Coronal temperatures of the AGN ESO 103–035 and IGR 2124.7+5058 from NuSTAR observations

D. J. K. Buisson1,⋆, A. C. Fabian1 and A. M. Lohfink2
1Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA
2Department of Physics, Montana State University, Bozeman, 59717-3840, MT, USA

ABSTRACT
We present measurements of the coronae of two AGN from hard X-ray observations made with NuSTAR: ESO 103–035, a moderately to highly obscured source with significant reflection; and IGR 2124.7+5058, a radio-loud source with a very hard spectrum. Using an exponentially cut-off powerlaw model for the coronal emission spectrum gives a high-energy cut-off of 100+90−30 keV for ESO 103–035 and 80+11−9 keV for IGR 2124.7+5058, within the typical range for AGN. Fitting with physical Comptonisation models shows that these correspond to a temperature of 22+19−6 and 20+3−2 keV respectively. These values are consistent with pair production limiting the coronal temperature.

Key words: accretion, accretion discs – black hole physics – galaxies: individual: ESO 103–035, IGR 2124.7+5058 – galaxies: Seyfert

1 INTRODUCTION
Active Galactic Nuclei (AGN) are powered by accretion onto a supermassive black hole (SMBH), converting gravitational potential energy to radiation across the electromagnetic spectrum. Due to the shape of the gravitational potential well, the majority of the energy is released in the innermost few gravitational radii (r_g = GM/\(c^2\)). Localised to this region is the X-ray emitting corona, which Compton scatters incident optical and UV photons to X-ray energies (e.g. Haardt & Maraschi 1991) and is typically regarded as a region of electron pair plasma.

The X-ray spectrum of emission from the corona may be approximated by a powerlaw up to some cut-off energy where emission quickly rolls over (Rybicki & Lightman 1979). The index of this powerlaw and the energy at which the cut-off occurs are then the primary observable characteristics from which conditions in the corona may be inferred.

Since the high-energy cut-off occurs when the electrons are no longer able to add energy to the photons in an interaction, its value is governed by the electron temperature (if the particles in the corona have a roughly thermal spectrum). If the cut-off is modelled as an exponential suppression of the emission (N(E) \(\propto E^{-\Gamma}e^{-E/E_{\text{cut}}}/E_{\text{cut}}\)), the value inferred is around 2–3 times the temperature (Petrucci et al. 2001, where energy and temperature are expressed in the same units by \(E = k_{\text{B}}T\)).

The hard X-ray surveys performed by INTEGRAL (Malizia et al. 2014) and Swift-BAT (Vasudevan et al. 2013; Ricci et al. 2017) have shown that this cut-off is typically around a few hundred keV: Malizia et al. (2014) find a median of 128 keV and a standard deviation of 46 keV; Ricci et al. (2017) find a median of 200 ± 29 keV. The cut-off energy also seems to decrease with Eddington rate (Ricci et al. 2018).

The mechanism by which the coronal temperature is regulated is, however, still an open question. One possibility is (electron) pair production in photon-photon collisions, the rate of which increases rapidly above a certain temperature. This provides many more particles to share the energy and makes further temperature increase difficult (Bisnovatyi-Kogan et al. 1971; Svensson 1982; Guilbert et al. 1983; Svensson 1984). This temperature then acts as an effective upper limit for the electron temperature. This possibility was explored in Fabian et al. (2015) and found to be reasonable: sources were seen to have temperatures close to the limit imposed by pair production.

Observations from NuSTAR (Harrison et al. 2013) are able to refine this picture: owing to its ability to focus hard (up to 78 keV) X-rays, NuSTAR allows more precise measurements to be made of dimmer sources with shorter observations. This increased signal also allows the effect of degeneracy between curvature due to the cut-off and due to reflection to be reduced.

Here, we present new studies of the coronae of two AGN, ESO 103–035 and IGR 2124.7+5058, from recent NuSTAR observations.
was also observed with BeppoSAX significant absorption (Wilkes et al. 2001; Akylas et al. 2001), again finding 1.1 ESO 103–035

EXOSAT observations showed absorption with variability with HEAO-A2 (Marshall et al. 1979; Phillips et al. 1979). (V´ eron-Cetty & V´ eron 2006) initially detected in X-rays

Table 1.

| Source | Campaign | OBSID | Start date | Exposure/ks | Swift OBSIDs | Exposure/ks |
|--------|----------|-------|------------|-------------|--------------|-------------|
| ESO 103–035 | EGS      | 60061288002 | 2013-02-25 | 27.3 | 00080219001 | 6.7 |
| EGS     | Cycle 3  | 60301004002 | 2017-10-15 | 42.5 | 00088113001 | 1.9 |
| IGR 2124.7+5058 | EGS   | 60061305002 | 2014-12-13 | 23.9 | 00080273001/2 | 6.8 |
| EGS     | Cycle 3  | 60301005002 | 2018-01-02 | 40.2 | 00088113001/2/3 | 4.0 |

1.1 ESO 103–035

ESO 103–035 (z = 0.013) is an optical Seyfert 2 galaxy (V´ eron-Cetty & V´ eron 2006) initially detected in X-rays with HEAO-A2 (Marshall et al. 1979; Phillips et al. 1979). EXOSAT observations showed absorption with variability by almost a factor of 2 in column density over 90 days, from 1.7 to 1.0 × 10^{23} \text{cm}^{-2} (Warwick et al. 1988). ESO 103–035 was also observed with BeppoSAX, in October of 1996 and 1997 (Wilkes et al. 2001; Akylas et al. 2001), again finding significant absorption (N_H = 1.79 ± 0.09 × 10^{24} \text{cm}^{-2}) and also an iron-K emission line. Wilkes et al. (2001) additionally find an iron absorption edge and a low cut-off (29 ± 10 keV).

Furthermore, the galaxy contains a nuclear maser source (Bennert et al. 2004) and the black hole mass has been estimated as M_{BH} = 10^{7.1±0.6} M_\odot (Czerny et al. 2001).

The Galactic absorption column is modest, N_{H,\text{Gal}} = 4.56 − 6.81 × 10^{20} (Kalberla et al. 2005), 6.42 − 7.86 × 10^{20} cm^{-2} (Dickey & Lockman 1990).

1.2 IGR 2124.7+5058 (4C 50.55)

IGR J21247+5058 (4C 50.55, z = 0.02, Masetti et al. 2004) is a bright radio loud Seyfert 1 galaxy. Optical studies of this source have been challenging due to its alignment with a Galactic star (Masetti et al. 2004).

Several X-ray missions have observed IGR 2124.7+5058. Molina et al. (2007) analyse XMM-Newton data, finding significant absorption (up to 10^{23} \text{cm}^{-2}) and weak reflection. Combining the XMM data with INTEGRAL data constrains the high-energy cut-off to E_{\text{cut}} = 100^{+55}_{-30} keV. The addition of Swift-BAT data refines this to 79^{+25}_{-12} keV.

Tazaki et al. (2010) apply Comptonisation models to Suzaku observations, finding τ_e ~ 3 and kT_e ~ 30 keV. Their modelling of the Fe-K line finds an inner disc radius R_{in} ~ 700 r_g, which they explain by the inner disc being either truncated or covered by the corona. The flux is stable throughout most of the 170 ks observation but increases by 30\% below 10 keV in the last 20 keV.

IGR 2124.7+5058 is a radio-loud source, so it is possible that the X-ray spectrum includes a contribution from a jet. Tazaki et al. (2010) calculate the likely contribution based on the radio to gamma-ray SED and conclude that any contribution is between 10^{-4} and 10^{-3} of the X-ray power in observations of similar flux to those analysed here.

The Galactic absorption to IGR 2124.7+5058 is significant, being measured at N_{H,\text{Gal}} = 0.855 − 1.16 × 10^{22} (Kalberla et al. 2005), 1.02 − 1.39 × 10^{22} cm^{-2} (Dickey & Lockman 1990). Since the total absorption to IGR 2124.7+5058 is higher still and the redshift is low, differences in Galactic emission are degenerate with intrinsic absorption, so we fix Galactic absorption to 10^{22} cm^{-2}.

2 OBSERVATIONS AND DATA REDUCTION

There are two Swift observations of each source, separated by several years; each observation has a simultaneous Swift snapshot (see Table 1). For each source, one observation was made as part of the NuSTAR Extragalactic Survey (EGS) and one as a Cycle 3 Guest Observer target; we therefore refer to the observations as ‘EGS’ and ‘Cycle 3’.

We reduced the NuSTAR data with NUSTARDAS version 1.8.0 and CALDB version 20171002. We produced clean event files using NUPipeline, choosing filtering options for the SAA based on the online background reports. In each case we did not use XRT data in spectral fits of ESO 103–035.

For ESO 103–035, the high absorption column means that the XRT data provide little signal below 3 keV (only one bin with the grouping used) and the greater effective area of NuSTAR means this data dominates above 3 keV, so we do not use XRT data in spectral fits of ESO 103–035.

We also compare with the Swift-BAT data of the sources. We use the spectra from the 105 month catalogue and light curves from the transient monitor (Krimm et al. 2013). Spectra from all instruments (apart from Swift-BAT) were grouped to a signal to noise level of 6. Fits were made in ISIS Version 1.6.2-42 (Houck & Denicola 2000); errors are given at the 90% level. We use the elemental abundances of Wilms et al. (2000) with cross sections from Verner et al. (1996).
3 RESULTS

We begin by producing a light curve and hardness ratio for each source (Fig. 1). While both sources have changed in flux between their two observations, the light curves show little variability within an observation for IGR 2124.7+5058 and moderate slow variability for ESO 103-035. Additionally, there is little change in hardness within any observation: each observation is consistent with constant hardness and there is little change in hardness within any observation: each observation is consistent with constant hardness. ESO 103-035 matches the (Γ = 2 powerlaw) in Fig. 3. Each source shows a hard spectrum from the whole of each observation of each source.

We show the spectra unfolded against a constant model (Γ = 2 powerlaw) in Fig. 3. Each source shows a hard spectrum with significant absorption. ESO 103-035 matches the long-term Swift-BAT spectrum well but IGR 2124.7+5058 exceeds the BAT flux by almost a factor of 2 at high energies (within the NuSTAR band). This higher flux is consistent with the variability in the long-term BAT light curve (Figure 2).

To show spectral features more clearly, we also plot the ratio of each spectrum to an absorbed powerlaw. Since this ratio is primarily for display, we fix the absorption to this ratio is primarily for display, we fix the absorption to 2.5 towards their two observations, the light curves show much weaker reflection (Refl = 0.06 ± 0.02 and 0.25 ± 0.05). Since IGR 2124.7+5058 has a jet, this would fit with a scenario in which coronal material in IGR 2124.7+5058 is the outflowing base of this jet and hence beamed away from the disc. Such a model has been proposed to explain the variability of Mrk 335 (Wilkins & Gallo 2015) and the relationship between radio Eddington luminosity and X-ray reflection fraction (King et al. 2017).

The cross-calibration between NuSTAR and Swift-XRT is slightly below that expected from IACHEC calibration observations (Madsen et al. 2017) but not unreasonable when allowing for source variability.

There is inevitably some degeneracy between curvature due to the high-energy cut-off and due to reflection. To quantitatively test this, we calculate confidence contours in the cut-off/reflection fraction plane (Figure 6). This shows (particularly for ESO 103-035) the expected degeneracy, in that the fit has either a lower cut-off energy or a higher reflection fraction. However, in each case both parameters are still constrained (though only weakly for the shallowest, ESO 103-035 EGS, observation).

To test the effect of different models, we perform a similar fit with the XMIX model (García et al. 2013), which has a more detailed model for the reflected spectrum. We fit for the same parameters as the PEXMON model and fix the additional ionisation parameter log(ξ/erg cm s⁻¹) = 0 to best match the neutral PEXMON reflection. This recovers very similar parameters (Tables 2 and 3).

3.1 Spectral fitting

We begin with a model with components to account for all of the spectral features mentioned. We use (2)TRABS (Wilms et al. 2000) for Galactic (z = 0) and intrinsic (matched to source redshift) absorption. We do not include the Galactic component for ESO 103-035 since this is insignificant compared to the intrinsic absorption. We initially use PEXMON to model the direct and reflected emission. This allows for a cut-off in direct coronal emission (modelled by an exponential cut-off) and reflection from neutral material with an iron-Kα line, calculated self-consistently for a given metallicity. We allow the coronal parameters (Γ and Ecut), reflection fraction and iron abundance to vary but freeze the inclination to the default value (θ = 60°).

This provides reasonable fits to each dataset (Tables 2,3). The iron abundance for IGR 2124.7+5058 is high (AFe > 12), although such high abundances have been found in other AGN (e.g. Fabian et al. 2009; Ponti et al. 2010). This could occur if there is significant enrichment of the nuclear gas by earlier generations of stars, through for example supernovae and stellar winds.

The cut-off energies, 130^{+450}_{-60} and 100^{+90}_{-30} keV for ESO 103-035 and 78^{+14}_{-12} and 80^{+15}_{-9} keV for IGR 2124.7+5058, are consistent between observations for both sources and in agreement with at least some previous observations (ESO 103-035: 57^{+14}_{-14} keV, Ricci et al. 2017; IGR 2124.7+5058: 79^{+12}_{-12} keV, Molina et al. 2007). The powerlaw indices are all relatively hard. IGR 2124.7+5058 in particular has a very hard spectrum (Γ = 1.53 ± 0.03 and 1.52 ± 0.03) but not harder than has been found previously for this source (Γ = 1.5, Molina et al. 2007).

The sources differ markedly in their reflection fractions. While ESO 103-035 has a reflection fraction around 1, as expected from illumination of a disc by an isotropic source away from strong relativistic effects, IGR 2124.7+5058 has much weaker reflection (Refl = 0.06 ± 0.02 and 0.25 ± 0.05). Since IGR 2124.7+5058 has a jet, this would fit with a scenario in which coronal material in IGR 2124.7+5058 is the outflowing base of this jet and hence beamed away from the disc. Such a model has been proposed to explain the variability of Mrk 335 (Wilkins & Gallo 2015) and the relationship between radio Eddington luminosity and X-ray reflection fraction (King et al. 2017).

The cross-calibration between NuSTAR and Swift-XRT is slightly below that expected from IACHEC calibration observations (Madsen et al. 2017) but not unreasonable when allowing for source variability.

There is inevitably some degeneracy between curvature due to the high-energy cut-off and due to reflection. To quantitatively test this, we calculate confidence contours in the cut-off/reflection fraction plane (Figure 6). This shows (particularly for ESO 103-035) the expected degeneracy, in that the fit has either a lower cut-off energy or a higher reflection fraction. However, in each case both parameters are still constrained (though only weakly for the shallowest, ESO 103-035 EGS, observation).

To test the effect of different models, we perform a similar fit with the XMIX model (García et al. 2013), which has a more detailed model for the reflected spectrum. We fit for the same parameters as the PEXMON model and fix the additional ionisation parameter log(ξ/erg cm s⁻¹) = 0 to best match the neutral PEXMON reflection. This recovers very similar parameters (Tables 2 and 3).

3.1.1 Comptonisation models

Having determined the shape of the high-energy roll-over phenomenologically, we now fit with physical Comptonisation models to obtain a direct constraint on the electron temperature.

We use the XMIX model so that the reflected component is calculated self-consistently with the illuminating Comptonised continuum, which is generated with the NTCOMP model (Zdziarski et al. 1996; Życki et al. 1999). We again allow equivalent parameters to our previous models to be free. Fits to this model are given in Tables 2,3. Most parameters are similar to those found for the previous models, but the fits to IGR 2124.7+5058 have a significantly softer photon index (Γ = 1.72 ± 0.01 rather than 1.52 ± 0.03).

The electron temperatures for ESO 103-035 are consistent with the expectation of a factor of 2 – 3 lower than the cut-off energy (Petrucci et al. 2001). For IGR 2124.7+5058, this difference is slightly larger (around a factor of 4, though we note that the fit quality for IGR 2124.7+5058 is not perfect). This could be due to the difference in shape of the reflected component (but this would be expected to have a larger effect in ESO 103-035, which has stronger reflection) or because the difference between Ecum and KE becomes larger at high optical depth, which corresponds to a harder spectrum (Petrucci et al. 2001).
Figure 1. *NuSTAR* (FPMA) light curve and hardness ratio with 300 s bins for ESO 103–035 (left) and IGR 2124.7+5058 (right). The first (blue) curve for each source shows the EGS observation, the second (yellow) cycle 3. The rate is given for 3–78 keV. Hardness is defined as \((H - S)/(H + S)\), where \(H\) is 10–50 keV rate and \(S\) is 3–10 keV rate.

Figure 2. *Swift*-BAT light curves of ESO 103–035 (left) and IGR 2124.7+5058 (right), binned to 20 days, with times of *NuSTAR* observations shown as vertical lines.

| Dataset | EGS | Cycle 3 |
|---------|-----|---------|
| Model   | PEXMON | XILLVER | XILLVERCP | RELXILLCP | PEXMON | XILLVER | XILLVERCP | RELXILLCP |
| \(N_H/10^{22}\)cm\(^{-2}\) | 17.1\(^{+1.3}_{-1.9}\) | 17.0\(^{+1.8}_{-1.6}\) | 17.3\(^{+1.6}_{-1.8}\) | 17.6\(^{+1.9}_{-1.7}\) | 15.6\(^{+1.2}_{-1.4}\) | 15.4\(^{+1.4}_{-1.2}\) | 16.4\(^{+1.2}_{-1.0}\) | 16.1\(^{+1.0}_{-1.0}\) |
| \(\Gamma\) | 1.82\(^{+0.16}_{-0.16}\) | 1.79\(^{+0.16}_{-0.14}\) | 1.84\(^{+0.16}_{-0.16}\) | 1.86\(^{+0.16}_{-0.16}\) | 1.74\(^{+0.13}_{-0.13}\) | 1.73\(^{+0.15}_{-0.15}\) | 1.82\(^{+0.16}_{-0.16}\) | 1.76\(^{+0.08}_{-0.08}\) |
| \(E_{\text{cut}}/\)keV | 130\(^{+40}_{-40}\) | 110\(^{+40}_{-40}\) | - | - | 100\(^{+30}_{-30}\) | 100\(^{+100}_{-100}\) | - | - |
| \(kT_0/\)keV | - | - | > 17 | > 20 | - | - | 27\(^{+200}_{-9}\) | 22\(^{+19}_{-6}\) |
| \(A_{\text{Fe}}\) | 0.8\(^{+0.4}_{-0.3}\) | 1.1\(^{+0.4}_{-0.5}\) | 1.5\(^{+0.6}_{-0.6}\) | < 7 | 0.8\(^{+0.3}_{-0.2}\) | 0.9\(^{+0.5}_{-0.3}\) | 1.6\(^{+0.8}_{-0.4}\) | 2.0\(^{+1.1}_{-1}\) |
| \(R_{\text{ refl}}\) | 1.1\(^{+0.3}_{-0.2}\) | 0.8\(^{+0.4}_{-0.2}\) | 0.7\(^{+0.2}_{-0.2}\) | 0.8\(^{+0.2}_{-0.5}\) | 1.2\(^{+0.3}_{-0.3}\) | 1.0\(^{+0.2}_{-0.2}\) | 0.8\(^{+0.6}_{-0.2}\) | 0.6\(^{+0.2}_{-0.2}\) |
| \(\theta/10^\circ\) | < 17 | - | - | - | - | - | - | - |
| \(C_{\text{FPMB/FPMA}}\) | 1.06\(^{+0.018}_{-0.018}\) | 1.06\(^{+0.018}_{-0.018}\) | 1.06\(^{+0.018}_{-0.018}\) | 1.06\(^{+0.018}_{-0.018}\) | 1.03\(^{+0.015}_{-0.015}\) | 1.03\(^{+0.015}_{-0.015}\) | 1.03\(^{+0.015}_{-0.015}\) | 1.03\(^{+0.015}_{-0.015}\) |
| \(\chi^2/\text{d.o.f.}\) | 634/645 | 635/645 | 636/645 | 638/642 | 768/778 | 775/778 | 759/778 | 743/775 |

Table 2. Parameters of fits to ESO 103–035. Models are labelled by their primary component; each model also contains intrinsic absorption (with column density \(N_H\)) and a cross-calibration constant between detectors (\(C_{\text{FPMB/FPMA}}\)).
Figure 3. Unfolded spectra of ESO 103–035 (left) and IGR 2124.7+5058 (right). Both sources have hard, absorbed spectra. ESO 103–035 shows similar hard-energy emission to the long-term average from Swift-BAT; IGR 2124.7+5058 is brighter and harder in the NuSTAR observations than the average. Swift-XRT (< 10 keV) is shown in black (EGS) and red (Cycle 3); NuSTAR (3 – 78 keV) in blue (EGS) and yellow (Cycle 3); and Swift-BAT (15 – 200 keV) in purple.

Figure 4. Ratio of spectra of ESO 103–035 (left) and IGR 2124.7+5058 (right) to an absorbed powerlaw. For each source, the absorption is fixed to the best fit value from fits presented later and powerlaw parameters are fit to each observation separately. Both sources show a roll-over at high energies, while reflection features are stronger in ESO 103–035.

Table 3. Parameters of fits to IGR 2124.7+5058. Models are labelled by their primary emission component; each model also contains Galactic absorption (with \( N_H = 10^{22}\) cm\(^{-2}\)) intrinsic absorption (with column density \( N_H \)) and cross-calibration constants between detectors (\( C_{FPMB/FPMA}, C_{XRT/FPMA} \)).
3.1.2 Alternative models

While the fit for ESO 103–035 is formally acceptable, residuals are apparent around the iron line. Therefore, we also test a model with relativistically blurred reflection, using RELXILLCP (Dauser et al. 2010; García et al. 2014). For the Cycle 3 observation, this gives a somewhat better fit, $\Delta \chi^2 = 15$ and shows only weak blurring ($R_{\text{in}} > 7 R_{\text{ISCO}}$). For the EGS observation, there is minimal improvement and parameters are consistent with the least blurring available to the model. Parameters of the Comptonised continuum are consistent with the unblurred model. For completeness, we also fit this model to the observations of IGR 2124.7+5058 but this does not provide a significant improvement.

We also consider a jet component in IGR 2124.7+5058: while Tazaki et al. (2010) estimate the contribution of a jet component to be subdominant, it is possible that even a small contribution has an effect on the more sensitive NuSTAR spectra presented here or that the jet emission has increased to a more significant level. Therefore, we also consider a model including a jet component approximated by a hard ($\Gamma < 1.5$) power law. This reduces the best-fit value of the coronal temperature, as the high-energy coronal emission is replaced by the jet; the exact value depends on the index assumed for the jet component. If allowing any value of jet power, our coronal temperature measurement could then be seen as an upper limit. However, a strong jet component requires a $> 78$ keV flux far above the *Swift*-BAT.
value so would require a highly variable jet. We therefore note this possible effect of jet emission but do not pursue the quantitative effect further.

### 3.2 Comparison to other sources

We compare the temperature and compactness of the coronae of ESO 103-035 and IGR 2124.7+5058 with that found for other sources by Fabian et al. (2015). Using the formulae in Fabian et al. (2015), we calculate compactness, $\ell$, and electron temperature, $kT_e$ for each observation. We take the required values of coronal luminosity and high-energy cut-off from the PEXMON fit, since this is the most commonly used model in fits to the other sources in the sample. Using values from the other models gives similar results. Since we have no strong constraint on the coronal size, we follow Fabian et al. (2015) in using a fiducial value of $10r_g$. For ESO 103-035 we use the mass estimate of Czerny et al. (2001), $M_{BH} = 10^{7.1\pm0.6} M_\odot$, and $M_{BH} = 10^{7.5\pm1.5} M_\odot$. This constraint in the $\ell - T$ plane is shown in Figure 7. Both sources have temperatures below the limit imposed by the pair thermostat and within the typical range of other sources of similar compactness. The upper limits for IGR 2124.7+5058 are significantly below the pair thermostat limit; this may indicate that some of the electrons in the corona have a non-thermal energy distribution (Fabian et al. 2017), as might the better description by an exponential roll-over than a thermal Comptonisation model.

### 4 DISCUSSION

We have presented new hard X-ray spectra of two AGN made by NuSTAR and compared the coronal parameters found with the predictions of the pair thermostat for coronal temperature regulation.

Both sources have features which differ from the simplest typical AGN, which often formed the basis for the first round of NuSTAR observations. ESO 103-035 has strong and variable obscuration ($\sim 1.7 \pm 0.2 \times 10^{23} \text{cm}^{-2}$ here, previously $1.0 - 1.7 \times 10^{23} \text{cm}^{-2}$, Warwick et al. 1988) and IGR 2124.7+5058 has both a very hard spectrum ($\Gamma \sim 1.5$) and significant radio emission (Ribo et al. 2004; Combi et al. 2005). The strong obscuration makes measuring other spectral properties harder as their effects must be separated from features of obscuration. Since NuSTAR has good sensitivity up to high energies, we can still constrain features including the high-energy cut-off (which principally affects the spectrum at higher energies than obscuration) although to a lesser extent than might be possible with similarly deep observations of unobscured sources. Despite their idiosyncrasies, both sources show coronal temperatures within the typical range for AGN (see Figure 7). This could indicate a controlled means of temperature regulation independent of the wider AGN environment, such as the pair thermostat.
Swift agrees with that found from previous instruments. The coronal temperature of ESO 103–035
able present an opportunity to cross-check results from previous instruments. The coronal temperature of ESO 103–035
8
D. J. K. Buisson et al.
that found with that found from Swift-BAT (Ricci et al. 2017) and that of IGR 2124.7+5058 agrees with INTEGRAL (Malizia et al. 2014). This is promising for the robustness of results such as the decrease of cut-off energy with increasing Eddington rate (Ricci et al. 2018) derived from such spectra.

We have also considered possible means of temperature regulation and found that both sources lie in the region of the $\ell - T$ plane allowed by the pair thermostat. The position relative to the annihilation limit is consistent with pair annihilation being an important means of regulation of the coronal temperature. Furthermore, IGR 2124.7+5058 has a temperature significantly below that implied by the pair thermostat. This could be due to the electron population including a non-thermal component, which tends to lower the limiting temperature (Fabian et al. 2017).

It is also possible that the compactness presented here is an under-estimate. Firstly, the $10r_g$ size is a relatively high value: AGN coronae have often been found to be significantly smaller (e.g. Parker et al. 2014), although this is usually accompanied by strong relativistic reflection. Secondly, the corona may have a highly inhomogeneous flux-density: it may composed of many much smaller regions of higher compactness within the overall $\sim 10r_g$ extent. Both these effects would move the points upwards, closer to the pair-production limit.

ACKNOWLEDGEMENTS

DJKB acknowledges financial support from the Science and Technology Facilities Council (STFC). ACF acknowledges support from the ERC Advanced Grant FEEDBACK 340442. This work made use of data from the NuSTAR mission, a project led by the California Institute of Technology, managed by the Jet Propulsion Laboratory, and funded by the National Aeronautics and Space Administration. This research has made use of the NuSTAR Data Analysis Software (NuSTARDAS) jointly developed by the ASI Science Data Center (ASDC, Italy) and the California Institute of Technology (USA). This work made use of data supplied by the UK Swift Science Data Centre at the University of Leicester.

REFERENCES

Akylas A., Georgantopoulos I., Comastri A., 2001, MNRAS, 324, 521
Bennett N., Schulz H., Henkel C., 2004, A&A, 419, 127
Bisnovatyi-Kogan G. S., Zel dovich Y. B., Syunyaev R. A., 1971, Soviet Astr., 15, 17
Combi J. A., Ribó M., Mirabel I. F., 2005, ApSS, 297, 385
Czerny B., Niko lajuk M., Piasecki M., Kuraszkiewicz J., 2001, MNRAS, 325, 865
Dauser T., Wilms J., Reynolds C. S., Brenneman L. W., 2010, MNRAS, 409, 1534
Dickey J. M., Lockman F. J., 1990, ARA&A, 28, 215
Evans P. A., et al., 2009, MNRAS, 397, 1177
Fabian A. C., et al., 2009, Nature, 450, 540
Fabian A. C., Lohfink A., Kara E., Parker M. L., Vasudevan R., Reynolds C. S., 2015, MNRAS, 451, 4375
Fabian A. C., Lohfink A., Belmont R., Malzac J., Coppi P., 2017, MNRAS, 467, 2566
García J., Dauser T., Reynolds C. S., Kallman T. R., McClintock J. E., Wilms J., Eilímmann W., 2013, ApJ, 768, 146
García J., et al., 2014, ApJ, 782, 76
Guilbert F. W., Fabian A. C., Rees M. J., 1983, MNRAS, 205, 593
Haardt F., Maraschi L., 1991, ApJ, 380, L51
Harrison F. A., et al., 2013, ApJ, 770, 103
Houck J. C., Denicola L. A., 2000, in Manset N., Veillet C., Crabtree D., eds, Astronomical Society of the Pacific Conference Series Vol. 216, Astronomical Data Analysis Software and Systems IX. p. 591
Kalberla P. M. W., Burton W. B., Hartmann D., Arnal E. M., Bajaja E., Morras R., Poppel W. G. L., 2005, A&A, 440, 775
King A. L., Lohfink A., Kara E., 2017, ApJ, 835, 226
Krimm H. A., et al., 2013, ApJS, 209, 14
Madsen K. K., Beardmore A. P., Forster K., Guainazzi M., Marshall H. L., Miller E. D., Page K. L., Stuhlinger M., 2017, AJ, 153, 2
Malizia A., Molina M., Bassani L., Stephen J. B., Bazzano A., Ubertini P., Bird A. J., 2014, ApJ, 782, L25
Marshall F. E., Boldt E. A., Holt S. S., Mushotzky R. F., Pravdo S. H., Rothschild R. E., Serlemitsos P. J., 1979, ApJS, 40, 657
Masetti N., Palazzi E., Bassani L., Malizia A., Stephen J. B., 2004, A&A, 426, L41
Molina M. et al., 2007, MNRAS, 382, 937
Oh K., et al., 2018, ApJS, 235, 4
Parker M. L., et al., 2014, MNRAS, 443, 1723
Petrucci P. O., et al., 2001, ApJ, 556, 716
Phillips M. M., Feldman P. R., Marshall F. E., Wamsteker W., 1979, A&A, 76, L14
Ponti G., et al., 2010, MNRAS, 406, 2591
Ribó M., Combi J. A., Mirabel I. F., 2004, The Astronomer’s Telegram, 235
Ricci C., et al., 2017, ApJS, 233, 17
Ricci C., et al., 2018, MNRAS, 480, 1819
Rybicki G. B., Lightman A. P., 1979, Radiative processes in astrophysics
Svensson R., 1982, ApJ, 258, 335
Svensson R., 1984, MNRAS, 209, 175
Tazaki F., Ueda Y., Ishino Y., Eguchi S., Isobe N., Terashima Y., Mushotzky R. F., 2010, ApJ, 721, 1340
Vasudevan R. V., Brandt W. N., Mushotzky R. F., Winter L. M., Baumgartner W. H., Shimizu T. T., Schneider D. P., Nousek J., 2013, ApJ, 763, 11
Verner D. A., Ferland G. J., Korista K. T., Yakovlev D. G., 1996, ApJ, 465, 487
Véron-Cetty M.-P., Véron P., 2006, A&A, 455, 773
Warwick R. S., Pounds K. A., Turner T. J., 1988, MNRAS, 231, 1145
Wilkes B. J., Mathur S., Fiore F., Antonelli A., Nicastro F., 2001, ApJ, 549, 248
Wilkins D. R., Gallo L. C., 2015, MNRAS, 449, 129
Wilms J., Allen A., McCray R., 2000, ApJ, 542, 914
Zdziarski A. A., Johnson W. N., Magdziarz P., 1996, MNRAS, 283, 193
Zycki P. T., Done C., Smith D. A., 1999, MNRAS, 309, 561

MNRAS 000, 1–9 (2018)
This paper has been typeset from a \TeX/\LaTeX\ file prepared by the author.