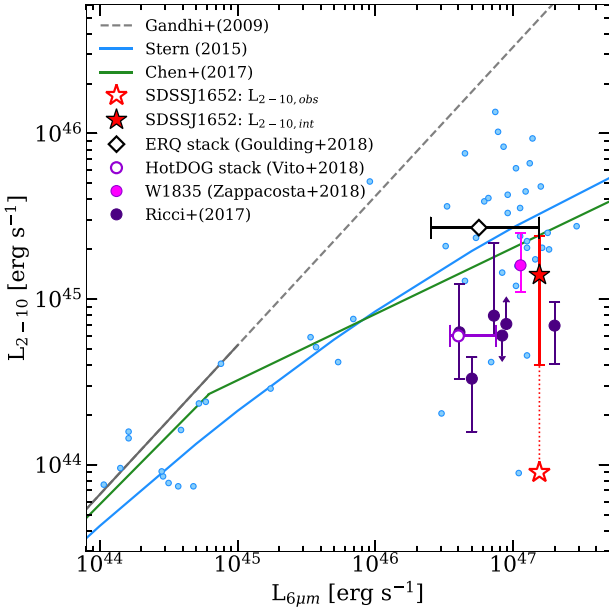


Figure 5. The $L_{6\mu\text{m}}-L_{2-10}$ relationships for selected targets, including SDSSJ1652 are shown. All L_{2-10} indicate the absorption corrected, intrinsic X-ray luminosities, unless otherwise noted. Since the original linear relation by Gandhi et al. (2009) was derived for $L_{12\mu\text{m}} < 10^{45} \text{ erg s}^{-1}$, the extrapolated relation at higher luminosities, corrected for $L_{6\mu\text{m}}$, is shown as a dashed grey line. Sublinear relationships derived for higher luminosities by Stern (2015) and Chen et al. (2017) are shown as solid blue and green lines; the blue data points correspond to Type I quasars used in Stern (2015). The observed (open star) and intrinsic (filled star) L_{2-10} of SDSSJ1652 using the MYTORUS model is shown with 90 per cent confidence. The stacked ERQ (Goulding et al. 2018) result is shown with the error bars spanning the observed $L_{6\mu\text{m}}$ range. Both the stacked ERQ and SDSSJ1652 results are consistent with the relationships derived for Type I quasars. We also compare selected hot dust-obscured galaxy (HotDOG) results (Ricci et al. 2017), including stacked analysis showing low L_{2-10} (Vito et al. 2018) and a deep observation of W1835+4355 with high L_{2-10} (Zappacosta et al. 2018).

absorption is accounted for. These results would suggest that despite the presence of extreme outflows, the heavily obscured SDSSJ1652 and other ERQs are not dominated by extreme coronal quenching that would otherwise result in extreme X-ray suppression, hence they are not intrinsically X-ray weak.

It is also possible for the measured $L_{6\mu\text{m}}$ to be underestimated due to obscuration or due to anisotropic emission (Zappacosta et al. 2018), which would imply L_{2-10} deficit compared to the standard relationships and strong X-ray suppression. This would require a correction of nearly an order of magnitude to impose a significant departure from the observed $L_{6\mu\text{m}}-L_{2-10}$ relationship, which is unlikely. Goulding et al. (2018) notes that the observed high luminosities and outflows in ERQs may be due to a combination of colour selection and orientation effects. Current observations of SDSSJ1652 and other ERQs suggest that they are dissimilar from X-ray weak BAL quasars in Luo et al. (2013) in terms of their relationship between extreme accretion, coronal quenching, and outflows. Therefore, it is possible that the ERQs have an outflow mechanism that is different from those of BAL quasars.

4.2 Obscuration properties

The obscuration geometry of the best-fitting MYTORUS model is broadly comprised of two components: the obscuring torus and

optically-thin scattering region. The $\theta_i = 85^\circ$ MYTORUS result is consistent with the near-edge-on line-of-sight geometry described by Alexandroff et al. (2018), which suggest the observed X-ray absorption must occur in same wind as the observed UV scattering (Goulding et al. 2018). In the Alexandroff et al. (2018) model, the polarized UV wind in SDSSJ1652 is likely due to dust scattering somewhere in the broad emission-line region (BELR) and broad absorption-line region (BALR) at scales greater than the obscuration. The inclined viewing angle inferred in the UV is based on the observed shape of the infrared SED. With the inclusion of the X-ray results, our MYTORUS model fits adds the absorbing torus and the warm/hot ionized electron scattering region surrounding the central engine. A cartoon picture of the combined SDSSJ1652 model is shown in Fig. 6.

The optically-thin scattered power-law continuum is commonly observed as a rise in the X-ray spectrum towards the low energies. The scattered spectrum is assumed to have the same shape (i.e. Γ) as the incident power-law spectrum and is assumed to be due to electron scattering. This means that the scattering fraction f_{sc} is the ratio of the scattered flux to the incident flux. This extended scattering region needs to be on scales larger than the central engine and the obscuring torus, which, in turn, must be larger than the derived dust sublimation region. Using the dust sublimation estimate (Barvainis 1987) and the extrapolated UV luminosity, we find that the dust sublimation distance is ~ 1 pc (Alexandroff et al. 2018).

We can describe f_{sc} modelled in MYTORUS in terms of the size of the scattering region and the density of the scattering particles (Zakamska et al. 2005). We assume scattering is dominated by Thomson electron scattering with scattering cross-section σ_T in a region of uniform electron density n_e with differential cross-section $d\sigma/d\Omega \sim \sigma_T/4\pi$ through a cone subtending $\Delta\Omega = 2\pi$, defined by MYTORUS in Fig. 6:

$$f_{\text{sc}} = \frac{d\sigma}{d\Omega} \Delta\Omega \int n_e(r) dr \sim \frac{1}{2} n_e \sigma_T h \left(\frac{\Delta\Omega}{2\pi} \right). \quad (1)$$

Interestingly, $f_{\text{sc}} \sim 3$ per cent is similar to the UV scattering estimated from Alexandroff et al. (2018), which was obtained by extrapolating the IR emission of ERQs using a Type I quasar SED to the observed UV flux. The similar geometry suggested by both X-ray modelling and UV spectropolarimetry, which is dominated by dust scattering, also suggests that the X-ray absorption occurs in the same wind as seen in spectropolarimetric observations. This is consistent with the Goulding et al. (2018) model. Thus, we consider the dust scatter scale height limits $h \sim 1-10$ pc from Alexandroff et al. (2018) in equation (1) to calculate the electron scattering density ranging between $n_e \sim 7.5 \times (10^2-10^3) \text{ cm}^{-3}$.

We also use the scale height to approximate the line-of-sight mass of the obscuring material. Gas dominates the absorption at X-ray energies (Hickox & Alexander 2018), so we consider a hydrogen cloud at fixed metallicity with a constant density n_H distributed over a spherical volume with a scale height h , based on the assumption that the scattering zone would be of scales similar to those of obscuration. To match a torus-like distribution, we take the volume $V = (1/3)h^3\Delta\Omega$, where $\Delta\Omega = 2\pi$ is the solid angle subtended by the torus, based on the MYTORUS model in Fig. 6. The resulting gas mass is therefore $M_{\text{obsc}} = m_H n_H V$. In terms of the measured column density $N_H = n_H h$, we have

$$M_{\text{obsc}} \sim 1.7 \times 10^6 M_\odot \left(\frac{N_H}{10^{24} \text{ cm}^{-2}} \right) \left(\frac{\Delta\Omega}{2\pi} \right) \left(\frac{h}{10 \text{ pc}} \right)^2. \quad (2)$$

Given the uncertainty in h and in the torus geometry, we calculate the mass range of the line-of-sight obscuration to $M_{\text{obsc}} \sim 1.7 \times$

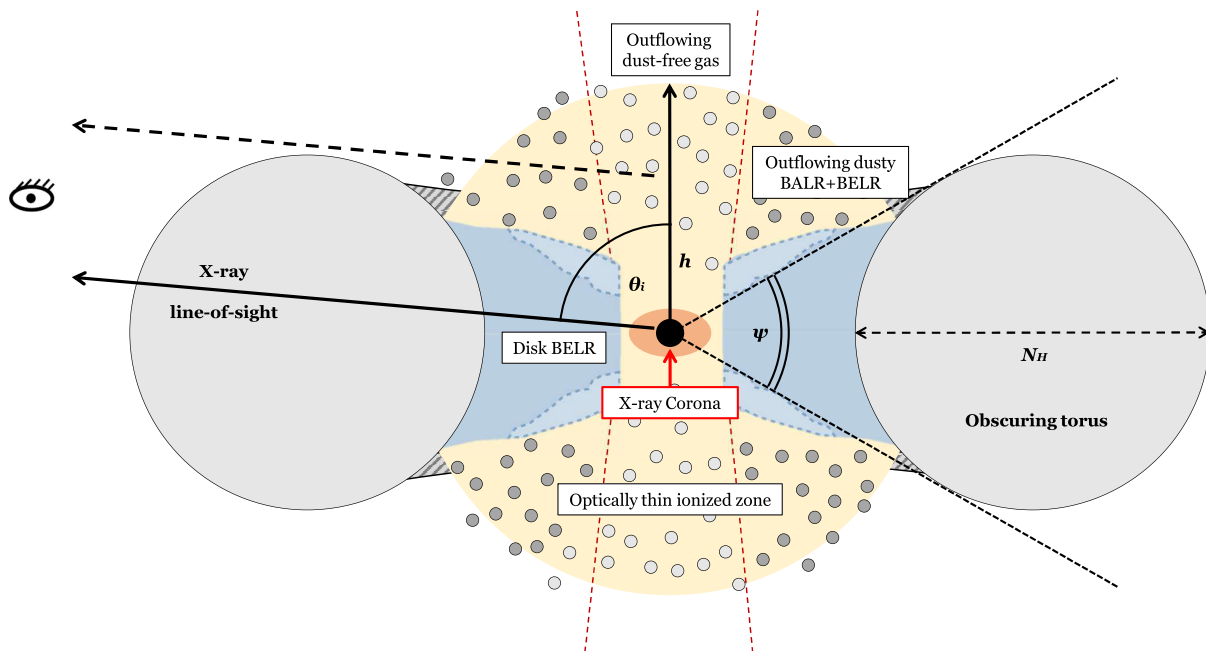


Figure 6. This diagram (not to scale) shows the preferred model picture for SDSSJ1652 adapted from Alexandroff et al. (2018) and combined with our best-fitting X-ray MYTORUS model parameters described in Table 4. The reprocessed MYTORUS model flux is shown in solid black line, and the scattered flux is in dashed line. This illustrates the cross-sectional view through obscuring torus. The model is inspired by Veilleux et al. (2016). The inner accretion disc is surrounded by a geometrically thick BELR accretion disc (in light blue), in which scattering of the dusty equatorial outflow that produces UV-polarization occurs higher in the dusty BALR and BELR. The torus (in grey) geometry is adapted from Murphy & Yaqoob (2009), which assumes a half-opening angle of $\psi = 60^\circ$ (equivalent to a covering factor of $\Delta\Omega/4\pi = 0.5$). The best-fitting MYTORUS model suggest a highly inclined near edge-on geometry of $\theta_i = 85^\circ$. Our model describes the X-ray power-law continuum experiencing photoelectric absorption, Compton-scattering, and electron scattering from the warm/hot ionized region surrounding the central engine (in yellow).

(10^4 – 10^6) M_\odot . Although it is more appropriate to properly model the the torus structure, we cannot set any limits on its size from MYTORUS. At most, we expect a small correction by a factor of a few.

4.3 Nature of the SDSSJ1652

We calculate the order-of-magnitude approximations for the central black hole accretion properties. The directly observed $L_{6\mu\text{m}}$ of $10^{47.19}$ erg s $^{-1}$ suggests that the bolometric luminosity may be of the order $L_{\text{Bol}} \sim 10^{47.48}$ erg s $^{-1}$, which is in agreement with the Perrotta et al. (2019) measurement of $L_{\text{Bol}} \sim 10^{47.73}$ erg s $^{-1}$. This would correspond to a X-ray bolometric correction $\kappa_X \approx 380$ for $L_{\text{Bol}} = \kappa_X L_{2-10, \text{obs}}$. This is roughly in agreement with values found for $z = 2$ –4 hyperluminous Type I quasars (Martocchia et al. 2017).

While there are many scaling relationships for black hole mass M_{BH} measurements (e.g. host stellar mass, $H\beta$ kinematics), there are many caveats that complicate direct comparison to ERQs, as noted by Zakamska et al. (2019). Without reliable X-ray to M_{BH} scaling relations, it is also difficult to independently measure M_{BH} from this study. With this in mind, we consider the $H\beta$ virial mass estimate of the SDSSJ1652 supermassive black hole by Perrotta et al. (2019): $M_{\text{BH}} = 3 \times 10^9 M_\odot$, which corresponds to an Eddington luminosity of $L_{\text{Edd}} = 4 \times 10^{47}$ erg s $^{-1}$. Combined with the Perrotta et al. (2019) bolometric luminosity, the Eddington ratio is estimated to be $L_{\text{Bol}}/L_{\text{Edd}} \sim 1.2$. Zakamska et al. (2019) explained that a possible argument against high Eddington ratios is an overestimated L_{Bol} . However, for obscured populations, underestimated L_{Bol} is more likely especially when the observed $L_{6\mu\text{m}}$ – L_{2-10} relationship

is consistent with Stern (2015) and Chen et al. (2017). Therefore, SDSSJ1652 is consistent with being a near- or super-Eddington, Compton-thick source, exhibiting high L_{2-10} and powerful outflows.

Assuming the material scattering X-rays has an outflowing component, we can also calculate its maximum kinetic energy power using the n_e estimates of the warm scattering region. We assume the same velocities $v \approx 3000$ km s $^{-1}$ seen in Alexandroff et al. (2018) launched at scale height $h = 10$ pc:

$$\dot{E}_{\text{sc}} \approx 4 \times 10^{45} \text{ erg s}^{-1} \times \left(\frac{n_e}{7.5 \times 10^3 \text{ cm}^{-3}} \right) \left(\frac{h}{10 \text{ pc}} \right)^2 \left(\frac{v}{3000 \text{ km s}^{-1}} \right)^3 \quad (3)$$

which makes up a small fraction of the bolometric output. Thus, the phase of gas responsible for producing the scattered X-rays is not an energetically important component of the quasar output.

4.4 Comparing with other observations

While there are X-ray studies of highly obscured quasars, most have been limited to low-redshift samples. Another class of reddened quasars are the HotDOGs, which have properties similar to those of ERQs in terms of spectral energy distribution, luminosity, and redshift (Eisenhardt et al. 2012; Assef et al. 2015). Despite these similarities, there are some interesting differences stemming from somewhat different selection methods. One such difference is that HotDOGs are well below the Stern (2015) and Chen et al. (2017) relationships (Ricci et al. 2017; Vito et al. 2018), while also showing Compton-thick obscurations (Piconcelli et al. 2015), in contrast to

ERQs explored in Goulding et al. (2018) and in this paper. We compare their $L_{6\mu\text{m}}-L_{2-10}$ properties in Fig. 5.

A recent *NuSTAR* observation of a $z = 2.298$ HotDOG (W1835+4355) showed Compton-thick obscuration, $N_{\text{H}} \approx 0.9 \times 10^{24} \text{ cm}^{-2}$, and absorption-corrected luminosity of $L_{2-10} = 1.6 \times 10^{45} \text{ erg s}^{-1}$ (Zappacosta et al. 2018) similar to those of SDSSJ1652 presented here. Compared to other HotDOGs, this target also exhibited higher X-ray luminosity, nearly consistent with the Stern (2015) and Chen et al. (2017) relations, shown in Fig. 5. In contrast to SDSSJ1652, their target was modelled with $\theta_i = 70^\circ$ and a larger model-dependent $f_{\text{sc}} \approx 5\text{--}15$ per cent. This suggest remarkable similarities between ERQs and HotDOGs with the only differences in the obscuration properties: θ_i and f_{sc} . This indicates a variety in HotDOG properties with some that have overlapping $L_{6\mu\text{m}}-L_{2-10}$ properties to ERQs.

5 CONCLUSION

We report on deep ~ 130 -ks *XMM-Newton* and ~ 218 -ks *NuSTAR* observations of SDSSJ1652, an obscured, extremely red quasar at $z = 2.94$. We characterize the intrinsic X-ray properties and obscuration geometry using *XMM-Newton*, which is sensitive to the absorbing column, and *NuSTAR*, which probes the intrinsically unobscured X-rays. We determine the accretion luminosity and the obscuration properties of SDSSJ1652 to provide verification for severely photon-limited studies of the high-redshift, obscured quasar population.

We extracted spectra from the *XMM-Newton* MOS and PN and the *NuSTAR* FPMA detectors. Unfortunately, we could only place a 3σ upper limit for the *NuSTAR* FPMB. We fit 0.5–10 keV *XMM-Newton* and 6–79 keV *NuSTAR* spectra with a physically motivated MYTORUS model that models the zeroth-order continuum reprocessing due to the intervening cold gas, Compton-scattered continuum, fluorescent line emission, and the optically-thin scattered power-law continuum due to electron scattering in the warm ionized region surrounding the central engine. We find the best-fitting model indicates a Compton-thick column density of $N_{\text{H}} = (1.02^{+0.76}_{-0.41}) \times 10^{24} \text{ cm}^{-2}$, a near edge-on geometry with the line-of-sight inclination angle of $\theta_i = 85^\circ$, and a warm electron scattering fraction of $f_{\text{sc}} \sim 3$ per cent.

From the measured obscuration parameters, we place estimates of the physical properties of the obscuration, assuming scale heights $h \sim 1\text{--}10$ pc for dust and electron scattering. From f_{sc} , we estimate the electron density driving the soft-energy scattering to be in the range $n_e \sim 7.5 \times (10^2\text{--}10^3) \text{ cm}^{-3}$. From N_{H} , we estimate the obscuration mass to be approximately $M_{\text{obs}} \sim 1.7 \times (10^4\text{--}10^6) M_{\odot}$. These values are highly uncertain due to uncertainties in the torus geometry.

The absorption-corrected, intrinsic X-ray luminosity is $L_{2-10} = (1.4^{+1}_{-1}) \times 10^{45} \text{ erg s}^{-1}$. This is consistent with the $L_{6\mu\text{m}}-L_{2-10}$ relationship for luminous Type I quasars, which indicates that SDSSJ1652 is not X-ray weak once corrected for the Compton-thick absorption. This trend is consistent with other ERQs, in contrast to other known luminous quasars. The observed $L_{6\mu\text{m}}-L_{2-10}$ would imply that SDSSJ1652 may not be experiencing coronal quenching that would nominally suppress X-ray radiation supposedly associated with high accretion. Moreover, the observed luminosity estimates support the energetics needed to drive the observed galactic scale outflows. These results indicate the ability of near- or super-Eddington, Compton-thick ERQs like SDSSJ1652 to drive powerful outflows without requiring intrinsically weak X-rays.

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DATA AVAILABILITY

The data underlying this paper are already available in the HEASARC Archives at <https://heasarc.gsfc.nasa.gov/docs/archive.html> and the XMM-Newton Science Archives at <http://nxsa.esac.esa.int/> and can be accessed with the corresponding ObsID.

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