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Letter to the Editor

# Clearing up the clouds around NGC 4151: evidence of a highly ionized absorber

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**ABSTRACT**

The Seyfert 1 galaxy NGC 4151 is characterized by complex X-ray absorption, well described by a dual absorber, composed of a uniform mildly ionized gas and a cold system that partially covers the central source. However, in one of the 5 *BeppoSAX* observations, the spectrum shows two peculiar features. An absorption feature is detected around 8.5–9 keV with a statistical significance of 99.96%. This feature can be fitted either with an absorption edge at $E = 8.62^{+0.34}_{-0.52}$ keV with optical depth $\tau = 0.06 \pm 0.03$ or with an absorption line with $9.5^{+1.3}_{-0.6}$ keV, width $\sigma = 0.95^{+1.2}_{-0.7}$ keV and $EW = 200$ eV. In the first case, we associate the feature to highly ionized iron at rest, like FeXXII-FeXXIII ($E_{\rm rest} = 8.4$–$8.5$ keV). In the second case the feature could be identified with a blend of FeXXV and FeXXVI lines, with an outflow velocity $v \approx (0.09$–$0.26)c$. This spectrum is also characterized by a substantial reduction of the absorption column density and the covering fraction of the dual absorber. In particular the column density of the mildly ionized and cold absorbers is ≈3–5 times lower than observed in the other states, and the covering fraction is reduced by ≈40 per cent. We propose a possible explanation linking the two properties in terms of a multi-phase ionized absorber.

**Key words.** galaxies: Seyfert – X-rays: galaxies – galaxies: individual: NGC 4151

## 1. Introduction

*Chandra* and *XMM-Newton* observations have shown evidence of narrow absorption lines (NAL) in X-ray spectra of Seyfert 1 galaxies (e.g. NGC 3783, Kaspi et al. 2002). The lines are often blueshifted, suggesting that the material where the NAL originate is flowing at velocities of a few hundred km s$^{-1}$. This is the same medium that produces absorption edges from ionized species (warm absorbers) but that is usually transparent in the Fe K spectral band above 6 keV. Gas outflowing at higher velocities has been recently found in the spectra of several quasars (PG 1211+143, Pounds et al. 2003a; PG 0844+349, Pounds et al. 2003b; PDS 456, Reeves et al. 2003, APM 08279+5255, Chartas et al. 2002), through blueshifted absorption lines. In these high luminosity sources the wind was found at velocity from 500 up to 120 000 km s$^{-1}$ (but see also Kaspi 2004; McKernan et al. 2004). In Seyfert galaxies no strong evidence of outflows with such large velocities has been found so far (but see the case of Mkn 509, Dadina et al. 2005).

In this letter we report on the peculiar absorption properties observed in one of the five observations of the bright Sy1 galaxy NGC 4151 by *BeppoSAX*. The broad-band analysis of these observations can be found in Piro et al. 2005 (hereafter P05). The absorber in NGC 4151 is usually well described by a dual absorber (PO5 and references therein): a cold one, associated with BLR clouds, that partially covers the source, and an external uniform screen, mildly photoionized by the primary continuum. In the December 2001 spectrum, however, there is also evidence of an absorption feature around 8–9 keV, along with a very low absorption in both the cold and mildly ionized absorbers. In particular, the column densities were lower by a factor of 3–5, and the covering fraction of the cold gas was reduced by about 40 per cent. It is worth noting that this combination of low absorption (both in column density and in covering fraction) has never been observed in NGC 4151. In Sect. 2 we test different spectral models to reproduce the absorption feature. These models will be discussed in Sect. 3 and our conclusions will be drawn in Sect. 4. We adopted the standard prescription (Fiore et al. 1999) for data reduction of *BeppoSAX* observations (P05). Hereafter errors and upper limits on spectral parameters correspond to $\Delta\chi^2 = 2.7$, i.e. 90 per cent confidence level for a single parameter of interest.

## 2. Evidence of absorption feature

The December 2001 spectrum, with net exposure times of 114 ks in the MECS(1.8–10 keV), 43 ks in the LECS(0.1–2 keV) and 53 ks in the PDS(13–200 keV), was the longest taken by *BeppoSAX*. The spectra of the three

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instruments were simultaneously fitted with a *baseline model* (BLM) which includes the following components:

A. The primary continuum described by $CE^{-\Gamma}\exp(-E/E_c)$ i.e a power law with an exponential cut-off. $C$, $\Gamma$ and $E_c$ are free parameters.
B. A Compton reflection component from cold matter (PEXRAV model in XSPEC, Magdziarz & Zdziarski 1995), with the cosine of the inclination angle of the reflector fixed to 0.95 and the spectral slope linked to that of the primary continuum. The normalization is a free parameter.
C. A narrow K$\alpha$ iron line modelled with a Gaussian profile with the intrinsic width set to 10 eV, with intensity and energy as free parameters.
D. The soft X-ray spectrum ($E < 2$ keV) is fitted with a combination of a thermal component model (MEKAL model in XSPEC with the temperature fixed to 0.15 keV and free normalization) and a scattering component by ionized material (described by a power-law with the same slope of the primary continuum and a free normalization)
E. The complex absorption is modelled with a dual absorber model. A fraction $f_{\rm cov}$ of the source is covered by a cold column density $N_{\rm Hcov}$. An additional uniform and ionized gas is responsible for additional absorption of the spectrum at low energies and for a mildly ionized Fe edge at ~7.5 keV (FeVII–FeVIII). This *mildly ionized* gas is characterized by a column density $N_{\rm Hwarm}$ and a ionization parameter $\xi = L_{\rm ion}/nR^2$, where $L_{\rm ion}$ is the source luminosity from 5 eV to 300 keV, $n$ is the hydrogen number density of the gas (in cm$^{-3}$) and $R$ its distance from the central ionizing source (in cm) (model ABSORI in XSPEC, Done et al. 1992). The parameters $f_{\rm cov}$, $N_{\rm Hcov}$, $\xi$ are left free.

We assume element abundances from Anders & Grevesse (1989). The Fe abundance in the cold and mildly ionized absorbers and in the reflection component is set to one and the same value, and left free to vary during the fit. This model assumes that only the cutoffed power-law and the cold reflection are subjected to complex absorption. Additional absorption through our own Galaxy is applied to *all* the emission components ($N_{\rm Hgal} = 2 \times 10^{20}$ cm$^{-2}$).

The residuals of the fit with the BLM to the spectrum of Dec. 2001 in the MECS 4–10 keV range (presented in Fig. 1, panel a) show evidence of an absorption feature around 9 keV. We can exclude that this feature is an artifact of the background or of the complex modelling required to describe the broad-band spectrum of NGC 4151. The background spectrum in the MECS in the 8–10 keV range is flat and it is more than two orders of magnitude lower than the source in the extracted source region. We note that in fitting the BLM, we left free to vary all the parameters specified above, thus tending to minimize deviations. We have additionally tested the robustness of the result as follows. First we have adopted a simpler model to fit the MECS and PDS data only. To avoid the complexity of modelling with a dual cold and mildly ionized absorber, we exclude the data below 4 keV and in the 7–8 keV, and adopted a (cut-off) power law with a single cold absorber plus reflection and a narrow emission line. All the parameters were left free. The residuals,

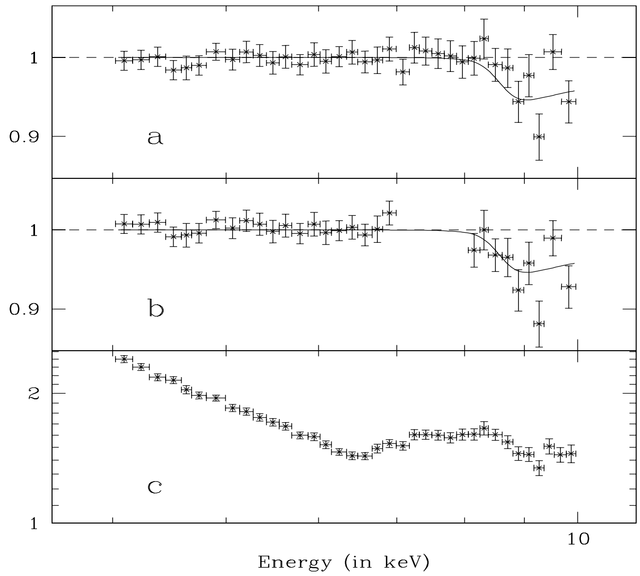


**Fig. 1.** A zoom in MECS 4-10 keV of data/model ratios when the spectrum is fitted with BLM (panel **a**) or with the simplified model described in the text (panel **b**). Data have been binned adopting 3 bins per resolution element (FWHM). This choice maximize the S/N ratio per bin still providing the minimum over-sampling to retain the spectral information. The continuous line is the profile of the absorption edge convoluted through the MECS response. Panel **c)** shows the ratio of Dec. 2001 to the sum of the other spectra.

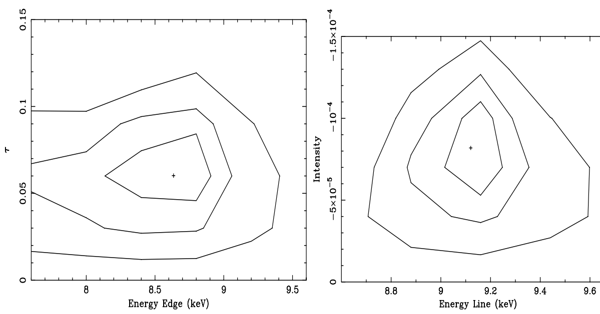


**Fig. 2.** Contour plot of the edge optical depth vs. energy (*left*) and absorption line intensity vs. energy (*right*). Confidence levels are at 68%, 90%, 99%

shown in panel b of Fig. 1, show a even more prominent absorption feature. Finally, we employ a model-independent test, by producing the ratio of the spectrum of Dec. 01 to the sum of spectra of all the other observations (where we do not find evidence of absorption feature, see below). This is shown in panel c of Fig. 1. Above 8.3 keV the ratio decreases sharply and is significantly below the adjacent points at lower energies, supporting the robustness of the absorption feature. We note that the presence of an iron line at 6.4 keV less variable than the intrinsic continuum (that was brighter in Dec. 01 compared to the other observations) compresses the amplitude of variations in the 5–7 keV region. A discussion on this issue goes beyond the scope of this paper and is reported elsewhere (P05). Here it is important to underline another feature that characterizes the spectrum of Dec. 01 in comparison with the others. Below 5.5 keV the ratio shows that the spectrum of Dec. 01 is markedly softer. In fact, the fit with BLM shows

**Table 1.** Best fit parameters fitting the absorption feature in *BeppoSAX* observation in Dec. 2001.

| Model[6] | [1]$E$;[2]$\xi$ | $\tau$;[3]$N_{\rm H,Fe}$;[4]$EW$ | $z$ | [5]$\chi^2$/d.o.f. |
|---|---|---|---|---|
| Edge | $8.62^{+0.34}_{-0.52}$ | $0.06^{+0.03}_{-0.03}$ | – | 58/70 |
| Ion Abs | >300 | $3.0^{+1.8}_{-1.8}$ | <0.07 | 63.2/69 |
| Abs line | $9.1^{+0.2}_{-0.2}$ | $100^{+45}_{-45}$ | 0.09-0.26 | 57.9/70 |

Note: [1] In keV; [2] In erg cm s$^{-1}$; [3] $N_{\rm H,Fe} = N_{\rm H} \times A_{\rm Fe}$, in $10^{22}$ cm$^{-2}$; [4] In eV; [5] BLM: $\chi^2$/d.o.f. = 71.4/72; [6] Component added to BLM.

that this is entirely due to a substantial decrease of the dual absorber in Dec. 01 ($f_{\rm cov} = 0.34 \pm 0.07$, $N_{\rm H,cov} = (3.5 \pm 0.9) \times 10^{22}$ cm$^{-2}$, $N_{\rm H,warm} = (0.9 \pm 0.2) \times 10^{22}$ cm$^{-2}$ vs. $f_{\rm cov} = 0.6 \pm 0.04$, $N_{\rm H,cov} = (19 \pm 4) \times 10^{22}$ cm$^{-2}$, $N_{\rm H,warm} = (7 \pm 1) \times 10^{22}$ cm$^{-2}$ derived from the summed spectrum of the other observations).

We attempted to reproduce the absorption feature with different models; the best fit values are shown in Table 1. First we added to the model an absorption edge, with energy $E$ and optical depth $\tau$ as free parameters. The improvement with respect to the BLM is $\Delta\chi^2 = 13$. This corresponds to a confidence level of 99.98 % for the addition of two parameters, i.e. taking into account that the energy was not known a priori. The energy of the edge was found at $E = 8.62^{+0.34}_{-0.52}$ keV and the optical depth is $\tau = 0.06^{+0.03}_{-0.03}$ (see the first line in Table 1 and the contour plot in Fig. 2). A similar result is derived from the addition of the edge to the simplified model described above. The chi square improves from $\chi^2/\nu = 64.4/37$ to $\chi^2/\nu = 38.4/35$ upon the addition of the edge with a slightly more significative confidence level of 99.99%. The profile of the edge (convoluted through the MECS response matrix), is shown in Fig. 1.

To have a more physical representation of the Fe absorption we fitted the *BeppoSAX*spectrum of Dec 2001 adding to our BLM a uniform highly ionized gas (ABSORI in XSPEC, Done et al. 1992). Iron abundance in the gas is the same as in the cold and mildly ionized absorbers and left free during the fit. This model gave us a good fit with $\Delta\chi^2 = 8$ (with the addition of three free parameters), with respect to the BLM (see the second line in Table 1). The gas is highly ionized ($\xi \gtrsim 300$ erg cm s$^{-1}$) and it is characterized by a column density of $N_{\rm H,ion} = 5^{+3}_{-3} \times 10^{21}$ cm$^{-2}$ and iron abundance $A_{\rm Fe} = 6.1^{+1.9}_{-1.1}$. We took into account a possible blueshift and we found an upper limit $v/c < 0.07$. A less ionized medium is excluded because the column density inferred from the edge depth ($N_{\rm H,Fe} = 3 \times 10^{22}$ cm$^{-2}$) would significantly affect the low energy spectrum. This in turn sets the upper limit to the velocity found above.

Finally we fitted the feature with an absorption line with a narrow Gaussian profile. This model gave $\Delta\chi^2 = 13$ (with the addition of two free parameters) with respect to the BLM (last line in Table 1). The energy of the line was found at $E = 9.1^{+0.2}_{-0.2}$ keV with an equivalent width $100 \pm 45$ eV (Fig. 2). When left free to be broad, the line is reproduced with energy $9.5^{+1.3}_{-0.6}$ keV, an intrinsic width $1.0^{+1.15}_{-0.80}$ keV and $EW \sim 200$ eV. However the fit is not significantly better than that with a narrow line.

We do not find statistically significant evidence of a similar feature in the other *BeppoSAX* observations. We have then checked if we can *exclude* the presence of a feature with the same properties as that observed in Dec. 2001. This has been done by adding an edge with the energy fixed at 8.6 keV. The resulting upper limits – for each single observation – are above, i.e. consistent, with the detection. This is not surprising, considering the much higher statistics available in Dec. 2001. A tighter upper limit $\tau \leq 0.04$ is derived from the summed spectrum of the other observations, a value that is below but still marginally consistent with the detection of Dec 2001. Considering this test as another independent search on a spectrum with a similar statistical weight as that of Dec. 2001, we conservatively adjust the significance of the feature to 99.96 %.

We performed the same analysis on the *XMM-Newton* spectra of NGC 4151 available in the public archive. *XMM-Newton* observed NGC 4151 on 2000 Dec. 21–23 and on 2003 May 25–27. The longer exposures were those of 2000 Dec. 22 and 21 (~62 ks and ~34 ks, respectively), the other observations were about ~20 ks long. We fitted all the spectra with our BLM, and we looked for the presence of an absorbing feature. We found only an upper limit to the optical depth of an absorption edge with the energy fixed to the value observed by *BeppoSAX*(8.62 keV) of $\tau \leq 0.02$. It is worth to note that none of these observations were characterized by a very low absorption as detected in Dec. 2001 by *BeppoSAX*.

## 3. Discussion

Let us first discuss the interpretation of the feature with an absorption line. Candidate resonant absorption lines are at 6.70 keV (FeXXV K$\alpha$), 7.88 keV (FeXXV K$\beta$) 6.97 keV (FeXXVI K$\alpha$) and 8.25 keV (FeXXVI K$\beta$), depending on the ionization state. Assuming a dispersion of ~1000 km s$^{-1}$, the measured equivalent width, ~100 eV, would indicate a column density of about $N_{\rm H} \sim 10^{23}$ cm$^{-2}$ (Bianchi et al. 2005) and a ratio K$\alpha$/K$\beta$ of about 1.6 and 2.6 for FeXXVI and FeXXV respectively (Risaliti et al. 2005). Taking the weighted average of the K$\alpha$ and K$\beta$ energies and comparing with the observed energy, we derive an outflow velocity of $v/c \sim 0.09$–$0.26$, depending on the association FeXXV or FeXXVI.

NGC 4151 would be one of the first case of high velocity ionized outflow through the detection of blueshifted Fe K absorption line in the X-ray spectrum of a Sy 1 with low accretion rate. Evidence of this feature has instead been found by *XMM-Newton* and *Chandra* in sources accreting close to the Eddington rate and requires an outflow of highly ionized gas at high velocity and with a large column density (e.g. PG 1211+143 $N_{\rm H} \sim 5 \times 10^{23}$ cm$^{-2}$ $\log\xi \sim 3.4$ and $v \sim 24\,000$ km s$^{-1}$; Pounds et al. 2003a, PG 0844+349 $N_{\rm H} \sim 4 \times 10^{23}$ cm$^{-2}$ $\log\xi \sim 3.7$ and $v \sim 60\,000$ km s$^{-1}$, Pounds et al. 2003b, PDS 456 $N_{\rm H} \sim 5 \times 10^{23}$ cm$^{-2}$ $\log\xi \sim 2.5$ and $v \sim 50\,000$ km s$^{-1}$, Reeves et al. 2003). These value are in good agreement with those found by *BeppoSAX* in the case of NGC 4151.

However the outflow rate in those quasars is comparable to the mass accretion rate, suggesting that the outflow could originate by wind driven by the radiation pressure of the accretion disk around the super-massive black hole. The case of NGC 4151 looks different. With $L_{\rm Edd} = 1.8 \times 10^{45}$ erg s$^{-1}$ and $L_{\rm bol} \sim 10^{44}$ erg s$^{-1}$, the accretion is taking place in a sub-Eddington regime, and therefore radiation pressure can not drive the outflow. In addition we can derive a rough estimation of the mass outflow rate as follows. When reproduced with an absorption line, the observed stage of ionization, FeXXV or FeXXVI, indicates a ionization parameter $\xi \gtrsim 1000$ erg cm s$^{-1}$. Given a ionization luminosity of $L_{\rm ion} \sim 2 \times 10^{43}$ erg s$^{-1}$, an upper limit to $nR^2 \lesssim 2 \times 10^{40}$ cm$^{-1}$ is obtained, where n is the number density of the gas and $R$ its distance from the Black Hole. The mass outflow rate is $\dot{M}_{\rm out} = \Omega n R^2 m_{\rm p} v$ where $\Omega$ is the solid angle in steradian subtended by the outflow, $m_{\rm p}$ the mass of a proton and $v$ the outflow velocity. Then we obtain $\dot{M}_{\rm out} \leq 4\Omega\, M_\odot\,{\rm yr}^{-1}$. In a stationary regime $\dot{M}_{\rm out} \sim \dot{M}_{\rm infl} \sim \frac{L_{\rm bol}}{\eta c^2} \sim 0.02\, M_\odot\,{\rm yr}^{-1}$, with an efficiency $\eta = 0.1$, thus requiring a highly collimated outflow ($\Omega \gtrsim 0.005$ sr) directed in our line of sight, which is unlikely.

Let us now discuss the association of the feature with an absorption edge. In this case the energy of the edge is consistent with a highly ionized gas with a low or zero velocity, so that the problem of the mass outflow rate and its consistency with the accretion flow does not apply. However this excludes the possibility to explain the transient presence of the feature in terms of a short-lived outflowing phenomenon.

We have explored another solution, that takes into account the coincidence between the appearance of the feature and the uncovering of the central source. In this scenario the gas producing the absorption edge is located outside the cold partially covering absorber. This gas is therefore subjected to a different ionizing flux depending on the covering fraction $f_{\rm cov}$ and the absorption column density $N_{\rm H,cov}$. This is shown in Fig. 3, where the weighted average energy of the absorption edge due to the most abundant ion stages, computed with the XSTAR code (Kallman 2005), is shown for representative cases. We have adopted a power-law spectrum with photon index $\Gamma = 1.7$ and a high energy cut-off at 130 keV as representative of the continuum. The intrinsic luminosity of the source has been set to the value, $L_{1\,{\rm Ry}-1000\,{\rm Ry}} = 10^{43}$ erg s$^{-1}$, as observed in Dec. 2001, to check whether different stages of ionization can be obtained by changing partial covering parameters only. The parameters of the ionized absorber (i.e. $nR^2$), were set by imposing that the average energy of the edge for the spectrum observed in Dec. 2001 ($f_{\rm cov} = 0.34$ and $N_{\rm H,cov} = 3.5 \times 10^{22}$ cm$^{-2}$) is $E \sim 8.5$ keV. The continuous line gives the result in the case of $N_{\rm H,cov} = 1.5 \times 10^{23}$ cm$^{-2}$, i.e. the typical value observed in NGC 4151, as function of $f_{\rm cov}$, while the diamond corresponds to the case of Dec. 2001. It is clear that, when the covering fraction is $\gtrsim$0.7, as typically observed in this source, the energy of the edge decreases to around 7.6–8 keV, i.e. near to that of the mildly ionized absorber.

In fact, it is tempting to identify the high and mildly ionized absorber with the same system, i.e. a multi-phase warm absorber, in which the predominant ionization stage is determined by the ionizing flux impinging on it. Interestingly, the column density of the mildly ionized phase in Dec. 2001 is the lowest ever observed in NGC 4151, this could (at least in part) due to the transformation into the highly ionized phase.

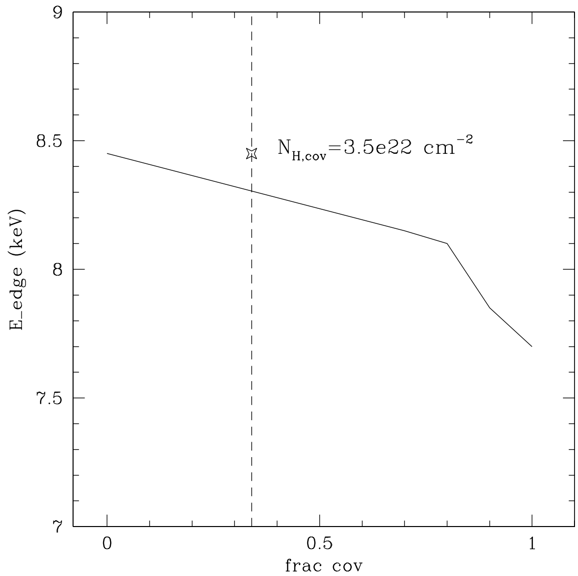


**Fig. 3.** XSTAR simulation. The energy of the Fe absorption edge in the external ionized gas is plotted versus the covered fraction of the internal cold gas with $N_{\rm H} = 1.5 \times 10^{23}$ cm$^{-2}$. The case of Dec. 2001 is plotted with a diamond. The incident continuum is a cut-off power–law with $\Gamma = 1.7$ and $E_{\rm c} = 130$ keV. The plot can explain the appearance of the absorption feature only in a peculiar state of NGC 4151 when the central source was almost uncovered.

The sum of the mild and high ionized column densities in Dec. 2001 is $\sim 1.5 \times 10^{22}$ cm$^{-2}$. As mentioned above, in the other *BeppoSAX* observations the gas should be mostly in a mildly ionized phase, so one would expect to observe a similar column density. However, the presence of variability, from 2 up to $8 \times 10^{22}$ cm$^{-2}$ (P05), does not allow an unambiguous conclusion.

We can derive an upper limit to the distance of the gas $R$ to the central source as follows. By taking $\xi \gtrsim 300$ erg cm s$^{-1}$ (see Table 1), $L_{\rm ion} \sim 2 \times 10^{43}$ erg s$^{-1}$ and the column density $5 \times 10^{21}$ cm$^{-2}$, we derive $R \lesssim 10^{19} f_{\rm V}$ cm, where $f_{\rm V}$ is the volume filling factor of the gas. This value is fully consistent with the variability of the observed absorption feature on yearly time scales.

## 4. Conclusions

We presented a study of a peculiar state of the Seyfert 1 NGC 4151 observed by *BeppoSAX* on December 2001. The evidence in the spectrum of an absorption feature around 9 keV suggests the presence of a highly ionized gas. In the same spectrum there was a a substantial decrease of the warm (mildly ionized) and cold absorbing gas that characterize the complex absorption in NGC 4151. Both the column densities and the cold covering fraction in Dec. 2001 were lower than in the other observations of the source. This combination has never been observed before in NGC 4151.

A first possible scenario is one in which the absorbing feature is identified with a blend of FeXXV and FeXXVI absorption lines, produced in a gas with an outflow velocity $v \approx (0.09–0.26)c$, depending on the line identification. However the mass outflow rate is much higher than the mass accretion rate, differently from the cases observed in high accretion rate quasars, where similar lines were detected.

In a second and most appealing scenario the absorbing feature is interpreted as an absorption edge of highly ionized iron at rest, like FeXXII or FeXXIII ($E_{\rm rest}$ = 8.4–8.5 keV). The gas where this feature is produced is external to the cold partial absorber, and it is therefore subjected to a different ionizing flux depending on the covering fraction and column density of the latter. This is fully consistent with the appearance of the absorption feature only in a peculiar state of NGC 4151 when the central source was almost uncovered.

It is then natural to identify the high and mildly ionized absorber with the same system, i.e. a multi-phase warm absorber, in which the predominant ionization stage is determined by the fraction of the continuum flux emerging from the inner cold absorber that partially covers the central source.

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