

COMPTON-THICK AGN IN THE *NuSTAR* ERA VII. A JOINT *NuSTAR*, *Chandra* AND XMM-*Newton* ANALYSIS OF TWO NEARBY, HEAVILY OBSCURED SOURCES

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ABSTRACT

We present the joint *Chandra*, XMM-*Newton* and *NuSTAR* analysis of two nearby Seyfert galaxies, NGC 3081 and ESO 565-G019. These are the only two having *Chandra* data in a larger sample of ten low redshift ($z \leq 0.05$), candidates Compton-thick Active Galactic Nuclei (AGN) selected in the 15–150 keV band with *Swift*-BAT that were still lacking *NuSTAR* data. Our spectral analysis, performed using physically-motivated models, provides an estimate of both the line-of-sight (l.o.s.) and average ($N_{H,S}$) column densities of the two torii. NGC 3081 has a Compton-thin l.o.s. column density $N_{H,z}=[0.58-0.62] \times 10^{24} \text{cm}^{-2}$, but the $N_{H,S}$, beyond the Compton-thick threshold ($N_{H,S}=[1.41-1.78] \times 10^{24} \text{cm}^{-2}$), suggests a “patchy” scenario for the distribution of the circumnuclear matter. ESO 565-G019 has both Compton-thick l.o.s. and $N_{H,S}$ column densities ($N_{H,z} > 2.31 \times 10^{24} \text{cm}^{-2}$ and $N_{H,S} > 2.57 \times 10^{24} \text{cm}^{-2}$, respectively). The use of physically-motivated models, coupled with the broad energy range covered by the data (0.6–70 keV and 0.6–40 keV, for NGC 3081 and ESO 565-G019, respectively) allows us to constrain the covering factor of the obscuring material, which is $C_{TOR}=[0.63-0.82]$ for NGC 3081, and $C_{TOR}=[0.39-0.65]$ for ESO 565-G019.

1. INTRODUCTION

One of the main goals of extragalactic astrophysics is to achieve a thorough knowledge of the processes responsible for the observed emission from Active Galactic Nuclei (AGN). Models of AGN unification (e.g., Antonucci 1993; Urry & Padovani 1995) require the presence of an obscuring structure (often associated with the obscuring torus) surrounding the central supermassive black hole (SMBH). Depending on the angle between the torus axis and the line-of-sight (l.o.s.) of the observer, the AGN emission will be attenuated if it intercepts the obscuring material. The AGN classification divides these sources into two main types: Type 1 and Type 2, according to the extinction, the width of the emission lines observed in their optical spectra and the shape of the continuum (see, e.g., Padovani et al. 2017).

In the X-ray band, Type 1 and Type 2 AGN are generally referred to as unobscured and obscured, respectively (Osterbrock 1978). The second type includes the so-called Compton-thin ($N_H \sim 10^{22-24} \text{cm}^{-2}$) and

Compton-thick (CT, $N_H \geq 10^{24} \text{cm}^{-2}$) sources (Comastri 2004); in this last case, the obscuring material strongly attenuates the nuclear emission below 10 keV. Studies on the AGN population have suggested that their emission can account for most of the Cosmic X-ray Background (CXB, i.e., the diffuse emission observed between ~ 0.5 –500 keV, Gilli et al. 2007); specifically, Type 2 AGN play an important role in shaping the CXB, as well as in the context of the AGN-galaxy co-evolution (Treister et al. 2010), especially at high redshift. On the one hand, unobscured AGN contribution to the CXB is nowadays almost completely resolved into point-like sources. On the other hand, the detection of obscured AGN, which are responsible for a significant fraction of the CXB emission ($\sim 40\%$ at the peak, Gilli et al. 2007; Ananna et al. 2019), is challenging.

Thus, the study of CT-AGN, can provide a better characterization of the CXB, especially around the peak ($E \sim 30$ keV, Ajello et al. 2008). From observations, the CT-AGN fraction at $z \sim 0$ results to be ~ 10 –20% (see e.g., Comastri 2004; Burlon et al. 2011; Ricci et al. 2015), that is lower than the one expected from CXB population synthesis models (20–50%, Gilli et al. 2007; Ueda et al. 2014; Buchner et al. 2015; Ananna et al. 2019; Zhao et al. 2020).

In order to fill the gap between observations and model predictions, a census of obscured AGN (in particular, CT-AGN) is needed, combining data at different wavelengths. In particular, since X-rays are energetic enough to penetrate the obscuring material (i.e., the torus) up to considerable amounts of column density, X-ray observations offer a unique possibility for the characterization of the inner regions of the AGN.

Since the effect of the absorption by the obscuring material varies with the photon energy, the radiation with energy below 10 keV becomes much more attenuated with respect to higher energy photons. For this

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reason, the NASA and ESA flagship X-ray telescopes, *Chandra* and *XMM-Newton* (active in the 0.3–10 keV energy band), cannot entirely characterize the spectral properties of such obscured sources at $z \sim 0$. Telescopes which cover a higher energy band, such as *Swift* Burst Alert Telescope (BAT, Barthelmy et al. 2005) or the Nuclear Spectroscopic Telescope Array (*NuSTAR*, Harrison et al. 2013), are thus required to create a more unbiased census of black holes.

Recent works (e.g., Burlon et al. 2011; Ricci et al. 2015) have been carried out using the *Swift*-BAT telescope data at high energies ($\sim 15 - 150$ keV), combined, if available, with 0.3 – 10 keV data. However, newer studies (e.g., Marchesi et al. 2018) reveal, in the comparison between *Swift*-BAT and *NuSTAR* spectra of heavily obscured AGN, the presence of an offset in the values of the photon index (Γ) and the intrinsic absorption (N_H), which are often overestimated when *NuSTAR* data are not used.

On the basis of these results, it is clear that a combination of high quality *Chandra* or *XMM-Newton* 0.3 – 10 keV data with deep *NuSTAR* observations in the 3 – 79 keV band is needed to have a broad-band characterization of the X-ray spectrum of heavily obscured sources. Such a multi-observatory synergy provides an optimal spectral coverage for the determination of the main spectral parameters, which would not be possible without one of the two bands. In order to obtain a proper characterization of the main spectral and physical properties of obscured AGN, physically motivated models (e.g., MYTorus and borus02; Murphy & Yaqoob 2009; Baloković et al. 2018) which make use of Monte-Carlo codes should be used to reproduce the evolution of the radiative transfer through the obscuring material. These models allow one to describe the geometrical distribution of the torus and its physical properties such as the l.o.s. and intrinsic column density ($N_{H,z}$ and $N_{H,s}$), and the torus covering factor (C_{TOR}).

In order to reach a complete census of Compton-thick AGN (in the local Universe) in the X-ray band, via the detailed study of their obscuring structure, an approved *NuSTAR* project (PI: S. Marchesi; proposal number 5197) “The Compton thick AGN Legacy project. A complete set of *NuSTAR*-observed nearby CT-AGNs” is being carried out. This project has multiple goals, and aims to achieve a complete X-ray characterization of the sample of 57 low-redshift CT-AGN candidates, selected from the 100-month *Swift*/BAT catalog, through almost simultaneous *XMM-Newton* and *NuSTAR* observations. This would allow us to obtain indications on the physical and geometrical properties of the source nuclear regions. In particular, the combined use of *XMM-Newton* and *NuSTAR* allows to precisely constrain physical and geometrical parameters of the obscuring torus (e.g., C_{TOR}), which allows us to study relations such as $L_X - C_{TOR}$, through which, and coupled with variability information, it may be possible to place constraints on the nature and geometry of the obscuring torus. Finally, another goal of this large program is the determination of the intrinsic fraction of CT-AGN, as well as the space density of these type of sources. In past works (see Marchesi et al. 2017a; Marchesi et al. 2018; Marchesi et al. 2019; Zhao et al. 2019a,b) the majority of the candidate CT-AGN in the 100-month BAT sample sources have been analyzed

by our group; in 2019, the last 10 sources of the sample, which were still lacking *NuSTAR* data, have been observed using *NuSTAR* and *XMM-Newton* (when lacking). In this work we present the spectral analysis of two nearby ($z = 0.008$ and $z = 0.016$) candidate CT-AGN (NGC 3081 and ESO 565-G019) selected from the 100-months *Swift*-BAT catalog. These are the only two objects, out of the 10 in the *NuSTAR* program, that also have *Chandra* data. For this reason, we decide to study them in a separate paper, with the goal of using *Chandra* subarcsecond resolution to investigate the properties of the diffuse emission around the accreting supermassive black hole. Also, the contribution of the *Chandra* data to the whole spectral counts (see Table 2), enables us to derive the parameters of interest with higher accuracy, disentangling, for example the effect of the thermal emission from the continuum scattered by thin material, at low energies.

The rest of the sample will be analyzed in a companion paper (Torres-Albà et al. submitted). The paper is organized as follows: in Section 2 we report the process of data reduction for the three data-sets available and the extraction of the spectra; in Section 3 we describe the different models used in the spectral analysis; in Section 4 we report the spectral analysis with the different models and in Section 5 we summarize our results, focusing particularly on the properties of the obscuring material. All reported uncertainties on spectral parameters are at 90% confidence level, if not otherwise stated. The standard cosmological constants adopted are: $H_0 = 70$ km s^{-1} Mpc $^{-1}$, $\Omega_M = 0.29$ and $\Omega_\Lambda = 0.71$.

2. SAMPLE AND DATA REDUCTION

NGC 3081 and ESO 565-G019 have simultaneous observations with *XMM-Newton* and *NuSTAR* (PI: Marchesi) which ensure a broad-band coverage ($\sim 0.3 - 70$ keV) and no variability effects. Moreover, for NGC 3081 and ESO 565-G019, *Chandra* archival data are also available (PIs: Maksym and Koss, respectively), which allow us, thanks to *Chandra*’s sub-arcsecond resolution, to detect diffuse emission from the region near the nucleus, which may be due to hot gas thermally emitting, scattering or photoionization effects. Furthermore, the availability of *Chandra* data contributes to improve the counts statistics in the 0.5–7 keV band, leading to a better spectral coverage.

According to the *NED* morphological and spectral classification, NGC 3081 is a SAB0 spiral galaxy and it is classified as a Sy 1 (Véron-Cetty & Véron 2006); however, Esparza-Arredondo et al. (2018) claim that it has a Type 2 nucleus. Ricci et al. (2017), using combined *XMM-Newton*/*XRT*, *Chandra* and *Swift*-BAT 0.3–150 keV data, found it to be heavily obscured, having $\log(N_H/cm^{-2}) = 23.91 \pm 0.04$.

ESO 565-G019 is a Sy2, E type galaxy (de Vaucouleurs et al. 1991). From *Swift*-BAT and *Suzaku* X-ray observation of ESO 565-G019 its emission results to be reflection dominated, with a column density larger than the Compton-thick threshold (Gandhi et al. 2013). In Table 1 we report the main information on the sources’ observations analyzed in this work.

2.1. *Chandra* data reduction

Table 1

ObsID, exposure time and start date for the *Chandra*, *XMM-Newton* and *NuSTAR* observations of NGC 3081 and ESO 565-G019. In the exposure time column, for the *XMM-Newton* observation the exposure time after the cleaning from background flares is reported.

	Instrument	ObsID	Exp. time [ks]	Start date
NGC 3081	<i>Chandra</i>	20622	29.4	2018-01-24
	<i>XMM-Newton</i>	0852180701	30.0	2019-12-24
	<i>NuSTAR</i>	60561044002	55.6	2019-12-23
ESO 565-G019	<i>Chandra</i>	22248	10.0	2019-06-06
	<i>XMM-Newton</i>	0852180601	27.0	2019-12-18
	<i>NuSTAR</i>	60561043002	50.4	2019-12-17

We use *Chandra* archival observations with an exposure time of ~ 29 ks for NGC 3081 and ~ 10 ks for ESO 565-G019. The images of NGC 3081 and ESO 565-G019 in the 0.3–7.0 keV energy range are shown in Figure 1. The sources in the *Chandra* images are not point-like, given how the emission is extended beyond the Encircled Energy Fraction (EEF, i.e., the circular region containing a certain fraction of the counts) radius. This is due to the excellent angular resolution of the *Chandra* telescope, that allows to distinguish the nuclear emission from the extended one. The spectra extraction has been done using the `specextract` task. This task requires the selection of an extracting region for the sources and for the background (the background region has to be unaffected by the presence of other sources). The source extraction has been chosen on the basis of the EEF for a point like source, at a fixed energy (in the case of the *Chandra* HRMA a circle with a radius of about 2 arcsec contains 90% of the total energy at 5 keV), so to minimize the contamination from non-nuclear emission we have chosen the energy centroid of the *Chandra* image in the $E = 2 - 7$ keV to better define the AGN. The source regions have been chosen with a radius of 2" and the background regions have a radius of ~ 25 ".

Finally we bin the spectra with the `grppha` task to have at least 15 counts per bin to apply χ^2 statistics. Because of the small number of spectral counts, in the case of ESO 565-G019, we have used C-stat instead of χ^2 statistics in this analysis (i.e., the spectral analysis has been carried out in the Poisson regime).

2.2. XMM-Newton data reduction

The *XMM-Newton* observations, which are quasi simultaneous to the *NuSTAR* ones (see Table 1), have an exposure time of ~ 30 ks and ~ 27 ks, for NGC 3081 and ESO 565-G019, respectively.

We create the lightcurve at energies $E > 10$ keV to select a threshold to remove part of observation particularly affected by noise (i.e., particle background noise). In the case of pn, we select a value of 0.4, and 0.35 counts/s for MOS1 and MOS2 for ESO 565-G019 and, in the case of MOS2, we choose 0.25 counts/s in order to remove a bright background flare for NGC 3081. In both cases the lightcurve were extracted from the whole field. We use extraction regions corresponding to an aperture which contains the 90% of total energy at 5.0 keV: 40" in the case of MOS1, 45" for MOS2 and 35" in the pn case. For both sources, the background regions have sizes of 70, 90 and 60 arcseconds, for the MOS1, MOS2 and pn, respectively.

Finally, we grouped the spectra to have at least 20

counts per bin, in order to apply the χ^2 statistics.

2.3. NuSTAR data reduction

The *NuSTAR* observations have exposures of ~ 56 ks and ~ 50 ks, for NGC 3081 and ESO 565-G019, respectively. The first step of *NuSTAR* data reduction is the creation of the calibrated events files which will be cleaned and used to produce an exposure map. This process can be carried out using `nupipeline`.

The choice of the source extraction regions was made selecting four circles with different radii and inspecting the background counts and signal-to-noise ratio (S/N) variations. In the first case (NGC 3081), the data show a linear increase of the S/N with the region diameter (almost until 80", with increasing background contribution), so the choice fell on the Half Power Diameter (HPD) which contains 50% of the encircled energy fraction and corresponds to a radius of 60". In the second case (ESO 565-G019), exceeding 40" leads to an increase of the background contribution. Lastly, we extract the spectra, producing the ARF and RMF matrix, and we bin them to have at least 20 counts per bin.

In table 2 we show the spectral information related to the extracted spectra.

Finally, we find no significant evidences of variability between the *Chandra*, *XMM-Newton* and *NuSTAR* observations.

3. SPECTRAL MODELS

In the following sections we describe the different models used in the spectral analysis. To perform a more physical and detailed analysis of the X-ray spectra, with respect to the classical phenomenological analysis, it is possible to use *physically motivated* models, such as `MYTorus` and `borus02` (Section 3.1 and 3.3). Both models describe the reprocessing material (i.e., the obscuring torus) in a physical way, using Monte-Carlo simulations. Also, these models allow us to calculate the intrinsic column density of the torus and, in the case of the `borus02` model, the covering factor, which corresponds to the torus opening angle.

3.1. MYTorus

In this section we will discuss the main properties and the use of the `MYTorus` model (Murphy & Yaqoob 2009). The `MYTorus` model was developed to be used in the `XSPEC` (Arnaud 1996) environment as a combination of additive and multiplicative tables, which represent different components of the nuclear emission. These components are: the zeroth-order emission component (`MYTZ`),

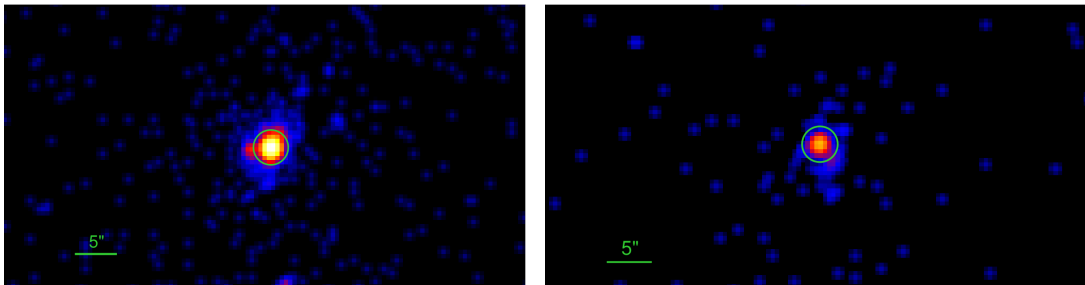


Figure 1. 0.3–7 keV *Chandra* images of NGC 3081 (left panel) and ESO 565-G019 (right panel). In both cases the source extraction regions are reported as a circle with a radius of 2". The boxes have dimensions 43" x 26". 1" corresponds to ~ 0.17 kpc and ~ 0.34 kpc for NGC 3081 and ESO 565-G019, respectively.

Table 2

Extraction radius in arcsec, spectral counts (source plus background) and signal-to-noise ratio (S/N) for NGC 3081 and ESO 565-G019 for the three data sets.

		NGC 3081			ESO 565-G019		
		Extraction radius	Counts	S/N	Extraction radius	Counts	S/N
<i>Chandra</i>		2"	2623 \pm 51	51.0 \pm 0.1	2"	123 \pm 11	11.1 \pm 0.1
<i>XMM-Newton</i>	pn	35"	3187 \pm 56	54.4 \pm 0.2	35"	742 \pm 27	24.0 \pm 0.5
	MOS1	40"	3234 \pm 57	54.8 \pm 0.2	40"	856 \pm 29	25.6 \pm 0.5
	MOS2	45"	8788 \pm 94	91.1 \pm 0.2	45"	2147 \pm 46	42.9 \pm 0.3
<i>NuSTAR</i>	FPMA	60"	16960 \pm 130	125.7 \pm 0.2	40"	1067 \pm 33	26.9 \pm 0.6
	FPMB	60"	16820 \pm 130	125.4 \pm 0.2	40"	1443 \pm 38	31.4 \pm 0.7

the scattered continuum (MYTS) and the iron line emission component (MYTL). *MYTorus* models the observed spectrum taking into account the absorbed and the scattered component of the emission, modeling also the presence of fluorescent Fe K α and K β emission lines at 6.4 keV and 7.06 keV respectively, which are thought to be almost ubiquitous in heavily obscured AGN spectra.

The *MYTorus* model can be used in two different settings, namely the *coupled* and the *de-coupled* configuration. In the first mode, the column density and the inclination angle of the three components (MYTZ, MYTS and MYTL) are tied together. Thus, in this configuration, all the components are produced in the same medium.

The *MYTorus* model simulates the interaction between input spectrum photons and the obscuring material. The circumnuclear environment is simulated as the classical doughnut-like and azimuthally symmetric structure. The distance from the black hole to the center of the torus section is indicated as c , and a is the radius of the section.

θ_{obs} is the inclination angle: the angle between the torus symmetry axis and the observer line of sight (l.o.s.). It can vary in the range $[0^\circ - 90^\circ]$, allowing to reproduce both the face-on ($\theta_{obs}=0^\circ$, i.e., the observer looks directly at the nucleus) and the edge-on ($\theta_{obs}=90^\circ$, i.e., the observer line of sight intercepts the torus equator).

The torus half-opening angle, which represents the fraction of the sky as seen from the center, is defined as $\alpha = [(\pi - \psi)/2]=60^\circ$ (with ψ being the angle subtended by the internal surface of the torus) corresponding to a covering factor $C_{TOR} = 0.5$. The fixed value for the covering factor is linked to the assumptions made on the fraction of obscured AGN with respect to the unobscured ones. Finally, N_H is the equatorial column density (i.e. the column density through the torus diameter); the line

of sight column density can be computed as:

$$N_{H,z} = N_H \left[1 - \left(\frac{c}{a} \right)^2 \cos^2 \theta_{obs} \right]$$

The first component in the *MYTorus* model is the so-called zeroth-order continuum or direct component. This component represents the photons escaping the absorbing medium (i.e., the torus) without being absorbed or scattered.

The second component is the scattered or reprocessed continuum, which represents the photons that escape the medium after being scattered one or more times.

The interaction is via Compton-scattering, thus the energy of the photon after the scattering will be lower with respect to the input photon's energy. The second component is responsible for the production of the feature observed at ~ 30 keV (i.e. the *Compton hump*). Moreover, in the *MYTorus* model the termination energy of the scattered component is variable between 160 keV and 500 keV (in our analysis we use a table with intrinsic continuum extending up to 500 keV). The value of the cut-off energy has been chosen to be consistent with previous similar works (see e.g., [Marchesi et al. 2017b](#); [Zhao et al. 2019b,a](#)). Moreover, recent works (e.g., [Baloković et al. 2020](#)) show that it is a reasonable value for the extension of the continuum.

The last component is the fluorescent emission. It takes into account the possibility to have fluorescent emission iron lines, produced in the reprocessing medium. The emission lines that *MYTorus* models are the Fe K α and K β only.

On the one hand, the line photons that escape after being produced by the fluorescence process, constitute the zeroth-order fluorescent emission component. On the other hand, if these photons interact with the reprocessor

by scattering processes, they can contribute to form the *Compton shoulder*.

3.2. MYTorus in “de-coupled” configuration

The MYTorus model in “coupled” configuration allows the inclination angle to vary, but does not permit a variation in the column density and in the geometrical properties of the different components. In this way it is not possible to properly characterize a clumpy torus structure. To overcome this problem, as described by [Yaqoob \(2012\)](#), it is possible to decouple the MYTorus components by fixing the zeroth-order continuum inclination angle to 90° , generating a pure line of sight component. Then, the column density of the scattered component can be untied with respect to the one of the direct continuum. In this way, the direct continuum column density represents the line of sight column density, whereas the scattered component column density represents the “global average” column density. Thus, the ratio between the “global average” column density and the line of sight column density represents a measure of the patchiness (or clumpiness) of the obscuring material: a ratio $\neq 1$ will then suggest a scenario in which the column density along the l.o.s. is higher (or lower) than the average column density of the torus, meaning that the structure could likely be clumpy rather than smooth. Following [Yaqoob et al. \(2015\)](#), we then fix the inclination angle of the scattered and fluorescent line components to be either $\theta_{S=L}=90^\circ$ or $\theta_{S=L}=0^\circ$, reproducing an edge-on and face-on geometry. Using the “de-coupled” mode, it is possible to take into account a scenario in which the different MYTorus components are produced with different interactions of the nuclear emission with the reprocessor. Using $\theta_{S=L}=0^\circ$ we model a scenario in which the emission is dominated by reflection in the far-side of the torus; if $\theta_{S=L}=90^\circ$, the emission is dominated by a near-side Compton-scattering.

3.3. BORUS02

Finally, we use the `borus02` model (table `borus02.v170323a.fits`), developed by [Baloković et al. \(2018\)](#) as an improvement of the `BNtorus` model ([Brightman & Nandra 2011](#)). The `borus02` model is based on grids of spectral templates obtained using Monte-Carlo simulations of radiative transfer through a neutral spherical torus with polar cut-outs.

The strength of this model lies in the possibility to fit the spectral data having as free parameters the average column density of the torus and its covering factor. The computation of the covering factor it is not possible by using MYTorus even in its “de-coupled” configuration. Due to the longer variability timescales (years), the average column density represents a more reliable parameter to characterize the thickness of an AGN in respect to the $N_{H,los}$, which variability has shown to be of the order of days and weeks, due to the movement of clouds through the line of sight (see e.g., [Risaliti et al. 2002](#); [Ricci et al. 2016](#)).

Despite this, a proper characterization of the covering factor is not simple. It can be affected by accretion or feedback phenomena taking place nearby the torus (e.g., [Heckman & Best 2014](#); [Netzer 2015](#)); it can depend on the luminosity (e.g., [Assef et al. 2013](#)) as well as on the

Eddington ratio (e.g., [Ricci et al. 2017](#)), and these dependencies could vary with redshift (e.g., [Buchner et al. 2015](#)). In this perspective, the `borus02` model represents an updated tool to compute the covering factor. `borus02` model is composed of a single additive table (instead of the three tables of MYTorus) which takes into account the reprocessed emission component, that is similar to the MYTorus “reprocessed component”, and the fluorescent line emission component, including $K\alpha$ and $K\beta$ lines.

The main parameters of the `borus02` model have the following possible values: the covering factor ranges from 0.1 to 1, corresponding to a torus opening angle between 84° and 0° ; the inclination angle is in the range $[18^\circ-87^\circ]$. Also, the cut-off energy is a parameter of the model and we fix it to be 500 keV, for consistency with MYTorus. Finally, the iron abundance is also a free parameter, but we fix it to 1, for consistency with the MYTorus analysis.

`borus02` does not include the l.o.s. absorption at the redshift of the source, which we model with combination of XSPEC components `zphabs * cabs` in order to take into account l.o.s. absorption and the losses out of the l.o.s. due to Compton scattering. The primary power law emission is represented by `cutoffpl1` that is multiplied by the previous expression; it is characterized by a photon index, cut-off energy and normalization, that must be tied to those of `borus02`. Also, to properly describe the l.o.s. column density, the `nH` parameter of `cabs` and `zphabs` must be tied together. The soft emission component and the emission lines are included, when needed, as described for the MYTorus modelling.

4. SPECTRAL ANALYSIS

In this Section we present the spectral analysis of NGC 3081 and ESO 565-G019. Since the background contribution dominates at energies higher than 70 keV and 40 keV, we analyze the spectra up to these energies. In order to obtain a physically detailed description of the observed emission, we carried out the analysis using the MYTorus and `borus02` physically motivated models. We also add a thermal component (`mekal`), to reproduce the emission at soft energies, and Gaussian lines at energies $\sim 0.92, 1.31$ and 1.80 keV, corresponding to Ne IX, Mg XI and Si XIII.

4.1. NGC 3081

4.1.1. MYTorus model

We use MYTorus in both the “coupled” and “de-coupled” configuration (the last one in the edge-on and face-on mode).

The best fit model consists of the three MYTorus components, the second power law, the `mekal` component (to model the soft thermal emission) and the emission lines. Moreover, we included other two constants to the models, A_S and A_L , to take into account the possible different normalizations of the other two components with respect to the zeroth-order continuum:

$$\text{Model } NGC_A = pha * (zpo1 * MYTZ + A_S * MYTS + A_L * MYTL + f_s * zpo2 + mekal + 3 * zgauss) \quad (1)$$

The photon index is $\Gamma_{MYT,c,B} = 1.59^{+0.03}_{-0.03}$. The column

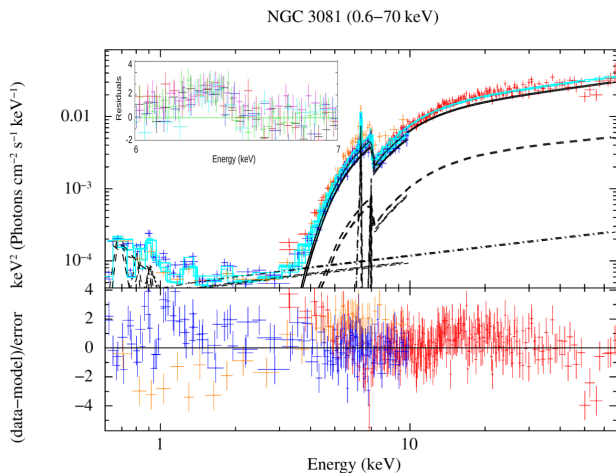


Figure 2. Unfolded *Chandra* (orange), *XMM-Newton* (blue) and *NuSTAR* (red) 0.6–70 keV combined spectrum of NGC 3081 modeled with MYTorus in the “coupled” configuration. The cyan solid line represents the best-fit model, while the individual components, MYTZ, MYTS, MYTL and the second power law, are reported as a black solid line, dashed lines and dash dotted line, respectively. Finally, the mekal component is plotted as a dashed line. In the top left corner the residuals for the iron $K\alpha$ line in the best-fit model without the line component are shown.

density, which is $N_{H,eq} = 0.62^{+0.02}_{-0.02} \times 10^{24} \text{ cm}^{-2}$, is below the Compton-thick threshold. We also fit our data leaving the inclination angle free to vary and we find no significant improvement in the fit statistic ($\chi^2/d.o.f. = 1773/1403$). Therefore, we fix the inclination angle to 90° . The best-fit model and the spectrum are reported in Figure 2. Also, we show the residuals for the iron $K\alpha$ line in the best-fit model without the line component. As it can be seen, the line component is required to improve the fit statistic.

In order to reach a more complete knowledge of the geometrical properties of the NGC 3081 torus, we fit the 0.6–70 keV spectrum with MYTorus in the “de-coupled” mode. The photon indices we obtain are $\Gamma_{\theta,S=90} = 1.81^{+0.07}_{-0.06}$ and $\Gamma_{\theta,S=0} = 1.75^{+0.03}_{-0.05}$, for the edge-on and face-on modes, respectively. Also the l.o.s. column densities are: $N_{H,z} = 0.60^{+0.02}_{-0.02} \times 10^{24} \text{ cm}^{-2}$ and $N_{H,S} = 1.59^{+0.19}_{-0.17} \times 10^{24} \text{ cm}^{-2}$ for the edge-on mode and $N_{H,z} = 0.66^{+0.02}_{-0.02} \times 10^{24} \text{ cm}^{-2}$ and $N_{H,S} = 3.00^{+0.69}_{-0.68} \times 10^{24} \text{ cm}^{-2}$ for the face-on mode. In both modes the photon index results to be steeper than the one found in the analysis with the “coupled” configuration (see Table 3); also the l.o.s. column densities are lower than the “global average” ones. The χ^2 statistics favors the edge-on configuration, with a $\chi^2/d.o.f. = 1723/1403$. We show in Figure 3 (left panel) the unfolded spectrum and the MYTorus model in the edge-on mode.

4.1.2. borus02 model

Finally, we model the 0.6 – 70 keV combined spectrum with the borus02 model. In addition to the main emission component and the reprocessed component, we also included the second power law and the thermal component to model the contribution in the soft part of the spectrum. Also, we add the three emission lines previ-

ously described.

$$\begin{aligned} \text{Model } NGC_B = & pha * (borus02 + zpha * cabs * cutoffpl1 \\ & + f_s * cutoffpl2 + mekal + 3 * zgauss) \end{aligned} \quad (2)$$

The best-fit model has a $\chi^2/d.o.f. = 1753/1403$; the photon index is $\Gamma = 1.80^{+0.06}_{-0.04}$; the l.o.s. column density is $N_{H,z} = 0.61^{+0.02}_{-0.02} \times 10^{24} \text{ cm}^{-2}$ and the average column density $N_{H,S} = 1.51^{+0.11}_{-0.10} \times 10^{24} \text{ cm}^{-2}$ is consistent with the torus being Compton-thick, as we also found using MYTorus in the edge-on configuration. In Figure 3 (right panel) we show the 0.6–70 keV spectrum. The borus02 model allows us to leave the covering factor as a free parameter; in the case of NGC 3081 we obtain $C_{TOR} = 0.73^{+0.09}_{-0.10}$.

4.1.3. Summary of the NGC 3081 spectral analysis results

We have analyzed the NGC 3081 0.6–70 keV *Chandra*, *XMM-Newton* and *NuSTAR* combined spectra, which have a high count statistics ($N_C = 53.6$ k-counts, considering all instruments). The spectral analysis has been done with both MYTorus and borus02 physically motivated models. The best fit model, in terms of lowest χ^2_ν , is the MYTorus one, used in the “de-coupled” mode in the edge-on configuration, with a reduced statistics $\chi^2_\nu = \chi^2/d.o.f. = 1723/1403$ (the borus02 best-fit model has $\chi^2_\nu = \chi^2/d.o.f. = 1753/1403$).

The main goal of the present work is the classification of the sources under investigation through the determination of the column density of the obscuring material (i.e., the torus). The MYTorus model (as well as the borus02 model), in its “de-coupled” mode, suits very well for this purpose, because it allows to distinguish between the l.o.s. column density ($N_{H,z}$) and the “global average” column density of the torus ($N_{H,S}$). From the best-fit model we find that along the l.o.s. NGC 3081 results to be Compton-thin ($\log(N_{H,z}/[\text{cm}^{-2}]) = 23.78^{+0.01}_{-0.02}$). However, the average column density of its torus ($\log(N_{H,S}/[\text{cm}^{-2}]) = 24.20^{+0.05}_{-0.05}$) is above the Compton-thick threshold. This scenario is typical of sources that are being observed through a lower density portion of the torus with respect to its average density, suggesting that a patchy or clumpy structure is preferred to the classical smooth, doughnut-like, geometry. Thus, we can affirm that NGC 3081 has a CT torus (at the 90% confidence level) observed through a Compton-thin portion of the obscuring material. In addition, from borus02 spectral analysis, which results on the main spectral parameters are consistent with the MYTorus ones, we can obtain the torus covering factor, that is found to be $C_{TOR} = 0.73^{+0.09}_{-0.10}$, corresponding to a torus half opening angle of $\sim 43^\circ$.

Although this analysis was focused on the investigation of the thickness and geometry of the obscuring material, we also study the properties of the soft X-ray emission. We find that contribution to the soft emission comes from several components: the fraction of photon that are scattered, rather than being absorbed, by Compton-thin material is lower than 1% of the main emission component, consistent with the average value obtained for obscured

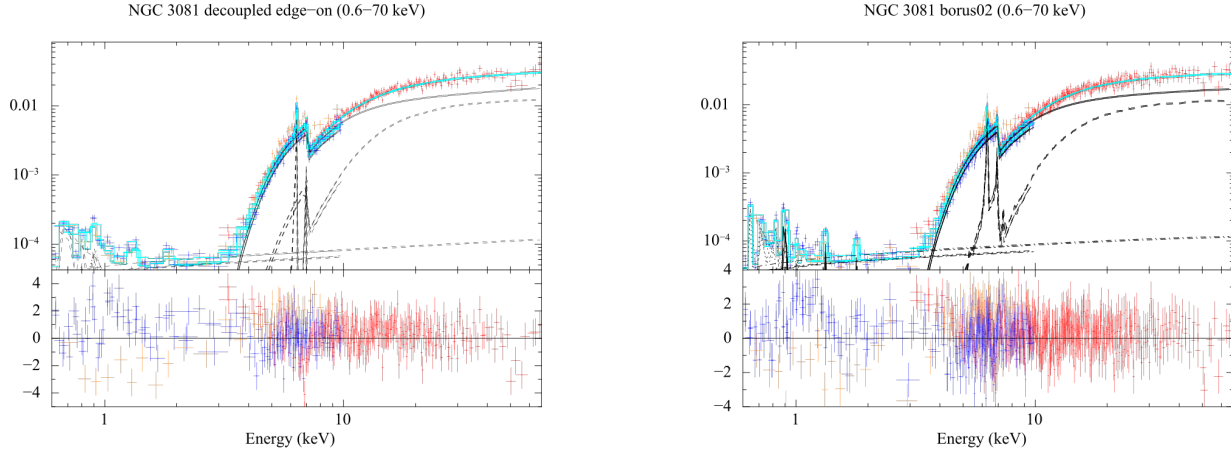


Figure 3. Unfolded *Chandra* (orange), *XMM-Newton* (blue) and *NuSTAR* (red) 0.6 – 70 keV combined spectrum of NGC 3081 modeled with *MYTorus* in the “de-coupled” configuration in the edge-on mode (left) and *borus02* (right). In the case of *MYTorus* the best fit model (cyan solid line) and the individual components are plotted as in Figure 2. The *borus02* and the emission line components are plotted as a dashed line, the first power law is plotted as a solid line and the second power law as a dot-dashed line.

Table 3

Summary table of the spectral results obtained with *MYTorus* (coupled and decoupled) and *borus02* applied to NGC 3081 data.

	NGC 3081			
	MYTorus “coupled”	MYTorus “de-coupled”		borus02
		edge-on	face-on	
$\chi^2/d.o.f.$	1774/1404	1723/1403	1747/1403	1753/1403
Γ	$1.59^{+0.03}_{-0.03}$	$1.81^{+0.07}_{-0.06}$	$1.75^{+0.03}_{-0.05}$	$1.80^{+0.06}_{-0.04}$
$N_{H,eq}$ ^a	$0.62^{+0.02}_{-0.02}$	...	...	...
$N_{H,z}$ ^b	...	$0.60^{+0.02}_{-0.02}$	$0.66^{+0.02}_{-0.02}$	$0.61^{+0.02}_{-0.02}$
$N_{H,S}$ ^c	...	$1.59^{+0.19}_{-0.17}$	$3.00^{+0.69}_{-0.68}$	$1.51^{+0.11}_{-0.10}$
$A_S = A_L$ ^d	$0.86^{+0.13}_{-0.12}$	$2.23^{+0.46}_{-0.37}$	$0.42^{+0.05}_{-0.05}$	...
θ_{obs} ^e	90^f	90^f	0^f	...
f_s ^g	$5.63^{+0.62}_{-0.56}$	$4.36^{+0.57}_{-0.62}$	$3.17^{+0.53}_{-0.34}$	$4.51^{+0.44}_{-0.55}$
EW ^h	$0.181^{+0.010}_{-0.003}$	$0.185^{+0.007}_{-0.007}$	$0.185^{+0.007}_{-0.007}$	...
C_{TOR} ⁱ	...	...	...	$0.73^{+0.09}_{-0.10}$
kT ^j	$0.26^{+0.02}_{-0.01}$	$0.25^{+0.02}_{-0.02}$	$0.26^{+0.02}_{-0.02}$	$0.26^{+0.02}_{-0.02}$
$F_{2-10\ keV}$ ^k	$4.50^{+0.11}_{-0.13}$	$4.40^{+0.10}_{-0.19}$	$4.45^{+0.11}_{-0.17}$	$4.38^{+0.10}_{-0.14}$
$F_{10-40\ keV}$ ^l	$4.12^{+0.07}_{-0.08}$	$4.19^{+0.05}_{-0.13}$	$4.16^{+0.03}_{-0.28}$	$4.18^{+0.10}_{-0.08}$
$\log(L_{2-10\ keV})$ ^m	$41.73^{+0.01}_{-0.01}$	$41.74^{+0.05}_{-0.05}$	$41.75^{+0.06}_{-0.06}$	$42.78^{+0.01}_{-0.01}$
$\log(L_{10-40\ keV})$ ⁿ	$42.56^{+0.02}_{-0.02}$	$42.57^{+0.01}_{-0.01}$	$42.66^{+0.07}_{-0.07}$	$42.83^{+0.01}_{-0.01}$

^aEquatorial column density in the *MYTorus* model, in the “coupled” configuration, in unit of $10^{24}\ \text{cm}^{-2}$.

^bColumn density along the l.o.s. in unit of $10^{24}\ \text{cm}^{-2}$.

^c“Global average” column density in unit of $10^{24}\ \text{cm}^{-2}$.

^dNormalization between the reprocessed *MYTorus* component and the zeroth-order continuum.

^eTorus inclination angle in degrees.

^fThe f indicates that a parameter is fixed.

^gFraction of the scattered component.

^hEquivalent width of the $K\alpha$ Iron line in unit of keV.

ⁱCovering factor of the torus, in the *borus02* model.

^jTemperature of the thermal component in keV.

^k2–10 keV flux in unit of $10^{-12}\ \text{erg s}^{-1}\ \text{cm}^{-2}$.

^l10–40 keV flux in unit of $10^{-12}\ \text{erg s}^{-1}\ \text{cm}^{-2}$.

^m2–10 keV intrinsic luminosity in unit of erg s^{-1} .

ⁿ10–40 keV intrinsic luminosity in unit of erg s^{-1} .

AGN (Marchesi et al. 2018); the 0.6–2 keV emission is well fitted by adding a thermal component, originated by presence of diffuse gas in the nuclear region, with a temperature of $kT \sim 0.3$ keV; we also detect several emission lines at energies ~ 0.92 , 1.31 and 1.80 keV, which are expected to arise from the continuum in the case of obscured sources (if the statistics is sufficiently high to detect them), associated to Ne IX, Mg XI and Si XIII (also found in other obscured AGN, related to the ionizing AGN flux, e.g., Brinkman et al. 2002; Piconcelli et al. 2011).

We also compute the mid-IR luminosity following the relation presented by Asmus et al. (2015). The mid-IR luminosity at $12\mu\text{m}$ is $\log(L_{12\mu\text{m}}) = 43.10^{+0.04}_{-0.04}$ erg s^{-1} using the *borus02* 2–10 keV luminosity and $\log(L_{12\mu\text{m}}) = 42.02^{+0.12}_{-0.13}$ erg s^{-1} with the *MYTorus* 2–10 keV luminosity. Since the value obtained by Asmus et al. (2015) is $\log(L_{12\mu\text{m}}) = 42.87^{+0.07}_{-0.07}$ erg s^{-1} it can suggest that the *borus02* model allows us to reach a representation of the intrinsic emission. Finally, we computed the iron $K\alpha$ emission line equivalent width, which is ~ 0.180 keV (see Table 3). Although this value is lower than the typical threshold for CT-AGN (~ 1 keV, see, e.g., Koss et al. 2016), there is evidence of similar sources in previous literature works (e.g., Marchesi et al. 2017b).

4.2. ESO 565-G019

4.2.1. MYTorus model

We firstly analyze the ESO 565-G019 0.6–40 keV spectrum with *MYTorus* in its “coupled” configuration, using the three *MYTorus* components plus the second power law and the thermal component to describe the soft part of the spectrum:

$$\text{model } ESO_A = \text{pha}(zpo1 * MYTZ + A_S * MYTS + A_L * MYTL + mekal + f_s * zpo2) \quad (3)$$

In this case, leaving the inclination angle free to vary, it is not possible to obtain a statistically acceptable solution for the fit ($\chi^2 > 2$). To this purpose, we tried two different configurations: one with the inclination angle fixed to 90° , and the other with $\theta_{obs} = 65^\circ$ (i.e., we are observing through the brink of the torus). We report the results of the spectral fitting in Table 4: both the photon index and the column density are very different in the two models, in particular we obtain $N_{H,MYT,c,65} = 10^{+0.00*}_{-1.29} \times 10^{24}$ cm^{-2} that is the *MYTorus* upper limit. We also try to fit the data fixing the angle to an intermediate value ($\theta_{obs} = 77^\circ$), but the statistics does not show significant improvement ($\chi^2_\nu = 297/212$). We report in Figure 4 the 0.6–40 keV spectrum of ESO 565-G019 fitted with *MYTorus* coupled with $\theta = 65^\circ$.

These fitting issues may be due to the limitations of the “coupled” mode, thus, using *MYTorus* in its “de-coupled” configuration, we expect to achieve a more physical description of the circumnuclear region for ESO 565-G019.

We then model the spectrum using the *MYTorus* model in the edge-on and face-on modes of the “de-coupled” configuration and adding both the second power law and the thermal component to reproduce the soft emis-

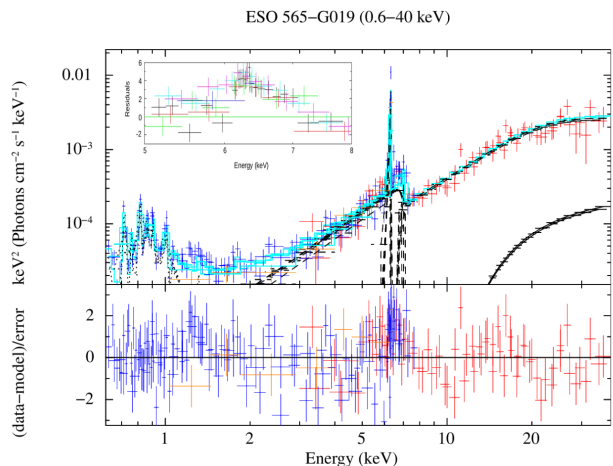


Figure 4. Unfolded *Chandra* (orange), *XMM-Newton* (blue) and *NuSTAR* (red) 0.6–40 keV combined spectrum of ESO 565-G019 modeled with *MYTorus* in the “coupled” configuration. The cyan solid line represents the best-fit model, while the individual components, MYTZ, MYTS, MYTL and the second power law, are reported as a black solid line, dashed lines and dash dotted line, respectively. Finally, the mekal component is plotted as dashed line. In the top left corner the residuals for the iron $K\alpha$ line in the best-fit model without the line component are shown.

sion. In the edge-on configuration the photon index is $\Gamma_{\theta,S=90} = 1.56^{+0.16}_{-0.16*}$; in the face-on mode is instead steeper $\Gamma_{\theta,S=90} = 2.22^{+0.12}_{-0.08}$. The l.o.s. column densities are $N_{H,z} = 2.96^{+0.53}_{-0.38} \times 10^{24}$ cm^{-2} for the edge-on mode and $N_{H,z} = 5.80^{+4.20*}_{-2.53} \times 10^{24}$ cm^{-2} in the face-on configuration. The “global average” column density is $N_{H,S} = 0.35^{+0.07}_{-0.05} \times 10^{24}$ cm^{-2} in the edge-on configuration and $N_{H,S} = 3.30^{+1.19}_{-1.80} \times 10^{24}$ cm^{-2} in the other one. For both modes the preferred scenario is the one in which we are observing through a particularly dense region of the torus, which has a lower “global average” column density. In Table 4 we report the spectral parameter for the 0.6–40 keV spectra: as it can be seen, the statistically favored scenario is the face-on ones, whose best-fit model with the spectrum is reported in Figure 5.

4.2.2. borus02 model

We finally analyze the ESO 565-G019 spectrum using the *borus02* spectral model. The model consists of the *borus02* table, the two powerlaws with a cutoff and the *mekal* component to take into account the soft emission:

$$\text{model } ESO_B = \text{pha} * (\text{borus02} + zpha * \text{cabs} * \text{cutoffpl1} + C2 * \text{cutoffpl2} + \text{mekal}) \quad (4)$$

The best fit model ($\chi^2/d.o.f. = 248/209$) is characterized by a photon index $\Gamma = 1.75^{+0.04}_{-0.22}$ and a l.o.s. absorption that is consistent with a Compton-thick scenario $N_{H,l.o.s.} = 3.72^{+*}_{-1.15} \times 10^{24}$ cm^{-2} . The average column density is also Compton-thick, but unconstrained in its upper bound and the covering factor is $C_{TOR} = 0.47^{+0.18}_{-0.08}$. We show the results in Table 4 and the combined 0.6–40 keV spectrum in Figure 5.

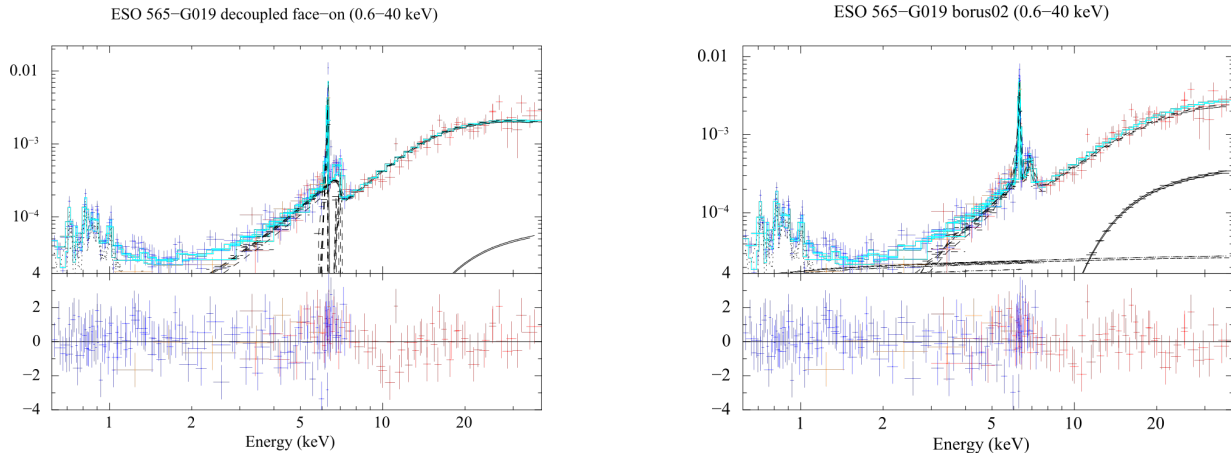


Figure 5. Unfolded *Chandra* (orange), *XMM-Newton* (blue) and *NuSTAR* 0.6–40 keV combined spectrum of ESO 565-G019 modeled with *MYTorus* in the “de-coupled” configuration in the face-on mode (left) and *borus02* (right). The best fit model and the individual components are plotted as in Figure 2, for the *MYTorus* model. The *borus02* and the emission line components are plotted as a dashed line, the first power law is plotted as a solid line and the second power law as a dot-dashed line.

Table 4

Summary table of the spectral results obtained with *MYTorus* (coupled and decoupled) and *borus02* applied to ESO 565-G019 data. The parameters are reported as in Table 3.

ESO 565-G019				
	<i>MYTorus</i> “coupled”	<i>MYTorus</i> “de-coupled”		<i>borus02</i>
		edge-on	face-on	
$\chi^2/d.o.f.$	286/212	292/211	256/211	248/209
Γ	$2.08^{+0.07}_{-0.08}$	$1.56^{+0.16}_{-*}$	$2.22^{+0.12}_{-0.08}$	$1.75^{+0.04}_{-0.22}$
$N_{H,eq}$	$5.30^{+*}_{-0.68}$	...	...	...
$N_{H,z}$	...	$2.96^{+0.53}_{-0.38}$	$5.80^{+4.20}_{-2.53}$	$3.00^{**}_{-0.69}$
$N_{H,S}$	...	$0.35^{+0.07}_{-0.05}$	$3.30^{+1.19}_{-1.80}$	$3.72^{+*}_{-1.15}$
$A_S = A_L$	1^f	1^f	1^f	...
θ_{obs}	65^f	90^f	0^f	...
f_s	$1.24^{+0.35}_{-0.42}$	$6.61^{+2.03}_{-1.53}$	$1.73^{+1.66}_{-0.60}$	$9.14^{+4.09}_{-4.58}$
EW	$1.90^{+*}_{-0.27}$	$1.42^{+0.18}_{-0.77}$	$1.60^{+*}_{-0.042}$	...
C_{TOR}$	...	...	...	0.47^{+0.18}_{-0.08}$
kT	$0.59^{+0.03}_{-0.03}$	$0.57^{+0.03}_{-0.05}$	$0.59^{+0.03}_{-0.04}$	$0.59^{+0.03}_{-0.03}$
$F_{2-10 \text{ keV}}$	$0.48^{+24.25}_{-0.10}$	$0.52^{+0.03}_{-0.10}$	$0.48^{+16.42}_{-0.09}$	$0.50^{+5.07}_{-0.39}$
$F_{10-40 \text{ keV}}$	$3.89^{+13.42}_{-0.07}$	$3.61^{+0.30}_{-0.86}$	$3.44^{+9.51}_{-0.18}$	$3.68^{+2.53}_{-2.79}$
$\log(L_{2-10 \text{ keV}})$	$43.17^{+0.05}_{-0.06}$	$42.87^{+0.03}_{-0.03}$	$43.03^{+0.04}_{-0.05}$	$42.48^{+0.25}_{-0.63}$
$\log(L_{10-40 \text{ keV}})$	$42.22^{+0.06}_{-0.07}$	$42.12^{+0.03}_{-0.04}$	$42.04^{+0.05}_{-0.06}$	$42.56^{+0.24}_{-0.56}$

4.2.3. Summary of the ESO 565-G019 spectral analysis results

ESO 565-G019 has lower spectral counts with respect to NGC 3081, being $N_C = 5.8$ k-counts. For ESO 565-G019 the best-fit model is the one given by the *borus02* analysis, with $\chi^2_\nu = 248/209$. *borus02* provides an estimate of the average column density of the obscuring torus. It results to be slightly larger than the l.o.s. column density, but still consistent with it (i.e., both have upper values consistent with the upper boundary allowed by the model). Within the uncertainties, the source is Compton-thick at the $> 3\sigma$ confidence level in both the l.o.s. and average column densities. Moreover, we com-

puted the covering factor, which is $C_{TOR} = 0.47^{+0.18}_{-0.08}$, that corresponds to an half opening angle of the torus $\sim 62^\circ$. The 10-40 keV flux is $4.18^{+0.10}_{-0.08} \times 10^{-12}$ erg s $^{-1}$ cm $^{-2}$, consistent with the *Swift*/BAT, but lower than the *Suzaku*/HXD (Gandhi et al. 2013), suggesting possible long-term flux variability.

The soft emission in ESO 565-G019 has been modeled combining a contribution of the scattered, unabsorbed fraction of the main emission and the thermal emission component with $kT \sim 0.6$ keV. For this AGN, we do not find any statistically significant emission line at soft energies ($E < 2$ keV). Finally, we computed the equivalent width of the iron $K\alpha$ emission line. Its value (~ 1.60 keV, see Table 4) is beyond the threshold usually adopted to

select candidate CT-AGN ($EW > 1$ keV, see, e.g., [Koss et al. 2016](#)).

5. DISCUSSION AND CONCLUSIONS

5.1. The advantages of the *NuSTAR* approach

We have analyzed the “soft” *Chandra* and XMM-*Newton* spectra alone in order to quantify the effect of adding the information from the *NuSTAR* data. From the 0.6–10 keV analysis of NGC 3081, we obtain a best fit model with $\Gamma = 1.91_{-0.16}^{+0.15}$ and $N_{H,z} = 0.74_{-0.07}^{+0.06} \times 10^{24}$ cm $^{-2}$. The spectral slope is in agreement with typical values observed in AGN. However, in order to increase the statistics and properly constrain the spectral parameters (in particular, the photon index and the column density), we have combined the *NuSTAR* data with the “soft” spectrum, obtaining the 0.6–70 keV NGC 3081 spectrum. As expected, the uncertainties on the main spectral parameters significantly decrease: the errors associated to the photon index decrease from $\sim 8\%$ to $\sim 4\%$ and those on the l.o.s. column density decrease from $\sim 8\%$ to $\sim 3\%$. Also, in accordance with [Marchesi et al. \(2018\)](#), we find a shift in both the photon index and the l.o.s. column density values. The first is reduced by $\sim 5\%$ (the average decrease in Γ value found by [Marchesi et al. 2018](#)) is $\sim 13\%$ and the $N_{H,z}$ one decreases by $\sim 19\%$ (the average value in [Marchesi et al. 2018](#)) is $\sim 32\%$; however, several sources in that sample only had low-count statistic *Swift*-XRT coverage in the 0.5–10 keV band). The smaller errors allow us to break the degeneracy between Γ and $N_{H,z}$. In Figure 6 we show the comparison between the 0.6–10 keV and 0.6–70 keV Γ - $N_{H,z}$ confidence regions. It is clear that, when adding *NuSTAR* data to the 0.6–10 keV spectrum, there is a shift in the spectral parameters to lower values and, also, a significant decrease of their uncertainties; this result highlights the strength of the X-ray broadband approach to characterize candidate CT-AGN, and the key role played by *NuSTAR* to achieve this goal.

5.2. Variability

We investigate possible variability between the *Chandra* data and the *NuSTAR* + XMM-*Newton* data. While *NuSTAR* and XMM-*Newton* observations are simultaneous, *Chandra* targeted NGC 3081 about one year before. In Figure 6 we show the contour plot between the normalization (indicator of the flux) and the column density (which accounts for the absorption properties). Variability can either be due to intrinsic variation of the emission from the central engine or of the absorbing structure. If there were a difference in both the normalization and in the column density (between the two sets of spectra), we may affirm that it can be due to variation in the geometrical properties of the torus through time (or variation of the accretion efficiency in the case of the normalization). In Figure 6 the superposed *Chandra* and the XMM-*Newton* + *NuSTAR* Normalization- N_H contour plots are shown. The XMM-*Newton* + *NuSTAR* contours plot (solid lines) is much smaller than the *Chandra* one (dashed lines); however, they are consistent, and no variability effects can be attested.

We also search for variability effects, for ESO 565-G019, between the *Chandra* and XMM-*Newton*+*NuSTAR* observations through the

Normalization- $N_{H,z}$ contour plots. We do not find indications of variability, although we note that the errors on the parameters, due to the limited photon statistics, are large.

5.3. Diffuse emission

Given the presence of *Chandra* observations, it is possible to study the properties of the extended emission in both NGC 3081 and ESO 565-G019, thus to establish a better portrait of the soft band spectrum.

Following the approach used in [Fabbiano et al. \(2017\)](#); [Jones et al. \(2020\)](#); [Ma et al. \(2020\)](#), we obtain the soft (i.e. 0.3–3.0 keV) and hard (i.e. 3.0–7.0 keV) *Chandra* images of both sources (see Figures 7 and 8). We can notice that the diffuse emission extends in the NW-SE and N-S direction, showing an elongated structure on projected scales of about 2 kpc and 3.5 kpc for NGC 3081 and ESO 565-G019, respectively.

To quantitatively assess the presence (or lack) of extended emission in our sources, we compare the radial distribution of their surface brightness with the one obtained from a simulated PSF in the two energy ranges using the *ChART* and *MARX* 5.5.1 tasks (see e.g., [Fabbiano et al. 2017](#); [Jones et al. 2020](#); [Ma et al. 2020](#), for a detailed description of this technique). Figure 9 shows the radial profiles of the emission vs. PSF expectations in the 0.3–3.0 keV and 3.0–7.0 keV energy bands. These profiles have been obtained from an annular region comprising 8 annuli from ~ 0.7 to ~ 8 arcsec. The 0.3–3.0 keV profiles of NGC 3081 and ESO 565-G019 show a significant emission above the PSF values up to ~ 7 arcsec, whose origin could be related to non-nuclear processes like star formation or diffuse emission on the host-galaxy scales. In Figure 10 the *Chandra* contours plotted over the optical DSS images are shown. As mentioned in Section 2, ESO 565-G019 has a SFR on the order of ~ 3 – $4 M_{\odot}/yr$ ([Gandhi et al. 2013](#)), thus, its X-ray diffuse emission could be ascribed to a thermal emission on the scales of the host with a possible contribution of star formation processes. Given the 0.5–2 keV spectrum, it is possible to compute the X-ray SFR for these sources following the relation between the 0.5–2 keV luminosity and the SFR (e.g., [Ranalli et al. 2003](#)). We find that ESO 565-G019 has a SFR = $4.4_{-0.7}^{+0.8} M_{\odot}/yr$ (the errors correspond to the dispersion of the relation we adopted), consistent with literature. For NGC 3081 there is little (nuclear SFR $< 0.05 M_{\odot}/yr$, [Esquej et al. 2014](#)) to no evidences for nuclear star formation activity (see, e.g., [Esparza-Arredondo et al. 2018](#); [Fuller et al. 2019](#)), therefore the diffuse emission could be produced by galaxy-scale processes (e.g., hot gas in the nuclear region of the galaxy). However, we cannot rule out the possibility that star formation also contributes to some extent. Indeed, from the 0.5–2 keV spectrum, we find a SFR = $1.2_{-0.2}^{+0.2} M_{\odot}/yr$.

In the hard-band profiles, where the AGN contribution is dominant and negligible contamination from non-AGN processes is expected, this extension is much more reduced, especially for ESO 565-G019. We also measure the excess fraction, defined as the ratio between the counts above the PSF and the total counts in the analyzed area. We find an excess fraction of $20 \pm 1.8\%$ for the 0.3–3.0 keV extended emission of NGC 3081 and $18.9 \pm 8.7\%$ for ESO 565-G019. In the 3.0–7.0 keV

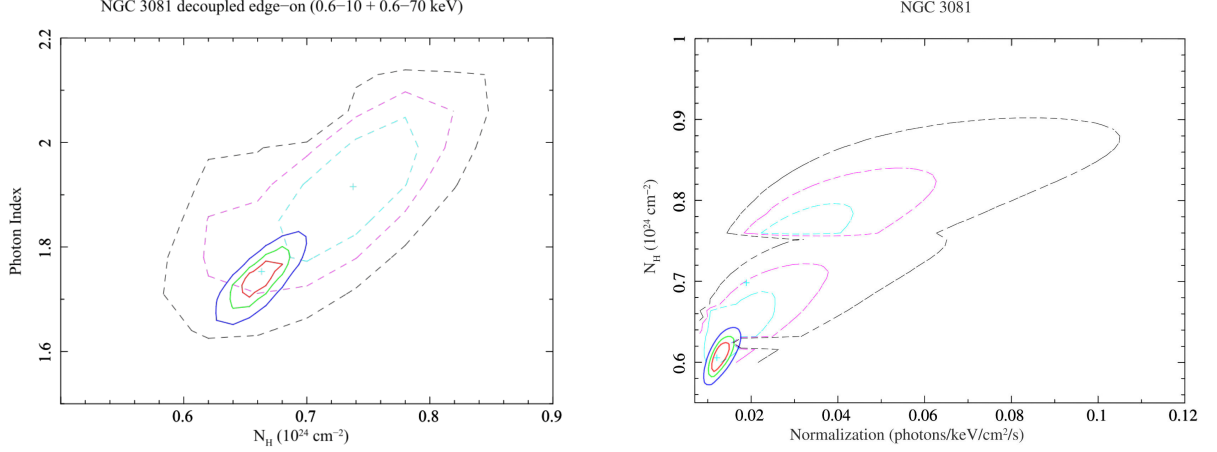


Figure 6. Confidence contours for the parameters Γ - N_H obtained using NGC 3081 spectra in the 0.6–10 keV and 0.6–70 keV energy band (left). On the right panel we show the confidence contours for the normalization of the continuum and $N_{H,z}$ of the 0.6–10 keV and 0.6–70 keV NGC 3081 spectra superposed. We report with solid lines the XMM-Newton + NuSTAR contour plots and with dashed lines the Chandra ones. The 0.6–70 keV contours are smaller than the Chandra ones, due to the larger photon statistic. Moreover, the Chandra confidence regions show a double minimum, meaning that there can be two statistically equivalent different combinations for the parameters of interest.

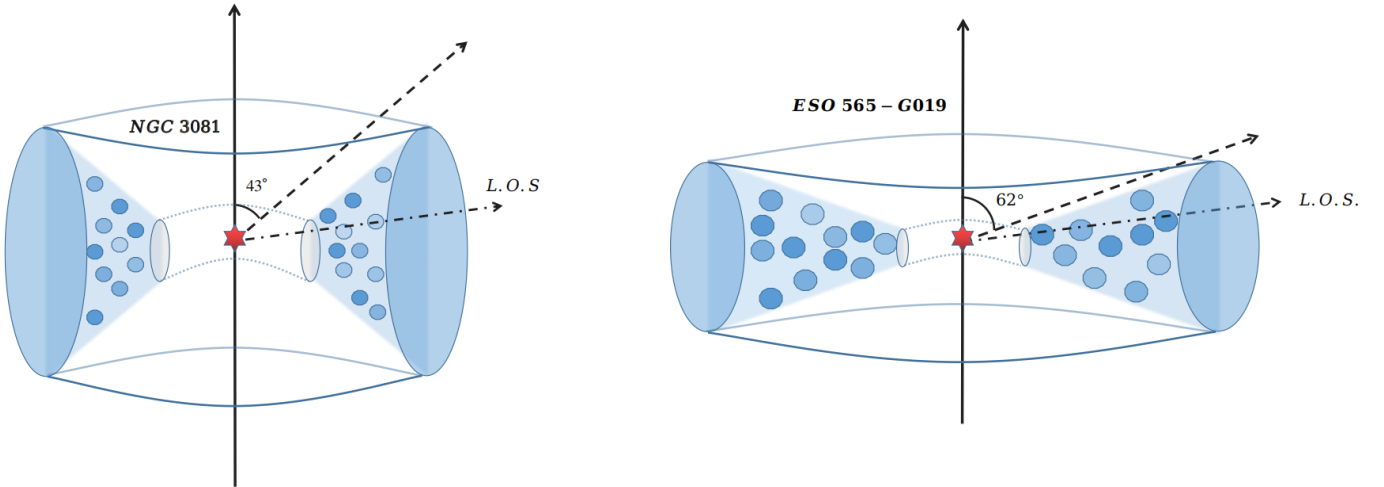


Figure 11. Schematic representation of the two torus configurations found for NGC 3081 (left) and ESO 565-G019 (right). The solid line indicates the torus axis, the dashed line represents the angle corresponding to the torus covering factor and the dash-dotted line is the line-of-sight. The torus clouds, represented as blue circles, are qualitatively color coded with respect to the column density: the darker the color, the higher is the column density.

range, the excess fraction is negative for both NGC 3081 (< -0.01) and ESO 565-G019 (< -0.07), meaning that the emission is consistent with the PSF in the 3.0–7.0 keV energy range.

The detection of a diffuse axial emission in the 0.3–7.0 keV interval is in agreement with the aforementioned works (Fabbiano et al. 2017; Jones et al. 2020; Ma et al. 2020). However, although we detect an excess in the soft data, we find no significant excess in the hard extended emission, which has been found to be 12–22% and likely due to the existence of reprocessed emission on scales beyond the torus (see e.g., Ma et al. 2020).

5.4. Comparison with the total sample

Based on the results of this work along with those reported by Torres-Albà et al. (submitted), eight out of

ten sources are incompatible, at 90% significance, with having the same line-of-sight and average torus column densities. This follows the overall trend observed for the full sample of 57 obscured AGN, in which the large majority ($\sim 91\%$) of sources show this discrepancy (see Fig. 4 in Torres-Albà et al., submitted). We link this observational evidence to the presence of a clumpy torus. Moreover, including the results from the 10 sample analysis, 13 out of 57 candidate CT-AGN (one of which is ESO 565-G019) have both l.o.s and average column density larger than 10^{24} cm^{-2} . With the addition of this source, the percentage of NuSTAR-confirmed CT-AGN in the BAT sample at $z \leq 0.05$ is $\sim 8\%$ (32/417)¹⁰, still much lower than the predictions. However, with the analysis of

¹⁰ <https://science.clemson.edu/ctagn/ctagn/>

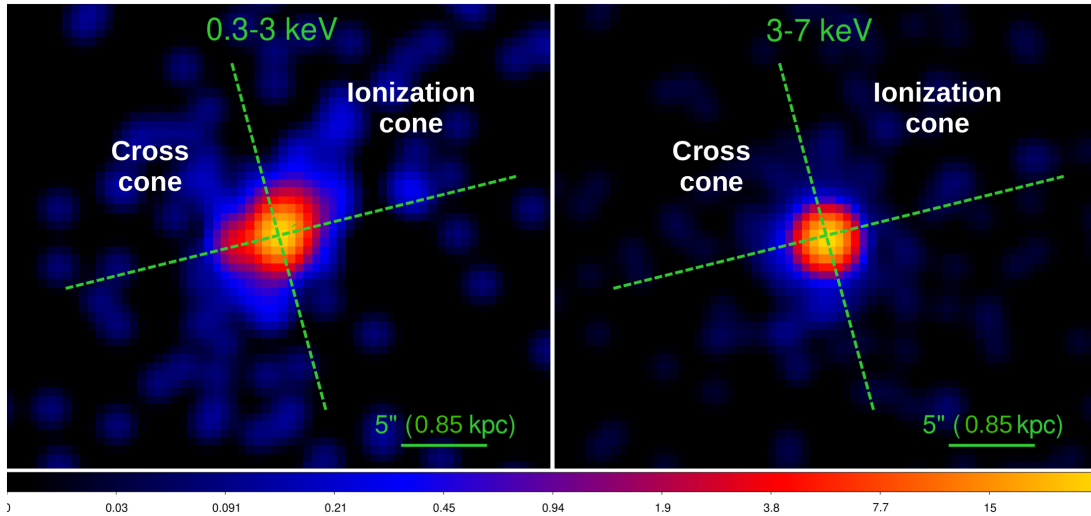


Figure 7. NGC 3081 soft (left) and hard (right) *Chandra* images. The green dashed lines indicate the regions where the extended emission is confined. The image is color-coded with the number of counts. Also, the physical scale is reported at the source distance.

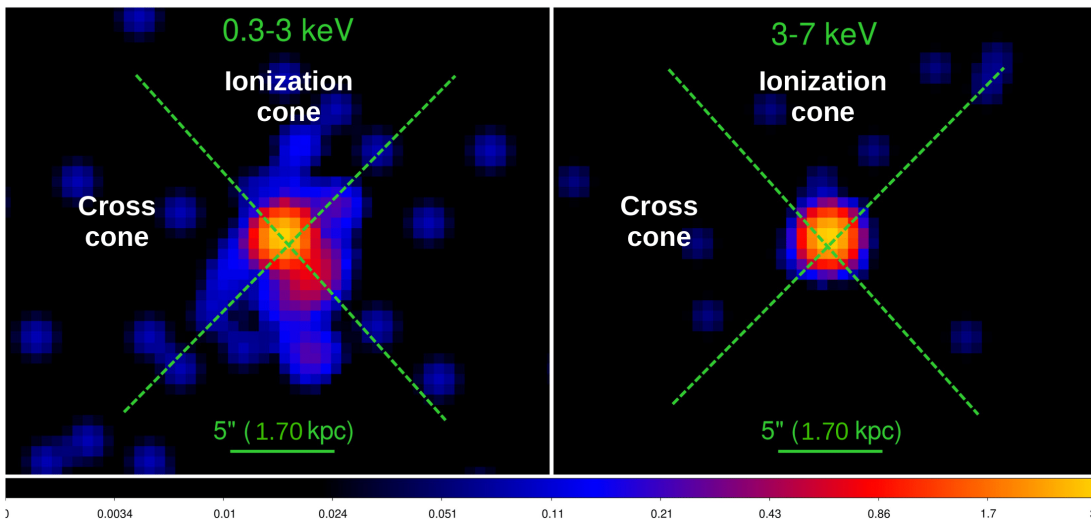


Figure 8. ESO 565-G019 soft (left) and hard (right) *Chandra* images. The green dashed lines indicate the regions where the extended emission is confined. The image is color-coded with the number of counts. Also, the physical scale is reported at the source distance.

the full ~ 60 source sample, Torres-Albà et al. (submitted) observed a significant decrease of the Compton-thick fraction with redshift. In fact, at $z < 0.01$, the fraction is $20.0 \pm 5.7\%$, which is much closer to the theoretical predictions.

5.5. Conclusion

Despite the many studies carried out over the last 20 years, the obscured AGN population is not entirely well characterized and many questions are still unresolved. The study of obscured AGN is relevant for several astrophysical issues concerning galaxy evolution, as well as

the CXB content and determination of the accretion history of the Universe (e.g., Alexander et al. 2003; Gilli et al. 2007; Treister et al. 2009). In fact, the quest for and characterization of Type 2 AGN provides a census of the population of galaxies which are thought to be in the phase of the building up of their mass (probably after a merger) or in the first phases of the nuclear activity (see, e.g., Chen et al. 2013; Azadi et al. 2015).

Combining the capabilities of *Chandra* and *XMM-Newton* at $E < 10$ keV with those of *NuSTAR* (3–79 keV), it is possible to properly characterize the spectral parameters (e.g., intrinsic column density and opening an-

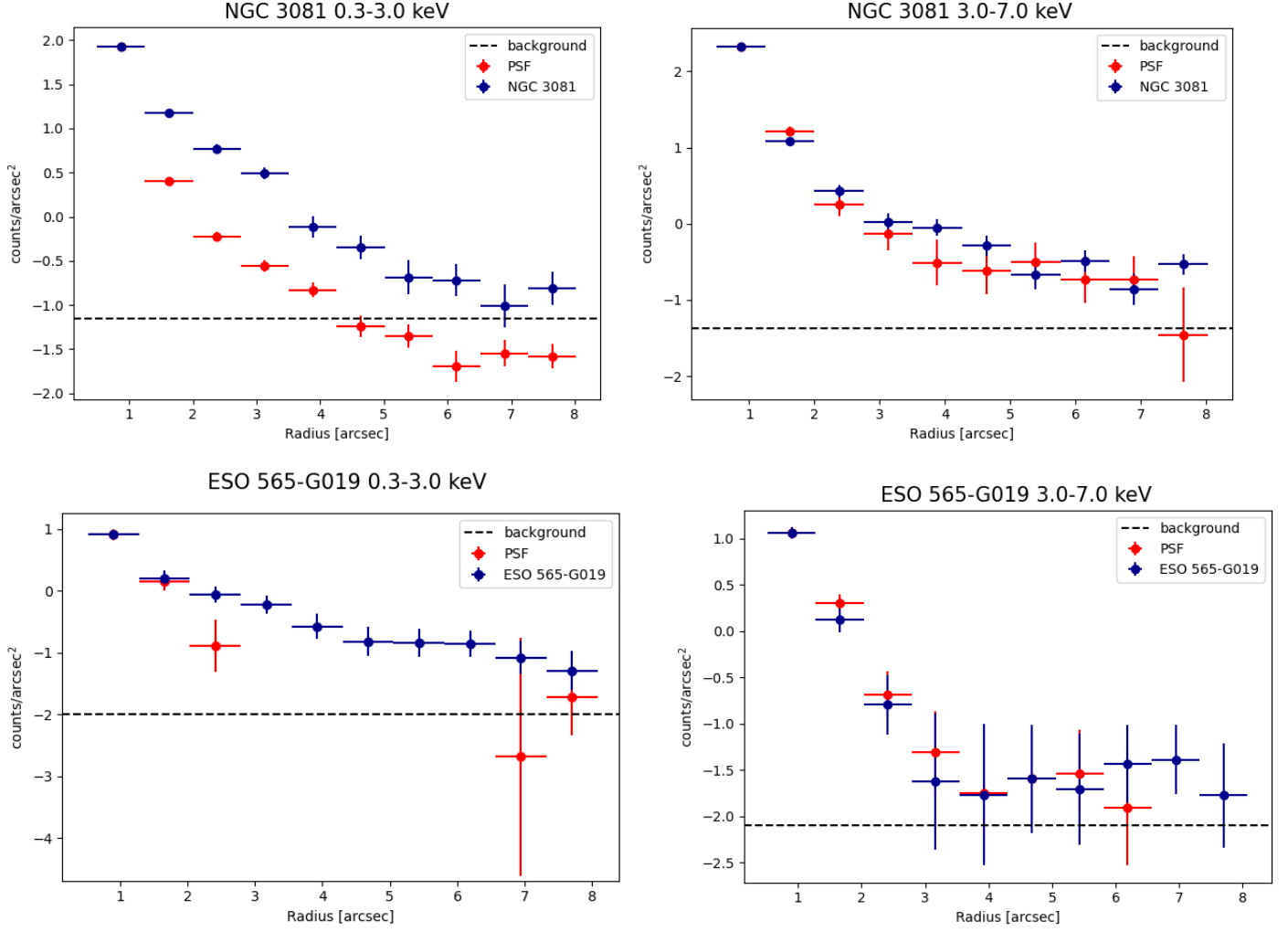


Figure 9. Radial profiles in the 0.3–3 keV and 3.0–7.0 keV energy bands for NGC 3081 and ESO 565-G019. The blue points are the source counts, whereas the red points represent the counts of the simulated PSF normalized to the first source point. The black dashed line indicates the background level.

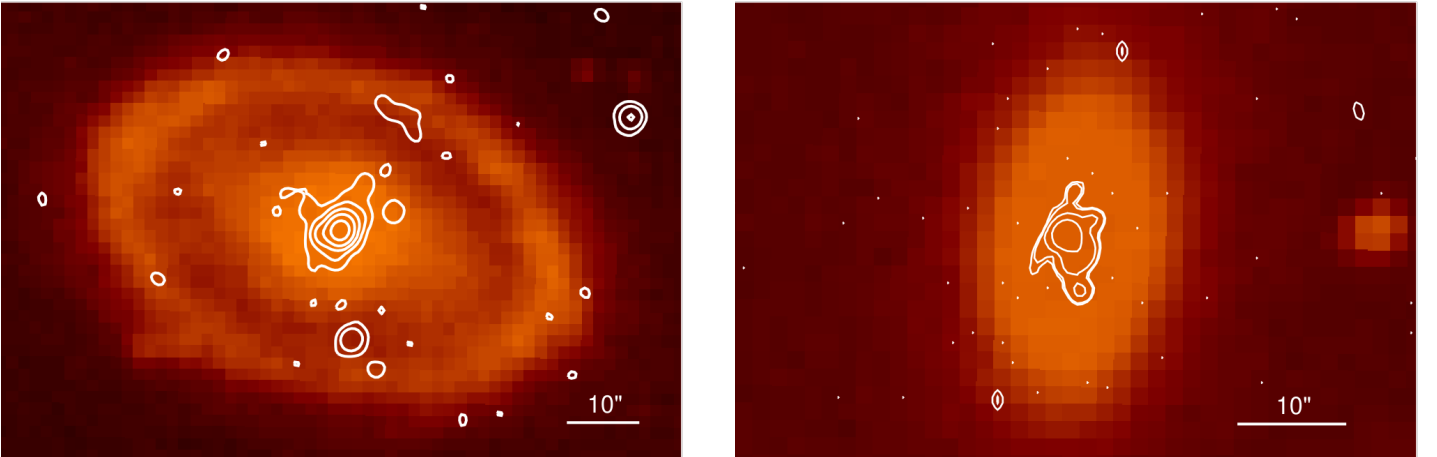


Figure 10. Optical DSS images of NGC 3081 and ESO 565-G019 in the IIIaJ band, centered at 4860 Å. White contours indicate the *Chandra* emission in the 0.3–3.0 keV energy range.

gle of the obscuring material) of heavily obscured AGN, allowing to distinguish between the Compton-thin and Compton-thick regime. These combined observations can also break the degeneracy between spectral parameters (e.g., between the photon index and the obscuring material column density) through the use of advanced, physically motivated spectral models (e.g., **MYTorus** and **borus02**).

In Figure 11 a schematic sketch of the best-fit configuration found for the two sources is reported. The torus is represented by several clumps distributed following the toroidal structure. In the figure the following properties are present: the covering factor is represented as the angle of the sky free from the torus by the central source point of view; the differences in the column density of the torus is represented by differences in the colors of the clumps, darker colors mean higher column density. Thus, NGC 3081 has an higher covering factor (lower angle) than ESO 565-G019. The l.o.s. column density of NGC 3081 is lower than the “global average” column density: the observer is looking at the central source through an under-dense region with respect to the torus average column density. ESO 565-G019 is characterized by a Compton-thick column density both on the l.o.s. and in average, and this is represented by over-dense clumps in the whole structure.

The conclusions of this work can be summarized as follows:

1. We have verified that the *NuSTAR* data significantly contribute to the determination of the main spectral parameters which characterize obscured AGN at low redshift ($z \leq 0.1$). Its contribution mainly consists in the decreasing of the errors of the parameters of interest and in breaking of degeneracy between them, thus allowing a better characterization of the spectral emission properties. Moreover, the use of *XMM-Newton* and *NuSTAR* simultaneous observations allows one to avoid variability effects.
2. The spectra of both sources present a significant emission at energies $< 2 - 3$ keV which cannot be ascribed solely to the main emission from the nucleus. We have modeled this emission with a thermal component and found that it can be produced by a medium with temperature between $10^6 - 10^7$ K. However, we do not place constraints on the origin of this emission. This thermal component can be due either to a thermally emitting gas in the nuclear region or to a population of X-ray emitting unresolved sources (e.g., X-ray binaries) or to a combination of the two phenomena. In the soft part of the spectrum of NGC 3081, we find evidences of emission lines, which are typical of obscured sources (e.g., Brinkman et al. 2002; Piconcelli et al. 2011).
3. We found that NGC 3081 is best fitted by the **MYTorus** model in the de-coupled mode (edge-on configuration), while ESO 565-G019 is best fitted by the **borus02** model. NGC 3081 is Compton-thin along the l.o.s., but with the obscuring material being, on average, Compton-thick. ESO 565-G019 is classified as Compton-thick in both the l.o.s. and average components of the column density.

4. For both sources we were able to compute the torus covering factor through the **borus02** modeling. NGC 3081 has $C_{TOR} = 0.73^{+0.09}_{-0.10}$, suggesting that the torus contributes in a significant way to cover the central emission. Moreover, the ratio between l.o.s. and average column densities is typical of a clumpy scenario. For ESO 565-G019 the lower covering factor $C_{TOR} = 0.47^{+0.18}_{-0.08}$, along with the ΔN_H , suggests a scenario in which the obscuring structure, which is Compton-thick, may be distributed in several individual clouds, responsible for the obscuration. The values are consistent, between the uncertainties, with the average covering factor found by Marchesi et al. (2019), $C_{TOR} \simeq 0.6$, for a ~ 30 CT-AGN candidates sample.

5. The main nuclear emission can be divided into the reprocessed component, which is heavily suppressed in Compton-thick AGN, and the component which is scattered (and unabsorbed) by Compton-thin material and can reach the observer at lower energies (i.e. < 5 keV). For both AGN presented in this work we find that this component represents a low fraction of the main emission, being $< 1\%$ and $\sim 1\%$ for NGC 3081 and ESO 565-G019, respectively. These results suggest that the Compton-thin material is a small fraction of the circumnuclear environment.

6. Thanks to the presence of *Chandra* data, we were able to investigate the extended emission of NGC 3081 and ESO 565-G019. We found significant diffuse emission in the 0.3–3.0 keV band extending for about 2 (NGC 3081) and 3.5 kpc (ESO 565-G019). However, we were not able to detect any diffuse emission in the 3–7 keV energy range.

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