

# The weak neutral Fe fluorescence line and long-term X-ray evolution of the Compton-thick AGN in NGC 7674

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## ABSTRACT

We present *NuSTAR* X-ray observations of the active galactic nucleus (AGN) in NGC 7674. The source shows a flat X-ray spectrum, suggesting that it is obscured by Compton-thick gas columns. Based upon long-term flux dimming, previous work suggested the alternate possibility that the source is a recently switched-off AGN with the observed X-rays being the lagged echo from the torus. Our high-quality data show the source to be reflection-dominated in hard X-rays, but with a relatively weak neutral Fe  $K\alpha$  emission line (equivalent width [EW] of  $\approx 0.4$  keV) and a strong Fe XXVI ionised line (EW  $\approx 0.2$  keV). We construct an X-ray light curve of NGC 7674 spanning 37 years and find that the observed 2–10 keV X-ray flux has remained constant for the past  $\approx 20$  years. Light travel time arguments constrain the minimum radius of the reflector to be  $\sim 3.2$  pc under the switched-off AGN scenario,  $\approx 30$  times larger than the expected dust sublimation radius, rendering this possibility unlikely. A combination of intrinsic fading and patchy obscuration cannot be ruled out. A Compton-thick AGN (CTAGN) solution requires a minimum line-of-sight column density ( $N_{\text{H}}$ ) of  $3 \times 10^{24}$  cm $^{-2}$ , and yields an intrinsic 2–10 keV luminosity of  $(3\text{--}5) \times 10^{43}$  erg s $^{-1}$ . Realistic uncertainties span the range of  $\approx (1\text{--}13) \times 10^{43}$  erg s $^{-1}$ . The source has one of the weakest fluorescence lines amongst *bona fide* CTAGN, and potentially a local analogue of bolometrically luminous systems showing complex neutral and ionised Fe emission. It exemplifies the difficulty of identification and proper characterisation of distant CTAGN based on the strength of the neutral Fe  $K\alpha$  line.

**Key words:** Seyfert – X-rays: individual (NGC 7674)

## 1 INTRODUCTION

Obscured active galactic nuclei (AGN) dominate the overall population of AGN in the cosmos, especially the efficiently-accreting sources which power the cosmic hard X-ray background radiation (e.g. Setti & Woltjer 1989; Comastri et al. 1995; Gandhi & Fabian 2003; Gilli et al. 2007; Treister et al. 2009; Ballantyne et al. 2011; Ueda et al. 2014). Yet, finding and characterising these objects is made difficult by the strong absorption they can suffer across the electromagnetic spectrum. In particular, the census of the sources hidden behind extreme obscuring column densities of gas – in particular Compton-thick AGN with column densities  $N_{\text{H}} \gtrsim 1.5 \times 10^{24}$  cm $^{-2}$ ; hereafter, CTAGN – remains highly incomplete (see Ricci et al. 2015 and Koss et al. 2016 for recent updates on the hard X-ray selected CTAGN census). Even locally,

very few robust (*bona fide*) CTAGN are known (Della Ceca et al. 2008; Goulding et al. 2012; Gandhi et al. 2014).

One candidate of a nearby, luminous CTAGN is NGC 7674, the brightest member of the Hickson 96 interacting galaxy group. NGC 7674 is a known Seyfert 2, showing strong narrow optical emission lines with full widths at half maximum (FWHM) of less than 500 km s $^{-1}$  in spectral observations carried out over three decades ago (Feldman et al. 1982). The source also shows a prolific outflow, which manifests as a prominent shoulder on the blue wings of all the prominent narrow optical lines. The outflow has been studied in detail using *HST* spectroscopy by Fischer et al. (2013), who find blueshifts of up to  $\sim 1700$  km s $^{-1}$  (and even larger FWHM) along the narrow line region aligned with the jet axis of the source. In the radio, NGC 7674 shows at least three separate com-

compact components in VLBI observations on scales of  $\approx 0.7$  arcsec corresponding to  $\approx 0.4$  kpc, and there have been suggestions that the collimated ejecta associated with the radio source could also drive the optical-emitting line outflow (Unger et al. 1988). Even higher resolution VLBI observations by Momjian et al. (2003) reveal a complex ‘S’-shaped structure, which could result from interactions of the jet with the interstellar medium. Using the [O III] emission line as a bolometric luminosity indicator, Xu et al. (1999) classify NGC 7674 as a radio quiet AGN.

The source was first reported to be a reflection-dominated AGN by Malaguti et al. (1998) from *BeppoSAX* X-ray observations carried out in 1996, with the direct (intrinsic) continuum being fully absorbed by a Compton-thick gas column. *BeppoSAX* detected NGC 7674 over the energy range of  $\sim 0.1$ –60 keV. Malaguti et al. reported a complex structure to the neutral Fe K $\alpha$  line, and estimated a high intrinsic AGN luminosity assuming a scattering geometry similar to NGC 1068.

But the *BeppoSAX* observation was not the first X-ray observation of the source. As detailed in a historical X-ray analysis by Bianchi et al. (2005), the source was likely detected by the *HEAO* mission in the late 1970s at a 2–10 keV flux level almost 30 times brighter (Grossan 1992) and subsequently with an intermediate flux by *Ginga* (Awaki et al. 1991). Bianchi et al. (2005) discuss several potential caveats to these detections, including *HEAO* contamination by nearby sources, and systematic uncertainties related to the background level<sup>27</sup> measured by *Ginga*, and conclude that the combined weight of evidence favours the historical source detections being real. The *Ginga* spectrum is a lightly absorbed power law (with  $N_{\text{H}} < 2 \times 10^{22} \text{ cm}^{-2}$ ) with an upper limit of 80 eV to the equivalent width (EW) of any neutral Fe K $\alpha$  emission line. The source then declined by an order of magnitude in continuum flux by the time it was observed by *BeppoSAX* to be Compton-thick. Such behaviour might argue for the source being a member of the class of ‘changing-look’ AGN (e.g., Matt et al. 2003), associated with clumps of obscuring clouds transiting across the line-of-sight (l.o.s) resulting in apparent changes in  $N_{\text{H}}$ (l.o.s). The most famous example of this class is NGC 1365 which shows dramatic  $N_{\text{H}}$  variability on timescales of days (Risaliti et al. 2005).

However, an *XMM-Newton* observation carried out 6 years later (in 2004) also showed a reflection-dominated spectrum completely consistent in shape as well as flux with *BeppoSAX*, unlike what may be expected in a changing-look AGN. Bianchi et al. (2005) interpret the source as potentially having switched-off, with the spectrum observed by *BeppoSAX* and *XMM-Newton* being the reflection component which is delayed with respect to the direct, illuminating power law (PL). Another source that has been discussed from these two opposing perspectives recently is NGC 7582 (Rivers et al. 2015). Bianchi et al. (2005) also found a weak Fe K $\alpha$  emission line, possibly blended with an ionised Fe XXVI line at 6.97 keV.

Approximately 10 years after the last *XMM-Newton* observation, NGC 7674 was observed by *Suzaku* in 2013 and then by *NuSTAR* in 2014, in addition to several snapshot observations by the *Swift* satellite between 2011 to 2014. Here, we present a spectral analysis of these unpublished observations, and combine this with historical data to study the long-term source evolution. We discuss and place constraints on the switched-off AGN as well as the CTAGN scenarios. Finally, we touch upon the relevance of the complex Fe lines for the identification and characterisa-

**Table 1.** Observation Log

Mission	Instrument(s)	Observation date	Exposure ks
<i>NuSTAR</i>	FPMA/B	2014-09-30	52.0/51.9
<i>Suzaku</i>	XIS0/1/3	2013-12-08	52.2/52.2/52.2
<i>Swift</i>	XRT	2011-01-28...2014-10-08 <sup>†</sup>	48.8 <sup>†</sup>

<sup>†</sup> For *Swift*, 17 observations are combined here. See Appendix for details.

tion of distant CTAGN. We assume  $H_0 = 67.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $\Omega_{\Lambda} = 0.685$  (Planck Collaboration 2014), corresponding to a distance of 126 Mpc corrected to the reference frame defined by the cosmic microwave background. The source systemic redshift is  $z = 0.0289$ . All X-ray spectral fitting is carried out with the XSPEC package v12.9.0 (Arnaud 1996) and uncertainties are quoted at 90% confidence, unless stated otherwise.

## 2 OBSERVATIONS

A log of the *NuSTAR*, *Suzaku* and *Swift* X-ray observations analysed herein is presented in Table 1, and the individual data sets are described in this section.

### 2.1 NuSTAR

NGC 7674 was observed by *NuSTAR* (Harrison et al. 2013) for about 52 ks of exposure on 2014 Sep 30 (ObsID 708023010). *NuSTAR* is the first orbiting telescope capable of focusing X-rays above  $\sim 10$  keV, operating over the energy range of 3–79 keV. The data were processed using standard steps and the *NuSTAR* Data Analysis Software (NUSTARDAS) v.1.3.0 which is provided as part of HEASOFT<sup>28</sup> and associated FTOOLS (Blackburn 1995). *NuSTAR* CALDB calibration files were used to generate cleaned event files after filtering for South Atlantic Anomaly passages and the standard depth cut, in order to reduce instrumental background.

Source spectra were extracted using a circular aperture 45'' in radius centred on the source position in both focal plane modules (FPMs). Background spectra were extracted from source free regions on the detector. The `nuproducts` task was used to extract these calibrated spectra and to generate corresponding response files. All spectra were grouped to a minimum signal-to-noise of at least 4 per grouped energy bin after background subtraction for fitting purposes.

The source is well detected in both FPMs with 3–78 keV count rates per second of  $2.92 \pm 0.08$  (FPMA) and  $2.53 \pm 0.08$  (FPMB).

### 2.2 Suzaku

About 52 ks of exposure were obtained on 2013 Dec 08 with *Suzaku*. The X-ray Imaging Spectrometer (XIS; Koyama et al. 2007) is sensitive over  $\approx 0.5$ –10 keV. Standard FTOOLS software for *Suzaku* was used for data reduction and cleaned event file generation with recommended filtering. Source counts were extracted from within a 3.4 arcmin radius aperture for integrating XIS source counts, and background counts from a larger source-free polygon.

<sup>27</sup> see also Smith & Done (1996).

<sup>28</sup> <https://heasarc.gsfc.nasa.gov>

The generated spectra and responses of the two front-illuminated (FI) detectors were combined together, and this was analysed simultaneously with the back-illuminated (BI) detector data. For the fitting, we ignore the energy ranges of 1.7–1.9 keV and 2.1–2.3 keV because of calibration uncertainties.

The source was also observed by the Hard X-ray Detector (HXD; Takahashi et al. 2007; Kokubun et al. 2007). The HXD/PIN data (the PIN array is sensitive between  $\approx 15$ –60 keV) were reduced using standard tasks. The `FTOOLS` routine `hxdpinxbpi` is a pipeline task that first extracts spectral counts and corrects these for deadtime. Using the ‘tuned’ background model for the target observation provided by the *Suzaku* team as a starting point (Fukazawa et al. 2009), `hxdpinxbpi` also outputs a background spectrum including the cosmic X-ray background (CXB) component. However, after background subtraction, the residual source count rate was found to be  $0.013 \text{ cts s}^{-1}$  (15–60 keV), which is  $\approx 5.0\%$  of the gross count rate and similar to the level of background reproducibility for observations after 2012.<sup>29</sup> We conservatively consider the source as a non-detection but note that fitting a PL to the detected net counts between 15 and 60 keV returns an observed flux  $F_{15-60} \approx 5 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ , which is similar to the observed *NuSTAR* flux in the same band with the best fit models that we will discuss in the Results section.

NGC 7674 is also too faint to be detectable in the HXD/GSO array sensitive to much higher energies, and those data are not considered here.

### 2.3 *Swift*

The source has been observed by *Swift* (Gehrels et al. 2004) on 17 occasions 2011 onwards, with exposure times ranging over  $\approx 470$ –5100 s using the X-Ray Telescope (XRT; Burrows et al. 2005) sensitive to photons between  $\sim 0.3$ –10 keV. The individual observations are listed in the Appendix. We extracted source and background spectra, together with response files, using the standard XRT Data Analysis Software tools with `HEASOFT`. The version of `XRTPIPELINE` used was 0.13.0. Source counts were extracted within a  $20''$  radius aperture, and background was extracted from an off-source sky region. Upper limits (for detection significance less than  $10^{-3}$ ) were estimated using the `sosta` command in the `XIMAGE` package.

We first analysed the spectra individually, but the source lies at the limit of detectability in these observations, yielding only weak detections for observations longer than 2 ks, and non-detections in other cases. Nevertheless, the individual observations (detections and limits) allow a first check for any strong variations with time. These fits are also described in the Appendix, and no significant variations are found.

We then extracted a coadded XRT spectrum by combining the event files of the individual observations. This yields a dataset with a total exposure time of 48.8 ks. The source is well detected in this combined exposure, with a net count rate of  $7.9 (\pm 0.4) \times 10^{-3} \text{ ct s}^{-1}$  over the energy range of 0.5–10 keV.

The source is classified as a non-detection by the Burst Alert Telescope (BAT; Barthelmy et al. 2005) sensitive over 14–195 keV using standard analysis adopted for the 70-month all-sky survey (Baumgartner et al. 2013), and we do not consider the BAT data

further in this work. We do note, however, that a custom analysis by Koss et al. (2013) finds a  $4.2\sigma$  detection at the position of NGC 7674 with a flux  $F_{14-195} = 9.9^{+5.1}_{-0.2} \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ , consistent with that inferred from our *NuSTAR* analysis described later.

### 2.4 Optical Spectroscopy

In preparation for, and in support of, the *NuSTAR* observations, we also obtained optical spectroscopy of NGC 7674 using the Low Resolution Imaging Spectrometer (LRIS) on the Keck Telescope (Oke et al. 1995). The observations were carried out on 2014 June 25 through a  $1''0$  wide slit, using both the blue (600 lines  $\text{mm}^{-1}$ ) grism and the red (400 lines  $\text{mm}^{-1}$ ) grating, with the D560 dichroic. The night was photometric, with seeing close to  $0''.7$ .

The blue spectral region is dominated by strong emission lines with blueshifted components, as reported in many previous works (e.g. Feldman et al. 1982). The red spectral region contains the isolated Ca II absorption triplet, which can be used to estimate the central black hole mass. This estimate is presented in the Appendix. The instrumental resolution in the red spectral region was measured to be  $7''.4 \text{ \AA}$  using arc lamp spectra, corresponding to a velocity resolution of  $\sigma_{\text{instr.}} = 107 \text{ km s}^{-1}$  close to the observed wavelength of the Ca triplet feature.

### 2.5 X-ray Spectral Analysis Methodology

In this section, we start by checking for consistency of the data between the various missions, and then describe the details of the spectral analysis models.

#### 2.5.1 Basic characterisation

Fig. 1 shows the *NuSTAR*, *Suzaku*, and *Swift* data sets overplotted in count rate units, stretching over two decades in observed energy from 0.5–78 keV. The spectral shape approximately matches between the missions and instruments over common energy ranges. In particular, there appears to be a broad hump dominating the *NuSTAR* band above 10 keV and a sharp emission feature around 6 keV. These are strongly reminiscent of reflection resulting from Compton scattering and neutral Fe fluorescence, a common characteristic of obscured AGN X-ray spectra. The hump extends down to  $\sim 3$  keV in all data sets, below which a different component appears to dominate in both the *Suzaku*/XIS and *Swift*/XRT data with the spectrum rising and peaking around 1 keV.<sup>30</sup>

Fitting a PL to the continuum<sup>31</sup> over the common energy range of 3–10 keV simultaneously to all missions returns a photon index  $\Gamma = 0.73 \pm 0.11$  with an acceptable fit statistic of  $\chi^2/\text{dof} = 99.9/92$ . This is much harder than the typical intrinsic photon indices ( $\langle \Gamma \rangle \sim 1.9$ ) seen in AGN X-ray spectra (cf. Nandra et al. 1997; Mateos et al. 2005; Piconcelli et al. 2005) and is suggestive of heavy obscuration. Fitting the same model to the data from each mission separately, the observed 2–10 keV fluxes span the range of  $F_{2-10} \approx (7\text{--}14) \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$  between the missions (with the harder *Swift* photon index giving the highest flux), and are fully consistent with each other at 90% confidence.

<sup>29</sup> [www.astro.isas.jaxa.jp/suzaku/analysis/hxd/pinxb/tuned/140530bgdd.pdf](http://www.astro.isas.jaxa.jp/suzaku/analysis/hxd/pinxb/tuned/140530bgdd.pdf)

<sup>30</sup> Related to the peak in the effective area, in the spectral units of Fig. 1.

<sup>31</sup> After ignoring the range of 5.5–7 keV around the neutral Fe  $K\alpha$  line.

We note a mild discrepancy in the *Swift* XRT data with respect to the other missions. When examining the individual photon indices in the above fit to each mission separately, we find  $\Gamma_{\text{XRT}} = -0.68 \pm 1.26$ . This is harder than the median  $\Gamma$  value from the other missions at 90% confidence. But at 95% confidence, we find that all missions do agree. The cause of this slight mismatch is not clear but is unlikely to be related to differing aperture sizes used for extracting spectra for the different missions, because we expect the unresolved AGN alone to be the dominant contributor at these energies. Instead, at soft energies, one may expect spatially extended emission and larger differences, which we will discuss later. In any case, since this discrepancy is relatively mild, and since all other observations are fully consistent with each other, we consider a joint analysis of the *NuSTAR*, *Suzaku* XIS, and coadded *Swift* XRT data to be justified, and this is the approach we follow in the rest of this paper.

### 2.5.2 Reflection models

For the detailed spectral fits, we will be fitting X-ray reflection models over much of the hard X-ray energy range. There are several canonical models available for fitting heavily obscured AGN spectra in XSPEC. Traditionally, PEXRAV (Magdziarz & Zdziarski 1995) and its successor PEXMON including fluorescence (Nandra et al. 2007) have been used to characterise reflection features. These assume a slab obscurer/reflector with an infinite optical depth, as may be expected in a standard geometrically-thin accretion disc. The incident source in X-rays is associated with power law radiation ( $\text{PL}_{\text{AGN}}$ ) from a hot electron accretion disc corona. More recently, there are models which simulate X-ray processing in finite optical depth toroidal media which are more physically appropriate for obscured AGN. Murphy & Yaqoob (2009) provide tabulated results of Monte Carlo simulations of an AGN illuminating a doughnut shaped torus with a fixed opening angle and covering factor of 0.5 (the MYTORUS model). Brightman & Nandra (2011) assume, instead, a torus defined as a conical section of a sphere with variable opening angle and hence variable covering factor (the TORUS model). Both models assume Solar abundances and treat absorption, reflection and Fe  $\text{K}\alpha$  fluorescence self-consistently. MYTORUS additionally allows the freedom to vary the parameters of the scatterer, the l.o.s. obscurer, and the fluorescer, decoupled from one another. Both torus models assume that there is no  $e$ -folding cut-off energy to  $\text{PL}_{\text{AGN}}$ . For consistency, we make the same assumption in PEXMON. All models assume a uniform gas density spatial distribution.

Since the geometry of the obscuring/reflecting medium is unknown, we will use all three geometries above and investigate the range in intrinsic properties that can satisfy the observations.

### 2.5.3 Additional model components

Fixed Galactic absorption ( $\text{PHABS}_{\text{Gal}}$ ) with  $N_{\text{H}} = 4.27 \times 10^{20} \text{ cm}^{-2}$  (Dickey & Lockman 1990) was included in all models. We also included constants to account for cross-calibration uncertainties between the various detectors and missions. We found that one or two APEC (Smith et al. 2001) components and a soft power law ( $\text{PL}_{\text{soft}}$ ) were required to represent the energy range below  $\sim 2 \text{ keV}$  in some models. We emphasise that these components are meant to serve as parametrisations only. Previous works have shown that the origin of the soft X-ray photons in obscured AGN is a complex mixture of AGN photoionisation, starburst emission, and low level contributions from X-ray

binaries, among various possible origins (e.g. Sako et al. 2000; Kinkhabwala et al. 2002; Cappi et al. 2006; Guainazzi & Bianchi 2007). Separating these various possible components in NGC 7674 will require high spatial and spectral resolution observations with *XMM-Newton* and *Athena*, respectively. Our main focus is the origin of the higher energy X-rays, so we use the APEC and  $\text{PL}_{\text{soft}}$  components simply to ensure that the spectral fits over the soft regime are statistically acceptable. In addition, we may expect spatially extended soft emission to contribute in differing amounts to the *Suzaku* and *Swift* spectra because of the differing spectral extraction apertures tuned to the sizes of the respective telescope point spread functions. We account for this simply by allowing the APEC components to vary independently between these two missions. The only cross-check applied in this regard is that the soft X-ray flux measured by *Swift* XRT (with the smaller aperture) should not exceed that observed in *Suzaku* XIS.

With regard to other components, some models preferred several layers of absorption in addition to Galactic, as follows:

(i) All models with a transmission component required a thick nuclear absorber, which we associate with the classical compact torus having a l.o.s. column density ‘ $N_{\text{H}}(\text{nuc})$ ’ well above  $10^{24} \text{ cm}^{-2}$ .

(ii) Most models preferred the inclusion of a weak absorber screening the soft thermal and power law components (denoted by ‘ $N_{\text{H}}(\text{host})$ ’ with values of a few times  $10^{21} \text{ cm}^{-2}$ ). This corresponds to weak host galaxy reddening and is consistent with optical reddening of the Narrow Line Region, as we discuss later.

(iii) One particular partial covering (PC) model that we will investigate requires an additional absorber with an intermediate column obscuring a fraction  $f_{\text{PC}}$  of the reflected and scattered AGN components (‘ $N_{\text{H}}(\text{PC})$ ’  $\sim 10^{23} \text{ cm}^{-2}$ ). This component is not required in all models, and we discuss the viability of this solution later.

Finally, we found that inclusion of a Hydrogen-like Fe XXVI line at 6.97 keV, probably related to the ionised scattered continuum, provided a significant improvement in all models.

Our model values at any energy  $E$  can most generically be described as follows.

$$F(E) = C e^{-\tau(\text{Gal})} e^{-\tau(\text{host})} [\text{APEC}(s) + \text{PL}_{\text{soft}} + e^{-\tau(\text{PC})} [\text{Torus}(\Gamma, N_{\text{H}}(\text{nuc})) + f_{\text{PC}} \text{PL}_{\text{AGN}}(\Gamma) + \text{Line}]],$$

where ‘Torus’ represents one of our three primary models including either (i) PEXMON (Model P), or (ii) Brightman & Nandra TORUS (Model T), or (iii) Murphy & Yaqoob MYTORUS (Model M), in order to model the primary nuclear obscurer and reflector with column density  $N_{\text{H}}(\text{nuc})$ . ‘ $C$ ’ represents cross-calibration constants,  $\tau$  is the optical depth  $N_{\text{H}} \times \sigma(E_z)$  at the rest-frame energy  $E_z$  of the absorber, and ‘Line’ refers to the Fe XXVI emission line. All components are functions of  $E$ . We emphasise that not all models require the complexity implied by the above generic description of components.

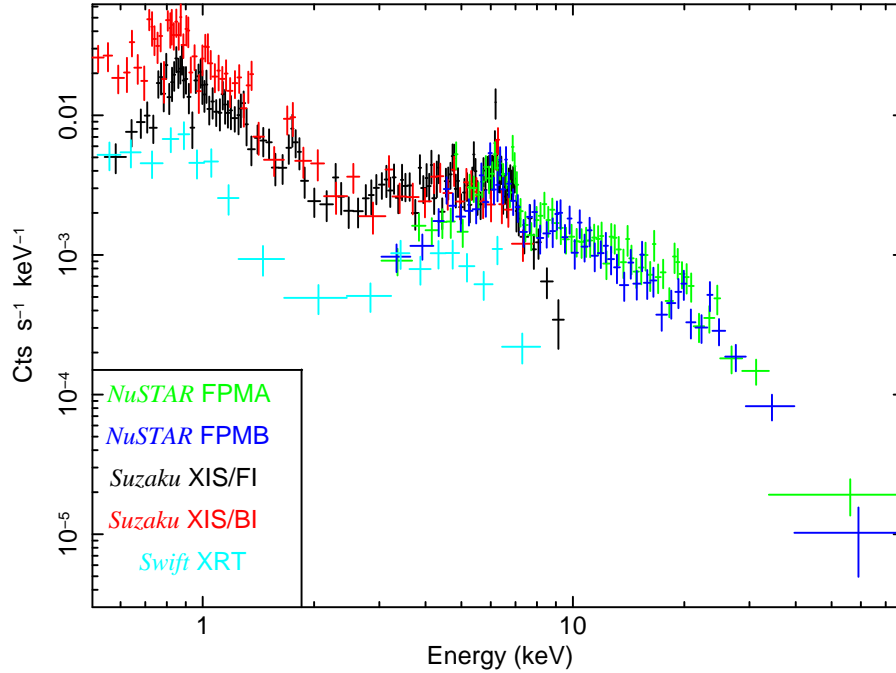


Figure 1. The *NuSTAR*, *Suzaku* and *Swift* data plotted in observed count rate units.

### 3 RESULTS

#### 3.1 Model P: PEXMON

We began with fitting Model P (PEXMON). This slab reflection model can fit the Compton hump successfully but strongly over-predicts the Fe  $K\alpha$  line strength when using fixed abundances at the Solar value. Letting the elemental abundance ( $A = A_{\text{Fe}}$ ) vary freely yields an acceptable solution ( $\chi^2/\text{dof} = 324.7/305$ ) with  $\Gamma = 2.1_{-0.1}^{+0.2}$ ,  $A = 0.5 \pm 0.1$  and a slab inclination of at least 77 deg. The inclination affects the ‘peakiness’ of the Compton hump, with lower inclinations being too ‘peaky’ as compared to the data. This model P solution is plotted in Fig. 2 and fit parameters are listed in Table 2. The bottom panel in the same figure demonstrates the strong Fe  $K\alpha$  residuals with  $A$  fixed to Solar and  $\Gamma = 2.1$  (fixed to the same value as the canonical model P); letting  $\Gamma$  vary freely did not provide a better fit than that stated in Table 2.

A transmitted component of the direct AGN power law ( $\text{PL}_{\text{AGN}}$ ) is included in this model. Compton scattering and photoelectric absorption by the torus are simulated with standard multiplicative models *CABS* and *ZPHABS*, respectively, with the gas column density  $N_{\text{H}}(\text{nuc})$  tied between the two models. The best-fit  $N_{\text{H}}(\text{nuc}) = 3.4_{-0.6}^{+0.8} \times 10^{24} \text{ cm}^{-2}$ . The reflection component dominates the absorbed transmitted component over the entire spectral range probed, i.e. the source is fully reflection-dominated. The excess of the reflection component is a factor of  $\sim 3$  around 30 keV. We note that excluding the transmission component results in a moderate increase in the fit statistic to  $\chi^2/\text{dof} = 334.5/305$ , which is only marginally significant at the  $3\sigma$  level. In other words, a transmission component is not strongly required.

We find that the cross-calibration constants between the various missions are consistent with 1 within the uncertainties. The strength of the Fe XXVI line is  $\text{EW}(\text{Fe XXVI}) \approx 200 \text{ eV}$ . At the soft end, the *Suzaku* XIS data require two APEC components with temperatures  $kT \approx 0.1$  and 0.6 keV, whereas the *Swift* XRT data probing smaller apertures require only a single lower temperature component. The APEC abundances are  $\sim 0.01$ – $0.2$ . Multiple ther-

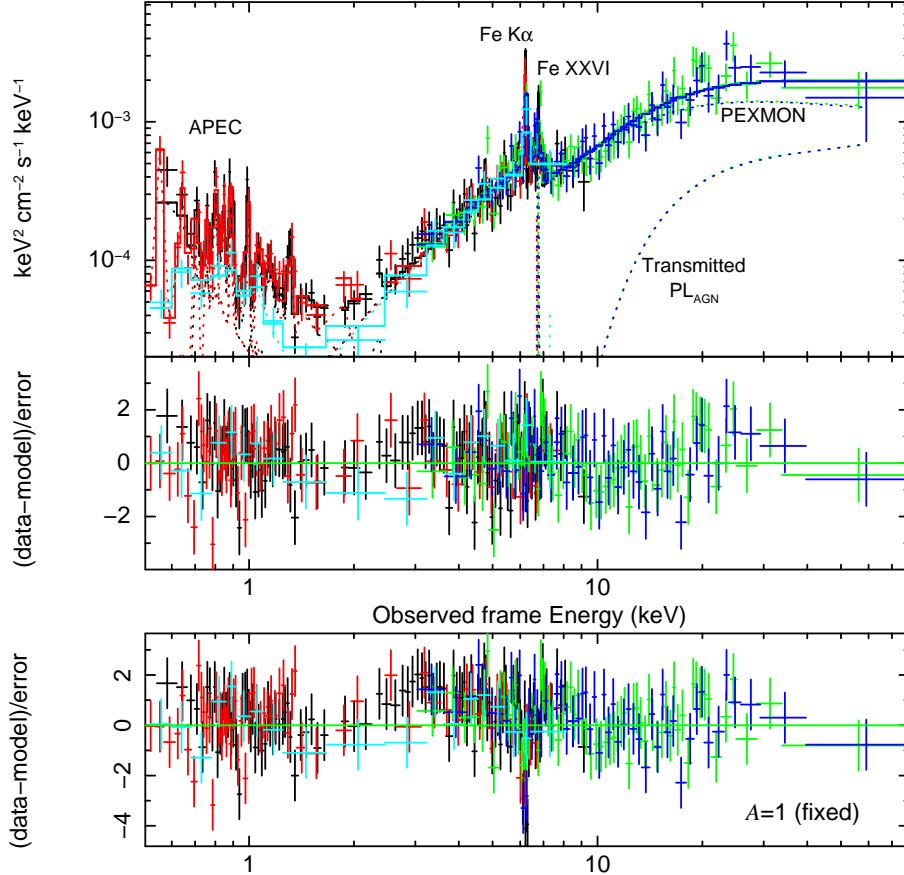
mal models with widely differing temperatures and abundances are quite common in luminous infrared galaxies (e.g. Ranalli et al. 2008) and have also been seen in other CTAGN (e.g. Konami et al. 2012). However, we emphasise that we are not attempting to constrain the origin of the soft X-ray emission in detail here.

The model is best fit with only one additional layer of absorbing column density  $N_{\text{H}}(\text{host}) = 4.0_{-1.6}^{+2.1} \times 10^{21} \text{ cm}^{-2}$ . This is a rather thin screen and corresponds to an optical extinction  $E_{\text{B}-\text{V}} = 0.7_{-0.3}^{+0.4} \text{ mag}$  for a standard Galactic gas-to-dust ratio (Bohlin et al. 1978). This is consistent with the reddening expected from the Balmer decrement of 4.80 (Bassani et al. 1999). Removing this layer significantly worsens the fit to  $\chi^2/\text{dof} = 342.1/306$ . But most of the change is concentrated at the softest energies (resulting in an increased APEC temperature) which we are not modelling in detail; the primary AGN reflection component is unaffected.

#### 3.2 Model T: TORUS

PEXMON assumes a slab geometry with infinite density, which is unlikely to be representative of the toroidal obscurer envisaged by AGN unification schemes. So we next turned to the Brightman & Nandra TORUS model. This also allows us to explore alternatives to our low  $A_{\text{Fe}}$  solution, because abundances are fixed at Solar values in this model. In this case, an acceptable solution may be found if we effectively dilute the continuum emission from the torus at the Fe  $K\alpha$  line energy with a stronger scattered component that we associate with a partially covered power law ( $\text{PL}_{\text{PC}}$ ).<sup>32</sup> Such a solution is plotted in Fig. 3, where  $N_{\text{H}}(\text{nuc})$  is above  $10^{25} \text{ cm}^{-2}$ , well within the Compton-thick regime. A fraction ( $f_{\text{PC}} \approx 4\%$ ) of  $\text{PL}_{\text{AGN}}$  is scattered into the l.o.s. and raises

<sup>32</sup> See the presentation by T. Yabooob at <http://cxc.cfa.harvard.edu/ChandraDecade/> for more discussions of such a warm scatterer scenario.



**Figure 2.** PEXMON model fit to the *Suzaku* XIS FI (black), XIS BI (red), *NuSTAR* FPMA (green), FPMB (blue) and *Swift* XRT (cyan) data. The central panel shows the fit residuals. The Fe abundance for this fit is close to 0.5 (Table 2). The bottom panel shows the residuals to a fit with fixed abundance  $A = 1$ . Notice the strong over-prediction at the neutral Fe  $K\alpha$  energy.

the continuum at the Fe  $K\alpha$  line energy enough to produce a fully acceptable fit ( $\chi^2/\text{dof} = 320.2/300$ ). For this fit, we froze the inclination angle  $\theta_{\text{inc}}$  of the torus to be close to edge-on, as is recommended for exploration of the full range of possible covering factors (Brightman et al. 2015).<sup>33</sup> Opening angles  $\theta_{\text{tor}}$  smaller than 51 deg are excluded because they produce a Compton hump peakier than required by the data. Large values of  $\theta_{\text{tor}}$  are allowed up to  $\theta_{\text{tor}} = 77$  deg, beyond which the torus effectively becomes too geometrically thin to produce a sufficiently strong Compton hump.

In this model, however,  $\text{PL}_{\text{PC}}$  itself must be obscured by an intermediate column  $N_{\text{H}}(\text{PC}) \sim 10^{23} \text{ cm}^{-2}$  so as not to overproduce the soft X-ray flux. This absorbing column is  $\approx 20$  times higher than the large-scale absorbing layer ( $N_{\text{H}}(\text{host})$ ) discussed in the previous sub-section, and would imply correspondingly higher optical reddening. NGC 7674 is a known luminous infrared galaxy with ongoing star formation and potential interaction with its neighbour NGC 7675 – all of which could result in obscuring matter being strewn around the host galaxy on multiple scales. Therefore, such an obscuring screen may be associated with an additional absorber in the innermost parts of the host galaxy which obscures the emergent flux from the nuclear regions (including the reflected and

scattered AGN flux). Detailed spatially resolved studies of the nuclear region so far neither require, nor rule out, such a screen. For example, the study of Fischer et al. (2013) does not show an obvious [O III] flux decrement at the nucleus, but the spatial resolution of their spectral sampling is  $\approx 30$  pc, much larger than the typical sizes of compact tori, and may potentially allow for additional absorbers below the resolution limit. Alternatively, the outflowing gas associated with the powerful nuclear outflow may also serve as a screening medium for X-rays. Finally, as will be discussed in the next section, relaxing the constraints on elemental abundances can alleviate the need for this screen altogether.

The soft energies can be fitted in a very similar fashion to Model P, with one difference being the presence of a significant, but faint,  $\text{PL}_{\text{soft}}$  component. We found that we needed to fix the  $\text{PL}_{\text{soft}}$  slope in this case, otherwise the fit attempted a very hard slope with contribution to the highest energy *NuSTAR* range. Since the purpose of this component is to account for the soft energies, we fixed  $\Gamma_{\text{soft}} = 2.0$ , similar to the spectral slope of the emission from X-ray binaries (e.g. Ranalli et al. 2003). We also checked that allowing small variations of  $\Delta \Gamma_{\text{soft}} = \pm 0.3$  do not affect the modelling of the main AGN component.

### 3.3 Model M: MYTORUS

We first fitted a standard ‘coupled’ MYTORUS model here with all parameters between the l.o.s. and toroidal scattering components tied to each other. This solution is very similar in essence to model

<sup>33</sup> There are uncertainties in this model at edge-on inclinations, as discussed by Liu & Li (2015). We checked that varying  $\theta_{\text{inc}}$  did not affect our final inferences. This is also apparent from the similarities between models T and M, with the latter being unaffected by the same uncertainties.

T, and the fit statistic of  $\chi^2/\text{dof} = 325/300$  is compatible with both previous models. Quantitatively, models T and M differ in that the derived equatorial column density through the torus ( $N_{\text{H}}(\text{eq})$ ) is pegged at the allowed upper model threshold of  $10^{25} \text{ cm}^{-2}$  in model M. Similarly,  $\theta_{\text{inc}}$  is just above (and very close to) the allowed lower model threshold of  $\theta_{\text{inc}} = 60^\circ$ . Such parameter pegging has been seen in other objects also, and reflects the constraint of the assumed doughnut geometry in this model as a result of which the value of  $N_{\text{H}}(\text{nuc})$  is directly coupled to  $\theta_{\text{inc}}$  (e.g., Gandhi et al. 2014; Baloković et al. 2014; Lansbury et al. 2015). Smaller inclination angles are not obscured by the torus in this model, whereas higher  $\theta_{\text{inc}}$  values produce a Compton hump which is too peaky relative to the data. Additional model components are also very similar to model T. The fitted parameters of this model are listed in Table 2 and the solution is shown in Appendix figure A1.

### 3.3.1 Decoupled MYTORUS model

We next tried several versions of the more complex ‘decoupled’ mode in MYTORUS. In this mode, the direct l.o.s. absorption, the toroidal Compton scattering emission, and the fluorescence emission components are not necessarily coupled to each other. By varying the  $N_{\text{H}}$ , the inclination angles or the relative normalisations associated with these components, one can effectively simulate a variety of scenarios including a clumpy obscurer or varying elemental abundances (for example). This can alleviate the need for the partial covering component that we introduced in Section 3.2 to dilute EW(Fe K $\alpha$ ). We confirmed that simply decoupling the normalisation constant of the fluorescence line  $A_L$  from the normalisation of the Compton scattering component  $A_S$  allowed a very good fit (with a fitted sub-unity value of  $A_L = 0.26 \pm 0.06$ ) with no partial covering required, equivalent to model P. The problem is that such a decoupling cannot be self-consistently interpreted as having sub-Solar abundances, because of the assumption of Solar abundances for the Compton scattering component that produces the overall continuum shape of the Compton hump.

We also attempted more complex scenarios that could potentially alleviate the need for partial covering, including having multiple scatterers. Such a scenario includes two components inclined at orthogonal angles of 0 [face-on] and at 90 deg [edge-on] with  $A_S = A_L$  for each component, and is discussed at length by Yaqoob (2012). But these models appeared to require extreme decoupling between the two scatterers. For instance, allowing freely varying cross-normalisation constants between these scatterers, the face-on reflection component ( $A_{S0}$  in Yaqoob’s terminology) prefers a normalisation  $\gtrsim 5$  times stronger than the edge-on component ( $A_{S90}$ ) responsible for the l.o.s. obscuration. This implies a strong departure from the default time-steady illuminated MYTORUS geometry with covering factor of 0.5. Such a scenario with strong variability on characteristic timescales relevant to the inner torus is discussed and argued against in Section 4.2.2.

Alternatively, the column densities between the two scatterers may also be untied. This is equivalent to simulating a clumpy medium with the line-of-sight obscuration differing from global. Such a solution is shown in Fig. 4. The spectrum can be crudely fit ( $\chi^2/\text{dof} = 371/301$ ) with a low l.o.s column associated with the edge on obscurer<sup>34</sup>  $N_{\text{H}}(\text{nuc}) = 1.3 (\pm 0.3) \times 10^{23} \text{ cm}^{-2}$ , but only with a very hard power law  $\Gamma = 1.40_{-u}^{+0.08}$  pegged at the lower limit allowed by the model. The out-of-sight global column from

the face-on scatterer is  $N_{\text{H}}(S0) = 2.4_{-0.8}^{+1.7} \times 10^{24} \text{ cm}^{-2}$ .<sup>35</sup> There is more than an order of magnitude difference between the two column densities. In order to prevent the strong normalisation departure mentioned in the preceding paragraph, we limited  $A_{S0}$  to a maximum value of 1.20, and the fit does, indeed, want to exceed this limit, with  $A_{S0}$  pegged at  $1.20_{-0.07}^{+u}$ . The scattered fraction (equivalent to ‘ $f_{\text{PC}}$ ’ in the previous section) of the intrinsic PL<sub>AGN</sub> is  $0.12_{-0.06}^{+0.04}$ . The fit statistic is much worse ( $\Delta\chi^2 = +46$ ) than the default model M solution shown in Table 2.

Scenarios with strong clumpiness have been discussed for Mrk 3 (Yaqoob et al. 2015; Guainazzi et al. 2016). But such a scenario is not obviously applicable to NGC 7674. Mrk 3 is known to be continuously variable in flux and line-of-sight column density, whereas NGC 7674 has been stable since the *BeppoSAX* observations in 1998. Furthermore, it is clear from the discussion of the pegged photon index and normalisation values above that the fit is attempting to converge on a harder, more reflection-dominated continuum shape, suggesting that it does prefer a higher line-of-sight column density.

Unless the direct PL<sub>AGN</sub> component can be *robustly* detected, such solutions are highly complex and degenerate, and do not yield any obvious physically useful insights on the nuclear medium beyond our three canonical models discussed in Table 2. This is particularly true for reflection-dominated AGN with no direct detection of PL<sub>AGN</sub> (e.g., see detailed discussion in Yaqoob 2012 on this point). Therefore, although we cannot rule out more complex models at this stage, we do not investigate the decoupled modes in greater detail herein. Future high signal-to-noise broadband spectra, and robust detections of reflection features such as the fluorescence Compton shoulder with X-ray calorimeters, could yield more insight on such models.

## 4 DISCUSSION

### 4.1 Intrinsic luminosity

Our three models return intrinsic  $L_{2-10}$  values ranging over  $\approx (3-5) \times 10^{43} \text{ erg s}^{-1}$  for the best fit parameters in Table 2. The narrow range of these luminosities is noteworthy, despite the differing geometries inherent to these models. Placing this range in the context of other well-known CTAGN, the luminosity of NGC 7674 is similar to NGC 1068, and is factor of  $\approx 2$  lower than Mrk 34 (Bauer et al. 2014; Gandhi et al. 2014). The former object is the prototypical reflection-dominated AGN, while the latter is the most luminous known bona fide CTAGN within  $\sim 250$  Mpc. For the *observed* (i.e. absorbed) spectra, we have  $F_{2-10}^{\text{obs}} = 7.7 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ , or  $L_{2-10}^{\text{obs}} = 1.5 \times 10^{42} \text{ erg s}^{-1}$  – a factor of  $\approx 20-30$  times lower than the inferred intrinsic power.

In order to estimate realistic uncertainties on the intrinsic luminosities, we stepped over a 2-dimensional grid of  $\Gamma$  and normalisation ( $N$ ) for the intrinsic PL<sub>AGN</sub> – the two parameters which determine the absorption-corrected flux (and hence direct luminosity). Carrying out fits over the grid yields a  $\chi^2$  value for each combination of  $\Gamma$  and  $N$ , and thus effectively for each value of  $L_{2-10}$ . Different combinations of the two starting parameters can return identical  $L_{2-10}$  values, so the 1-dimensional space of  $\chi^2$  as a function of  $L_{2-10}$  is not unique. But the overall uncertainties can be gauged from the *envelope* of  $\chi^2$  contours for all combinations. This envelope is plotted in Fig. 5 for both models M and T. The figure

<sup>34</sup> denoted by MYT(Z90) in the figure, as in Yaqoob 2012]

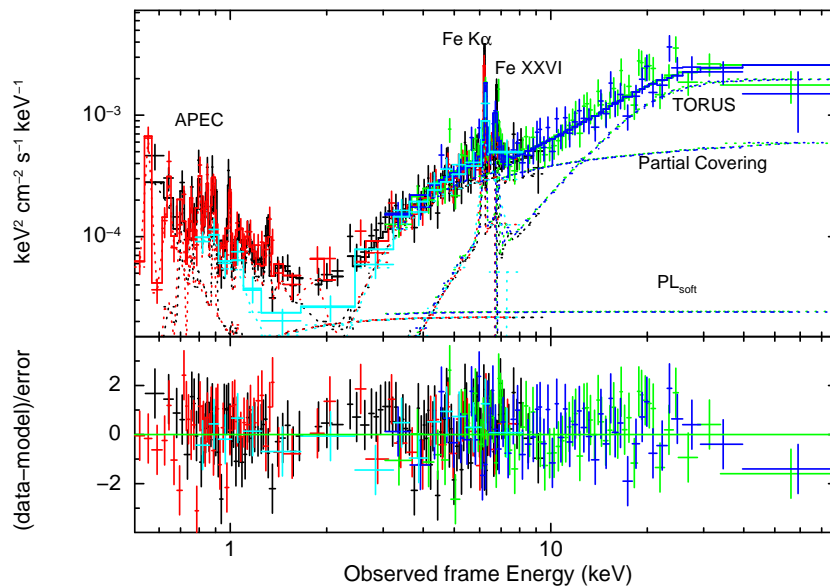
<sup>35</sup> denoted by MYT(S0) and MYT(L0); Ibid.

**Table 2.** Results of X-ray spectral fitting to NGC 7674

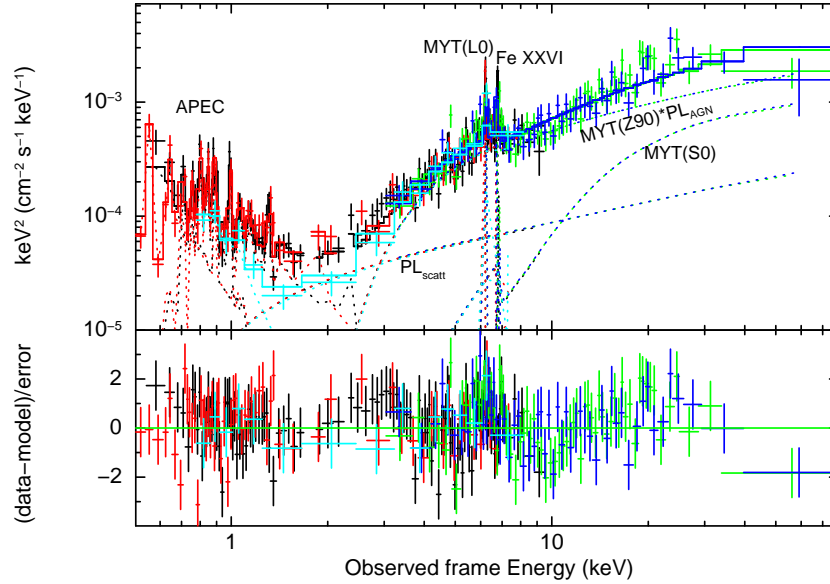
Component	Parameter	Model P	Model T	Model M	Units
Primary Absorber/Reflector	$N_{\text{H}}(\text{nuc})$	$3.4^{+0.8}_{-0.6}$	$36^{+u}_{-10}$	$5.5^{+u}_{-2.3}$	$10^{24} \text{ cm}^{-2}$
	$N_{\text{H}}(\text{eq})$	"	"	$10.0^{+u}_{-4.1}$	$10^{24} \text{ cm}^{-2}$
	$\theta_{\text{inc}}$	$85^{+u}_{-8}$	$87.1^f$	$65^{+9}_{-4}$	deg
	$\theta_{\text{tor}}$	-	$62^{+15}_{-11}$	-	deg
	$R$	$-1^f$	-	-	
	$A_{\text{Fe}}$	$0.51^{+0.10}_{-0.11}$	-	-	
	EW(Fe K $\alpha$ )	.....	$0.38^{+0.10}_{-0.09}$	..... <sup>†</sup>	keV
EW(Fe XXVI)	.....	$0.20^{+0.11}_{-0.09}$	..... <sup>†</sup>	keV	
PL <sub>AGN</sub>	$\Gamma$	$2.07^{+0.15}_{-0.11}$	$1.80^{+0.15}_{-0.11}$	$1.93^{+0.28}_{-0.12}$	
<i>Additional components</i>					
ZPHABS <sub>host</sub>	$N_{\text{H}}(\text{host})$	$4.0^{+2.1}_{-1.6}$	$3.1^{+1.7}_{-1.1}$	$3.4^{+0.2}_{-0.2}$	$10^{21} \text{ cm}^{-2}$
APEC <sub>1</sub> <sup>a</sup>	$kT_{\text{apec}1}$	$0.11^{+0.03}_{-0.02}$	$0.12^{+0.03}_{-0.03}$	$0.11^{+0.04}_{-0.04}$	keV
	$A_{\text{apec}1}$	$0.1^{+u}_{-0.08}$	$0.1^{+0.6}_{-0.09}$	$0.1^{+0.8}_{-0.07}$	
APEC <sub>2</sub> <sup>a</sup>	$kT_{\text{apec}2}$	$0.56^{+0.07}_{-0.07}$	$0.59^{+0.07}_{-0.07}$	$0.59^{+0.09}_{-0.08}$	keV
	$A_{\text{apec}2}$	$0.3^{+0.8}_{-0.1}$	$0.2^{+0.5}_{-0.1}$	$0.3^{+0.5}_{-0.2}$	
APEC <sub>3</sub> <sup>a</sup>	$kT_{\text{apec}3}$	$0.17^{+0.05}_{-0.04}$	$0.15^{+0.06}_{-0.04}$	$0.14^{+0.06}_{-0.04}$	keV
	$A_{\text{apec}3}$	$0.01^{+0.07}_{-u}$	$0.01^{+0.11}_{-y}$	$0.01^{+0.16}_{-y}$	
POW <sub>soft</sub>	$\Gamma_{\text{soft}}$	-	$2.0^f$	$2.0^f$	
	Norm	-	$2.5^{+1.2}_{-1.5}$	$2.5^{+1.4}_{-1.5}$	$10^{-5} \text{ ph keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$
Partial Covering	$f_{\text{PC}}$	-	$3.5 \pm 1.2$	$6.1^{+3.6}_{-3.1}$	$10^{-2}$
ZPHABS <sub>PC</sub>	$N_{\text{H}}(\text{PC})$	-	$9.4 \pm 2.5$	$10.6^{+3.3}_{-2.3}$	$10^{22} \text{ cm}^{-2}$
$C_{\text{XIS FI}}^{\text{XIS BI}}$ cross-calib	CONST	$1.00 \pm 0.07$	$1.01 \pm 0.07$	$1.00^{+0.07}_{-0.07}$	
$C_{\text{XIS FI}}^{\text{FPMA}}$ cross-calib	CONST	$1.06^{+0.08}_{-0.07}$	$1.11 \pm 0.08$	$1.12^{+0.09}_{-0.08}$	
$C_{\text{XIS FI}}^{\text{FPMB}}$ cross-calib	CONST	$1.04^{+0.09}_{-0.07}$	$1.10^{+0.05}_{-0.08}$	$1.11^{+0.09}_{-0.09}$	
$C_{\text{XIS FI}}^{\text{XRT}}$ cross-calib	CONST	$0.98^{+0.13}_{-0.13}$	$1.01 \pm 0.14$	$1.00^{+0.15}_{-0.14}$	
$\chi^2/\text{dof}$		325/305	320/300	325/300	

Model P: PEXMON component fit (Nandra et al. 2007).

Model M: MYTORUS coupled component fit (Murphy &amp; Yaqoob 2009).

Model T: TORUS model component fit (Brightman & Nandra 2011). <sup>u</sup>unconstrained. <sup>f</sup>fixed.<sup>†</sup>Equivalent width measured using a simple Gaussian atop a locally fitted powerlaw continuum.<sup>a</sup>APEC<sub>1</sub> and APEC<sub>2</sub> represent thermal components in *Suzaku* XIS, and APEC<sub>3</sub> is for *Swift* XRT.**Figure 3.** *Suzaku*, *Swift* and *NuSTAR* data fits with the reflection model T. Colours are as in Fig. 2.





**Figure 4.** Decoupled MYTORUS model fit with the direct component absorber (MYTZ90) orientation being 90 deg, and the reflection being dominated by the face-on scatterer MYTS0 and its corresponding fluorescence emission from MYTL0.

shows that realistic  $L_{2-10}$  uncertainties span the range of  $\approx (1.3-13) \times 10^{43} \text{ erg s}^{-1}$ , or about an order of magnitude.

Our estimate of the mass of the supermassive black hole (SMBH) in NGC 7674 is  $M_{\text{BH}} < 10^{7.43} M_{\odot}$  (see Appendix). Using our best-fit  $L_{2-10}$  range of  $(3-5) \times 10^{43} \text{ erg s}^{-1}$  together with a bolometric correction likely range of  $L_{\text{Bol}}/L_{2-10} \approx 10-20$  (Vasudevan & Fabian 2007), we estimate an Eddington ratio range of  $L_{\text{Bol}}/L_{\text{Edd}} > 0.09-0.29$ . Including the full range of X-ray luminosity uncertainties expands this range to  $L_{\text{Bol}}/L_{\text{Edd}} > 0.04-0.74$ , implying the presence of an efficiently accreting AGN.

#### 4.1.1 Multiwavelength comparisons

Multiwavelength scaling relations are very useful for comparison of intrinsic luminosity estimates, especially in the heavily Compton-thick regime where the direct X-ray emission is not detected. Two commonly used multiwavelength indicators of intrinsic AGN power are the mid-infrared continuum and the optical forbidden emission line luminosities, in particular the [O III] 5007 Å line doublet (e.g. Gandhi et al. 2009; Lamastra et al. 2009, and references therein). We compare NGC 7674 to these relations here.

NGC 7674 has been observed at high angular resolution in the mid-infrared using 8 m class telescopes. It is found to have a  $12 \mu\text{m}$  infrared luminosity of  $L_{12} = 1.8(\pm 0.3) \times 10^{44} \text{ erg s}^{-1}$  (Asmus et al. 2014). Using this value of  $L_{12}$ , the relation between infrared and X-ray luminosities for local AGN (Asmus et al. 2015; Gandhi et al. 2009) predicts an intrinsic  $L_{2-10}$  range of  $(6-9) \times 10^{43} \text{ erg s}^{-1}$  at 68% confidence, which is marginally higher than the mean best fit luminosities from our spectral analysis, but entirely consistent with the full confidence regions for both models shown in Fig. 5. Assuming a  $6 \mu\text{m}$  luminosity lower by a factor of 2 as compared to  $L_{12}$  (cf. Goulding et al. 2012) together with the  $L_6/L_{2-10}$  relation by Stern (2015) relevant for high luminosity AGN, the predicted  $L_{2-10}$  decreases by a further 0.1 dex. The angular resolution of the mid-infrared observations used (seeing-limited at  $\approx 0.4 \text{ arcsec}$ ) corresponds to a physical scale of  $\approx 0.24 \text{ kpc}$  for the unresolved nuclear emission at the distance of NGC 7674, and represents the best direct measure of

the intrinsic AGN power, with emission from surrounding star formation being resolved out. A further check on any contamination by non-AGN components may be obtained from the mid-infrared colour of NGC 7674 as tabulated in the WISE/AllWISE catalogue (Wright et al. 2010; Cutri et al. 2013). The  $W1-W2$  colour is  $1.16 \pm 0.03 \text{ mag}$ , which places the source above the colour threshold of  $W1-W2 > 0.8$  identified by Stern et al. (2012) where the mid-infrared emission is likely to be AGN-dominated.

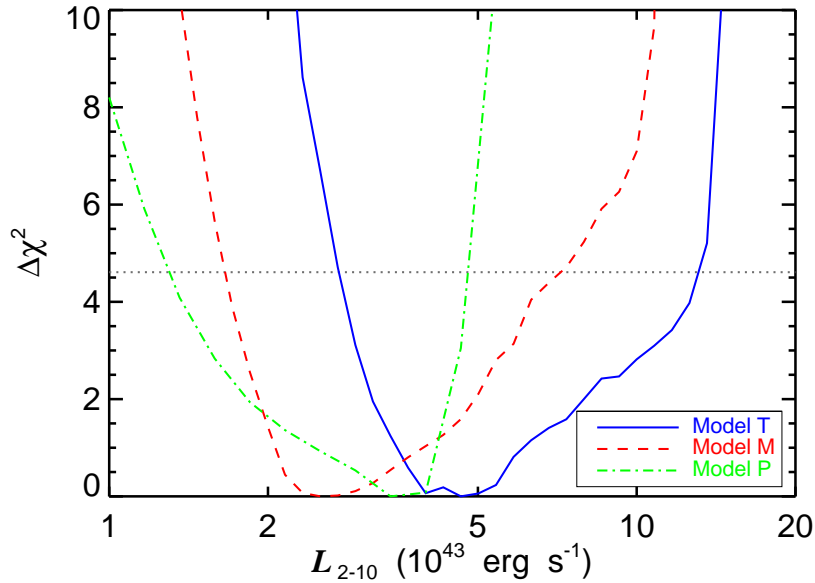
Comparing next to the [O III] emission line, Bassani et al. (1999) present the [O III] 5007 luminosity of the source as  $L_{[\text{O III}]} = 3.5(\pm 0.2) \times 10^{42} \text{ erg s}^{-1}$ . This value is derived after correcting for dust reddening based upon a Balmer decrement of 4.80. Using the  $L_{2-10}/L_{[\text{O III}]}$  relationship presented in Lamastra et al. (2009) with a scatter of 0.6 dex, we expect  $L_{2-10} = 5^{+7}_{-4} \times 10^{43} \text{ erg s}^{-1}$  at 68% confidence, overlapping well with our spectrally modelled intrinsic luminosity range.

In summary, the best fit X-ray luminosity measured from our spectral analysis agrees well with the multiwavelength comparisons above, especially when considering the full range of realistic uncertainties on the spectral modelling (Fig. 5). This is encouraging given that this source appears to be heavily Compton-thick and that the true torus geometry is unknown. Broadband spectral modelling of high signal-to-noise X-ray data is what enables us to get such good agreement.

#### 4.1.2 The soft X-ray component

The absorption-corrected luminosity in the XIS 0.5–2 keV band is  $L_{0.5-2}^{\text{APEC}} \approx 4.5 \times 10^{42} \text{ erg s}^{-1}$ . This is for both APEC components combined, but is dominated by a factor of 4 by the lower temperature component. Using the relation for star-forming galaxies by Mineo et al. (2012) between the thermal component luminosity and the star formation rate (SFR), we estimate an X-ray derived  $\text{SFR}_{\text{X-ray}} \approx 9 \times 10^3 M_{\odot} \text{ yr}^{-1}$ .

This may be compared to the infrared derived SFR, based upon the far-infrared continuum luminosity  $L_{\text{IR}}$  and its relation to  $\text{SFR}_{\text{IR}}$  (Kennicutt 1998). For NGC 7674,  $L_{\text{IR}} \approx 10^{11.56} L_{\odot}$  (Koss et al. 2013), which yields  $\text{SFR}_{\text{IR}} \approx 60 M_{\odot} \text{ yr}^{-1}$ . This is



**Figure 5.**  $\chi^2$  contours as a function of  $L_{2-10}$  for models T, M and P. Luminosities are computed over the two-dimensional parameter space of randomised  $\Gamma$  and PL normalisation  $N$  values, and the overall one-dimensional *envelope* of corresponding  $\chi^2$  values is then plotted. The dotted horizontal line corresponds to  $\Delta\chi^2 = 4.61$ , or 90% confidence for the two starting parameters  $\Gamma$  and  $N$ , relative to the minimum  $\chi^2$  for each model.

more than two orders of magnitude lower than the estimated  $\text{SFR}_{\text{X-ray}}$ , and implies that starburst-powered APEC components alone are an unphysical representation of the soft X-ray emission in NGC 7674. Photoionisation could instead power some of this, as we have already alluded to on several occasions.

We note, however, that the  $\text{SFR}_{\text{IR}}$  is certainly large. For example, it is about 10 times above the SFR of the prototypical starburst galaxy M82 (e.g. Telesco & Harper 1980). Such high star formation is likely to power extended ionised gas emission, and we will return to possible implications of this in Section 4.3.3.

## 4.2 The nature of the long-term source flux decline

Fig. 6 shows the long-term X-ray lightcurve of NGC 7674 over a period of about 37 years. As first noted by Bianchi et al. (2005), the source showed a dramatic decline by a factor of  $\sim 30$  in the 2–10 keV band between the first measurement by *HEAO* and the *BeppoSAX* identification of the source as a CTAGN by Malaguti et al. (1998). Thereafter, the source flux has remained constant with no significant spectral or flux variation for the past  $\approx 20$  years. This now includes the most recent *Suzaku* and *NuSTAR* observations. The individual *Swift* observations spanning the period of 2011–2014 detailed in the Appendix also show fluxes or detection limits broadly consistent with *BeppoSAX*, *Suzaku* and *NuSTAR*. Finally, the custom analysis of the *Swift*/BAT maps by Koss et al. (2013) shows a weak detection consistent with *NuSTAR*. NGC 7674 transitioned from a declining flux to a constant level sometime between  $\approx 18$ –25 years before the *NuSTAR* observation – the period spanned by the *Ginga* (1989) and *BeppoSAX* (1996) observations.

### 4.2.1 On the possibility of contamination by another source

Could the pre-*BeppoSAX* flux decline be associated with a contaminating source, unrelated to the AGN? The observed luminosities at

the *HEAO* and *Ginga* epochs are above  $10^{42} \text{ erg s}^{-1}$  – already too high to be easily associated with X-ray binaries (XRBs) within the host galaxy. An XRB within our Galaxy which just happens to lie along the same l.o.s. as NGC 7674 cannot be ruled out, though the high Galactic latitude ( $b = -48^\circ$ ) makes this unlikely.

Regarding contamination by other AGN, there is only one possible bright source in the recent 70 month all sky *Swift*/BAT hard X-ray survey that could potentially have contaminated both the *HEAO* and *Ginga* fields of view. This is PKS 2325+093 which lies at a separation of 0.9 deg from NGC 7674 and shows a BAT flux of  $F_{14-195} \approx 3 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$  (Baumgartner et al. 2013). However, this source lies outside the *HEAO* positional error box of NGC 7674 (Bianchi et al. 2005). Moreover, PKS 2325+093 shows a very hard spectrum, at least in the BAT band, with  $\Gamma_{\text{BAT}} = 1.29 \pm 0.28$ . This is much harder than the spectral shape inferred for the *Ginga* observation below  $\approx 10 \text{ keV}$  by Bianchi et al. (2005). Although a drastic change in spectral curvature around 10 keV cannot be ruled out, the combined weight of evidence appears to disfavour contamination.

If the luminosity change is instead associated with the AGN in NGC 7674 itself, there are then two possible interpretations of these observations which we investigate here: the AGN could either have faded dramatically (an effective ‘switch-off’, as is referred to hereafter), or it could have become gradually enshrouded within Compton-thick material.

### 4.2.2 The ‘switched-off’ scenario

In the switched-off AGN scenario, the observed reflection spectrum dominating at hard X-rays is delayed with respect to the incident  $\text{PL}_{\text{AGN}}$  which has now faded. In this picture, the ab-

sorbed ‘partial covering (PL<sub>PC</sub>)’ component included in our models T and M (cf. Fig. 3) would also be interpreted as a delayed component scattered in to the l.o.s from material on  $\sim$  pc scales, or larger. The current PL<sub>AGN</sub> flux level cannot be higher<sup>36</sup> than that this PL<sub>PC</sub> component, which has a deabsorbed luminosity  $L_{2-10}^{\text{PC}} \approx 2 \times 10^{42} \text{ erg s}^{-1}$  – an order of magnitude fainter than inferred during the *Ginga* observation epoch (1989) and a factor of  $\approx 30$  fainter than the *HEAO* peak (1977). In model P, where no PC component is required (cf. Fig. 2), the constraint on the current intrinsic AGN luminosity is even more stringent, with  $L_{2-10}$  expected to be 10 times lower still.

Assuming that the source switched off between the *Ginga* (1989) and *BeppoSAX* (1996) epochs around 1993, i.e.  $21 \pm 3$  years before the *NuSTAR* observation, the absence of any flux change since then places a minimum limit on the radius ( $R$ ) of an axisymmetric reflector  $R = 3.2 \text{ pc}$  based upon a simple consideration of the light travel time from the far wall of a nearly edge-on reflector. Furthermore, this is likely a conservative estimate because, as Fig. 6 shows, the source intrinsic flux had already been declining strongly for the  $\sim 15$  years before *BeppoSAX*, so one may have expected to see a corresponding change in the reflected flux as well unless  $R$  is much larger still.

Considering the average travel time over the full body of the reflector, and/or intermediate inclinations angles, would push up the lower limit on  $R$ . While extended reflectors on scales of up to  $\sim 150 \text{ pc}$  have been observed in several CTAGN (e.g. NGC 4945, Marinucci et al. 2012; Circinus, Arévalo et al. 2014; NGC 1068, Bauer et al. 2014), the studies so far find that these extended components make relatively minor flux contributions compared to the compact reflectors. Detailed studies of Type 1 AGN have shown that the bulk of the neutral Fe  $K\alpha$  emission line arises at nuclear distances on the scale of the dust sublimation radius ( $R_{\text{sub}}$ ) or smaller (see detailed discussion in Gandhi et al. 2015a), and in the orientation-based unification scheme, this would also hold for obscured and CTAGN viewed at higher inclination angles.

For NGC 7674,  $R_{\text{sub}}$  is estimated to be  $\approx 0.1_{-0.04}^{+0.05} \text{ pc}$  based upon infrared luminosity scaling relations determined at high angular resolution where the AGN can be effectively isolated from surrounding star formation (Hönig et al. 2010). This size scale is about 30 times smaller than the lower limit on  $R$  above. In other words, in the switched-off AGN scenario, a typical (sub)-pc scale torus reflector would be expected to respond to a decline of the intrinsic continuum on timescales faster than seen in Fig. 6. Consistent with this, some clear evidence for a decreasing reflection flux on relatively short timescales in NGC 7674 was already presented by Bianchi et al. (2005), in the form of a measured decrease by a factor of  $\sim 1.8 \pm 1.0$  in the neutral Fe  $K\alpha$  line flux between the *BeppoSAX* (1998) and the *XMM-Newton* (2004) observations separated by  $\approx 6$  years. But given that we find a very similar EW( $K\alpha$ ) value to Bianchi et al., there is no evidence of further fading since. Unless the torus happens to have an idealised torus geometry such that the expected decrease in solid angle with distance is compensated for in a fine-tuned manner over a factor of  $\sim 30 \times R_{\text{sub}}$ , we would have expected to see some change in the reflected flux under the switched-off AGN scenario by now.

#### 4.2.3 Clumpy Compton-thick obscurer scenario

In the obscured AGN scenario, the source gradually became obscured between the *HEAO* (late 1970s) and the *BeppoSAX* (1998) epochs, and is now fully covered by CT material along the l.o.s. We can place some tentative constraints on the size and geometry of this material, as follows. Firstly, we argue that the source is unlikely to be obscured either by a single compact CT cloud, or by a few clouds with low covering factor. This is because the reflection component we observe is strong. The observed reflected luminosity ( $L_{\text{obs}}$ ) scales approximately with intrinsic luminosity ( $L_{\text{int}}$ ) as

$$L_{\text{obs}} \sim L_{\text{int}} \Omega a \quad (1)$$

where  $\Omega$  is the solid angle of the reflector and  $a$  is the albedo. The physical models that we have used in our spectral fits assume fairly typical geometrical covering factors for the torus, and yield estimates of  $L_{\text{int}}$  which are in reasonable agreement (to within a factor of a few) with other multiwavelength indicators (§ 4.1.1). If the reflector had small covering factor  $\Omega$ , the corresponding geometrical correction would imply much higher values of  $L_{\text{int}}$ .

The complete lack of recent X-ray flux variability also supports this. Whereas an extended distribution of clouds can naturally spread out and dampen variations in the reflected flux relative to any variability in the direct AGN radiation, this is not possible in the low covering factor limit. Indeed, most reflection-dominated CTAGN are observed to show little, or no flux variations at all (cf. two well-studied examples include Circinus [Arévalo et al. 2014] and NGC 5643 [Annuar et al. 2015], although sensitive observations have recently caught a transient column density change in NGC 1068 [Marinucci et al. 2016]). Sources where significant flux variability is observed (e.g. NGC 4945 [Puccetti et al. 2014], ESO 565–G019 [Gandhi et al. 2013], and IC 751 [Ricci et al. 2016]) tend to be *mildly* Compton-thick AGN or significantly clumpy, with the direct transmitted component being stronger than the reflection component over at least some portion of the hard X-ray regime. In particular, many observations support the presence of a small  $\Omega$  for the obscurer in NGC 4945 (e.g. Madejski et al. 2000, though there are other possible scenarios as discussed by Brightman et al. 2015).

The emerging scenario for NGC 7674 then is that a patchy distribution of clouds obscures the nucleus with a covering factor fairly typical of standard torus models. By the time of the *BeppoSAX* observation in 1996, a cloud ensemble with CT column density had fully obscured the l.o.s to the nucleus, and this ensemble has continuously covered the l.o.s. ever since. A complementary point of view is that the past high state caught by *HEAO* and *Ginga* was actually a transient near-complete *unveiling* of the nucleus caused by the l.o.s passing through a hole in the patchy obscurer. The unveiling would have begun years before the *HEAO* observation, when the source was likely caught in the process of being veiled again.

The physical characteristics of typical veiling clouds in this patchy obscurer may be crudely estimated from the observed veiling time of the nucleus. For a cloud of size (diameter)  $D$  moving with velocity  $v$ , we have

$$D = v \Delta t \quad (2)$$

where  $\Delta t$  is the crossing time of the cloud across the nucleus and we can set a lower limit of  $\Delta t > 19 \text{ y}$  between the *HEAO* ( $\approx 1977$ ) and *BeppoSAX* (1996) epochs, i.e. between first observation and

<sup>36</sup> modulo small changes related to a slightly differing  $\Gamma$ .

full covering.<sup>37</sup> If we assume circumnuclear virial motion of the cloud around the central SMBH at a distance  $R$ ,

$$v = \sqrt{G M_{\text{BH}} / R}. \quad (3)$$

These equations allow  $v$  to be eliminated, resulting in

$$D > 0.04 \sqrt{\left(\frac{M_{\text{BH}}}{10^8 M_{\odot}}\right) \left(\frac{0.1 \text{ pc}}{R}\right) \left(\frac{\Delta t}{19 \text{ y}}\right)} \text{ pc}. \quad (4)$$

This estimate of  $D$  is fully consistent with cloud size estimates based upon clumpy torus models for a dust sublimation radius  $R_{\text{sub}} \approx 0.1 \text{ pc}$  for NGC 7674 (e.g. Hönig et al. 2010). In other words, a torus origin for the CT cloud is plausible.

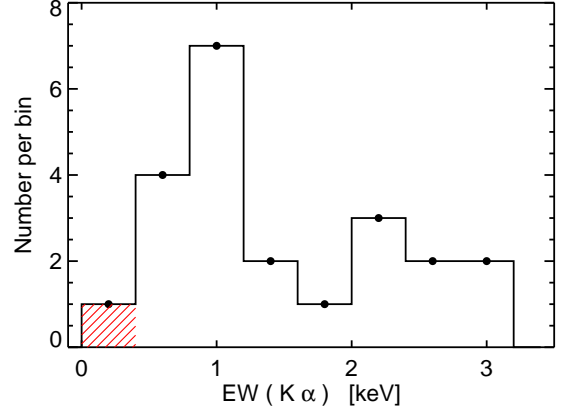
But we cannot rule out much larger or smaller scales. For example, the derived cloud scales are also similar to those expected in clumpy accretion disc winds (e.g. Kaastra et al. 2014). If  $R$  were much larger, though,  $D$  would be smaller, pushing down the probability of a l.o.s. crossing. And if  $R$  is much smaller than  $R_{\text{sub}}$  (see, e.g., discussion on several such sources in Gandhi et al. 2015a and references therein), we can expect substantial broadening of the narrow Fe  $K\alpha$  line core as has been found in many other AGN studied by the high energy grating on *XMM-Newton*, assuming that this broad component is not fully obscured by the torus. For instance, Shu et al. (2010) and Shu et al. (2012) measured full width at half maximum of order  $10^3\text{--}10^4 \text{ km s}^{-1}$  in a number of nearby AGN, implying  $R \lesssim R_{\text{sub}}$  if the gas motion is virial. Following the loss of the *Hitomi* mission (Takahashi et al. 2014) in March 2016, testing this scenario on NGC 7674 will probably have to await the calorimeter on board *Athena* (Nandra et al. 2013).

Interestingly, converting the observed 1989 *Ginga* flux of  $8(\pm 2) \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$  (Bianchi et al. 2005) to a luminosity yields  $L_{2-10} \approx 2 \times 10^{43} \text{ erg s}^{-1}$ , again consistent with our spectral analysis results (Section 4.1). The effect of absorption in the *Ginga* spectrum appears minimal. This would also support the obscured AGN scenario for a constant (intrinsic) X-ray luminosity. On the other hand, the *HEAO* luminosity from  $\approx 1977$  is a factor of a  $\approx 3$  higher still, implying at least some intrinsic continuum flux variability.

### 4.3 On the weakness of the Fe $K\alpha$ line

Compton-thick AGN are usually associated with strong Fe  $K\alpha$  emission lines with equivalent widths (EW) of  $\gtrsim 1 \text{ keV}$ . Our work shows a much weaker  $\text{EW} \approx 0.4 \text{ keV}$  (also reported by Bianchi et al. 2005), but our spectral modelling of NGC 7674 also consistently finds high Compton-thick column densities using several different spectral models. In fact, comparing to other reflection-dominated AGN (such as NGC 1068, NGC 5643, Mrk 34 and others with  $N_{\text{H}} \gtrsim 10^{25} \text{ cm}^{-2}$ ) amongst the local *bona fide* CTAGN population (Della Ceca et al. 2008; Goulding et al. 2012; Gandhi et al. 2014), NGC 7674 appears to have one of the weakest neutral Fe fluorescence lines. This is demonstrated in Fig. 7, where NGC 7674 stands out in the distribution of EW distribution of *bona fide* CTAGN compiled by Gandhi et al. (2014). The EW values are taken from relevant recent references in the same paper, or (where recent values are not published) from the compilation of Della Ceca et al. (2008). They are mostly

<sup>37</sup> with the obvious caveat that we cannot exclude extra variability between the *HEAO*, *Ginga*, and *BeppoSAX* observational epochs.



**Figure 7.** Distribution of equivalent widths (EWs) of the neutral Fe  $K\alpha$  emission line for the bona fide CTAGN compiled in Gandhi et al. (2014). The red hatched region corresponds to NGC 7674 ( $\text{EW} = 0.38^{+0.10}_{-0.09} \text{ keV}$ ).

based upon power law fits to the continuum together with Gaussian line components. Three sources have been excluded because of published works questioning their bona fide CTAGN nature, or showing that they have highly complex geometries: Mrk 3 ( $\text{EW} \approx 1.0 \pm 0.3 \text{ keV}$ ; Yaqoob et al. 2015; Guainazzi et al. 2016), NGC 7582 ( $\text{EW} \approx 0.6^{+0.6}_{-0.1} \text{ keV}$ ; Rivers et al. 2015); and NGC 4939 ( $\text{EW} \approx 0.5^{+0.4}_{-0.2} \text{ keV}$ ; Maiolino et al. 1998). With regard to recent CTAGN studies, one new bona fide addition is IC 3639 ( $\text{EW} \approx 2.7^{+3.0}_{-0.9} \text{ keV}$ ; Boorman et al., in prep.), whereas we did not include NGC 4785 ( $\text{EW} \approx 1.7^{+0.7}_{-0.4} \text{ keV}$ ; Gandhi et al. 2015b) because it only has one published X-ray analysis so far. None of these additions or exclusions affects the relative position of NGC 7674 at the lower end of the distribution.

We have shown that the broad band spectrum can be fit with either a low elemental abundance (model P), or an absorbed partial covering solution (models T and M). Here we briefly investigate other possibilities.

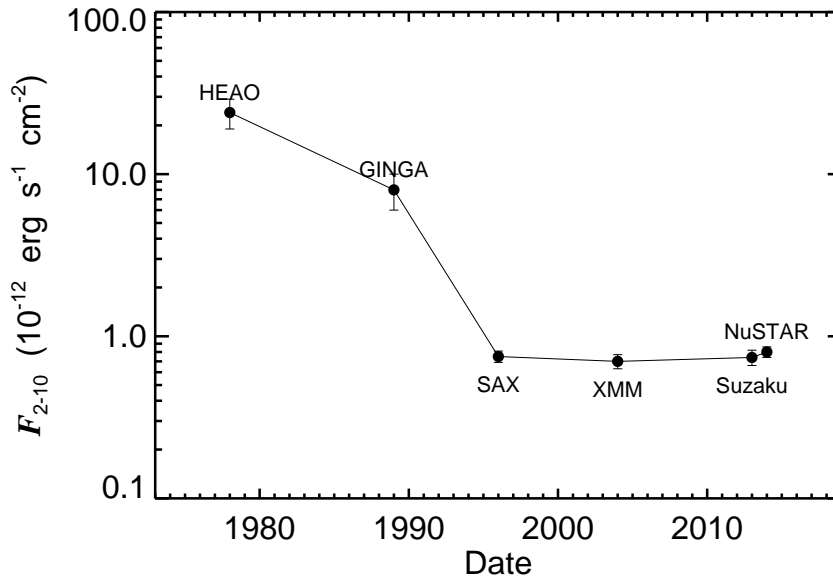
#### 4.3.1 A possible Compton-thin solution?

Lower nuclear column densities will result in lower EW values, as a result of weaker continuum absorption. So the question arises whether the source may actually be Compton-thin, despite our fits arguing others.

In Section 3.3.1, we allowed for the possibility of differing l.o.s and out-of-sight column densities in the decoupled model M. A Compton-thin value for  $N_{\text{H}}(\text{nuc})$  was found to be viable. But this also required the intrinsic  $\text{PL}_{\text{AGN}}$  slope to become extremely hard, and the reflection component stronger than the default MYTORUS geometry.

We further tested the viability of a Compton-thin solution by modifying model T and limiting  $N_{\text{H}}(\text{nuc})$  to a maximum of value of  $9 \times 10^{23} \text{ cm}^{-2}$ , which is close to the high end of the Compton-thin range. The best solution is shown in Fig. 8 and has a fit statistic of  $\chi^2/\text{dof} = 338/301$ . As expected, the lower column density implies an intrinsically weaker fluorescence line leaving no dramatic residuals at the line energy, and also alleviating the need for partial covering and sub-Solar abundance.

Although this solution is formally acceptable with a null hypothesis probability of 0.07, there are several problems. Firstly, the



**Figure 6.** Long-term 2–10 keV observed flux light curve of NGC 7674 spanning  $\sim 1977/78$  (the *HEAO* epoch) to late 2014 (*NuSTAR*).

fit statistic is significantly worse than for the base model T listed in Table 2, with a  $\Delta\chi^2 = +18$ .

Secondly, and importantly,  $N_{\text{H}}(\text{nuc})$  is pegged at the forced upper limit of  $9 \times 10^{23} \text{ cm}^{-2}$ , implying that the fit is trying to converge on even higher  $N_{\text{H}}(\text{nuc})$  values in the Compton-thick regime.

Thirdly, it turns out that the torus inclination angle  $\theta_{\text{inc}}$  is only marginally larger than the opening angle  $\theta_{\text{tor}}$ . For the plotted solution,  $\theta_{\text{inc}} = 27.5^{+0.2}_{-1.7}$  deg. This is a very narrow range just slightly more inclined than  $\theta_{\text{tor}}$  which is pegged at the lower model limit of 25.8 deg. Examining the joint parameter space between  $\theta_{\text{inc}}$  and  $\theta_{\text{tor}}$ , we find that this Compton-thin scenario always prefers  $\theta_{\text{inc}}$  very close to (and just marginally larger than)  $\theta_{\text{tor}}$ . This allows the direct l.o.s. to be obscured without the Compton hump being too peaky, but is a rather fine-tuned scenario.

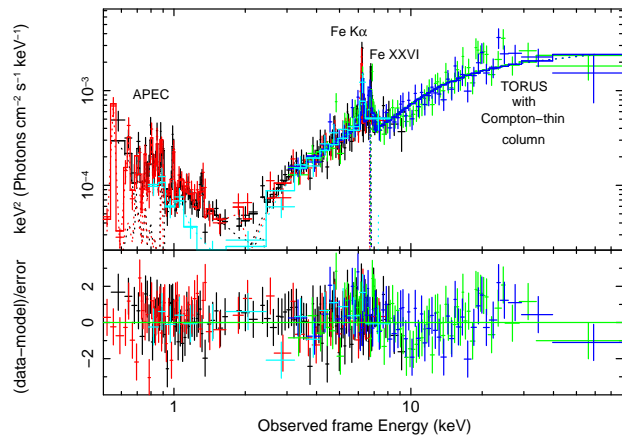
Finally, the intrinsic luminosity of this Compton-thin solution is  $L_{2-10} \approx 5 \times 10^{42} \text{ erg s}^{-1} \text{ cm}^{-2}$ , easily more than an order of magnitude lower than that implied by both the multiwavelength indicators investigated in § 4.1.1.

For all of the above reasons, the Compton-thick solution appears to be far more viable than the Compton-thin one.

#### 4.3.2 Dilution by a jet?

One other possibility may be that a jet is diluting the continuum underlying the Fe K $\alpha$  emission line and hence effectively weakening the observed EW. Such dilution has been inferred in several broad-line radio galaxies (e.g. Eracleous et al. 2000), and also in broad absorption line quasars (e.g. Luo et al. 2013).

In the case of NGC 7674, however, we consider this possibility to be unlikely for several reasons. Although NGC 7674 is a known radio source, it is classified as radio quiet (Xu et al. 1999). Then there is the distinct lack of X-ray variability at 2–10 keV as probed by several missions over the past  $\sim 20$  years. Non-thermal emission from a jet is expected to be significantly variable, especially when probed on multiple (long) timescales that we are now able to sample (Fig. 6).



**Figure 8.** *Suzaku* + *NuSTAR* data fits to a forced Compton-thin TORUS model with  $N_{\text{H}}(\text{nuc})$  limited to  $\leq 9 \times 10^{23} \text{ cm}^{-2}$ .

Finally, one may try to quantify the expected flux from a jet irrespective of the above considerations. The core of NGC 7674 has a morphology extended over  $\approx 1$  kpc, characteristic of radio galaxies (e.g. Momjian et al. 2003). There is evidence of complex interactions of the radio ejecta with the interstellar medium – complex enough that the location of the AGN itself is unclear in the radio (Momjian et al. 2003). The reported integrated 5 GHz nuclear radio flux density is 67 mJy (Condon et al. 1991), corresponding to a monochromatic luminosity density of  $L_{5 \text{ GHz}} = 1.3 \times 10^{30} \text{ erg s}^{-1} \text{ Hz}^{-1}$ .

The above luminosity is lower than the power typically associated with radio-loud (RLQs) as well as radio-intermediate quasars (RIQs). For example, Miller et al. (2011) studied samples of RIQs and RLQs and showed that there exists an ‘X-ray excess’ above that seen in radio-quiet sources. The excess scales with radio luminosity and could be associated with a jet contribution to X-rays. At the

observed luminosity density of NGC 7674, the correlation between the X-ray excess and radio luminosity found by Miller et al. (2011) is consistent with no jet-related X-ray excess.<sup>38</sup>

Instead of using the correlation for quasars, one may instead try using the correlation between radio power and the jet-related unabsorbed X-ray powerlaw luminosities for lower luminosity 3CRR sources presented by Hardcastle et al. (2009).<sup>39</sup> From the reported 5 GHz radio flux density, we predict  $L_{X,u} \approx 10^{41} \text{ erg s}^{-1}$ , or  $F_{2-10} = 3 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$ . This is more than a factor of 20 fainter than our observed  $F_{2-10}$ . Accounting for a scatter of 0.56 dex in the relation of Hardcastle et al. (2009), the predicted jet X-ray flux is still lower than the observed flux by a factor of 6, rendering this scenario unlikely.

#### 4.3.3 On the strength of ionised Fe and the relation to other powerful infrared galaxies

A variety of studies have found that distant sources with high bolometric power, including ultraluminous infrared galaxies (ULIRGs) and sub-mm galaxies, show preferentially strong ionised Fe lines such as Fe XXV (6.7 keV) and Fe XXVI (6.97 keV; e.g. Iwasawa et al. 2009; Lindner et al. 2012; Gilli et al. 2014). The neutral Fe K $\alpha$  (6.4 keV) line is extremely weak or undetected in many of these systems. This may be attributable either to the neutral reflection component being heavily embedded within the torus as seen by us, or to a highly ionised interstellar medium that is being energised by starburst activity, or a combination of the two effects. Iwasawa et al. (2012) further suggest that preferentially strong ionised emission lines may be connected to high accretion rates on the central AGN.

With a bolometric infrared power of  $10^{11.56} L_{\odot}$  (Koss et al. 2013), NGC 7674 lies in the regime of luminous infrared galaxies. This is lower than, but approaching, the regime associated with ULIRG luminosities. Such an intermediate luminosity could explain why the source displays *both* a neutral and an ionised Fe line with strengths comparable to within a factor of about 2. Our estimate of the Eddington ratio of the AGN in § 4.1 is as high as  $\approx 0.4$ , and this could be even higher if  $M_{\text{BH}}$  has been overestimated (see Appendix). Brightman et al. (subm.) also present evidence that some CTAGN (with steep X-ray power law photon indices) may exhibit high Eddington fractions. If so, NGC 7674 would be a local analogue of the more bolometrically luminous systems with high accretion rates studied by Iwasawa et al. (2012). A more robust  $M_{\text{BH}}$  estimate will be needed to test these parallels.

Finally, we note that a strong ionised Fe XXVI emission feature may be accompanied by an ionised underlying continuum. So it is possible that the ‘scattered PL<sub>PC</sub>’ component introduced in Section 3.2 actually arises from photoionised or hot collisionally ionised gas which also self-consistently produces Fe XXVI and some of the soft emission. The possible need for a photoionised component was discussed in Section 4.1.2. We attempted to fit the data as such, by replacing the absorbed PL<sub>PC</sub> component from our base model T with a photoionised model based upon the publicly-available CLOUDY code (Ferland et al. 1998). Examples

<sup>38</sup> Their correlation needs to be extended below their lower luminosity limit and would instead predict an X-ray deficit of  $-0.14 \pm 0.09$  in their adopted units of  $\ell_x - \ell_{x,\text{RQQ}}$ .

<sup>39</sup> In the terminology used by the authors, the X-ray power law luminosity is  $L_{X,u}$ , with the X-ray band being  $\approx 0.4\text{--}8 \text{ keV}$ , and a fixed spectral slope  $\Gamma_{\text{jet}} = 2$ .

of such fits can be found for various other AGN, including Mrk 573 (Bianchi et al. 2010) and ESO 138–G001 (De Cicco et al. 2015). Reasonable fits were possible without PL<sub>PC</sub>, but we found that the photoionised component was required to be extremely strong relative to the Compton-thick torus, and that it dominated over the entire energy range to up  $\sim 10 \text{ keV}$ . Although we cannot rule out such a model, photoionised components are usually much fainter (Bianchi et al. 2005; De Cicco et al. 2015). High spectral resolution observations will be required to test this scenario in further detail.

#### 4.4 Implications for identifying Compton-thick AGN at low X-ray signal-to-noise

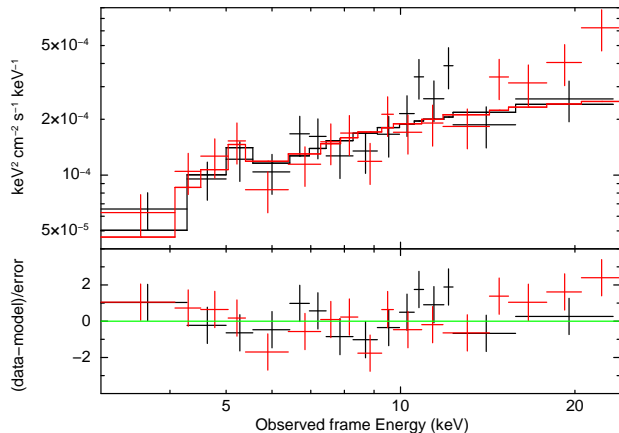
Although the Compton-thick solution is preferred for several reasons over the Compton-thin one (see § 4.3.1), the Compton-thin solution cannot be rejected immediately on statistical grounds alone. Therefore, it is worth studying the pattern of residuals in the Compton-thin case in Fig. 8. A comparison with our baseline model T in Fig. 3 shows that there are no extra strong and sharp residuals at any particular energy in the Compton-thin case. Rather, the rising slope of the data between  $\approx 10$  and  $30 \text{ keV}$  is better reproduced by the more pronounced hump that results from the Compton-thick scenario.

This relatively mild difference (in terms of the reproducibility of the spectrum) has important implications for the study of more distant AGN in deep surveys where the signal-to-noise is typically much weaker than in our data. Using simulations, Koss et al. (2015) found that robust characterisation of typical nearby CTAGN such as NGC 3393 is only possible at relatively low redshifts of  $z \lesssim 0.2$  if one relies upon detection of the Fe K $\alpha$  emission line and broadband continuum for spectral modelling.

Our results on NGC 7674 further complicate the study of distant CTAGN. With a value of EW(Fe K $\alpha$ ) weaker by a factor of  $\approx 3$  than in NGC 3393, it becomes even more difficult to identify an object as being Compton-thick. We demonstrate this by carrying out a simulation of a source with a model spectrum identical to NGC 7674, but with a lower flux of  $F_{8-24} = 5 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ . Although four times fainter than NGC 7674 in the same band, this flux level lies more than an order of magnitude above the deepest flux level being probed in ongoing deep and wide *NuSTAR* surveys (Mullaney et al. 2015; Civano et al. 2015; Aird et al. 2015; Harrison et al. 2015). We simulated *NuSTAR* spectra for both FPMs using the default background and response simulation files<sup>40</sup> provided by the *NuSTAR* team, and assuming an exposure time of 100 ks. We also introduced a small redshift  $z = 0.25$ , effectively assuming an intrinsic X-ray luminosity  $L_{2-10} \approx 10^{45} \text{ erg s}^{-1}$ , characteristic of luminous AGN likely to be found in deep surveys.

The simulated spectra are shown in Fig. 9. The rising continuum slope (from the Compton hump of our baseline model T) is clearly visible. We first fitted the simulated data with a simple power law model (not shown), which yielded  $\Gamma = 1.1 \pm 0.2$  with  $\chi^2/\text{dof} = 27/29$ . No additional Fe K $\alpha$  emission line is required for the fit. This hard slope is suggestive of the need for obscuration. However, including redshifted photoelectric absorption and reflection with a TORUS model implies an  $N_{\text{H}}$  of only  $2.2^{+0.9}_{-0.8} \times 10^{23} \text{ cm}^{-2}$  for a fixed canonical  $\Gamma = 1.8$ , i.e. a Compton-

<sup>40</sup> <http://sc.nustar.caltech.edu>



**Figure 9.** *NuSTAR* simulated spectra for two FPMs assuming our model T best fitting model to NGC 7674, but with a flux lower by a factor of 4 and shifted to  $z=0.25$ . The simulation is for 100 ks of exposure time per FPM. The histograms show best fitting TORUS model to the faked data, and are fitted with  $N_{\text{H}} = 2.2^{+0.9}_{-0.8} \times 10^{23} \text{ cm}^{-2}$  and  $\Gamma = 1.8$  for canonical fixed values of  $\theta_{\text{tor}} = 60$  deg and  $\theta_{\text{inc}} = 87$  deg, i.e. a Compton-thin solution. The fit statistic is  $\chi^2/\text{dof} = 34/29$ .

thin solution (the solution shown in the figure). This is a direct result of the lack of a strong Fe K $\alpha$  emission line.

The newer torus models are now being widely used by the community for self-consistent modelling of the nuclear obscuring material, and these have proven to be very successful at characterising objects well into the Compton-thick regime. However, most of the publicly available torus models do not allow varying elemental abundances which, as we discuss in §3.2, means that sources like NGC 7674 cannot be fit without additional complexity such as partial covering components. In any case, such model complexity is often not viable for fitting low signal-to-noise data, with the result that the column density, and hence intrinsic luminosity, of distant AGN may be underestimated.

A full assessment of the resultant bias in deep surveys is beyond the scope of the present paper, until the frequency of weak Fe K $\alpha$  CTAGN such as NGC 7674 can be established. Independent selection of large samples of CTAGN candidates based upon X-ray spectral diagnostics and on multiwavelength indicators (i.e. high ratios of  $L_{\text{MIR}}$  or  $L_{[\text{O III}]}$  to observed  $L_{2-10}$ ) could be an informative first step in this direction (cf. Rovilos et al. 2014). Similarly, we recommend the use of varying elemental abundances as an additional free parameter in model fitting when signal-to-noise allows.

If we are to make robust progress on the Compton-thick selection problem, multiple redundant cross-checking methods must be employed (the work of Brandt & Alexander 2015 contains a recent, comprehensive analysis of various techniques in the literature).

## 5 SUMMARY

We have presented *NuSTAR* spectroscopy of the local reflection-dominated AGN NGC 7674. Together with unpublished *Suzaku* and *Swift* data, we carried out broadband X-ray modelling of the 0.5–78 keV spectrum assuming three geometries of the nuclear obscurer/reflector. The best fitting model in all cases requires a nuclear column density of obscuring gas  $N_{\text{H}}(\text{nuc})$  of at least  $3 \times 10^{24} \text{ cm}^{-2}$  and possibly much higher (Table 2), with an absorption-corrected luminosity  $L_{2-10} = (3-5) \times 10^{43} \text{ erg s}^{-1}$ ,

agreeing with mid-infrared continuum and forbidden optical [O III] emission line indicators (Section 4.1). The full uncertainty range on  $L_{2-10}$  spans  $\approx (1-13) \times 10^{43} \text{ erg s}^{-1}$  (Fig. 5). A relatively weak neutral Fe K $\alpha$  emission line (EW  $\approx 0.4$  keV) at 6.4 keV is seen, together with a comparatively strong ionised Fe line with an identification consistent with Fe XXVI. We explore a variety of scenarios to explain the line complex and suggest that NGC 7674 may be similar to more powerful ULIRGs which also show similar trends of line complexity, possibly related to a high accretion rate (Section 4.3.3).

We have presented an X-ray light curve spanning 37 years (Fig. 6), and find that the observed source X-ray flux has remained constant for about 20 years, prior to which it was brighter by a factor of up to  $\approx 30$  when observed by *HEAO*. A faded/switched-off AGN scenario requires a reflector size of at least 3 pc, which is  $\approx 30$  times larger than the dust sublimation radius of the canonical pc-scale torus in NGC 7674, and thus is not, by itself, a preferred explanation for the observed fading (Section 4.2.2).

The alternative scenario is that a clumpy Compton-thick obscuring medium has been continuously obscuring the source for  $\approx 21 \pm 3$  years since the mid 1990s. If a steady-state patchy obscurer does surround the nucleus, the past high state of NGC 7674 could have represented a temporary unveiling of the nucleus (Section 4.2.3). It is noteworthy, however, that the source has been an optical Seyfert 2 for more than 30 years, implying that the source has shown no evidence of being a ‘changing-look’ AGN in the optical.

While a clumpy obscurer appears to be the preferred explanation for the long-term light curve and the present reflection-dominated X-ray spectral shape, there are two pieces of evidence favouring at least some intrinsic AGN fading in the past – 1) the very high *HEAO* flux in  $\approx 1977$ , which was at least a factor of 3 higher than the inferred unobscured flux from all subsequent missions, and 2) the inferred fading by a factor of  $\approx 2$  of the neutral Fe K $\alpha$  line between the *BeppoSAX* (1996) and *XMM-Newton* (2004) observations. These facts mean that we cannot rule out a combination of the two scenarios. The relation between the strong nuclear outflow and the X-ray-obscuring medium, and whether the outflow is connected to the past fading, also remains to be investigated. Continued monitoring of the source will be important, as will high spatial and spectral resolution multiwavelength observations to understand these connections.

The weakness of the neutral Fe K $\alpha$  emission line implies that canonical torus covering factors and Solar metallicities cannot be used in order to derive absorption correction factors. This is relevant for surveys of distant, fainter AGN where the signal to noise of the data do not allow detailed fitting of individual sources and simplifying assumptions are introduced for spectral modelling (Section 4.4).

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## A1 APPENDIX

### A1.1 Individual *Swift* observations

A total of 17 *Swift* XRT observations of NGC 7674 are available from the HEASARC archive.<sup>41</sup> Their spectra were extracted from the standard data products, and fit with simple power laws. Fixed Galactic absorption was included in these fits. In cases of insignificant detection, the gross count rate at the source position was converted to an upper limit on the observed flux assuming a power law of fixed  $\Gamma = 1$  because we expect the source to be obscured and display an effectively hard photon index. The resultant fits are listed in Table A1. There is no evidence for significant variability amongst these measured fluxes.

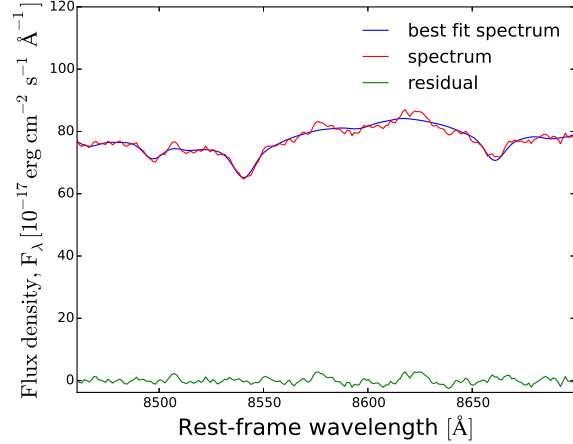
### A1.2 Model M spectral fit

Fig. A1 shows the fit to the default (coupled) model M incorporating MYTORUS (§ 3.3). The fit parameters are listed in the last data column in Table 2. This fit is qualitatively very similar to that of model T, shown in Fig. 3.

### A1.3 Black hole mass estimate from optical spectroscopy

We use the penalised PiXel Fitting software (pPXF, Cappellari & Emsellem 2004) to measure the central stellar velocity dispersion ( $\sigma$ ). For a stellar library, we used templates from the Miles Indo-U.S. Catalogue (MIUSCAT) library of stellar spectra (Vazdekis et al. 2012) with coverage of the wavelength range of the Ca II triplet (8450–8700 Å). The data and fit are presented in Fig. A2. The fit yielded a stellar velocity dispersion of  $\sigma = 91 \pm 48 \text{ km s}^{-1}$  (1-sigma uncertainty). This value is entirely consistent with, and slightly below, the instrumental resolution  $\sigma_{\text{instr.}} = 107 \text{ km s}^{-1}$ . Measurements near the resolution limit can be unreliable, so we conservatively interpret the measurement and its uncertainty to be equivalent to an upper limit of  $\sigma = 91 + 48 = 139 \text{ km s}^{-1}$ . Using the  $M_{\text{BH}}-\sigma$  relation from McConnell & Ma (2013) implies an upper limit of  $M_{\text{BH}} < 10^{7.43} M_{\odot}$ .

The measurement quoted by Nelson & Whittle (1995)



**Figure A2.** Keck/LRIS red grism spectrum of NGC 7674 spanning the Ca II triplet absorption feature, fitted with a pPXF algorithm. The intrinsic velocity dispersion is measured to be  $91 \pm 48 \text{ km s}^{-1}$ .

is  $\sigma = 144 \pm 32 \text{ km s}^{-1}$ , which has been used to infer  $M_{\text{BH}} = 10^{7.56} M_{\odot}$  in the literature (Bian & Gu 2007). Nelson & Whittle used the KPNO 2.1 m telescope with the TI CCD, a slit width of  $1''.5$ , and  $600 \text{ lines mm}^{-1}$  grating, observed under  $1''.9$  seeing. The grating would have had higher spectral resolution than our LRIS observations, so it is a bit surprising that their measurement of  $\sigma$  is larger than our inferred upper limit.

However, we note that the uncertainty of  $32 \text{ km s}^{-1}$  suggests that the discrepancy is relatively mild. Their use of a wider slit, the bad seeing during their observation, and use of a far smaller telescope than Keck may have all resulted in lower signal-to-noise than our data. In fact, a comparison by eye of our Fig. A2 with the spectrum presented in Fig. 3a of Nelson & Whittle (1995) shows this to be a plausible solution to the above mismatch. A sensitive, higher resolution optical spectrum, with  $1200 \text{ lines mm}^{-1}$ , for instance, should be able to resolve this issue.

## REFERENCES

- Aird J. et al., 2015, *ApJ*, 815, 66  
 Annuar A. et al., 2015, *ApJ*, 815, 36  
 Arévalo P. et al., 2014, *ApJ*, 791, 81  
 Arnaud K. A., 1996, in *ASP Conf. Ser. 101: Astronomical Data Analysis Software and Systems V*, eds. George H. Jacoby and Jeannette Barnes, Vol. 5, p. 17  
 Asmus D., Gandhi P., Hönig S. F., Smette A., Duschl W. J., 2015, *MNRAS*, 454, 766  
 Asmus D., Hönig S. F., Gandhi P., Smette A., Duschl W. J., 2014, *MNRAS*, 439, 1648  
 Awaki H., Koyama K., Inoue H., Halpern J. P., 1991, *PASJ*, 43, 195  
 Ballantyne D. R., Draper A. R., Madsen K. K., Rigby J. R., Treister E., 2011, *ApJ*, 736, 56  
 Baloković M. et al., 2014, *ApJ*, 794, 111  
 Barthelmy S. D. et al., 2005, *Sp. Sc. Rev.*, 120, 143  
 Bassani L., Dadina M., Maiolino R., Salvati M., Risaliti G., della Ceca R., Matt G., Zamorani G., 1999, *ApJS*, 121, 473  
 Bauer F. E. et al., 2014, *ApJ* submitted, arXiv:1411.0670

<sup>41</sup> <http://heasarc.gsfc.nasa.gov/docs/archive.html>

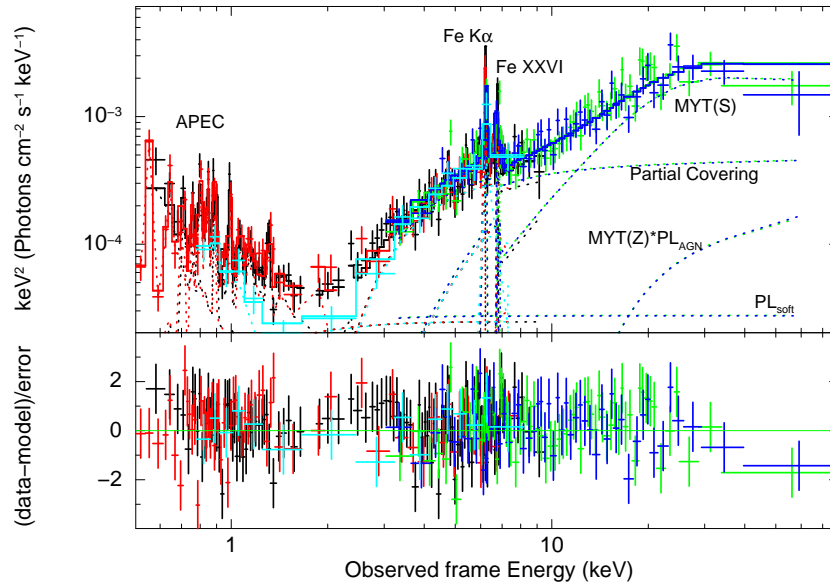


**Table A1.** *Swift* XRT observations of NGC 7674.

Date	ObsID	Exposure ks	$\Gamma$	$F_{2-10}$ $10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$
2011-01-28	00040884001	1492	$1^f$	< 2.15
2011-10-03	00040884002	845	$1^f$	< 1.49
2011-10-04	00040884003	845	$1^f$	< 2.87
2011-10-28	00040884004	4952	$-1.52^{+1.55}_{-u}$	$2.13^{+1.96}_{-1.09}$
2011-10-30	00040884005	3696	$-0.23^{+1.20}_{-1.16}$	$1.46^{+1.11}_{-0.66}$
2011-11-03	00040884006	2831	$-0.46^{+1.76}_{-1.68}$	$1.63^{+1.16}_{-0.92}$
2011-11-08	00040884007	2782	$-1.11 \pm u$	$1.46^{+3.01}_{-1.01}$
2011-11-11	00040884008	4701	$3.15^{+3.0}_{-2.58}$	$0.94^{+1.42}_{-0.36}$
2011-11-13	00040884009	4997	$-0.03^{+1.31}_{-1.32}$	$0.98^{+0.85}_{-0.45}$
2011-11-15	00040884010	3929	$-1.88^{+2.21}_{-u}$	$2.40^{+2.55}_{-1.60}$
2011-11-17	00040884011	467	$1^f$	< 2.73
2011-11-19	00040884012	5077	$-0.11^{+2.70}_{-2.67}$	$0.99^{+1.5}_{-0.48}$
2011-11-21	00040884013	4679	$0.46^{+1.84}_{-1.90}$	$0.94^{+1.15}_{-0.44}$
2013-01-29	00049851001	1454	$1^f$	< 1.02
2014-09-30	00080798001	1041	$1^f$	< 2.34
2014-10-03	00080798002	3078	$1^f$	< 0.98
2014-10-08	00080798003	2395	$0.55^{+1.79}_{-1.86}$	$0.92^{+1.59}_{-0.53}$

$^f$  fixed photon indices used for flux upper limit determinations.

$^u$  unconstrained.



**Figure A1.** *Suzaku* + *NuSTAR* data fits with the reflection model M. This is very similar to model T presented in Fig. 3. The MYT(Z) and MYT(S) components represent the absorption of the direct component, and the Compton-scattered component, respectively. The third MYTORUS component is the fluorescence component producing the Fe K $\alpha$  and related emission features and the Compton shoulders (this would be equivalently named MYTL).

Baumgartner W. H., Tueller J., Markwardt C. B., Skinner G. K., Barthelmy S., Mushotzky R. F., Evans P. A., Gehrels N., 2013, *ApJS*, 207, 19  
 Bian W., Gu Q., 2007, *ApJ*, 657, 159  
 Bianchi S., Chiaberge M., Evans D. A., Guainazzi M., Baldi R. D., Matt G., Piconcelli E., 2010, *MNRAS*, 405, 553  
 Bianchi S., Guainazzi M., Matt G., Chiaberge M., Iwasawa K., Fiore F., Maiolino R., 2005, *A&A*, 442, 185  
 Blackburn J. K., 1995, in *Astronomical Society of the Pacific Conference Series*, Vol. 77, R. A. Shaw, H. E. Payne, & J. J. E. Hayes, ed, *Astronomical Data Analysis Software and Systems IV*, p. 367

Bohlin R. C., Savage B. D., Drake J. F., 1978, *ApJ*, 224, 132  
 Brandt W. N., Alexander D. M., 2015, *A&AR*, 23, 1  
 Brightman M. et al., 2015, *ApJ*, 805, 41  
 Brightman M., Nandra K., 2011, *MNRAS*, 413, 1206  
 Burrows D. N. et al., 2005, *Sp. Sc. Rev.*, 120, 165  
 Cappellari M., Emsellem E., 2004, *PASP*, 116, 138  
 Cappi M. et al., 2006, *A&A*, 446, 459  
 Civano F. et al., 2015, *ApJ*, 808, 185  
 Comastri A., Setti G., Zamorani G., Hasinger G., 1995, *A&A*, 296, 1  
 Condon J. J., Frayer D. T., Broderick J. J., 1991, *AJ*, 101, 362  
 Cutri R. M. et al., 2013, *Explanatory Supplement to the AllWISE*

- Data Release Products, Technical report
- De Cicco M., Marinucci A., Bianchi S., Piconcelli E., Violino G., Vignali C., Nicastro F., 2015, *MNRAS*, 453, 2155
- Della Ceca R. et al., 2008, *Mem SAI*, 79, 65
- Dickey J. M., Lockman F. J., 1990, *ARA&A*, 28, 215
- Eracleous M., Sambruna R., Mushotzky R. F., 2000, *Hard X-Ray Spectra of Broad-Line Radio Galaxies from the Rossi X-Ray Timing Explorer*
- Evans P. A. et al., 2009, *MNRAS*, 397, 1177
- Feldman F. R., Weedman D. W., Balzano V. A., Ramsey L. W., 1982, *ApJ*, 256, 427
- Ferland G. J., Korista K. T., Verner D. A., Ferguson J. W., Kingdon J. B., Verner E. M., 1998, *PASP*, 110, 761
- Fischer T. C., Crenshaw D. M., Kraemer S. B., Schmitt H. R., 2013, *ApJS*, 209, 1
- Fukazawa Y. et al., 2009, *PASJ*, 61, 17
- Gandhi P., Fabian A. C., 2003, *MNRAS*, 339, 1095
- Gandhi P., Hönig S. F., Kishimoto M., 2015a, *ApJ*, 812, 113
- Gandhi P., Horst H., Smette A., Hönig S., Comastri A., Gilli R., Vignali C., Duschl W., 2009, *A&A*, 502, 457
- Gandhi P. et al., 2014, *ApJ*, 792, 117
- Gandhi P. et al., 2013, *ApJ*, 773, 51
- Gandhi P., Yamada S., Ricci C., Asmus D., Mushotzky R. F., Ueda Y., Terashima Y., La Parola V., 2015b, *MNRAS*, 449, 1845
- Gehrels N. et al., 2004, *ApJ*, 611, 1005
- Gilli R., Comastri A., Hasinger G., 2007, *A&A*, 463, 79
- Gilli R. et al., 2014, *A&A*, 562, A67
- Goulding A. D., Alexander D. M., Bauer F. E., Forman W. R., Hickox R. C., Jones C., Mullaney J. R., Trichas M., 2012, *ApJ*, 755, 5
- Grossan B. A., 1992, Ph.D. thesis, Massachusetts Institute of Technology, Cambridge.
- Guainazzi M., Bianchi S., 2007, *MNRAS*, 374, 1290
- Guainazzi M. et al., 2016, *MNRAS* in press, arXiv:1605.02467
- Hardcastle M. J., Evans D. A., Croston J. H., 2009, *MNRAS*, 396, 1929
- Harrison F. A. et al., 2015, *ApJ* submitted, arXiv:1511.04183
- Harrison F. A. et al., 2013, *ApJ*, 770, 103
- Hönig S. F., Kishimoto M., Gandhi P., Smette A., Asmus D., Duschl W., Polletta M., Weigelt G., 2010, *A&A*, 515, A23
- Iwasawa K. et al., 2012, *A&A*, 537, A86
- Iwasawa K., Sanders D. B., Evans A. S., Mazzarella J. M., Armus L., Surace J. A., 2009, *ApJL*, 695, L103
- Kaastra J. S. et al., 2014, *Science*, 345, 64
- Kennicutt R. C., Jr., 1998, *ARA&A*, 36, 189
- Kinkhabwala A. et al., 2002, *ApJ*, 575, 732
- Kokubun M. et al., 2007, *PASJ*, 59, 53
- Konami S., Matsushita K., Gandhi P., Tamagawa T., 2012, *PASJ*, 64, 117
- Koss M., Mushotzky R., Baumgartner W., Veilleux S., Tueller J., Markwardt C., Casey C. M., 2013, *ApJL*, 765, L26
- Koss M. J. et al., 2016, *ApJ* in press, arXiv:1604.07825
- Koss M. J. et al., 2015, *ApJ*, 807, 149
- Koyama K. et al., 2007, *PASJ*, 59, 23
- Lamastra A., Bianchi S., Matt G., Perola G. C., Barcons X., Carrera F. J., 2009, *A&A*, 504, 73
- Lansbury G. B. et al., 2015, *ApJ*, 809, 115
- Lindner R. R., Baker A. J., Beelen A., Owen F. N., Polletta M., 2012, *ApJ*, 757, 3
- Liu Y., Li X., 2015, *MNRAS*, 448, L53
- Luo B. et al., 2013, *ApJ*, 772, 153
- Madejski G., Życki P., Done C., Valinia A., Blanco P., Rothschild R., Turek B., 2000, *ApJL*, 535, L87
- Magdziarz P., Zdziarski A. A., 1995, *MNRAS*, 273, 837
- Maiolino R., Salvati M., Bassani L., Dadina M., della Ceca R., Matt G., Risaliti G., Zamorani G., 1998, *A&A*, 338, 781
- Malaguti G. et al., 1998, *A&A*, 331, 519
- Marinucci A. et al., 2016, *MNRAS*, 456, L94
- Marinucci A., Risaliti G., Wang J., Nardini E., Elvis M., Fabbiano G., Bianchi S., Matt G., 2012, *MNRAS*, 423, L6
- Mateos S. et al., 2005, *A&A*, 433, 855
- Matt G., Guainazzi M., Maiolino R., 2003, *MNRAS*, 342, 422
- McConnell N. J., Ma C.-P., 2013, *ApJ*, 764, 184
- Miller B. P., Brandt W. N., Schneider D. P., Gibson R. R., Steffen A. T., Wu J., 2011, *ApJ*, 726, 20
- Mineo S., Gilfanov M., Sunyaev R., 2012, *MNRAS*, 426, 1870
- Momjian E., Romney J. D., Carilli C. L., Troland T. H., 2003, *ApJ*, 597, 809
- Mullaney J. R. et al., 2015, *ApJ*, 808, 184
- Murphy K. D., Yaqoob T., 2009, *MNRAS*, 397, 1549
- Nandra K. et al., 2013, *The Hot and Energetic Universe: A White Paper presenting the science theme motivating the Athena+ mission*
- Nandra K., George I. M., Mushotzky R. F., Turner T. J., Yaqoob T., 1997, *ApJL*, 488, L91
- Nandra K., O'Neill P. M., George I. M., Reeves J. N., 2007, *MNRAS*, 382, 194
- Nelson C. H., Whittle M., 1995, *ApJS*, 99, 67
- Oke J. B. et al., 1995, *PASP*, 107, 375
- Piconcelli E., Jimenez-Bailón E., Guainazzi M., Schartel N., Rodríguez-Pascual P. M., Santos-Lleó M., 2005, *A&A*, 432, 15
- Planck Collaboration , 2014, *A&A*, 571, A16
- Puccetti S. et al., 2014, *ApJ*, 793, 26
- Ranalli P., Comastri A., Origlia L., Maiolino R., 2008, *MNRAS*, 386, 1464
- Ranalli P., Comastri A., Setti G., 2003, *A&A*, 399, 39
- Ricci C. et al., 2016, *ApJ*, 820, 5
- Ricci C., Ueda Y., Koss M. J., Trakhtenbrot B., Bauer F. E., Gandhi P., 2015, *ApJL*, 815, L13
- Risaliti G., Elvis M., Fabbiano G., Baldi A., Zezas A., 2005, *ApJL*, 623, L93
- Rivers E. et al., 2015, *ApJ*, 815, 55
- Rovilos E. et al., 2014, *MNRAS*, 438, 494
- Sako M., Kahn S. M., Paerels F., Liedahl D. A., 2000, *ApJL*, 543, L115
- Setti G., Woltjer L., 1989, *A&A*, 224, L21
- Shu X. W., Wang J. X., Yaqoob T., Jiang P., Zhou Y. Y., 2012, *ApJL*, 744, L21
- Shu X. W., Yaqoob T., Wang J. X., 2010, *ApJS*, 187, 581
- Smith D. A., Done C., 1996, *MNRAS*, 280, 355
- Smith R. K., Brickhouse N. S., Liedahl D. A., Raymond J. C., 2001, *ApJL*, 556, L91
- Stern D., 2015, *ApJ*, 807, 129
- Stern D. et al., 2012, *ApJ*, 753, 30
- Takahashi T. et al., 2007, *PASJ*, 59, 35
- Takahashi T. et al., 2014, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 9144, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 25
- Telesco C. M., Harper D. A., 1980, *ApJ*, 235, 392
- Treister E., Urry C. M., Virani S., 2009, *ApJ*, 696, 110
- Ueda Y., Akiyama M., Hasinger G., Miyaji T., Watson M. G., 2014, *ApJ*, 786, 104

Unger S. W. et al., 1988, MNRAS, 234, 745  
 Vasudevan R. V., Fabian A. C., 2007, MNRAS, 381, 1235  
 Vazdekis A., Ricciardelli E., Cenarro A. J., Rivero-González J. G.,  
 Díaz-García L. A., Falcón-Barroso J., 2012, MNRAS, 424, 157  
 Wright E. L. et al., 2010, AJ, 140, 1868  
 Xu C., Livio M., Baum S., 1999, AJ, 118, 1169  
 Yaqoob T., 2012, MNRAS, 423, 3360  
 Yaqoob T., Tatum M. M., Scholtes A., Gottlieb A., Turner T. J.,  
 2015, MNRAS, 454, 973

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