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Uncovering the geometry of the hot X-ray corona in the Seyfert galaxy NGC 4151 with IXPE

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ABSTRACT

We present an X-ray spectropolarimetric analysis of the bright Seyfert galaxy NGC 4151. The source has been observed with the *Imaging X-ray Polarimetry Explorer* (*IXPE*) for 700 ks, complemented with simultaneous *XMM–Newton* (50 ks) and *NuSTAR* (100 ks) pointings. A polarization degree $\Pi = 4.9 \pm 1.1$ per cent and angle $\Psi = 86^\circ \pm 7^\circ$ east of north (68 per cent confidence level) are measured in the 2–8 keV energy range. The spectropolarimetric analysis shows that the polarization could be entirely due to reflection. Given the low reflection flux in the *IXPE* band, this requires, however, a reflection with a very large (>38 per cent) polarization degree. Assuming more reasonable values, a polarization degree of the hot corona ranging from ∼4 to ∼8 per cent is found. The observed polarization degree excludes a 'spherical' lamppost geometry for the corona, suggesting instead a *slab*-like geometry, possibly a *wedge*, as determined via Monte Carlo simulations. This is further confirmed by the X-ray polarization angle, which coincides with the direction of the extended radio emission in this source, supposed to match the disc axis. NGC 4151 is the first active galactic nucleus with an X-ray polarization measure for the corona, illustrating the capabilities of X-ray polarimetry and *IXPE* in unveiling its geometry.

Key words: polarization – galaxies: active – galaxies: individual: NGC 4151 – galaxies: Seyfert.

1 INTRODUCTION

The common paradigm for active galactic nuclei (AGNs; Antonucci 1993) postulates the presence of a corona of hot electrons ($kT_e \simeq$ 10–100 keV), responsible for the primary continuum in the hard X-rays through inverse Comptonization of ultraviolet (UV) photons (Sunyaev & Titarchuk 1980; Zdziarski, Poutanen & Johnson 2000).

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Despite widespread acceptance of this process, the source of energy for the plasma and the conditions leading to its formation remain open questions. The geometry of this region further contributes to these debates, ranging from a *slab*-corona model (Haardt & Maraschi 1991, 1993; Merloni 2003), in which the energy dissipation and electron heating occur over a large volume, to a compact source located on the accretion disc axis (lamppost geometry; Martocchia & Matt 1996; Fabian et al. 2017) and whose possible origin could be an aborted jet (see Henri & Petrucci 1997; Ghisellini, Haardt & Matt 2004). Compton scattering will produce a polarization signal that is strongly sensitive to the geometry of the scattering material. Although spectroscopy and timing alone were not been able to distinguish between geometrical models so far, their application alongside polarization can aid in determining the characteristics of the corona such as the Thomson optical depth τ and the electron temperature $kT_{\rm e}$ (Shapiro, Lightman & Eardley 1976). X-ray polarimetry is thus a powerful tool that can be used to bring new insights on the innermost regions of AGNs. In particular, from 'spherical' lamppost coronae, a polarization degree of 1 per cent or so is expected, while larger values are anticipated when the scattering medium is distributed as a *slab* over the accretion disc (Poutanen & Svensson 1996; Tamborra et al. 2018; Ursini et al. 2022).

The *Imaging X-ray Polarimetry Explorer* (*IXPE*; Weisskopf et al. 2022), launched on 2021 December 9, is a NASA/ASI mission and the first X-ray imaging polarimeter in orbit after 40 yr. Thanks to three telescopes with polarization-sensitive imaging detectors (Gas Pixel Detector; Costa et al. 2001) effective in the 2–8 keV energy band, X-ray polarimetric studies on AGNs are being carried out for the first time. So far a total of four radio-quiet AGNs (i.e. MCG-05-23-16, the Circinus galaxy, NGC 4151, and IC 4329A) have been observed by *IXPE*. A polarization degree $\Pi < 4.7$ per cent was derived for MCG-05-23-16, in agreement with expectations from a lamppost 'spherical' geometry of the corona, or a *slab* geometry if the inclination angle of the system is less than 50° (Marinucci et al. 2022). On the other hand, the Circinus galaxy shows a very high $\Pi \sim 28 \pm 7$ per cent with a polarization angle perpendicular to the radio jet at about $\psi_{\rm X} \sim 18^\circ \pm 5^\circ$ (Ursini et al. 2023). However, this source is Compton-thick with no direct view of the corona, so all the polarization is ascribed to reflection from an equatorial torus, as expected from the standard unification model.

NGC 4151 is one of the brightest Seyfert galaxies in the local Universe. It has been classified as a changing-look AGN (Penston & Perez 1984; Puccetti et al. 2007; Shapovalova et al. 2008), going from optical type 1.5 at high-flux states (in which the source reaches up to $F_{0.5-10\,\rm keV} \sim 2.8 \times 10^{-10}$ erg s^{-1} cm^{-2}) to optical type 1.8 at low-flux states ($F_{0.5-10\,\rm keV} \sim 8.7 \times 10^{-11}$ erg s^{-1} cm^{-2}; see Antonucci & Cohen 1983; Shapovalova et al. 2012; Beuchert et al. 2017). NGC 4151 has been intensively observed by all major X-ray satellites. It is characterized with significant spectral variability, and a complex absorption structure, both from neutral gas and from ionized gas (e.g. Beuchert et al. 2017). Below ~2 keV, the soft X-ray emission is dominated by emission lines (e.g. Schurch et al. 2004), likely arising from photoionized gas in the narrow-line region, as commonly found in obscured AGNs (Bianchi, Guainazzi & Chiaberge 2006; Guainazzi & Bianchi 2007; Bianchi et al. 2019). Previous studies found evidence for relativistic reflection off the accretion disc, suggesting a near-maximal spinning black hole (Cackett et al. 2014; Keck et al. 2015a; Beuchert et al. 2017). Given a black hole (BH) mass of 4.57×10^7 M$_\odot$ (from optical and UV reverberation; Bentz et al. 2006), the source has a relatively low Eddington ratio, 1 per cent (Keck et al. 2015a).

In the following, we present the spectral and spectropolarimetric analyses of the combined data from *IXPE*, *XMM–Newton*, and *NuSTAR*, providing the most complete view to date of the inner accretion flow in NGC 4151. The paper is organized as follows. In Section 2, we describe the *IXPE*, *XMM–Newton*, and *NuSTAR* observations and data reduction. In Section 3, we report on the spectral and spectropolarimetric analyses. In Section 4, the results are discussed.

2 OBSERVATIONS AND DATA REDUCTION

IXPE (Weisskopf et al. 2022) observed NGC 4151 starting on 2022 December 8 with its three detector units (DU), for a net exposure time of about 632 ks. The data were calibrated with a standard *IXPE* pipeline from the Science Operation Center.[1] The pipeline mainly contains the correction processes on the photoionization events and the track reconstruction process following a standard moment analysis (Bellazzini et al. 2003; Fabiani & Muleri 2014; Di Marco et al. 2022). In addition, variations on gain properties that are caused by susceptibility of gas status (e.g. temperature and pressure) inside the Gas Pixel Detector (Costa et al. 2001; Bellazzini et al. 2007; Fabiani et al. 2012; Baldini et al. 2021) and non-uniformity of the charging on the Gas Electron Multiplier material are accounted for. The onboard calibration data were utilized to deal with the small time-scale variations (Ferrazzoli et al. 2020). The spurious modulation was also taken into account in this process (Rankin et al. 2022). The scientific analysis was performed using the IXPEOBSSIM software version 30.2.1 (Baldini et al. 2022). Source and background data were extracted centred on the source position in the detector frame that covered the entire source emission and source-free regions, respectively. For the region selection criteria, we applied a 72 arcsec circle for the source and an annulus with inner and outer radii of 150 and 240 arcsec, respectively, for the background (Di Marco et al. 2023). In order to estimate the polarization properties, we created (1) the polarization cube (`PCUBE`) based on the Kislat et al. (2015) method, which provided results independent of any spectral modelling, and (2) *I*, *Q*, and *U* spectra using PHA1, PHAQ1, and PHAU1 algorithms in the `xpbin` tool inside IXPEOBSSIM. We utilized the version 12 instrument response functions for both methods, which are contained in IXPEOBSSIM. We adopted a minimum of 30 counts binning for spectra *I* and 0.2 keV constant energy binning for *Q* and *U* spectra in order to perform spectropolarimetric analysis based on χ^2 statistics. For the spectra, we employed the weighted method (Di Marco et al. 2022) using the `alpha075` response matrix to improve the sensitivity of polarimetry measurements. In contrast, this feature is not currently available within the `pcube` algorithm.

XMM–Newton observed NGC 4151 on 2022 December 17 for 50 ks of elapsed time with the EPIC pn (Strüder et al. 2001) and the two MOS (Turner et al. 2001) cameras, operating in small window and thin filter mode to avoid pile-up effects. Background flares were present during the observation, and after the filtering process, the effective exposure time resulted to be about 33 ks for the pn spectrum. The extraction radii for the source and the background spectra are 20 and 30 arcsec, respectively. The effective area was corrected with the new SAS keyword, APPLYABSFLUXCORR, expressly implemented to provide a better agreement with simultaneous *NuSTAR* data. In the following fits, we allow for an energy shift of the order of 1000 km s^{-1} (modelled with `vashift`) at the iron line to mitigate some

[1] https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/IXPE-SOC-DOC-009-UserGuide-Software.pdf

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residual calibration issues, as noted also in other recent observations of bright AGNs (Ingram et al. 2023; Serafinelli et al. in preparation).

The *NuSTAR* (Harrison et al. 2013) observation started on 2022 December 16 simultaneously to *XMM* and *IXPE* pointings, with both coaligned X-ray telescopes with Focal Plane Module A (FPMA) and B (FPMB). The `Nupipeline` task and the latest calibration files available in the data base (CALDB 20221229) were used to produce and calibrate cleaned event files. In this case, the source and background extraction radii are 2 and 1.22 arcmin, respectively. The net exposure time for the FPMA and FPMB resulted to be 97 and 96.3 ks, respectively. Significant deviations from the pn spectrum were still present in the *NuSTAR* spectra below 4 keV, even after applying the correction mentioned above. Therefore, we will consider *NuSTAR* data only above 4 keV (see e.g. Madsen et al. 2020). Moreover, an energy shift between the two instruments is evident at the iron line.[2] On the other hand, the MOS data are in agreement with the pn, although with larger uncertainties. In the following fits, we thus applied a linear GAIN FIT of ~ -60 eV to the *NuSTAR* spectra. We note here that a similar shift is found in AGN observations taken $\sim$1 month before and after our data set (Ingram et al. 2023; Serafinelli et al. in preparation).

All the uncertainties are given at 68 per cent (1σ) confidence level, unless otherwise stated, while the upper/lower limits are quoted at 99 per cent (2.6σ) confidence level for one interesting parameter. Throughout our analysis, we adopt a redshift $z = 0.003326$ for NGC 4151 (Wolfinger et al. 2013), and the cosmological parameters $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Lambda_0 = 0.73$, and $\Lambda_m = 0.27$.

3 DATA ANALYSIS

3.1 *IXPE* polarimetric analysis

We report the first significant polarization detection from NGC 4151 using `PCUBE` analysis. The measured polarization parameters from the three combined DUs are $\Pi_X = 4.9$ per cent $\pm$ 1.1 per cent and $\psi_X = 86^\circ \pm 7^\circ$ in the 2–8 keV band with background subtraction. The detection significance of these polarization properties is above 99.99 per cent confidence level ($\sim 4.4\sigma$). In order to examine the energy dependence of the polarization, we tested against the hypothesis that Q and U Stokes parameters are constant via a χ^2 test, adopting different energy binnings (from 2 to 12 bins over the entire energy band, e.g. Di Gesu et al. 2022). We found a statistically significant (>99 per cent confidence level) deviation from the constant behaviour in Q, when adopting three and four bins. Fig. 1 and Table 1 show the data into three energy bands: 2.0–3.5, 3.5–5.0, and 5.0–8.0 keV. In the polarization contour plot, significant detections are found for the two higher energy bins (3.5–5.0 and 5.0–8.0 keV), while only a marginal detection can be claimed for the first bin (2.0–3.5 keV), possibly suggesting also a variation of the polarization angle, thus confirming the variability in Q mentioned above.

3.2 Spectral analysis: *XMM–Newton* and *NuSTAR*

The spectral analysis of NGC 4151 is performed with XSPEC 12.13.0 (Arnaud 1996), taking into account the simultaneous 0.5–10 keV *XMM–Newton* and 4–79 keV *NuSTAR* spectra. In the new observations, the source has been detected in a high flux state with $F_{0.5-10\,\mathrm{keV}} \sim 1.7 \times 10^{-10}$ erg s^{-1} cm^{-2}.

As mentioned in Section 1, the X-ray spectrum of this source is remarkably complex with different emission and absorption components (e.g. Weaver et al. 1994; Zdziarski, Johnson & Magdziarz 1996; Yang, Wilson & Ferruit 2001; De Rosa et al. 2007; Kraemer, Schmitt & Crenshaw 2008; Lubiński et al. 2010). Our best-fitting model implements and tries to simplify those adopted by Keck et al. (2015a) and Szanecki, Niedźwiecki & Zdziarski (2021) for the previous *XMM–Newton*, *Suzaku*, and *NuSTAR* observations of the source. The Galactic absorbing column density, modelled with `tbabs`, is set to $N_H = 2.3 \times 10^{20}$ cm^{-2} (Kalberla et al. 2005) and multiplicative constants (found to be of the order of $\sim$1.20) take into account cross-calibration uncertainties between the two FPM modules and EPIC pn, as well as some flux variability of the source during the longer elapsed time of the *NuSTAR* observation. We adopt the default abundance table in XSPEC (Anders & Grevesse 1989).

In previous studies, a strong Fe K α emission line with a weak relativistic component was reported in high flux states (e.g. Yaqoob et al. 1995; Zoghbi, Miller & Cackett 2019; and references therein). In the new *XMM–Newton* and *NuSTAR* observations, the Fe K α line

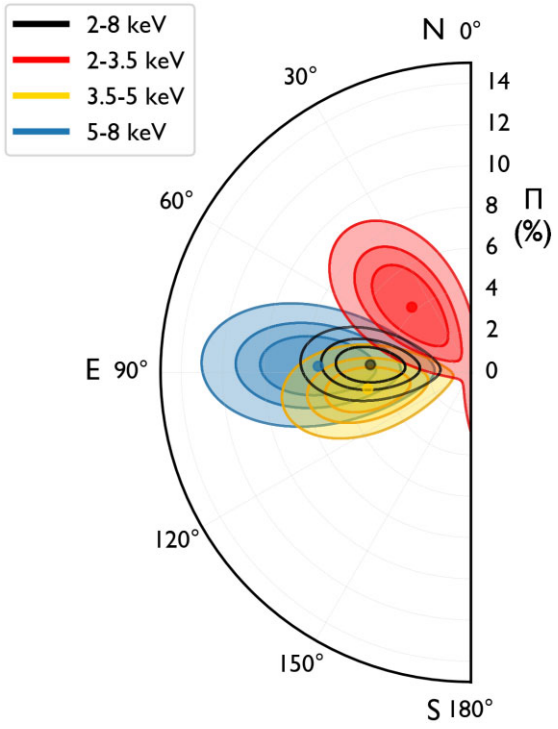

Figure 1. Polarization contours (68, 90, and 99 per cent confidence levels for two degrees of freedom) for the polarization degree Π_X and the polarization angle ψ_X with respect to the north direction. Colours refer to the 2.0–8.0 keV (black), 2.0–3.5 keV (red), 3.5–5.0 keV (yellow), and 5.0–8.0 keV (blue) energy ranges.

Table 1. Polarization parameters for different energy bands.

Energy range (keV)	$\Pi_X \pm 1\sigma$ (per cent)	$\psi_X \pm 1\sigma$ (deg)
2.0–8.0	4.9 ± 1.1	86 ± 7
2.0–3.5	4.3 ± 1.6	42 ± 11
3.5–5.0	5.0 ± 1.4	99 ± 8
5.0–8.0	7.4 ± 1.9	88 ± 7

[2]The shift is still present if strictly simultaneous *NuSTAR–XMM* spectra are considered, and is relative between the two instruments, so on top of the more modest 'absolute' shift described above for the EPIC pn spectrum.

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profile is well modelled by a single Gaussian with an equivalent width of EW $= 100 \pm 6$ eV and a resolved width of $\sigma = 40 \pm 10$ eV. Such a width is routinely measured in high-quality spectra both of obscured and unobscured AGN, suggesting an origin of the line in the broad line region or in the torus (e.g. Shu, Yaqoob & Wang 2010, 2011). Therefore in the following, also to simplify the spectropolarimetric fit presented in Section 3.3, we will not include any relativistic reflection component in our model, as instead used in Keck et al. (2015a) and Szanecki et al. (2021). In any case, we note here that we verified that including a relativistic reflection component to our broadband model gives a similar fit, not affecting in a significant way the other main parameters of the model.[3]

We model the primary continuum with a thermally Comptonized continuum (`nthcomp` in XSPEC; Zdziarski et al. 1996; Życki, Done & Smith 1999), assuming seed photons from a disc-blackbody with temperature fixed at $kT_{\rm bb} = 8$ eV (as expected from a standard accretion disc with the BH mass and observed luminosity of NGC 4151; Shakura & Sunyaev 1973). For the reflection component, we used `BORUS` (Baloković et al. 2018; Baloković, García & Cabral 2019), which models reprocessing from a torus with variable covering factor, self-consistently illuminated by a `nthcomp` spectrum with the same photon index and electron temperature as the primary continuum. In view of the joint spectropolarimetric fit with the *IXPE* data presented in Section 3.3, we separated the reflection component from the corresponding fluorescent lines with the two dedicated `BORUS` tables, linking all the parameters (including the normalization). Since they are not constrained by the fit, we fixed the cosine of the inclination and the covering factor of the torus to 0.6 (appropriate for an intermediate Seyfert galaxy) and 0.5 (default value in `BORUS`), respectively. Moreover, in order to account for the modest broadening of the iron line as reported above, we convolve the `BORUS` tables with a `gsmooth` of 28^{+15}_{-17} eV.

The X-ray spectrum of NGC 4151 is well known to be strongly affected by complex absorption. Similarly to Keck et al. (2015a), we used two partial-covering neutral absorbing layers (PC, modelled by `zpcfabs`) and a warm absorber (WA, modelled with `zxipcf` and covering factor fixed at 1). The presence of a second WA phase at lower ionization, which has been observed in some prior studies (e.g. Keck et al. 2015a; Zoghbi et al. 2019; Szanecki et al. 2021), is not required by the data ($\Delta\chi^2 = -3$ for 2 d.o.f. less). However, it is plausible that one of the neutral PCs may already mimic a low-ionization WA. Finally, as suggested by the presence of emission lines at ∼0.5 and ∼ 0.9 keV and by previous results based on high-resolution spectra (Schurch et al. 2004; Guainazzi & Bianchi 2007; Bianchi et al. 2019), the remaining soft X-ray emission is modelled with a photoionized plasma emission component, produced with CLOUDY (Ferland et al. 1998) closely to what described in Bianchi et al. (2010). Some further residuals due to an imperfect modellization of the photoionized gas around the O VII emission-line triplet at ∼0.5 keV are modelled with a Gaussian component.

In summary, our model can be written in XSPEC as (tbabs)∗(CLOUDY + zgauss + PC∗PC∗WA∗(gsmooth∗(BORUS 1 + BORUS 2) + nthcomp)). This gives a good representation of the *XMM–Newton* + *NuSTAR* data with χ^2/d.o.f $= 743/660$.

[3]An equivalent fit ($\Delta\chi^2 = +2$ for the same dof) is obtained by instead deconvolving the reflection components with `rdblur`, which introduces relativistic effects from an accretion disc around a non-rotating black hole (Fabian et al. 1989). As expected, given the modest broadening of the line, the best-fitting inner radius is very large ($r_{\rm in} = 110^{+40}_{-20}\, r_{\rm g}$, where $r_{\rm g} = GM/c^2$ is the gravitational radius), and the inclination very low ($i = 3^{+5}_{-2}$ deg). All the other parameters are the same, within errors, with respect to those of the best fit.

Table 2. Best-fitting parameters from the spectropolarimetric analysis.

Parameter	Value
`CLOUDY(Photoionized emitter)`	
$\log U$	1.35 ± 0.01
$\log (N_{\rm H}/{\rm cm}^{-2})$	21.63 ± 0.02
`PC 1(Neutral absorber 1)`	
$\log (N_{\rm H}/{\rm cm}^{-2})$	23.02 ± 0.01
Cf	0.78 ± 0.01
`PC 2(Neutral absorber 2)`	
$\log (N_{\rm H}/{\rm cm}^{-2})$	22.64 ± 0.01
Cf	0.95 ± 0.01
`WA(Warm absorber)`	
$\log (N_{\rm H}/{\rm cm}^{-2})$	23.13 ± 0.03
$\log (\xi/{\rm erg\ cm\ s}^{-1})$	4.12 ± 0.02
`BORUS 1/2(Neutral reflector 1/2)`	
$\log (N_{\rm H}/{\rm cm}^{-2})$	24.45 ± 0.01
$A_{\rm Fe}$	0.62 ± 0.01
norm	0.09 ± 0.01
`nthcomp(Comptonized primary continuum)`	
Γ	1.85 ± 0.01
$kT_{\rm e}$ (keV)	60^{+7}_{-6}
norm	0.09 ± 0.01
$\log (F_{2-10\,{\rm keV}}/{\rm erg\,cm}^{-2}\ {\rm s}^{-1})$	-9.78 ± 0.01
$\log (L_{2-10\,{\rm keV}}/{\rm erg\ s}^{-1})$	42.61 ± 0.01

The best-fitting parameters are reported in Table 2, while spectra and residuals are shown in Fig. 2. It is important to note that in this model the contribution of the reflection component to the total 2–8 keV flux is of the order of 6 per cent, reaching up to ∼ 16 per cent in the 6–8 keV band, due to the presence of the Fe K α line. In the 2–3.5 keV band, no contribution from the photoionized emission is present, since it becomes significant only at lower energies (see Fig. 2). On the other hand, in this band there is an excess with respect to the absorbed primary continuum, which our model treats as the leakage of the primary emission through the partial coverers. Any other component, used to model this excess, would contribute up to 20 per cent of the total flux in the 2–3.5 keV band.

3.3 Spectropolarimetric analysis: *XMM–Newton*, *NuSTAR*, and *IXPE*

We added the *IXPE* data (*I*, *Q*, and *U* spectra of the three detectors) to the *XMM–Newton* + *NuSTAR* best-fitting presented above, with all the spectral parameters linked to the other instruments, allowing only an inter-calibration constant (found to be of the order of ∼0.80) for each detector to vary. We then add separate `polconst` multiplicative models to account for the polarization of each additive component of the global model. The polarization degree Π and angle Ψ are set to 0 for the `BORUS` component producing the emission lines, since they are expected to be intrinsically not polarized, as well as for the CLOUDY component, which does not contribute at all in the *IXPE* energy band (see the previous section). On the other hand, the primary Comptonized continuum and the reflection component associated with the other `BORUS` table have Π and Ψ free to vary. The best fit gives $\chi^2/{\rm dof} = 1433/1264$, with no appreciable variations in the spectral parameters with respect to the one without *IXPE*, being indeed dominated by the much higher sensitivity, spectral resolution and broad band coverage of *XMM–Newton* and *NuSTAR*. Considering the complex X-ray spectrum of NGC 4151 with multiple components

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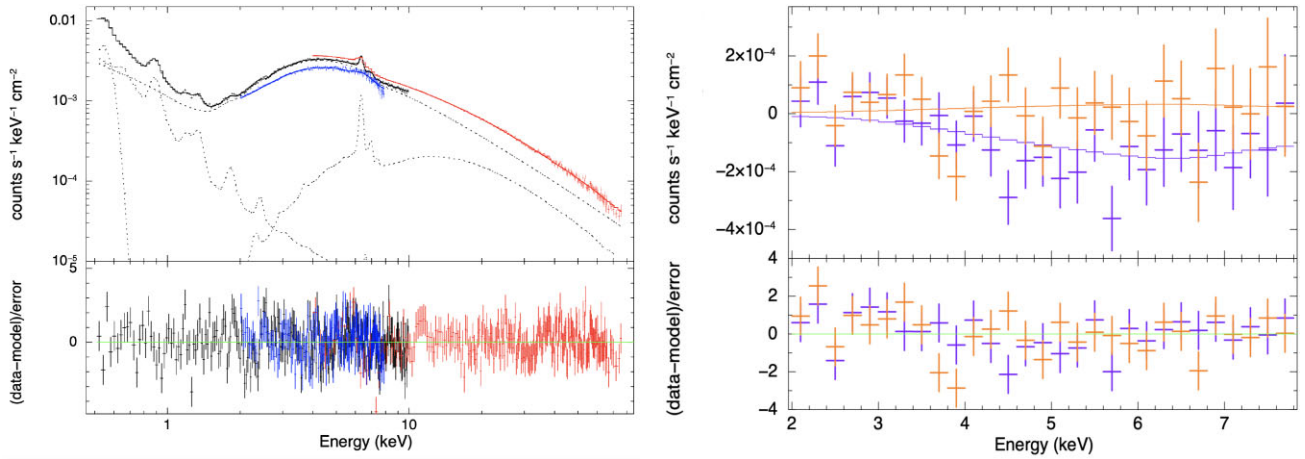

Figure 2. *Left-hand panel: XMM–Newton*/EPIC pn (in black), grouped *NuSTAR* FPMA and FPMB (in red), *IXPE* grouped Stokes *I* (in blue) simultaneous spectra of NGC 4151 with residuals. The dashed lines represent the different model components. *Right-hand panel: Q* (in purple) and *U* (in orange) grouped Stokes spectra are shown with residuals.

in absorption and emission, the cross-calibration uncertainties among the several different instruments used, the variability of the source and the much longer exposure time of *IXPE* with respect to *XMM–Newton* and *NuSTAR*, we find this fit, if not ideal, acceptable given the goal of the paper. We note that the fit applied only to the *IXPE* data gives a significantly better fit (χ^2/dof = 672/612), confirming that the model is a good representation of the data in the 2–8 keV band, where all the polarimetric information is present. Moreover, the polarimetric parameter themselves are only sensitive to the IXPE data, and are not directly affected by the spectroscopic fit on the other data sets.

In this configuration, we get loose constraints for the polarimetric parameters, i.e. $\Pi < 5$ per cent and unconstrained angle for the primary continuum, and $\Pi > 38$ per cent and $\Psi = 96^\circ \pm 16^\circ$ for the reflection component. We thus linked the angles of the two components, either to be equal or to be differ by 90°. In both cases, we still obtain that the polarization is dominated by the reflection component, and the polarization degree of the primary emission is an upper limit. We therefore fixed the polarization properties of the reflection component to physically motivated values, 15, 20, 30 per cent (as found, for example, for the reflection-dominated Circinus galaxy; Ursini et al. 2023), constraining its polarization angle to be at 90° with respect to that of the primary emission. The resulting fits are marginally worse than the best fit, the χ^2 being 1452, 1453, and 1455 for 1266 dof, respectively, and the polarization degree of the primary continuum is now constrained at $\Pi = 4.1 \pm 0.8$ per cent, $\Pi = 4.3 \pm 0.8$ per cent, and $\Pi = 4.6 \pm 0.8$ per cent with polarization angles $\Psi = 82^\circ \pm 7^\circ$, $\Psi = 81^\circ \pm 7^\circ$, and $\Psi = 80^\circ \pm 8^\circ$, respectively.

These results may be driven by the lower Π and different Ψ observed in the 2–3.5 keV band (see Table 1), possibly due to another spectral component that dilutes the polarization of the primary continuum. We therefore modified the best-fitting model with a spectroscopically equivalent one, but decoupling the soft X-ray emission leaking through the partial coverers from the primary emission, which allows us to assign another `polconst` to this component.[4] We set its Π and Ψ to 0 – this is physically motivated by the possibility that the leaked continuum comes from a variety of line of sights, or that this further soft component has instead another origin, independent from the primary continuum and not taken into account by our modelling. Interestingly, the observed variability of NGC 4151 peaks at 2–3 keV, where it is indeed significantly larger than at higher energies (e.g. Beuchert et al. 2017; Igo et al. 2020). This can be attributed to strong absorption variability, but may further suggest the presence of another spectral component. In this new configuration, with the two polarization angles forced to differ by 90°, the best fit is statistically equivalent to the initial one (χ^2/dof = 1441/1265), but now all the polarization is attributed to the primary continuum, with $\Pi = 7.7 \pm 1.5$ per cent and $\Psi = 87^\circ \pm 6^\circ$, while only an upper limit is found for the reflection component $\Pi < 27$ per cent. A similar result is obtained if the polarization angles are forced to be the same, but the polarization degree of the reflection component is completely unconstrained in this case.

[4]Each `zpcfabs` has been replaced by the equivalent expression `c*zphabs + (1-c)`, where *c* is the same covering factor determined in the best fit.

4 DISCUSSION

4.1 The geometry of the X-ray corona

The high measured polarization degree of NGC 4151, determined by both the model-independent and spectropolarimetric analyses, is driven by the signal at higher energies, where the emission from the hot corona dominates. This immediately excludes a 'spherical' lamppost along the disc axis as a possible geometry for the hot corona in this source. Indeed, such a geometry is very symmetric, so the polarization degree is expected to be lower than 1−3 per cent, even for very high inclinations (e.g. Poutanen & Svensson 1996; Tamborra et al. 2018; Ursini et al. 2022). Moreover, the corresponding polarization angle is expected to be perpendicular to the disc axis, while the measured Ψ is in the direction of the radio emission (∼83°; Harrison et al. 1986; Ulvestad et al. 1998, and references therein), suggesting instead that the polarization occurs on the equatorial plane. Two other possible coronal geometries are viable and will be considered here: a *slab* extending above and below the accretion disc, and a *wedge*, in which the accretion disc is truncated and the X-ray corona acts as hot accretion flow extending down to the innermost stable circular orbit (ISCO) with a defined opening angle (Tagliacozzo et al. 2023). The *slab* geometry is investigated even if it is known to produce relatively soft spectra (Γ

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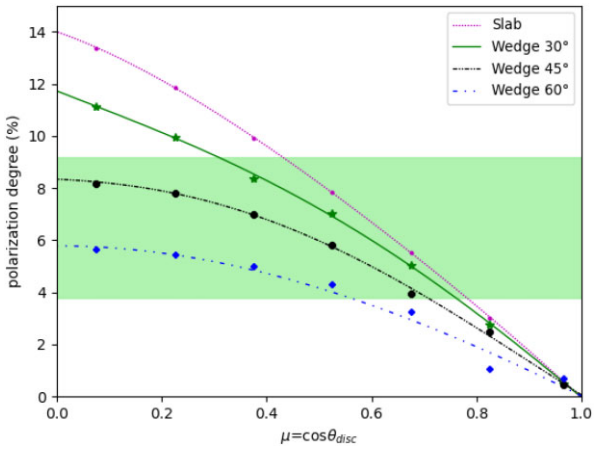

Figure 3. Monte Carlo simulations performed with the Comptonization code MONK. Both *wedge* and *slab* geometries have been considered. The light green band shows the polarization degree range resulting from the model-independent (see Section 3.1) and the spectropolarimetric analysis (see Section 3.3). We adopt for all the simulations $kT_e = 60$ keV and $\tau = 0.5$. The obtained PA is always parallel to the disc axis. See the text for details.

≥ 2) when radiative equilibrium between the disc and the corona is established (see e.g. Haardt & Maraschi 1993; Stern et al. 1995; and relevant discussion in Poutanen, Veledina & Zdziarski 2018). The somewhat harder photon index observed in NGC 4151 can still be accommodated with this geometry assuming that the cold accretion disc is truncated at some radius and the inner part is occupied by the hot accretion flow. The seed photons for Comptonization in this case may come from the outer cold disc or be internal synchrotron photons (Veledina, Vurm & Poutanen 2011). It is very difficult to distinguish between these two scenarios, because in both cases photons undergo many scatterings before they reach the *IXPE* energy band.

We followed the approach of Ursini et al. (2022), performing various simulations with the two geometries, using the general relativistic Monte Carlo radiative transfer code MONK (Zhang, Dovčiak & Bursa 2019). We have also cross-checked these results with those obtained with an iterative radiation transport solver (Poutanen & Svensson 1996; Veledina & Poutanen 2022). In our simulations, we assumed a BH mass of 4.57×10^7 M$_\odot$ (Bentz et al. 2006), a spin $a = 0.998$, and an Eddington ratio $L_{\rm Bol}/L_{\rm Edd} = 1$ per cent. As for the corona, we adopted a temperature of 60 keV, as derived from our spectral analysis (see Table 2), and the Thomson optical depth (defined with respect to the half-thickness of the slab/wedge[5]) $\tau = 0.5$, which reproduces the observed photon index ($\Gamma = 1.85$) in both geometries for the given temperature. For both geometries, we consider the X-ray corona inner radius at the ISCO ($R_{\rm in} = 1.24 r_{\rm g}$), while the outer radius is at $100 r_{\rm g}$ for the *slab* geometry, and coincides with the inner radius of the accretion disc, $R_{\rm out} = R_{\rm in}^{\rm disc} = 25 r_{\rm g}$, for the *wedge*. For the latter geometry, the tested opening angles are 30°, 45°, and 60°. The height of the slab is $1 r_{\rm g}$.

It is worth stressing that in all cases the expected polarization angle is parallel to the disc axis, so in agreement with the observed one. The resulting polarization degree is shown in Fig. 3, as a function of the cosine of the inclination angle with respect to the observer. It is clear that the observed polarization degree in NGC 4151 is well reproduced in all cases, only assuming moderate inclinations ($i \gtrsim 40°-50°$), as reasonable for an intermediate Seyfert galaxy. In particular, the inclination results to be more constrained in the case of the *slab* and for low opening angles of the *wedge*, being in the range $40°-70°$. On the other hand, for larger opening angles of the *wedge*, the required inclination can be higher. Note that these different geometries also agree with the lack of a significant variation of the polarization degree with energy (e.g. Ursini et al. 2022) in agreement with the observations (see Section 3.1 and Table 1).

The disc inclination in NGC 4151 is very uncertain (Marin 2016). It ranges from $i = 0°$ to 33° when estimated via the relativistic reflection component in the X-rays (Nandra et al. 1997; Keck et al. 2015b; Beuchert et al. 2017; Miller et al. 2018), but a much more inclined system (∼58°) is suggested by reverberation studies of the broad-line region (BLR; Bentz, Williams & Treu 2022). The mismatch between the various values comes from both the technique and the location of the probed region (the disc or the BLR). Miller et al. (2018) suggested that a warp between the innermost and outer parts of the accretion disc in NGC 4151 might resolve this apparent discrepancy in inclination. However, it does not fit the *IXPE* results. In fact, the inclination estimated from BLR reverberation studies matches better the one obtained from the X-ray polarization. A more systematic analysis of bright and nearby Seyfert-1s is needed to verify this conclusion.

4.2 Comparison to lower energy polarization

Marin et al. (2020) presented the most extensive review of the ultraviolet, optical, and infrared linear continuum polarization of NGC 4151. From the ultraviolet to the near-infrared (≤1 μm), the polarization degree is wavelength dependent but does not exceed 2 per cent, while the polarization position angle remains constant at 80°–90°. Because the polarization angle is parallel to the parsec-scale radio axis, NGC 4151 optical polarization emerges from reprocessing along the equatorial plane. Gaskell et al. (2012) proved, using polarization reverberation mapping, that the polarization emerges from scattering in a flattened region within the low-ionization component of the BLR. The time lag and polarization angle are inconsistent with both scattering on to the dusty torus and an intrinsic polarization of the continuum. However, the polarized light spectrum of NGC 4151 appears to corroborate the existence of an optically thick, thermally heated accretion disc structure, at least in its outer near-IR emitting radii (Marin et al. 2020). In the infrared, a smooth rotation of the polarization position angle down to ∼45° indicates the onset of dichroic absorption from aligned dust grains in the torus. We note that a similar polarization angle is found here in the 2–3.5 keV band ($\psi_{\rm X} = 42° \pm 11°$, see Table 1), although with lower statistical confidence than at higher energies. Interestingly, this angle would be in agreement with the extended narrow-line region observed with *Chandra* (Wang et al. 2011) and *HST* (45° ± 5°; Evans et al. 1993; Das et al. 2005).

The X-ray polarization degree we measured is different from the archival and contemporaneous[6] ultraviolet, optical, and infrared polarization of NGC 4151. It indicates that X-ray polarization comes from a different region than the BLR or the torus, and is indeed consistent with an origin in a slab-like corona. The polarization angle,

[5]This definition is the same as in `compTT` (Titarchuk 1994), while it is half that of `compPS` in the standard configuration (Poutanen & Svensson 1996).

[6]*B*, *V*, *R*, and *I* broad-band polarimetry of NGC 4151 was obtained contemporaneously to the *IXPE* observation using the Perkins Telescope Observatory. Those new measurements are in all respects similar to the archival data and will be presented in a future publication compiling recent optical polarimetric data from changing-look AGNs.

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however, is the same as in the ultraviolet and optical, indicating that reprocessing mainly occurs along the equatorial plane from the X-rays to the near-infrared. A deeper analysis of the X-ray to infrared polarization of NGC 4151 will be presented in a future paper. Future *IXPE* observations catching the source at different flux and spectral states will be crucial to further disentangle the contribution of each spectral component to the observed X-ray polarization.

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DATA AVAILABILITY

The *IXPE* data used in this paper are publicly available in the HEASARC data base (https://heasarc.gsfc.nasa.gov/docs/ixpe/archive/). The *XMM–Newton* and *NuSTAR* data underlying this article are subject to an embargo of 12 months from the date of the observations. Once the embargo expires, the data will be publicly available from the *XMM–Newton* science archive (http://nxsa.esac.esa.int/) and the *NuSTAR* archive (https://heasarc.gsfc.nasa.gov/docs/ nustar/nustar_archive.html). The MONK simulation data supporting the findings of the article will be shared on reasonable request.

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