A VIEW OF PKS 2155-304 WITH \textit{XMM-NEWTON} REFLECTION GRATING SPECTROMETERS

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ABSTRACT

We present the high resolution X-ray spectrum of the BL Lac object PKS 2155-304 taken with the RGS units onboard \textit{XMM-Newton} in November 2000. We detect a O VII Kα resonant absorption line from warm/hot local gas at 21.59 A (\(\sim\) 4.5 \(\sigma\) detection). The line profile is possibly double peaked. We do not confirm the strong 20.02 A absorption line seen with \textit{Chandra} and interpreted as \(z \sim 0.05\) O VIII Kα. A 3 \(\sigma\) upper limit of 14 mA on the equivalent width is set. We also detect the \(\sim\) 23.5 A interstellar O I 1s\(\rightarrow\)2p line and derive a factor \(\lesssim 1.5\) subsolar O/H ratio in the ISM along PKS 2155-304 line of sight.

\textit{Subject headings:} BL Lacertae objects: individual (PKS 2155-304) — intergalactic medium — large-scale structure of universe — quasars: absorption lines

1. INTRODUCTION

The observed baryon density at \(z > 2\) (e.g.)\textsuperscript{2,98,97} agrees well with Standard Big-Bang nucleosynthesis predictions, when combined with observed light-element ratios (Burles & Tytler, 1998). At lower redshift, however, less than 1/3 of the baryons observed at \(z > 2\) have been detected so far (Fukugita, Hogan, & Peebles, 1998). According to simulations for the formation of structures in the Universe, most of such baryons would be located at the present epoch, in low density intergalactic gas, which has been shock-heated to temperatures of \(\sim 10^5 - 10^7\) K (e.g. the warm-hot intergalactic medium WHIM, e.g.)\textsuperscript{98}. The most efficient way to detect the presence of WHIM is through resonant absorption lines from highly ionized metals (e.g. O VI, O VII, O VIII, Ne IX) imprinted in the far UV (FUV) and soft X-ray spectra. However, despite the large relative abundances of “X-ray” ions in the WHIM, the current sensitivity and resolution of X-ray spectrometers has allowed so far only the strongest (EW \(\gtrsim 10\) mA) of these systems to be detected, and only against spectra of very bright background sources (Nicastro et al. 2002; Mathur, Weinberg & Chen 2003; Fang et al. 2002; Fang, Weinberg & Canizares 2003; with \textit{Chandra} and Rasmussen, Kahn & Paerels 2003 with \textit{XMM-Newton}; for a recent review see Paerels & Kahn 2003).

Three out of these six detections have been made against the spectrum of the bright (\(F_{2-10\text{keV}} \sim 2 \times 10^{-11} - 5 \times 10^{-10}\) erg cm\(^{-2}\) s\(^{-1}\)), nearby (Falomo, Pesce, & Treves, 1993, \(z = 0.116\)), blazar PKS 2155-304 (Nicastro et al., 2002; Fang et al., 2002). A high quality (\(\gtrsim 700\) counts per resolution element at the relevant wavelengths) \textit{Chandra} (HRCs/LETG) observation of PKS 2155-304, revealed the existence of O VII, O VIII and Ne IX absorption lines at \(z \sim 0\), identified with a WHIM system, pervading our Local Group (Nicastro et al., 2002). Lower quality \textit{Chandra} (ACIS/LETG) spectra of PKS 2155-304 confirmed the above findings (Fang et al., 2002), and also show a line at 20.02 A, that Fang et al. (2002) identify as the O VIII WHIM counterpart of a known Ly\(\alpha\) and O I system at \(z \sim 0.05\), where a concentration of galaxies is seen (?and references therein\textsuperscript{88,98,93}). However it is not clear why such a feature is not detected in the higher quality HRCs/LETG spectrum published by Nicastro et al. (2002). Additional data are needed to clarify this issue.

In this paper we present the analysis of the high resolution \textit{XMM-Newton} Reflection Grating Spectrometers (RGS hereinafter) spectra of PKS 2155-304. The structure of the paper is as follows: in § 2 we report on the RGS data reduction and analysis. The spectral fitting and comparison with previous measurements is given in § 3. The discussion of the detected features is presented in § 4.

2. OBSERVATIONS AND DATA REDUCTION

PKS 2155-304 was observed by \textit{XMM-NEWTON} in revolution 174 (Nov 19-21, 2000) in two short and two long pointings described in Table 1. \textit{XMM-NEWTON} is equipped with three
coaligned X-ray telescopes and provides images over a 30' field of view with moderate spectral resolution using the European Photon Imaging Camera (EPIC), which consists of two MOS and one PN CCD arrays. High-resolution spectral information is provided by the Reflection Grating Spectrometers (RGS-1 and RGS-2) that deflect half of the beam of the two of the three X-ray telescopes. Due to a failure in the read-out electronics of two RGS CCDs (CCD 4 in RGS-2 and CCD 7 in RGS-1) the total effective area is reduced by a factor 2 in the wavelength bands originally covered by these CCDs (10.5–14.0 A and 20.1–23.9 A). The observatory also has a co-aligned 30 cm optical/UV telescope, i.e., the Optical Monitor (OM). In this paper we concentrate on the RGS spectra of PKS 2155-304 (\(\Delta E/E\) from 100 to 500, FWHM, in the energy range 0.33–2.5 keV - 5–38 A), the first and second order spectra of which are clearly visible in both RGS. EPIC and OM data are discussed in Maraschi et al (2002) and Maraschi et al. (2003, in preparation).

We reprocessed the data using the Science Analysis System (SAS) software version 5.3.0 and the calibration files as of May 31st 2002. Since the wavelength calibration of XMM grating spectra depends strongly on the position of the 0th order, we used the VLBI position as centroid of the 0th order source (Ma et al., 1998). Extraction regions, for source and background, were chosen to be, respectively, within the 95% and outside the 98% of the PSF. Since XMM-RGS observations can be affected by high particle background periods caused by solar activity, we extracted RGS1 and RGS2 background lightcurves from CCD-9, the closest to the optical axis of the telescope and therefore the most affected by background flares. We excluded all the time intervals for which the background count rate was higher than 10^{−3} count s^{−1} and report the net exposures in Table 1. Note that the short observation at the end of the run (Obs. Id. 0080940501) is completely affected by background flares and will not be further considered in this paper, which discusses the first three observations only. For each observation and for each RGS unit we extracted first and second order source and the background spectra, for a total of 12 spectra, but since second order spectra have a significantly lower number of photons, we will concentrate on first order only.

3. SPECTRAL FITTING

We modeled the continuum of each RGS-1 and RGS-2 observation of PKS 2155-304 in the energy range 0.35 – 2.0 keV using version 11.2.0 of XSPEC. We adopted an absorbed power law model of the form

\[
F(E) = F(E_0)E^{-\Gamma} \exp(-\sum_i \alpha_i N(X_i) \sigma_X)
\]

where \(f(E_0)\) is a normalization factor at \(E_0 = 1\) keV, \(\Gamma\) is the photon index and the photoelectric absorption is characterized by a column density \(N(X)\) and an absorption cross section \(\sigma_X\) for each element (Morrison & McCammon, 1983). The Galactic hydrogen column density is fixed at \(N_H = 1.36 \times 10^{20} \text{ cm}^{-2}\) (Lockman & Savage, 1995). The best fit slopes and the source fluxes during the observations are reported in Table 2. Errors in the paper represent 1 \(\sigma\) confidence levels unless stated otherwise.

To determine the line parameters we prefer the simultaneous fit of the three data sets because we can promptly see false absorptions caused by flickering hot pixels/columns in an observation which appear normal in the other observations, and can remove the problematic data set from the fitting procedure (e.g. OVII K\(\beta\), see Table 3).

3.3. Lines

To better model the underlying continuum in the proximity of absorption/emission features, we did not adopt the broad band
absorbed power law results presented above, but we divided the RGS-1 and RGS-2 spectra into ~ 2 – 3 A wavelength bins and performed a simultaneous fit with a local absorbed power law. In the following sections we will discuss the features with significance > 2 σ.

3.3.1. The shift

To determine the absolute line position in RGS-1 we used the 23.5 A interstellar O I 1s→2p line (see § 3.3.3) to determine the positions of the OVII lines, we extracted the RGS-1 spectra of the Crab nebula and of another BL Lac object: H 1426+428. No OVII Kα is detected in the 46 ks long observation of the BL Lac; but a ~20 % feature at 18.65 A is visible. Similarly the Crab spectrum shows a ~10 % drop in the same region. Therefore the OVII Kβ, detected in RGS-1 at ~ 18.64 A (see Figure 4, left panel), is likely to be affected by the presence of this effective area drop. Since we cannot correct for this effective area feature, the line EW reported in Tab. 3 is to be considered as an upper limit only. The EW ratio of OVII Kα and Kβ limit is > 1.29±0.07, consistent with Nicastro et al. (2002) value of ~ 1.41, and with the oscillator strength ratio of 4.77.

We do not detect any OVIII Lyα at 18.97 A. Fixing the line width to the value obtained for OVII Kα, we find a 3 σ upper limit of 12.61 mA for the line EW (Tab. 3). We note however that the 3 σ upper limit corresponds to a OVIII Lyα normalization 11% of the power-law value, comparable to the depth of a nearby (18.92 A) effective area drop.

At the redshift of the intervening concentration of galaxies (z ~ 0.005) we do not confirm the strong OVIII Kα present in PKS 2155-304 Chandra spectrum of Fang et al. (2002) but not present in Nicastro et al. (2002) nor in Rasmussen, Kahn, & Paerels (2003). The 20.02 A line EW in Fang et al. (2002) is ~ 14±2 mA, comparable to the 21.6 A OVII Kα EW and to the 18.6 A OVII Kβ in this spectrum. Since we detect the OVII Kα (with EW consistent with) but not OVII Kβ, the lack of detection of the 20.02 A feature is unlikely to be the result of insufficient statistics in our continuum. An upper limit can be set on the equivalent width of a putative absorption line at 20.02 A of 14.0 mA, at 3 σ confidence level, i.e. the value observed by Fang et al. (2002).

It is not possible to determine if any NeIX absorption is present because RGS-2 only is active in this wavelength range and it presents a ~21% drop in the effective area at ~13.45 A. We detect at 1.4 σ at ~ 22.72 ± 0.03 A with EW of ~ 6 mA the 22.77 A line already seen in PKS 2155-304 and also in MRK 421 RGS spectra by de Vries et al. (2003). The best fit parameters to the 23.5 A interstellar O I 1s→2p line, discussed in § 3.3.1, are reported in Table 3.

4. DISCUSSION

At z ~ 0 we confirm the existence of a OVII Kα absorption feature, but we do not detect features of higher ionization elements (OVIII, NeIX and NeX) seen by Chandra (Nicastro et al., 2002). This lack of detection is likely to be related to the limited number of photons (e.g. ~ 15300 photons between 19.5 and 20.5 A, i.e. ~ 100 photons per 0.0065 A resolution element) collected in the XMM-Newton observation, when the source was ~2–3 times fainter than in Nicastro et al. (2002).
The OVII Kα appears to be unsaturated and the curve of growth presented in (Nicastro et al., 2002) suggests an OVII column density of $\sim 10^{16}$ cm$^{-2}$. If the weak evidence of a double peak in the profile of the OVII Kα line is considered real, such shape may indicate that we are starting to detect the different sheets of the local filament.

The 3σ upper limit on the OVIII Lyα line EW, computed fixing the line FWHM to the OVII Kα FWHM value, is 12.61 mA, consistent with the value of 9.0$^{+2.4}_{-1.4}$ mA found by Rasmussen, Kahn, & Paerels (2003) in the RGS spectrum of PKS 2155-304. Under the assumption of unsaturated lines the EW ratios between different ions of the same element depend on the gas temperature and density. Using the ratio between the upper limit on the EW of OVIII Lyα to the OVII Kα (best fit value $\sim 2\sigma$), we obtain an upper limit on the gas redshift of $\sim 2.5-3.5 \times 10^5$ K, for a gas density of $10^{-6}-1$ atom cm$^{-3}$ (see Figure 5 in Nicastro02). These values are consistent with the temperature range predicted for the WHIM.

It is not possible to discriminate with the present data whether the OVII features are produced by a WHIM, as proposed by Nicastro et al. (2002) or by radiatively cooling gas within our Galaxy, as proposed by Heckman et al. (2002). In the FUSE spectrum of PKS 2155-304 Nicastro et al. (2002) found two unsaturated OVII absorption lines: a narrow component (FWHM = 106$^{+9}_{-6}$ km s$^{-1}$) at $cz = 36^{+6}_{-5}$ km s$^{-1}$ with EW = (2.1 $^{+0.2}_{-0.3}) \times 10^3$ eV, probably related to a cloud in the Galactic disk, and a broad component (FWHM = 158$^{+26}_{-21}$ km s$^{-1}$) at $cz = -135^{+14}_{-13}$ km s$^{-1}$ with EW = (1.6 $^{+0.4}_{-0.3}) \times 10^3$ eV possibly associated with a WHIM filament. Using our OVII Kα EW and the EW of the OVII broad component from Nicastro et al. (2002) we derive a temperature range of $\sim (4.5-200) \times 10^5$ K for a gas density of $\sim 10^{-6}-10^{-5}$ cm$^{-3}$, which restricts to $\sim (4.5-25) \times 10^5$ K once the upper limit from the OVIII is considered. We note, however, that the OVII absorption features at local redshift have been found in the spectra of other 4 AGNs (3C 273 Fang, Sembach & Canizares (2003); MRK 421 Nicastro et al. (2001); Cagnoni (2002); NGC 4593 McKernan et al. (2003) and NGC 3783 Kaspi et al. (2002)) and might be associated to the high velocity OVI lines (sampling a gas at $T \sim 10^5-10^6$ K) recently seen in the spectra of bright AGNs by FUSE (Sembach et al., 2003; Nicastro et al., 2003). If this is the case, the “local” OVII Kα would indicate the presence of WHIM within the Local Group (Nicastro et al., 2003).

The line at 23.5 Å is the interstellar O I 1s$^2$S$^2$P$^0$ transition (see references therein in MC98). Assuming a neutral ISM gas, no consistent velocity broadening and unsaturated lines, the comparison of the measured EW with the curve of growth derived using Stolte et al. (1997) cross sections implies $\sim 2 \times 10^{16}$ O atoms cm$^{-2}$. The H absorbing column density in PKS 2155-304 direction is $1.36 \times 10^{20}$ cm$^{-2}$ (Lockman & Savage, 1995), which brings to a O/H ratio of 1.4 $\times 10^{-4}$. This value is $\sim 6$ times smaller than in the Solar system (7, 8.5 $\times 10^{-4}$) and 89, but consistent with the ISM elemental abundances in the Magellanic Clouds (S., e.g. Jrus90). Assuming that the line EW is enhanced by velocity broadening would further decrease the O/H ratio. If we adopt the theoretical cross-sections of (McLaughin & Kirby, 1998), as in (see their Fig. 3) we derive $\sim 7 \times 10^{16}$ O atoms cm$^{-2}$, i.e. a O/H ratio of $\sim 5 \times 10^{-4}$, still $\sim 1.5$ times lower than the Solar value. We note that de Vries et al. (2003) OI 1s$^2$S$^2$P$^0$ EW in PKS 2155-304 direction, derived from a coaddition of RGS observations for a total of 346 ks, is $15 \pm 3$ mA consistent with our measurement (17.5$^{+1.3}_{-0.8}$ mA) and the line curve of growth presented in the paper takes saturation effects into account, but still there is indication of a subsolar O/H ratio.

We do not confirm the OVIII Kα line by Fang et al. (2002). Note that the lack of detection of WHIM outside our Local Group is consistent with the expectations of theoretical models. In fact only one OVIII absorption line with EW > 3 mA (i.e. detectable by the present X-ray satellites) in the spectrum of a random background source at $z \sim 0.3$ is predicted (see their Fig. 3). Assuming a neutral ISM, we derive $\sim 7 \times 10^{16}$ O atoms cm$^{-2}$, i.e. a O/H ratio of $\sim 10^{-4}$.

Our XMM-Newton PKS 2155-304 spectrum shows a hint (4σ detection; EW $\sim 5.5$ mA) of a 22.7 Å feature, seen by de Vries et al. (2003) in the XMM-Newton spectra of PKS 2155-304 and MRK 421, and in the Chandra spectrum of PKS 2155-304. Since they do not find evidence of such line in the XMM-Newton spectra of Sco X-1 and 4U 0614+091, they exclude a possible instrumental origin of the line and tentatively identify it with O IV absorption from a local WHIM filament. Higher statistics and other time spaced observations are needed to investigate the reality of the 22.7 Å absorption feature.

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References


**Fig. 1.**—RGS-1 (left) and RGS-2 (right) combined first order spectra of PKS 2155-304 and best fit absorbed power law model folded with the instrument response. The residuals to the fits are reported in the bottom panels (see text for details).

**Fig. 2.**—RGS-1 (left) and RGS-2 (right) combined first order effective areas.
**Fig. 3.**—Top panel: RGS-1 first order spectrum and best fit absorbed power law model folded with the instrument response (dashed line). The middle panel shows the residuals to the fit and the bottom panel shows the position of the absorption features.
Fig. 4.— Same as 3 for RGS-1 (left) and RGS-2 (right) first order spectra in the 18.4 - 20.5 Å range.
FIG. 5.— Top panel: RGS-1 first order spectrum and best fit absorbed power law model folded through the instrument response in the 21–22 Å region. Residuals to the fit are reported in the bottom panel.
A XMM-Newton RGS View of PKS 2155–304

### Table 1

**XMM-Newton RGS Observations of PKS 2155-304 in Revolution 174.**

<table>
<thead>
<tr>
<th>Obs. Id.</th>
<th>Starta</th>
<th>Stopb</th>
<th>Total Exposureb</th>
<th>Net Exposurec</th>
</tr>
</thead>
<tbody>
<tr>
<td>0080940401</td>
<td>19, 15:36:56</td>
<td>19, 18:30:22</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>0080940101</td>
<td>19, 18:38:20</td>
<td>20, 11:26:51</td>
<td>60</td>
<td>58</td>
</tr>
<tr>
<td>0080940301</td>
<td>20, 12:53:01</td>
<td>21, 05:56:27</td>
<td>61</td>
<td>44</td>
</tr>
<tr>
<td>0080940501</td>
<td>21, 05:58:37</td>
<td>21, 07:28:45</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

*a days of November 2000, time is Terrestrial Time. RGS 1 and RGS 2 were operated simultaneously and have start and stop time differing of few seconds only.

b Total RGS on time in ks.

c In ks after the high particle background times rejection.
### Table 2
Fit to the RGS-1 and RGS-2 spectra with an absorbed power law model with absorption fixed to the Galactic value ($N_H = 1.36 \times 10^{20} \text{ cm}^{-2}$).

<table>
<thead>
<tr>
<th>Obs. Id.</th>
<th>RGS 1</th>
<th>RGS 2</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Gamma$</td>
<td>Norm.</td>
<td>Flux $^a$ (0.5-2.0 keV)</td>
<td>$\Gamma$</td>
</tr>
<tr>
<td>0080940401</td>
<td>2.438 ± 0.013</td>
<td>4.08 ± 0.03</td>
<td>8.76 ± 0.07</td>
<td>2.426 ± 0.012</td>
</tr>
<tr>
<td>0080940101</td>
<td>2.488 ± 0.006</td>
<td>3.25 ± 0.01</td>
<td>7.01 ± 0.03</td>
<td>2.469 ± 0.005</td>
</tr>
<tr>
<td>0080940301</td>
<td>2.573 ± 0.008</td>
<td>2.58 ± 0.01</td>
<td>5.59 ± 0.03</td>
<td>2.555 ± 0.007</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2.491 ± 0.005</td>
<td>3.06 ± 0.01</td>
<td>6.59 ± 0.02</td>
<td>2.472 ± 0.005</td>
</tr>
</tbody>
</table>

$^a$ at 1 keV in units of $10^{-2} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$

$^b$ In units of $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$
### Table 3

**Best-fitting RGS-1 absorption line parameters and 1σ errors derived from a local simultaneous fit (see text for details).**

<table>
<thead>
<tr>
<th>Line ID</th>
<th>λ</th>
<th>( c' )</th>
<th>FWHM</th>
<th>EW</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(A)</td>
<td>(km s(^{-1}))</td>
<td>(10(^{-2}) A)</td>
<td>(mA)</td>
<td></td>
</tr>
<tr>
<td>OVII Kβ(^{-})</td>
<td>18.646 ± 0.10</td>
<td>282(^{+113}_{-161})</td>
<td>0.003(^{+3.30}_{-0.003})</td>
<td>15.13(^{+6.12}_{-5.15})</td>
<td>3.7</td>
</tr>
<tr>
<td>O(\text{viii}) Lyα(^{e})</td>
<td>18.967</td>
<td>0</td>
<td>0.12</td>
<td>&lt; 12.61</td>
<td>0.7</td>
</tr>
<tr>
<td>OVII Kα</td>
<td>21.586 ± 0.017</td>
<td>-222(^{+222}_{-236})</td>
<td>5.97(^{+3.94}_{-5.97})</td>
<td>19.50(^{+7.89}_{-8.17})</td>
<td>4.5</td>
</tr>
<tr>
<td>molecular O(\text{i})</td>
<td>23.066 ± 0.038</td>
<td>0</td>
<td>4.16(^{+3.04}_{-4.16})</td>
<td>10.20(^{+6.80}_{-5.81})</td>
<td>2.2</td>
</tr>
<tr>
<td>molecular O(\text{i})(^{f})</td>
<td>23.350 ± 0.007</td>
<td>115(^{+132}_{-92})</td>
<td>0.003(^{+1.298}_{-0.003})</td>
<td>22.58(^{+6.62}_{-5.34})</td>
<td>5.5</td>
</tr>
<tr>
<td>O(\text{i}) Kα</td>
<td>23.510 ± 0.015</td>
<td>16(^{+192}_{-189})</td>
<td>5.20(^{+2.78}_{-3.38})</td>
<td>17.57(^{+1.21}_{-5.81})</td>
<td>4.6</td>
</tr>
<tr>
<td>O(\text{viii}) Kα(^{g})</td>
<td>20.02</td>
<td>16624</td>
<td>6.49</td>
<td>1.54(^{+1.47}_{-1.54})</td>
<td>0.4</td>
</tr>
</tbody>
</table>

\(^{a}\)Note that we applied a \(-35\) mA shift to RGS-1 wavelength calibration in order to match Nicastro et al. (2002) position for the interstellar O\(\text{i}\) 1s→2p line.

\(^{b}\)The EW is computed as the mean of the EW of the line in the three spectra as a result of a simultaneous fit. The errors are computed as the mean of the three values obtained allowing the line and the power laws normalization to vary within their 1σ limits.

\(^{c}\)Results obtained excluding the first observation (ID 90080940401) because of the presence of an effective area feature on the line position.

\(^{d}\)The line parameters are likely to be affected by calibration uncertainties. The line EW and FWHM can be regarded as an upper limits only.

\(^{e}\)The line position and line width are fixed to the expected value and to the OVII Kα value respectively. The EW corresponds to the 3σ upper limit.

\(^{f}\)The line position and the line width are fixed to the value and to the 90% upper limit in Fang et al. (2002) respectively.