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The X-ray emission of the Seyfert 2 galaxy MCG-01-24-12

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ABSTRACT

We present a detailed X-ray spectral analysis of the nearby Seyfert 2 galaxy MCG-01-24-12 based on a multi-epoch data set. Data have been taken with different X-ray satellites, namely *XMM-Newton*, *NuSTAR*, *Swift* and *Chandra* and cover different time intervals, from years down to a few days. From 2006 to 2013 the source had a 2-10 keV flux of $\sim 1.5\times10^{-11}$ erg cm^{-2} s^{-1}, consistent with archival observations based on *HEAO* and *BeppoSAX* data, though a 2019 *Chandra* snapshot caught the source in an extreme low flux state, a factor of ∼10 fainter than its historical one. Based on phenomenological and physically motivated models, we find the X-ray spectrum of MCG-01-24-12 to be best modelled by a power-law continuum emission with $\Gamma=1.76\pm0.09$ with a high energy cut-off at $E_c = 70^{+21}_{-14}$ keV that is absorbed by a fairly constant column density of $N_H=(6.3\pm0.5)\times10^{22}$ cm^{-2}. These quantities allowed us to estimate the properties of the hot corona in MCG-01-24-12 for the cases of a spherical or slab-like hot Comptonising plasma to be $kT_e=27^{+8}_{-4}$ keV, $\tau_e=5.5\pm1.3$ and $kT_e=28^{+7}_{-5}$ keV, $\tau=3.2\pm0.8$, respectively. Finally, despite the short duration of the exposures, possible evidence of the presence of outflows is discussed.

Key words. galaxies: active - galaxies: Seyfert - X-rays: galaxies - X-rays: individual: MCG-01-24-12

1. Introduction

Seyfert 2 galaxies are a class of active galactic nuclei (AGNs) whose optical spectra lack broad emission lines. These emission lines are not observed because the Broad Line Region (BLR) is hidden by matter with column density in the range 10^{22-24} cm^{-2} and our line-of-sight passes through this obscuring circumnuclear medium, thought to be toroidal in structure. The so-called dusty torus absorbs and reprocesses (transmits and/or reflects) the X-ray nuclear continuum imprinting some characteristic features on the emerging spectrum. Although this obscuring structure is predicted to be ubiquitous in AGN by the unification model (Antonucci 1993), there are still uncertainties on its exact location, composition and overall geometry. In recent years both short- and long- term variability of the obscurer column density (N_H) have been observed in nearby AGNs such as NGC 1365 (e.g. Risaliti et al. 2005; Rivers et al. 2015), NGC 4388 (e.g. Elvis et al. 2004), NGC 4151 (Puccetti et al. 2007), and NGC 7582 (e.g. Piconcelli et al. 2007; Bianchi et al. 2009; Rivers et al. 2015; Braito et al. 2017) and changes in the column density have also been measured in heavily obscured AGN, i.e. NGC 1068 (e.g. Zaino et al. 2020). As a result, the standard picture of a smooth 'doughnut' shaped torus was ruled out in favour of a more inhomogeneous structure comprised by a distribution of a large number of individual clumps (e.g., Risaliti et al. 2002; Markowitz et al. 2014).

The high piercing power of X-rays, unless the obscuring matter has a column density larger than the inverse of the Thomson cross section ($N_H > \sigma^{-1}_{\rm Th.} \sim 1.5\times10^{24}$ cm^{-2}), can allow for the direct observation of the central regions where the primary X-rays originate (e.g. Nandra & Pounds 1994; Turner et al. 1997a; Guainazzi et al. 2005; Awaki et al. 2006). X-ray photons are produced by inverse-Compton scattering disc optical-UV photons from thermal electrons, the so-called hot corona (details in Haardt & Maraschi 1991, 1993). Both variability and microlensing arguments (Chartas et al. 2009; Morgan et al. 2012; De Marco et al. 2013; Kara et al. 2016) agree with this hot plasma being compact and likely lying close to the SMBH. As expected on a theoretical basis, the physical quantities of the X-ray emitting region (its opacity and temperature) characterise the emerging spectrum in terms of photon index (Γ) and high energy cut-off (E_c, e.g. Rybicki & Lightman 1979; Ghisellini 2013). The relation between physical and phenomenological quantities has been the object of different studies (e.g. Beloborodov 1999; Petrucci et al. 2000, 2001; Middei et al. 2019). *NuSTAR* played a fundamental role in such a framework; due to its unrivalled capability of focusing X-rays up to about 80 keV, it allowed for an increasingly number of high energy cut-off measurements (e.g. Fabian et al. 2015, 2017; Tortosa et al. 2018), hence estimates of

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Table 1. The observation log of the presented data set is reported. For four pointings out of six, the *NuSTAR* and *Swift* observatories have simultaneously observed MCG-01-24-12.

Satellite	Detector	Obs. ID	Obs.	Net exposure ks	Start-date yyyy-mm-dd
XMM	*pn/MOS*	0307000501		8.3/15.4	2006-04-25
NuSTAR	*FPMA/B*	60061091002	1	12.3	2013-04-03
Swift	*XRT*	00080415001		7.5	
NuSTAR	*FPMA/B*	60061091004	2	9.3	2013-04-10
Swift	*XRT*	00080415002		1.9	
NuSTAR	*FPMA/B*	60061091006	3	12.1	2013-04-18
Swift	*XRT*	00080415003		2.9	
NuSTAR	*FPMA/B*	60061091008	4	14.0	2013-05-05
NuSTAR	*FPMA/B*	60061091010	5	15.3	2013-05-12
Swift	*XRT*	00080415005		1.8	
NuSTAR	*FPMA/B*	60061091012	6	12.2	2013-05-22
Chandra	*ACIS-S*	703907		9.1	2019-06-27

the coronal temperature (kT$_e$) and optical depth (τ_e).

The primary X-ray continuum can be reflected off the black hole surroundings and this emission may leave two major signatures on the emerging spectrum: a Fe Kα line at 6.4 keV due to fluorescence and a bump of counts at ~30 keV (e.g. George & Fabian 1991; Matt et al. 1991), the so-called Compton hump.

Due to their variable emission, multi epoch data sets are particularly suitable for studying AGNs spectral properties. In this context, we report on the analysis of MCG-01-24-12, a bright spiral galaxy at redshift z=0.0196 (e.g. Koss et al. 2011) hosting a Seyfert 2 nucleus (de Grijp et al. 1992). This AGN, firstly studied by Piccinotti et al. (1982) in the 2-10 keV band, has been subsequently analysed by Malizia et al. (2002) that used *Beppo-SAX* data to discuss its X-ray spectral properties. In particular, the source 2-10 keV band was characterised by a narrow Fe Kα emission line and an absorption feature at about 8 keV, while softer X-rays were absorbed by an obscurer with $N_H \sim 7 \times 10^{22}$ cm^{-2}. In the hard X-band (20-100 keV) they measured a flux of ~4× 10^{-11} erg cm^{-2} s^{-1}. Later, MCG-01-24-012 has been reported by Ricci et al. (2017, 2018) who, using *Swift* data, measured its flux to be $F_{14-195\ \mathrm{keV}}$=4.1×10^{-11} erg cm^{-2} s^{-1}. Finally, MCG-01-24-12 black hole mass has been estimated to be $M_{BH}=1.5^{+1.1}_{-0.6} \times 10^7\ M_\odot$ (La Franca et al. 2015).

2. Archival data

MCG-01-24-12 was observed several times in the X-ray band. In Table 1 we report the log of the observations considered in this work.

The standard *XMM-Newton* Science Analysis System (*SAS*, Version 18.0.0) has been used to obtain the scientific products for the different instruments on-board the observatory, namely *pn* (Strüder et al. 2001) and the *MOS* cameras (Turner et al. 2001). To select the extraction radius and to screen for high background time intervals we used an iterative process that maximises the Signal-to-Noise Ratio (S/N) ratio (see details in Piconcelli et al. 2004). For the *pn* data, we used a 21 arcsec radius circular region to extract the source spectrum and the background was computed with a circular area of 50 arcsec radius close to the source. The spectrum was then binned to have at least 30 counts for each bin, and not to oversample the instrumental energy resolution by a factor larger than 3. Radii of 21 and 22 arcsec were adopted for *MOS1* and *MOS2*, respectively, to extract the source spectrum, while we obtained the background using a circular area with 40 arcsec radius. The same binning strategy used for *pn* data has been applied to *MOS* spectra. We notice that these *XMM-Newton* data are not affected by significant pile-up this being in agreement with the *SAS* standard task *epatplot*. Moreover, we checked for the eventual *Cu* emission possibly affecting the *pn* spectrum and no evidence of it was found.

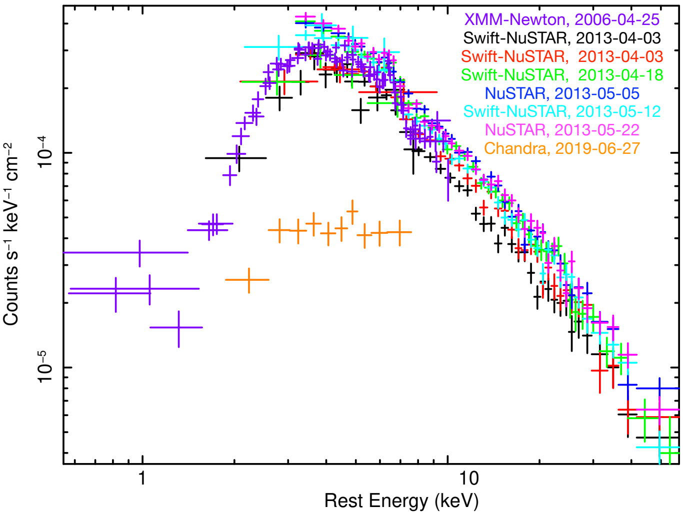

Fig. 1. MCG-01-24-12 spectra as observed by the different observatories as folded by a power-law with Γ=2 and unitary normalisation.

To calibrate and clean raw *NuSTAR* data we used the NuSTAR Data Analysis Software (*NuSTARDAS*, Perri et al., 2013[1]) package (v. 1.8.0). Level 2 cleaned products were obtained with the standard *nupipeline* task and the scientific products were computed thanks to the *nuproducts* pipeline and using the calibration database "20191219". A circular region with a radius of 40 arcsec was used to extract the source spectrum. The background has been calculated using the same circular region but centered in a blank area nearby the source. The *FPMA/B* spectra have been binned in order not to oversample the instrumental resolution by a factor larger than 2.5 and to achieve a S/N larger than 3 in each spectral channel.

Swift-XRT data were taken in photon counting mode and we derived the scientific products using the facilities provided by the Space Science Data Center, (SSDC, `https://www.ssdc.asi.it/`) of the Italian Space Agency (ASI). The source spectrum was extracted with a circular region of ~ 60 arcsec and we used a concentric annulus for the background. Then spectra have been binned in order to have at least 20 counts in each bin. Due to their short exposures, we do not show the *XRT* light curves.

An approximately 10 ks long exposure of MCG-01-24-12 was carried out by *Chandra* on the 27th June 2019 with the Advanced CCD Imaging spectrometer (ACIS-S; Garmire et al. 2003). The data was reduced by adopting the Chandra Interactive Analysis of Observation software (*CIAO* v. 4.12 Fruscione et al.

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[1] `https://heasarc.gsfc.nasa.gov/docs/nustar/analysis/nustar_swguide.pdf`

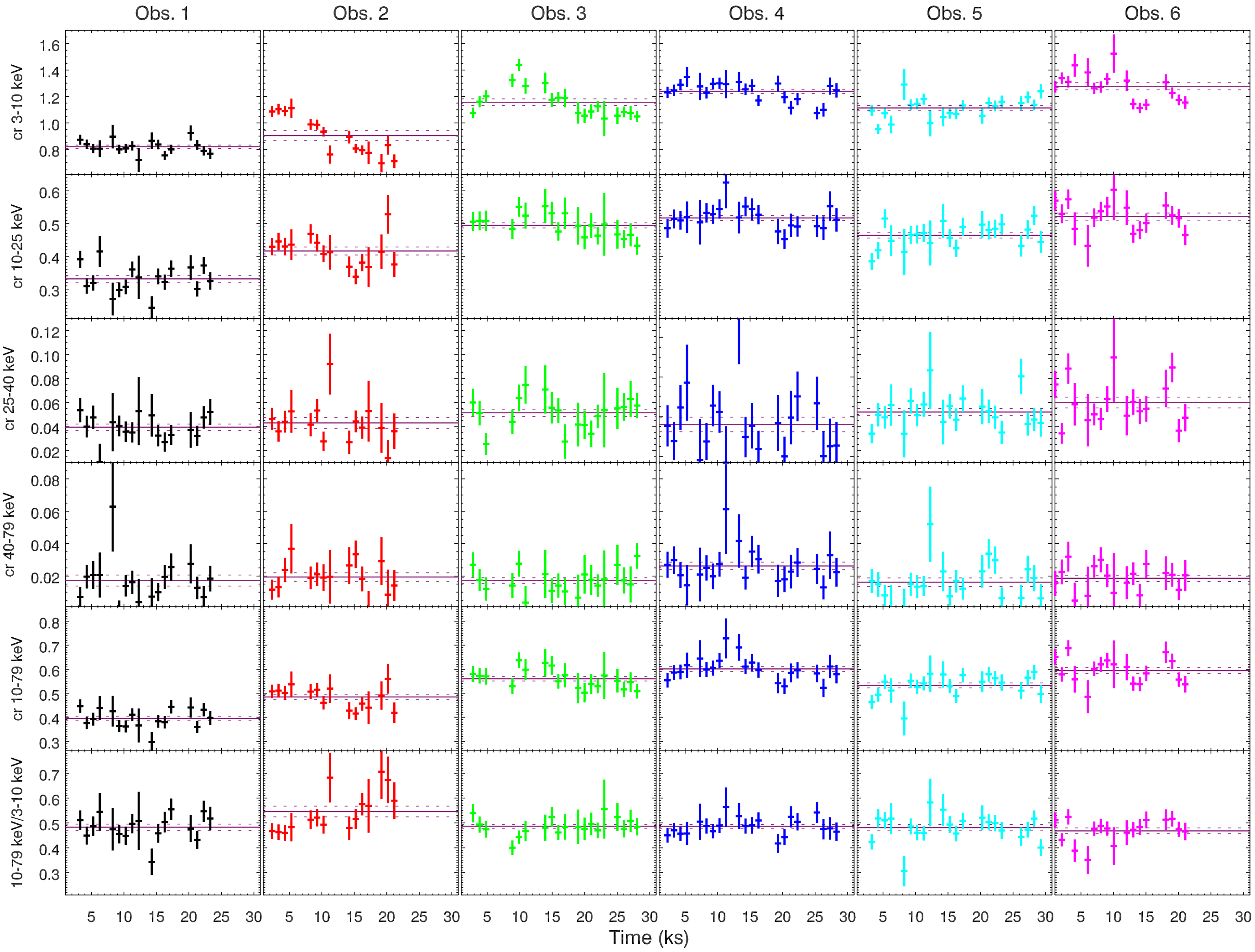

Fig. 2. Background subtracted *NuSTAR* light curves of MCG-01-24-12 calculated with a temporal bin of 1000 sec. Light curves account for co-added module A and B and the various energy bands are labelled on the y-axis. For each observation a specific colour is used and we adopted such a colour code throughout the whole paper. Orchid horizontal straight lines are used to quantify the average count rate within each observation for the different bands, while dashed ones account for 1σ uncertainties around the mean.

2006) and the latest Chandra Calibration Data Base (*CALDB* version 4.9.2.1). The source and background spectra were extracted using a circular region of 2.5″ and 4.0″ radius respectively. Furthermore the resulting spectrum was re-binned by a minimum of 20 counts per energy bin and with a total net count of 610 for a net exposure time of 9133 *s*.

In all the fits of simultaneous *Swift*-*NuSTAR* observations, the inter-calibration between the different *NuSTAR* modules and the *Swift*'s X-ray telescope is taken into account by a cross-normalisation constant. The *FPMA/B* modules were always found consistent within a 3% with the exception of observation 1 in which they agree within a 30%. In particular, the *FPMB* spectrum has about 1000 counts more than *FPMA/B*. In this latter module, the source was found to lie between the detector chips, this explains the decreased number of photon counts. However, by fitting individually the *FPMA/B* spectra with an absorbed power-law the returned photon indices were consistent within the errors, hence we decided to include data from both modules in the forthcoming analysis. In all but one pointing *Swift/XRT* and *NuSTAR* are consistent within $\lesssim$10%, in accordance with Madsen et al. (2015). On the other hand, for Obs. 4 we obtained const=1.5±0.3 as *NuSTAR* caught the source in a higher flux state than the shorter *Swift* snapshot. For a quick look comparison of the data, we show in Fig. 1 all the data. Finally, *MOS1* and *MOS2* are consistent with *pn* data within 3%.

We preliminarily computed the MCG-01-24-12 light curves for the *NuSTAR* data. In Fig. 2, we report the corresponding time series in various bands as labelled on the y-axis while in the last row we show the ratios between the 3-10 and 10-79 keV bands. X-ray variability is typical of AGNs and it has been measured down to ks timescales up to decades (e.g. Green et al. 1993; Uttley et al. 2002; Vagnetti et al. 2011; Ponti et al. 2012; McHardy et al. 2007; Vagnetti et al. 2016; Middei et al. 2017; Paolillo et al. 2017). Regarding MCG-01-24-12, Observation 2 varies by a factor of 50% in the 3-10 keV energy band over a few ks while the other exposures have a more constant behaviour in the same energy band. On the other hand, variations are witnessed when comparing light curves at different observing epochs. The maximum amplitude change, about a factor of 2, occurred in the 3-10 keV energy band over a timescale of about 1 month (between observations 1 and 6). The ratios between the 3-10 keV and the 10-79 keV bands have a rather constant behaviour, with the exception of Obs. 2 in which the source hardness increased as the flux decreased. However, the short exposure does not allow to

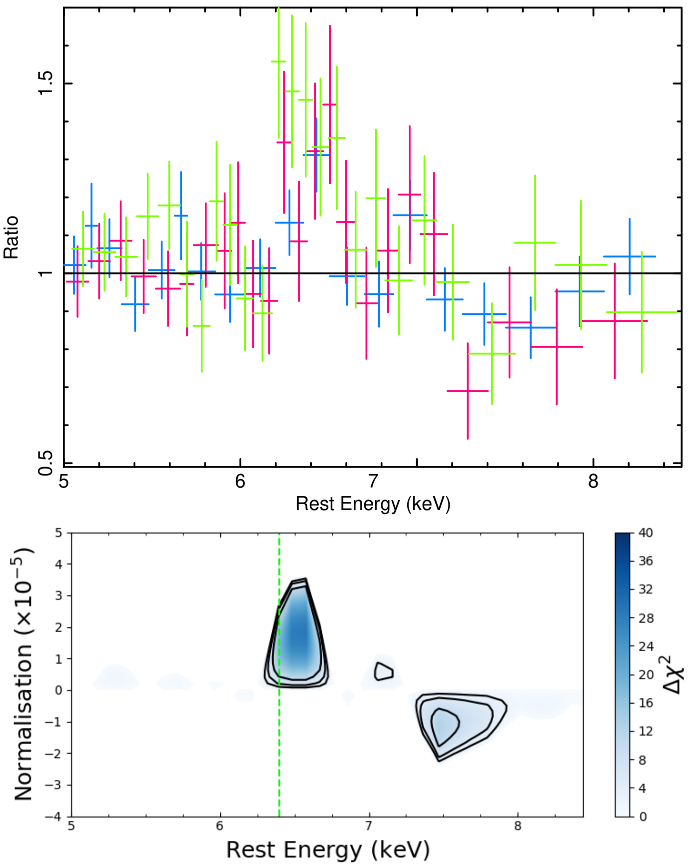

Fig. 3. Top panel: Ratio of the Epic spectra in the 5-8.5 keV energy range with respect to an absorbed power-law. All the instruments (*pn* in blue, *MOS1* in magenta and *MOS2* in green) detected the Fe Kα and found a trough at about 7.5 keV. Bottom panel: Blind line scan result between the normalisation and line energy, adopted on the *pn-MOS* spectra, where a Gaussian is left free to vary in the 5-8.5 keV energy range. The colour bar on the right indicates the significance of the lines for 2 degree of freedom and the solid black contours correspond to 68%, 90% and 99%.

perform a time-resolved spectral analysis of Obs. 2, hence we used the time-averaged spectra to improve the fit statistics of all the observations. All errors reported in the plots account for 1σ uncertainty, while errors in text and tables are quoted at 90% confidence level.

3. Spectral Analysis

We used *XSPEC* (Arnaud 1996) to fit the data with the Galactic column density kept frozen to the value N_H=2.79×10^{20} cm^{-2} (HI4PI Collaboration et al. 2016). Moreover, the standard cosmology ΛCDM (H_0=70 km s^{-1} Mpc^{-1}, Ω_m=0.27, Ω_λ=0.73) is adopted throughout the analysis.

3.1. The Epic cameras view: 0.3-10 keV band

We started studying the 0.3-10 keV *EPIC* data using a simple model (*const*×*tbabs*×*ztbabs*×*power-law*, in *XSPEC* notation) whose components account for the inter-calibration between the cameras, the Galactic absorption, the MCG-01-24-12 intrinsic absorption and its primary continuum emission. Such a model leaves prominent residuals in the soft X-ray band and the fit is unacceptable on statistical grounds (χ^2=355 for 243 d.o.f.). The excess in the soft X-rays may be due to a fraction of the coronal primary emission that is scattered/reflected possibly by distant material. Such a behaviour in obscured AGNs is quite typical. This energy band is generally dominated by emission lines from a photonionised gas coinciding with the Narrow Line Region (NLR, e.g. Bianchi et al. 2006; Guainazzi & Bianchi 2007) though the lack of high statistics or the low-resolution of X-ray spectra makes it possible to model such a component with a simple power-law (e.g. Awaki et al. 1991; Turner et al. 1997a,b). Since our spectra do not show any of these features, we model the scattered component in the *EPIC* data adding an additional power-law. A test fit has shown that the photon indices of the power-laws accounting for the primary X-ray continuum and the scattered emission to be compatible within the errors, hence, in the following fits, we tied these parameters. The normalisation of the scattered component has been fitted and found to be a few percent of the primary continuum (e.g. Bianchi & Guainazzi 2007). The addition of this new component is beneficial in terms of statistics and the fit improved by $\Delta\chi^2/\Delta$d.o.f.=-83/-1.

Residuals are still visible in the Fe Kα band and are reported in the top panel of Fig. 3 and further supported by the blind lines scan shown in the bottom panel of the same figure. The blind line scan was carried out by using an absorbed power-law and a Gaussian model with a fixed line width of 1 eV (i.e. much lower than the CCD resolution) with line energy allowed to vary in the range 5 − 10 keV and normalisation from -6×10^{-5} to 10^{-4} ph keV^{-1} cm^{-1} s^{-1} with 50 steps. This test suggests the presence of a strong Fe Kα emission line at the rest-frame energy of E = 6.39 ± 0.05 keV and an absorption trough at ∼ 7.4 ± 0.1 keV at ∼ 5σ and ∼ 3σ confidence levels respectively. We accounted for these features by adding two Gaussian components, one for reproducing the Fe Kα feature, the other the trough above ∼7 keV. For both these components we fitted the line's energy centroid, its width and normalisation. Since we only get an upper limit for the width of the absorption component $\sigma_{\rm Fe\ K}$<160 eV, we fixed this parameter to this value. The addition of the Gaussian emission improved the overall statistic by $\Delta\chi^2$=18 for 3 d.o.f. less, while a $\Delta\chi^2/\Delta$d.o.f.=-10/-2 corresponds to the line in absorption. The described procedure led to a best-fit of χ^2=243 for 237 d.o.f. for which we report best-fit parameters in Table 2. The *EPIC* spectra are therefore well described by a power-law continuum (Γ = 1.68 ± 0.04) absorbed by an obscurer with column density of N_H = 6.4 ± 0.3 × 10^{22}cm^{-2}. The continuum is accompanied by a moderately broad (σ = 80 ± 60 eV) neutral Fe emission line and a weak absorbing signature. Finally, the soft X-ray band is dominated by a fraction of the primary continuum scattered, see Fig. 4.

3.2. Broad-band Swift/NuSTAR view: I the phenomenological model

We started analysing the *NuSTAR* data by fitting each observation separately with an absorbed power-law and the corresponding residuals are shown in Fig 5. To better quantify the possible variability of the Fe Kα and to further investigate for the presence of any additional features, we performed a blind line scan over the spectra. The line scan procedure was the same described for the *XMM-Newton* data. The resulting contour plots are reported in Fig 6. The Fe Kα line appears stronger in Observations 2 and 6 while it is only marginally detected in all the remaining pointings. Interestingly, in Obs. 6, the energy spectrum suggests the presence of an absorbing signature above ∼7 keV. A fit of such a feature with a narrow Gaussian component returns E=7.35±0.10 keV, N=(1.8±0.8)×10^{-5} ph. cm^{-2} s^{-1} and EW=-80±35 eV, with an improvement of the fit statistics

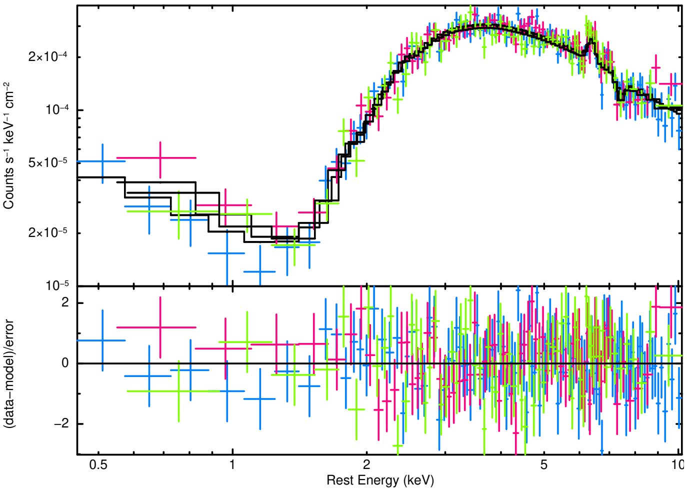

Fig. 4. Best-fit model to the EPIC-pn&MOS with a corresponding statistics of χ^2=243 for 237 d.o.f. .

Table 2. The *XMM-Newton* best-fit values (χ^2=243 for 237 d.o.f.) as derived with the simple phenomenological model reported in Sect. 3.1. .The crux desperationis † is used to identify a frozen parameter.

Parameter	Best-fit value	Units
N_H	6.4±0.3	$\times10^{22}$ cm^{-2}
Γ	1.68±0.04	
$N_{\rm primary}$	4.7±0.3	$\times10^{-3}$ ph. keV^{-1} cm^{2} s^{-1}
$E_{\rm Fe\ K\alpha}$	6.39±0.05	keV
$\sigma_{\rm Fe\ K\alpha}$	80±60	eV
$EW_{\rm Fe\ K\alpha}$	95±30	eV
$N_{\rm Fe\ K\alpha}$	2.5±0.7	$\times10^{-5}$ ph. cm^{-2} s^{-1}
$E_{\rm Fe\ K}$	7.4±0.1	keV
$\sigma_{\rm Fe}$†	160	eV
$EW_{\rm Fe\ K}$	-70±35	eV
$N_{\rm Fe\ K}$	-1.3±0.6	$\times10^{-5}$ ph. cm^{-2} s^{-1}
$N_{\rm scattered}$	1.9±0.4	$\times10^{-5}$ ph. keV^{-1} cm^{-2} s^{-1}
$F_{2-10\ \rm keV}$	1.3±0.1	$\times10^{-11}$ erg cm^{-2} s^{-1}

of $\Delta\chi^2$/d.o.f.=-14/-2. We then considered also the *Swift* data and fitted the *Swift-NuSTAR* observations using a Gaussian line to account for the Fe Kα emission plus an absorbed cut-off power-law for reproducing the continuum, written in *XSPEC* syntax as *tbabs×ztbabs×(cutoffpl+zgauss)*. The high energy cut-off for the primary emission is included in order to model the counts drop observed above ∼40 keV in Fig. 5 for Obs. 3, 5 and 6. The current data, with Obs. 6 being a possible exception, does not allow for an appropriate characterisation of the troughts in the spectra, thus we did not account for them in the modelling. The fitting procedure was performed allowing the photon index, the high energy cut-off and the continuum normalisation to vary in each observation. Then we calculated the emission line normalisation, while the energy centroid was set to 6.4 keV. We assumed the line to have a narrow profile with σ fixed to 1eV. After a preliminary fit showing the obscurer column density to be consistent within the uncertainties in all the pointings, we tied the *ztbabs* between the different observations. The *Swift-XRT* data have too poor statistics to constrain any scattered emission (see Fig. 1) and, for this reason, we do not include an additional power-law accounting for such a component. This fit leads to a fit characterised by χ^2/d.o.f.=1309/1256 and in Table 3 we quote the corresponding best-fit parameters.

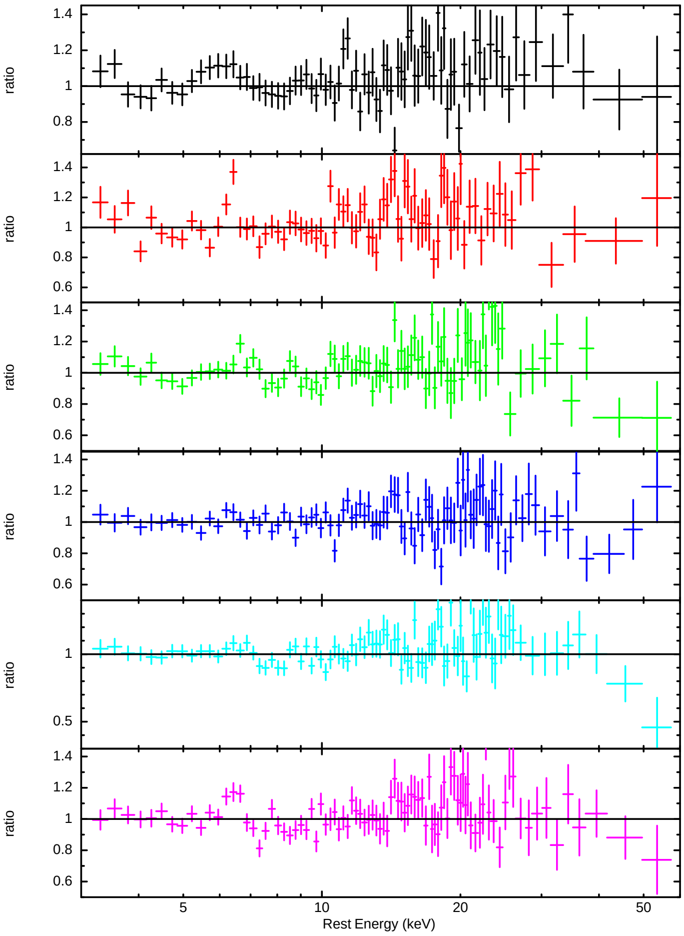

Fig. 5. Ratios between the *NuSTAR FPMA/B* spectra. The underlying model accounts for an absorbed power-la *const×tbabs×ztbabs×po* for each observation.

The current phenomenological model is consistent with a power-law with constant shape that is absorbed by an average column density N_H=(6.6±0.4)×10^{22} cm^{-2}. Moreover, the Fe Kα emission line, assumed to have a narrow intrinsic profile, seemed to be variable, at least on Observations 2 and 6. To further assess the actual variability of such a component, we assumed the emission line flux to be the same over the whole campaign. In other words, starting from the phenomenological best-fit, we fitted the data tying the Fe Kα normalisation between the observations. The obtained fit has a worse statistics ($\Delta\chi^2$/Δd.o.f.=+23/+5), thus further supporting the line to be variable with significance larger than 95%.

3.3. Broad-band Swift/NuStar view: II the reflection signature with Xillver

As a subsequent step, we studied the *XRT-FPMA/B* spectra using *xillver* (e.g. García et al. 2014; Dauser et al. 2016) a model that self-consistently calculates the underlying nuclear emission (a cut-off power-law) and the reflected component from the illuminated accretion disc. Then, we left free to vary and compute in each observation the photon index, the reflection parameter R and the model normalisation. We considered the reflecting matter close to be neutral, we fixed the ionisation parameter $\log\xi$ to a value of 0 and we calculated the Fe abundance ($A_{\rm Fe}$) tying its value between the different observations. Though we know the *ztbabs* component does not vary significantly during the mon-

Table 3. *Swift-NuSTAR* best-fit parameters derived using an absorbed power-law plus a Gaussian component accounting for the Fe Kα emission line (*tbabs×ztbabs×(zgauss+power-law)* in *XSPEC*) corresponding to $\Delta\chi^2$/d.o.f.=1309/1256. The † labels those parameters that have been fitted but tied between the observations.

Parameter	Obs. 1	Obs. 2	Obs. 3	Obs. 4	Obs. 5	Obs. 6	Units
N_H†	6.6±0.4						$\times10^{22}$ cm^{-2}
Γ	1.81±0.04	1.73±0.04	1.79±0.03	1.77±0.04	1.77±0.04	1.77±0.03	
$N_{primary}$	4.6±0.5	4.7±0.6	5.2±0.6	8.0±0.6	7.4±0.9	7.9±0.5	$\times10^{-3}$ ph. keV^{-1} cm^2 s^{-1}
$E_{FeK\alpha}$†	6.4						keV
$EW_{Fe\ K\alpha}$	85±50	210±60	43±38	45±35	55±35	105±40	eV
$N_{Fe\ K\alpha}$	1.4±0.8	4.1±1.2	0.85±0.76	1.4±1.1	1.6±1.0	3.3±1.2	$\times10^{-5}$ ph. cm^{-2} s^{-1}
$F_{3-10\ keV}$	1.23±0.08	1.41±0.18	1.44±0.16	2.23±0.10	2.13 ±0.23	2.29±0.11	$\times10^{-11}$ erg cm^{-2} s^{-1}

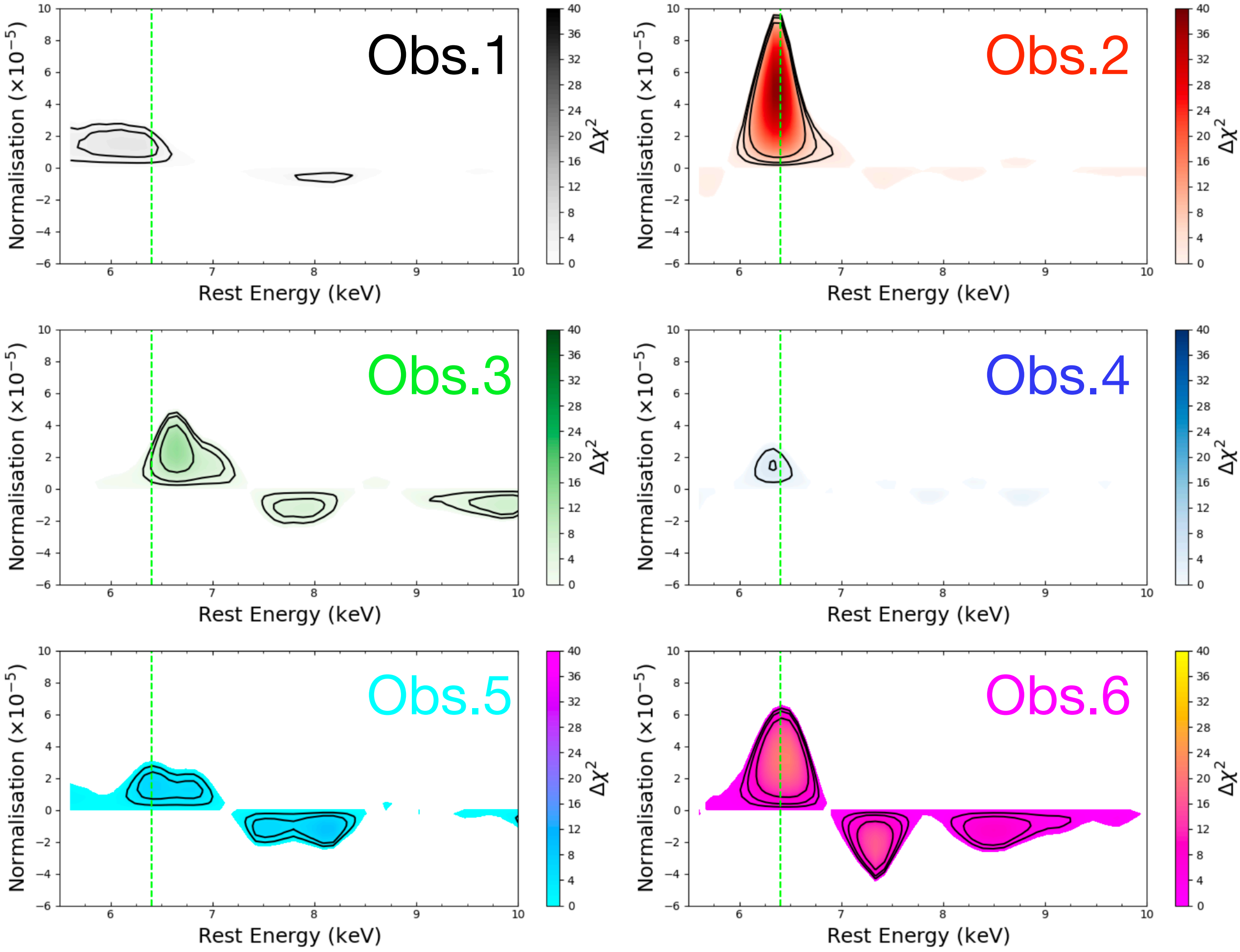

Fig. 6. Result of a blind line scan performed to all six *NuSTAR* observations plotted between the 5.5 − 10 keV band. The colour bar on the right of each panel indicates the significance of the lines for 2 degree of freedom and the solid black contours correspond to 68%, 90% and 99%. The lime-green vertical dashed line indicates the position of the rest frame energy of the Fe Kα emission line at E = 6.4 keV

itoring, we fitted this component in all the observations. Such steps led to the best-fit parameters in Table 4 and characterised by a statistic of χ^2/d.o.f.=1252/ 1258. The overall fit is consistent with a primary emission continuum absorbed by an average column density of N_H=(6.3±0.5)×10^{22} cm^{-2} and the reflecting matter arising from a cold disc region with a Solar metal abundance A_{Fe}=1.3±0.6. The photon index of the primary continuum varies in the range 1.68-1.93, though the obtained best-fit values are consistent within the uncertainties. In similar fashion, marginal variability is observed for the high energy cut-off and the reflection parameter, and, as expected from the light curves in Fig. 2, the normalisation of *xillver* is found to vary. We report best-fit parameters in Table 4 and contours plot referring to the photon index, the reflection fraction and the high energy cut-off are shown in Fig 8.

We further tested the data using the same model but tying the photon index, the reflection fraction, the high energy cut-off and the column density of the obscurer between the exposures.

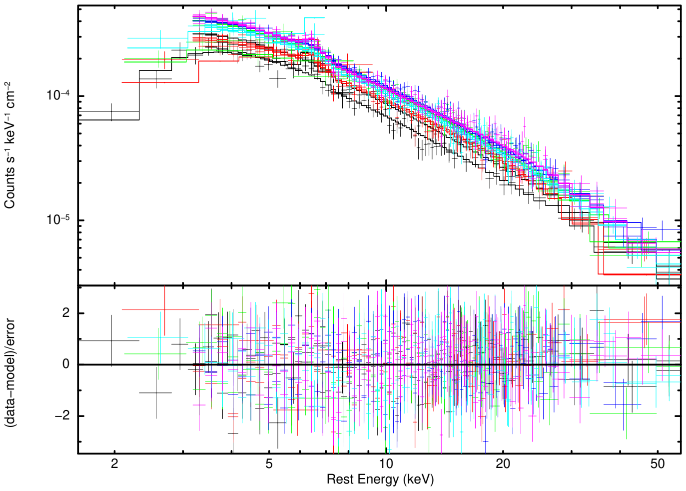

Fig. 7. Best-fit (χ^2/d.o.f.=1252/1257) to the simultaneous *Swift-NuSTAR* data obtained using *xillver* .

The fit returns a statistic of χ^2 1300 for 1278 d.o.f., not far from the previous one, and further supports a weak variability of the parameters.

3.4. Broad-band Swift/NuStar view: III the reflection signature with MyTorus

In the above fitting, in Sect. 3.3, *Xillver* assumes a geometrically simple slab reflector. Therefore, as an alternative scenario, we replaced both the *Xillver* and the simple neutral absorber (*ztbabs*) with *MyTorus* (Murphy & Yaqoob 2009). This model takes into account the physical properties of the absorbing medium such as its toroidal geometry, the Compton-down scattering effect and it includes self-calculated reflected components (continuum plus Fe K emission lines). The overall *MyTorus* model adopted here is composed by three publicly available tables (two additive and one multiplicative), developed for *XSPEC*, which self-consistently compute the reflected continuum (*MyTorusS*), the Fe Kα, Fe Kβ fluorescent emission lines (*MyTorusL*) and the zeroth-order line-of-sight attenuation (*MyTorusZ*). The model assumes a fixed geometry of the toroidal X-ray reprocessor, a single value for the covering factor of the torus corresponding to an half–opening angle of 60°.

We first constructed the *MyTorus* model according to the ‘coupled’ solution (Yaqoob 2012), where our line-of-sight angle that intercepts the torus is the directly co-joined (or coupled) to the scattered one. In other words, it is assumed that the fluorescent and reflected emissions emerge from the same medium that is also responsible for the line-of-sight attenuation of the X-ray underlying continuum. Thus we set the column density of each *MyTorusS*, *MyTorusL* and *MyTorusZ* grid to be the same within each observation but free to vary between the six pointings; whilst their normalisations are tied with the one of a power-law accounting for the primary continuum. In a similar fashion, the photon-index of the three grids was linked with the nuclear one that has been computed for each observations. These steps lead to fit to the data of χ^2/d.o.f.=1316/1255 and considerably improves once the viewing inclination angle ($\theta_{\rm obs}$ - kept constant between the observations) is measured; by ($\Delta\chi^2$/Δd.o.f.= $-25/+1$). However, the returned value of line-of-sight inclination angle is $\theta_{\rm obs}$ = $61.1^{+0.4}_{-0.2}$ deg, just at the extremity of *MyTorus*'s parameter space (i.e., $\theta_{\rm obs}$ = 60 deg).

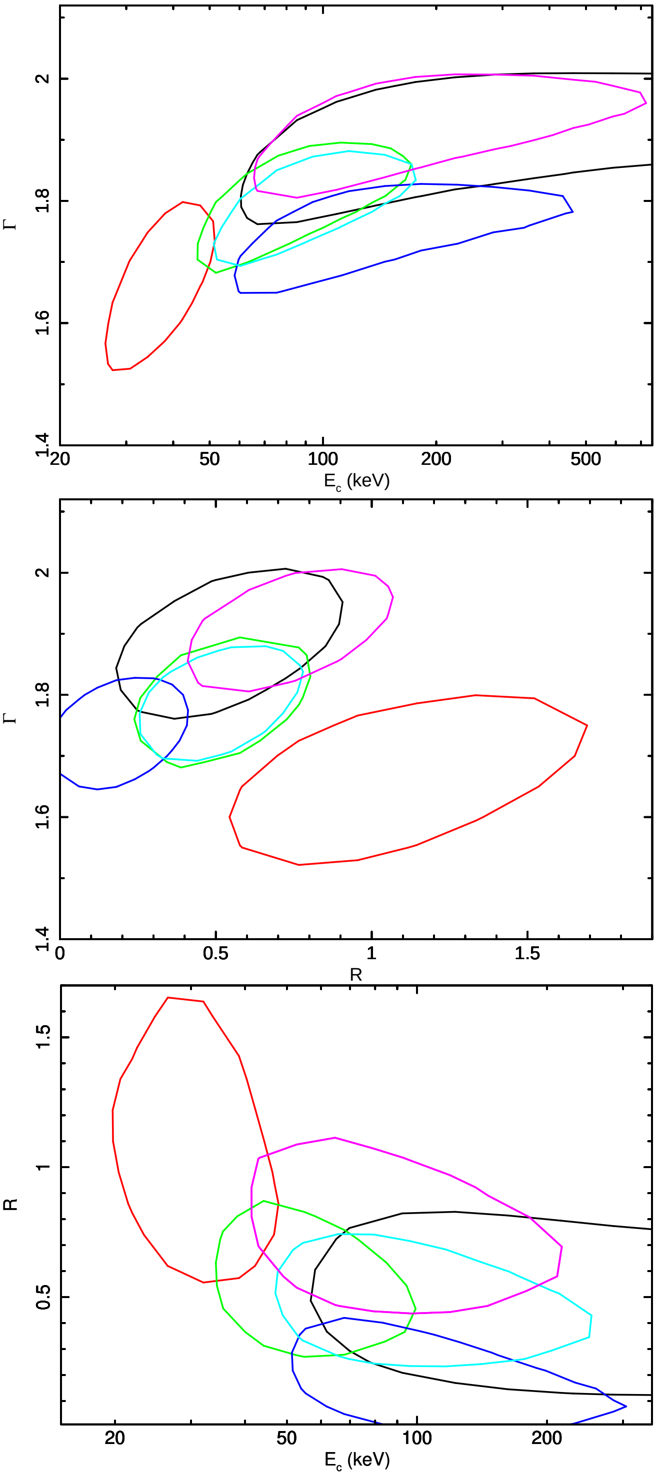

Fig. 8. Contours at 90% confidence level ($\Delta\chi^2$=4.61 for two parameters) between the photon index Γ and the high energy cut-off (E$_{\rm c}$, top hand panel) and the reflection fraction (middle). Contours in the bottom panel refer to the high energy cut-off and the reflection fraction. All the contours have been computed with the column density, the photon index, the high energy cut-off the reflection fraction and the *xillver*'s normalisation free to vary in all the observations.

We then considered a more complex morphology (i.e. clumpy medium), *MyTorus* further allows us to test a scenario in which the reflected and the transmitted components emerge from matter with different column densities (decoupled solution see Yaqoob 2012, for more details) in a system character-

Table 4. *Swift-NuSTAR* best-fit values derived using *tbabs*×*ztbabs*×*xillver* in *XSPEC* notation and to which corresponds a statistic χ^2/d.o.f.=1252/1257.

Parameter	Obs. 1	Obs. 2	Obs. 3	Obs. 4	Obs. 5	Obs. 6	all tied	Units
N_H	7.2±1.0	7.2±1.9	6.1±0.9	6.2±1.1	6.2±0.9	6.1± 1.0	6.3±0.5	$\times10^{22}$ cm^{-2}
Γ	1.93±0.12	1.68±0.15	1.76±0.11	1.71±0.09	1.78±0.09	1.89±0.10	1.76±0.09	
R	0.50±0.25	0.96±0.40	0.50±0.20	0.20±0.15	0.50±0.20	0.70±0.25	0.40±0.15	
E_c	>75	40^{+30}_{-10}	65^{+60}_{-20}	90^{+140}_{-35}	75^{+70}_{-30}	120^{+300}_{-50}	70^{+21}_{-14}	keV
N_{Xill}	9.3±2.1	7.3±2.1	8.0±1.5	14.2±2.5	12.1±2.4	14.2 ± 2.6		$\times10^{-5}$ ph. cm^{-2} s^{-1}

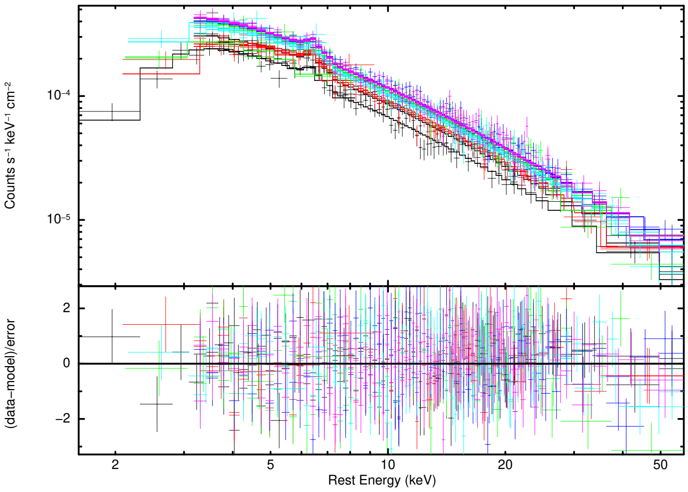

Fig. 9. Simultaneous *Swift-NuSTAR* observations as fitted using *MyTorus* in its decoupled configuration (χ^2/d.o.f.=χ^2=1274 for 1258 d.o.f.).

ized by a more 'patchy' distribution of reprocessing clumps. In fact, in such a configuration, our line-of-sight might intercept the transmitted (or zeroth-order) component through one region of the torus and the reflected emission that is back scattered from a different location of the torus itself (see Yaqoob 2012, Fig. 2). Such a solution, was obtained by decoupling the inclination parameter ($\theta_{\rm obs}$) of the zeroth-order (i.e., line-of-sight) and reflected table components with respective column densities defined as; $N_{\rm H,Z}$ (line-of-sight $N_{\rm H}$) and $N_{\rm H,S}$ (global $N_{\rm H}$). The corresponding inclination parameters are fixed at $\theta_{\rm obs,Z}$ = 90°and $\theta_{\rm obs,S}$ = 0°for the zeroth-order and reflected continua components, respectively. In this scenario we find that the global column density is rather larger than the zeroth-order, measured at $N_{\rm H,S} = 1.3^{+0.5}_{-0.3} \times 10^{24}\,{\rm cm}^{-2}$ and the corresponding data best-fit is shown in Fig. 9. Such a model is in accordance with an emission spectrum nearly Compton-thick out the line-of-sight, and Compton-thin along the line-of-sight. The decoupled configuration yielded a χ^2=1274 for 1258 d.o.f.; see Table 5 for the corresponding *MyTorus* best-fitted values. This result also suggests that the overall column density of the torus might be inhomogeneous in nature and indeed the upper parts are less dense than the central one.

3.5. Joint XMM-Newton, Swift and NuSTAR data

The lack of substantial spectral variability between the *XMM-Newton* pointing and the 2013 monitoring campaign encouraged us to perform a broadband fit based on all these data. Therefore, we simultaneously tested the two physically motivated models in Sect. 3.3 and Sect. 3.4 on the entire data-set, i.e. on the *XMM-Newton*, *Swift* and *NuSTAR* spectra.

We started using *xillver* for which we fitted the photon index, the high energy cut-off and the reflection fraction tied between the pointings. We also included the scattered power-law component for which we only fitted the normalisation as its photon index was linked to the *xillver*'s one. To account for the flux variability we used a constant free to vary in all but the *XMM-Newton* exposure in which the *xillver*'s normalisation was computed instead. This procedure returned a fit with statistic χ^2= 1528 for 1508 degree of freedom. The best-fit parameters were consistent with what previously found: $N_{\rm H}$=(6.6±0.2)×10^{22} cm^{-2}, Γ=1.75±0.05, E_c=70±15 ± keV, $A_{\rm Fe}=1.5^{+1.0}_{-0.6}$, R=0.45±0.15, and the constant varied in the range 1.04-1.95.

Then, we tested the decoupled solution of *MyTorus*. We fitted the data similarly to what reported in previous Sect. 3.4 and we used a free to vary constant to account for the variations in the different observations. As we have done for the case of *xillver*, we also added a scattered power-law. These steps yielded a χ^2= 1559 for 1510 d.o.f. for which the derived best fit quantities are consistent with those quoted in Table 5.

These tests further points towards a fairly constant behaviour of the primary continuum shape and the absorbed component in MCG-01-24-12, at least for the data from 2006 to 2013. Although the ionised reflection model is somewhat preferred in terms of the fit statistic, both the *xillver* and *MyTorus* solutions give good fits. In Fig. 10, we report the data best-fit and the corresponding underlying model for the cases of *xillver* and *MyTours*..

As a final test, we modeled the absorption trough at ~7.4 keV on the complete dataset. In particular, we used an *XSTAR* (Kallman et al. 2004) table assuming an input spectrum of Γ=2 across the 0.1-10^6 eV band and a high energy cut-off at E_c=100 keV. The elemental abundance was set to the Solar one (Asplund et al. 2009) and we assumed a velocity broadening $v_{\rm turb}$=5000 km s^{-1} and the absorber to be fully covering. In the fit, we allowed the absorber's column density, ionisation state and redshift to vary and we tied these parameters between the different observations. This additional component improved the fit with $\Delta\chi^2/\Delta$d.o.f.=-11/-3, with $N_{\rm H}=(2.3^{+4.2}_{-1.4})\times10^{22}$ cm^{-2}, log(ξ/erg cm^{-2}s^{-1})>3.1 and $z_{\rm obs} = -0.075 \pm 0.030$ (corresponding to a velocity v_{xstar}=-0.097±0.032). However, as suggested in Fig. 6 such an absorption feature seemed to be more prominent in Obs. 6. For this reason, we untied and fitted the absorbers parameters in this observation finding an additional enhancement of the fit statistics ($\Delta\chi^2/\Delta$d.o.f.=-13/-3). The derived best fit values are consistent with each other as we obtained $N_{\rm H}=(1.3^{+3.2}_{-0.8})\times10^{23}$ cm^{-2}, log(ξ/erg cm^{-2}s^{-1})=3.2±0.4 for $z_{\rm obs}$=-0.076±0.018. By untying these parameters across all the observations, would lead to a marginal improvement of $\Delta\chi^2/\Delta$d.o.f.=-21/-15. Finally, these values are fully compatible within each other and with the parameters commonly measured for these absorbers in other AGNs (e.g. Gofford et al. 2013; Tombesi et al. 2013).

Table 5. *Swift-NuSTAR* best-fitted values for the parameters obtained using the decoupled *MyTorus*'s solutions. The symbol † is used when a parameter has been fitted but tied between the observations.

Decoupled	Parameter	Obs. 1	Obs. 2	Obs. 3	Obs. 4	Obs. 5	Obs. 6	Units
power-law	Γ	1.98±0.06	1.99±0.07	1.90±0.05	1.90±0.06	1.94±0.05	1.89±0.06	
MyTorusS	N_H†	$1.3^{+0.5}_{-0.3}$						$\times10^{24}$ cm^{-2}
	Norm	6.7 ±1.1	8.9±2.2	6.0±1.2	9.7±1.4	10.2±2.0	9.5±1.3	$\times10^{-3}$ ph. keV^{-1} cm^{-2} s^{-1}
MyTorusZ	N_H	8.5±1.2	10.1±1.6	7.0± 1.1	7.1±1.2	8.1±1.1	6.4±1.1	$\times10^{22}$ cm^{-2}

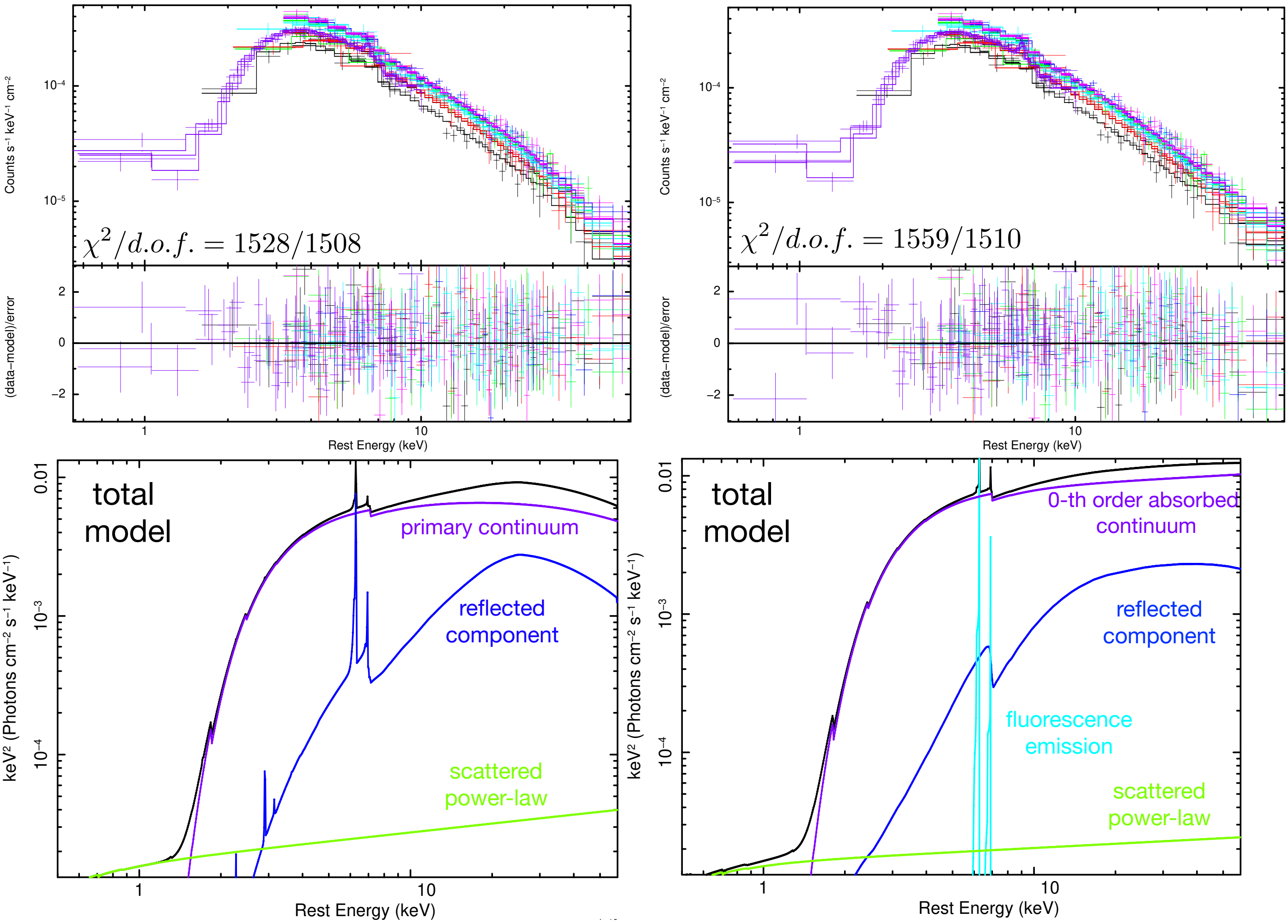

Fig. 10. Left Panels: *XMM-Newon/Swift/NuSTAR* data best-fit using *xillver* (top). The different spectral components are reported in the corresponding bottom graph. Right panels: *XMM-Newon/Swift/NuSTAR* data best-fit (top) and model components (bottom) corresponding to the decoupled *MyTorus* solution.

3.6. The 2019 ACIS/S spectrum

The poor statistics of the Chandra snapshot did not allows us to do a detailed spectral analysis. In fact, a simple phenomenological model such as an absorbed power-law fails in reproducing the hard continuum and returned a photon index $\Gamma \lesssim 1$. Then, we tested a scenario in which the source had an intrinsic flux drop likely due to a change in its luminosity. To do this, we applied the best-fit model used for the EPIC data (see 2) on the *Chandra* spectrum and we refit this data only allowing the primary normalisation to vary. This procedure yielded a fit with χ^2=56 for 29 d.o.f. and returned a primary normalisation N_{po}=(7.0±0.5)×10^{-4} ph. keV^{-1} cm^{-2} s^{-1} and an observed flux $F_{2-10\ keV}$=(2.15±0.15)×10^{-12} erg cm^{-2} s^{-1}, a factor of 10 lower than what previously measured. Such an intrinsic flux drop seems to be favoured with respect to a scenario in which the N_H of the neutral obscurer changed: keeping fixed the normalisation of the primary power-law at the best-fit value as reported in Table 2 and letting free to vary only the column density of the neutral obscurer returned a $\chi^2/d.o.f.$ >11. A simultaneous fit of both the primary continuum normalisation and the obscuring column led to a fit statistic of χ^2/d.o.f.=53/28 with N_H=7.4±1.0 ×10^{22} cm^{-2} and N_{po}=(7.5±0.8)×10^{-4} ph. keV^{-1} cm^{-2} s^{-1}. The fit of the Fe Kα energy centroid normalisation enhanced the fit by $\Delta\chi^2/\Delta$d.o.f.=-12/-2. The Fe Kα has energy E=6.5±0.1 keV, a normalisation $N_{Fe\ K\alpha}$=(1.1±0.8)× 10^{-5} ph. cm^{-2} s^{-1} and EW=320±230 eV with this feature being consistent within the errors with what previously observed. The limited bandwidth of the data did not allow us to further investigate the presence of any absorption features nor to firmly determine the physical origin of such a low flux state.

4. Discussion and Conclusions

We reported on the X-ray emission properties of the Seyfert 2 galaxy MCG-01-24-12 based on observations taken with several X-ray facilities over a time interval spanning about 13 years. In the following we summarise and discuss our findings.

4.1. Variability and phenomenological modelling

XMM-Newton and *NuSTAR* data are consistent with a moderate variability of the source flux in the 3-10 keV band with values in the range of 1.2-2.3$\times10^{-11}$ erg cm^{-2} s^{-1}. Interestingly this flux state is consistent with what was measured using *BeppoSAX* data (Malizia et al. 2002) and by Piccinotti et al. (1982).
We computed the bolometric luminosity and Eddington ratio of the source assuming an average flux state which corresponds to a luminosity $L_{2-10\ \mathrm{keV}}$ ~1.5$\times10^{43}$ erg s^{-1}. Following the prescription in Duras et al. (2020) and using a SMBH mass M_{BH}=1.5$\times10^{7}$ $M_{\odot}$ (La Franca et al. 2015), we derived L_{Bol} ~1.9$\times10^{44}$ erg s^{-1} and L_{Bol}/L_{Edd} ~11%, respectively. As displayed in Fig. 2, variations occurred on weekly time scales and intra-observation changes are weak, with the only exceptions of Obs. 2 and 3 where the hardness ratios also suggest some spectral change down to ksecs timescales. On the other hand, the 2019 exposure performed with *Chandra* caught the source in an unprecedented observed faint state ($L_{2-10\ \mathrm{keV}}$ ~2$\times10^{42}$ erg s^{-1}). The source faded by a factor of ~10 from the last *NuSTAR* exposure. Different physical origins explained remarkable variations in other AGNs: (i) an increase in the neutral obscuration in which the column density swings from Compton-thin to thick in timescales of hours-days as seen in the prototype changing-look AGN NGC 1365 (see Risaliti et al. 2005), (ii) an obscuration event due to the clumpy highly ionised disc-wind as seen in MCG-03-58-007 (Braito et al. 2018; Matzeu et al. 2019), (iii) strong intrinsic variability but neutral N_H fairly constant see e.g. the case of NGC 2992 discussed in Murphy et al. (2007) and Middei et al., in preparation.

From a phenomenological prospective, the primary emission of MCG-01-24-12 is consistent with an absorbed power-law where the column density and spectral shape had a fairly constant behaviour within the *NuSTAR* monitoring and when these 2013 data are compared with those from *XMM-Newton* and *BeppoSAX*. The Fe Kα emission line seems to vary in the *NuSTAR* spectrum and is strongly detected in Obs. 2 and 6. In this respect, we notice that the strongest Fe Kα is observed in Obs. 2 (see Table 3 and Fig.6) and that the line flux seems not to follow the weak variations of the continuum. Such a behaviour can be explained by the reverberation of the Fe Kα line (see e.g. Zoghbi et al. 2019) that, produced in a distant region such as the BLR, would have a delayed response with respect to the primary continuum.

The short duration of the exposures coupled with the instrumental spectral resolution prevented a detailed analysis on line profile that was set to be narrow. On the other hand, the EPIC data are consistent with a moderately broad Fe Kα emission line (σ=80±60 eV) corresponding to a region of some hundredths of a parsec[2]. Interestingly, troughs above 7 keV have been observed in both *NuSTAR* and *XMM-Newton* spectra, possibly suggesting for the presence of fast and highly ionised outflows.

4.2. Physically motivated modelling

Xillver provided the best fit to the *Swift-NuSTAR* data, i.e. a cut-off power law continuum plus its associated Compton reflected spectrum absorbed by a column density of about (6.3 ± 0.5)$\times10^{22}$ cm^{-2}. The chemical abundance of the reflecting material is consistent with being Solar (A_{Fe}=1.3±0.6) and the continuum photon index, high energy cut-off and reflection fraction are constant within the errors in all but Obs. 2, see Fig. 8. This observation is the only one characterised by a variable ratio of the 3-10 and 10-79 keV light curves and this possibly explains the discrepancies between Obs. 2 and the other observations. Such a case of short term spectral variability is quite peculiar for MCG-01-24-12 since the analysis of the other exposures agrees with an intra-observations constancy of the primary photon index. However, when the fit is performed with the photon index, the high energy cut-off and the reflection fraction tied between the observations a statistic of χ^2= 1300 for 1278 d.o.f., with the best-fit obtained computing the various parameters in all the observations.

For this reason, we used the average values for the photon index (Γ=1.76±0.09) and the high energy cut-off (E_c = 70^{+21}_{+14} keV (these values are also consistent with those found in Baloković et al. 2020) to derive the properties of the hot corona. The physical conditions of the emitting plasma are indeed responsible for the spectral shape and the high energy curvature of the X-ray continuum (e.g. Rybicki & Lightman 1979; Beloborodov 1999; Petrucci et al. 2000, 2001; Ghisellini 2013; Middei et al. 2019). The relations between Γ-E_c and kT_e-τ_e have been recently derived by Middei et al. (2019) that used extensive simulations computed with *MoCA* (Monte Carlo code for Comptonisation in Astrophysics, Tamborra et al. 2018) for studying the Comptonised spectrum of AGNs (see also Marinucci et al. 2019; Lanzuisi et al. 2019, for further applications of this code). In particular, using Eqs. 2, 3, 4 and 5 in Middei et al. (2019), we found the hot corona in MCG-01-24-12 to be characterised by kT_e=27^{+8}_{-4} keV, τ_e=5.5±1.3 and kT_e=28^{+7}_{-5} keV, τ=3.2±0.8 for a spherical emitting plasma and a slab-like one, respectively. These values are fully in agreement with average temperature and opacity found in literature (e.g. Fabian et al. 2015, 2017; Tortosa et al. 2018; Middei et al. 2019). Then, we used the coronal temperature and opacity to include this source in the compactness-temperature l-θ_e) diagram (e.g. Fabian et al. 2015, 2017). We calculate the dimensionless coronal temperature θ_e=$kT_e/m_e c^2$ and the compactness parameter l = $L\sigma_T/Rm_e c^3$, in which L accounts for the coronal luminosity in the 0.1-200 keV band and R for its radius that is assumed to be 10 gravitational radii (R10). Following these prescriptions, we derived θ_e=$0.053^{+0.015}_{-0.08}$ and l ≃55. These values are in agreement with the bulk of measurements presented by Fabian et al. (2015) and show that the source lies in the so-called permitted region in which annihilation is still dominant with respect to the pair production.

We find *MyTorus* can provide a good representation of the *Swift-NuSTAR* data. In fact, although the coupled solution is not adequate to described the overall spectrum of MCG-01-24-12 (with this mainly due to the relatively small curvature at low energies of *NuSTAR* data and the poor statistic of *XRT* spectra), the decoupled configuration provides a statistically acceptable representation of the *Swift-NuSTAR* spectra of MCG-01-24-12. We measured a considerable difference between the column densi-

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[2] This approximate estimate is derived via the Virial Theorem from which the Fe Kα emission line is originated at r=$(E/\Delta E)^2 \times r_g$. In our case, this estimate returns r~1.4$\times10^{16}$ cm.

ties of the global (out of the line-of-sight) and transmitted reprocessors. The nuclear radiation is absorbed by a neutral medium with the column density $N_{H,Z}$ in the range (5.3-11.7)$\times 10^{22}$ cm^{-2} and the reflected component is back mirrored by matter with global $N_{H,S} = 1.3^{+0.5}_{-0.3} \times 10^{24}$ cm^{-2}. Such distinction between the zeroth-order and the global density has been already observed in other Seyfert 2 galaxies, e.g. NGC 4945, (Yaqoob 2012), Mrk 3 (Yaqoob et al. 2015), MCG-03-58-007, (Matzeu et al. 2019), NGC 4507 (Zaino et al., sub.), NGC 4347 (Kammoun et al. 2019) and described further in Kammoun et al. (2020). Thus the emerging picture is consistent with an overall inhomogeneous or 'patchy' toroidal absorber, broadly Compton-thin, with a distribution of relatively small and thicker equatorial clouds out of the line-of-sight. In most recent torus models the 'viewing probability' of the absorber, which is strongly correlated on its size and location, tend to be typically distributed towards the equatorial plane. The inhomogeneous gas distribution of the torus is now a well established scenario within the scientific community, where a variety of models have been developed taking into account this physical framework (e.g., Elitzur & Shlosman 2006; Nenkova et al. 2008a,b; Tanimoto et al. 2019).

4.3. Is there a variable wind in MCG-01-24-12?

The inhomogeneous nature of the absorber and a viewing angle that possibly just passes through a semi-transparent obscurer, allowed us to observe the nuclear regions of the MCG-01-24-12. Such a framework was found suitable for the star-forming galaxy MCG-03-58-007 (Braito et al. 2018). This source hosts a very powerful ($v_{\rm out} \sim 0.1 - 0.3$ c), variable ($\delta t \lesssim 1$day) and multi-structured disc-wind launched between tens to hundreds of gravitational radii from the black hole (see Matzeu et al. 2019, Fig. 9). The possible detection of blue-shifted absorption lines on *XMM-Newton* and *NuSTAR* Obs 6 spectra may suggest MCG-01-24-12 to be similar to MCG-03-58-007. If the absorption troughs are associated with Fe XXVI Lyα they would correspond to a highly ionised gas outflowing at $v_{\rm out} \sim (0.06 \pm 0.01)$c [3]. Interestingly, in accordance with the blind line scan, the absorption feature above ~7 keV has a significance ≳90% in 3 *NuSTAR* observations and in the *XMM-Newton* one. These troughts, together with the one found by Malizia et al. (2002) in *BeppoSAX/PDS* data, may suggest for the presence of a persistent wind. We finally noticed that a powerful disc-wind has been invoked to explain a low flux state observed in MCG-03-58-007 (Braito et al. 2018; Matzeu et al. 2019) where the authors found the source variability to be caused by a highly ionised fast wind rather than by a neutral clumpy medium. The low counts of the *Chandra* snapshot did not allow us to test such a scenario and a longer *XMM-Newton* exposure is needed to confirm the putative outflow in MCG-01-24-12 and to further understand the physics behind its low flux state. Moreover, future observations through the high resolution micro-calorimeter detectors on board of *XRISM* and *ATHENA* will provide unprecedented details of these obscuration events.

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[3] This outflowing velocity has been derived in accordance with $v_{z_{\rm abs}} = \left((1+z_{abs})^2 - 1\right) / \left(1 + z_{abs})^2 + 1\right)$ and $v_{\rm out}/c = \left(u - v_{z_{\rm abs}}\right) / \left(1 - (u v_{z_{\rm abs}})\right)$; where z_{abs} is the redshift of the feature and u is the systemic velocity of MCG-01-24-12.

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