XMM–Newton and Suzaku analysis of the Fe K complex in the type 1 Seyfert galaxy Mrk 509

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ABSTRACT
We report on partially overlapping XMM–Newton (∼260 ks) and Suzaku (∼100 ks) observations of the iron K band in the nearby, bright type 1 Seyfert galaxy Mrk 509. The source shows a resolved neutral Fe K line, most probably produced in the outer part of the accretion disc. Moreover, the source shows further emission bluewards of the 6.4 keV line due to ionized material. This emission is well reproduced by a broad line produced in the accretion disc, while it cannot be easily described by scattering or emission from photoionized gas at rest. The summed spectrum of all XMM–Newton observations shows the presence of a narrow absorption line at 7.3 keV produced by highly ionized outflowing material. A spectral variability study of the XMM–Newton data shows an indication for an excess of variability at 6.6–6.7 keV. These variations may be produced in the red wing of the broad ionized line or by variation of a further absorption structure. The Suzaku data indicate that the neutral Fe Kα line intensity is consistent with being constant on long time-scales (of a few years), and they also confirm as most likely the interpretation of the excess blueshifted emission in terms of a broad ionized Fe line. The average Suzaku spectrum differs from the XMM–Newton one in the disappearance of the 7.3 keV absorption line and around 6.7 keV, where the XMM–Newton data alone suggested variability.

Key words: galaxies: active – galaxies: individual: Mrk 509 – galaxies: Seyfert – X-rays: galaxies.

1 INTRODUCTION
Deep investigations of the Fe K band in the brightest active galactic nuclei (AGN) allow us to probe the presence of highly ionized emitting/absorbing components from the innermost regions around the central black hole (BH). The high-sensitivity X-ray satellites XMM–Newton and Chandra have shown that the presence of a narrow core of the lowly ionized Fe Kα line is nearly ubiquitous (Yaqoob & Padmanabhan 2004; Guainazzi, Bianchi & Dovčiak 2006; Nandra et al. 2007), and that ionized components of the line generally associated with emission from photoionized and/or collisionally ionized distant gas are also common (NGC 5506, NGC 7213, IC 4329A; Bianchi et al. 2003; Page, Davis & Salvi 2003; Ashton et al. 2004; Reynolds et al. 2004; Longinotti et al. 2007; see also Bianchi et al. 2002, 2005). The presence of broad (neutral or ionized) components of Fe K lines can only be tested via relatively long exposures of the brightest sources (e.g. Guainazzi et al. 2006; Nandra et al. 2007). Moreover, the observational evidence for broad lines and their interpretation in terms of relativistic

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effects may be questioned when an important absorbing ionized component is present. Spectral variability studies help in disentangling different, often degenerate, spectral components (Iwasawa, Miniutti & Fabian 2004; Ponti et al. 2004, 2006; Petrucci et al. 2007; Tombesi et al. 2007; DeMarco et al., in preparation).

Mrk 509 (z = 0.034397) is the brightest type 1 Seyfert galaxy of the hard (2–100 keV) X-ray sky (Malizia et al. 1999; Revnivtsev et al. 2004; Sazonov et al. 2007) that is not strongly affected by a warm absorber component (Pounds et al. 2001; Yaqoob et al. 2003). The HETG Chandra observation confirms the presence of a narrow component of the Fe K line with an equivalent width (EW) of 50 eV (Yaqoob & Padmanabhan 2004). The presence of a second ionized component of the Fe K line at 6.7–6.9 keV has been claimed by Pounds et al. (2001) who fitted it using a relativistic profile, but Page et al. (2003) showed that the same spectral feature was also consistent with a simple Compton reflection component from distant material. The broad-band BeppoSAX spectrum and, in particular, the soft excess have been fitted by De Rosa et al. (2004) with a reflection component from an ionized disc in addition to a neutral reflection component. Finally, Dadina et al. (2005) found evidence of absorption due to transient, relativistically red–blueshifted ionized matter.

Here, we present the spectral and variability analysis of the complex Fe K band of Mrk 509, using the whole set of XMM–Newton and Suzaku observations. This paper is organized as follows. Section 2 describes the observations and the data reduction. In Section 3, the spectral analysis of the EPIC-pn data of the Fe K band (using phenomenological models) is presented. In particular, in Section 3.3, to check for the presence of an absorption line, the EPIC-MOS data have also been considered. In Section 3.4, the spectral variability analysis, within the XMM–Newton observations, is presented. Section 4 describes the spectral analysis of the Fe K band of the Suzaku summed (XIS0 + XIS3) data and the detailed comparison with the spectrum accumulated during the XMM–Newton observations. In Section 4.1, the HXD-pn data are introduced in order to estimate the amount of reflection continuum present in the source spectrum. Finally, a more physically self-consistent fit of the EPIC spectra of all the EPIC instruments (EPIC-pn plus the two EPIC-MOS) is investigated in Section 5. The results of our analysis are discussed in Section 6, followed by conclusions in Section 7.

2 OBSERVATIONS AND DATA REDUCTION

Mrk 509 was observed five times by XMM–Newton on 2000 October 25, 2001 April 20, 2005 October 16 and 20 and 2006 April 25. All observations were performed with the EPIC-pn CCD camera operating in small window observing mode and with the applied thin filter. The total pn observation time is of about 260 ks. Since the live-time of the pn CCD in small window mode is 71 per cent, the net exposure of the summed spectrum is of about 180 ks. The analysis has been made with the SAS software (version 7.1.0), starting from the ODF files. Single and double events are selected for the pn data, while only single events are used for the MOS camera because of a slight pileup effect. For the pn data, we checked that the results obtained using only single events (that allow a superior energy resolution) are consistent with those from the MOS, finding good agreement. The source and background photons are extracted from a region of 40 arcsec within the same CCD of the source both for the pn and MOS data. Response matrices were generated using the SAS tasks RMFGEN and ARFGEN.

Suzaku observed Mrk 509 four times on 2006 April 25, 2006 October 14, 2006 November 15 and 27. The last XMM–Newton and the first Suzaku observations overlap over a period of ~ 25 ks. Event files from version 2.0.6.13 of the Suzaku pipeline processing were used, and spectra were extracted using XSELECT. Response matrices and ancillary response files were generated for each XIS using XISRMFGEN and XISSIMARFGEN (version 2007-05-14). The XIS1 camera data are not considered here because of the relatively low effective area in the Fe K energy interval, while the XIS2 is unavailable for observations performed after 2006 November. We used the data obtained during the overlapping interval to check whether the EPIC-pn and MOS data on the one hand and the Suzaku XIS0 and XIS3 data on the other hand are consistent within the intercalibration uncertainties. We found an overall good agreement between the data from the two satellites, the parameters related to the main iron emission features and the power-law continuum being the same within the errors (except for the XIS2 camera above 8 keV). The total XIS observation time is about 108 ks. The source and background photons are extracted from a region of 4.3 arcmin within the same CCD of the source. For the HXD/PIN, instrumental background spectra and response matrices provided by the HXD instrument team have been used. An additional component accounting for the CXB has been included in the spectral fits of the PIN data.

All spectral fits were performed using the XSPEC software (version 12.3.0) and include neutral Galactic absorption (4.2 × 1020 cm−2;Dickey & Lockman 1990), the energies are rest frame if not specified otherwise, and the errors are reported at the 90 per cent confidence level for one interesting parameter (Avni 1976). The sum of the spectra has been performed with the MATHPHA, ADDRMF and ADDARF tools within the HEASOFT package (version 6.1).

3 FE K BAND EMISSION OF MRK 509: THE XMM–NEWTON DATA

The primary goal of this investigation is the study of the Fe K line band; therefore, in order to avoid the effects of the warm absorber (although not strong; Yaqoob et al. 2003; Smith, Page & Branduardi-Raymont 2007) and of the soft excess, we concentrate on the analysis of the data in the 3.5–10 keV band only. A detailed study of the warm absorber and its variations will be performed by Detmers et al. (in preparation); we can nevertheless anticipate that the warm absorber has negligible effect in the Fe K energy band and thus on the results presented here. Fig. 1 shows the source light curve in the 3.5–10 keV energy band obtained from the

![Figure 1. 3.5–10 keV EPIC-pn light curves of the XMM–Newton observations. The abscissa shows the observation time in seconds. The time between the different observations is arbitrary. The black, red, green, blue and light-blue show the light curves on 2000 October 25, 2001 April 20, 2005 October 16 and 20 and 2006 April 25 observations, respectively.](https://academic.oup.com/mnras/article-abstract/394/3/1487/1069510)
XMM–Newton pointings. Mrk 509 shows variations of the order of ~30 per cent over the different observations, while almost no variability is detected within each observation. Only during the fourth observation the source shows significant variability, with a mean fractional rms of about 0.04.

We start the analysis of the XMM–Newton data considering the spectra from the EPIC-pn camera only (including the EPIC-MOS data only when a check of the significance of a feature is required; see Section 3.3). We have fitted a simple power-law model to the 3.5–10 keV data, and found that the spectral index steepens with increasing flux. It goes from 1.54 ± 0.03 to 1.72 ± 0.03 for fluxes of $2.5 \times 10^{-11}$ and $3.3 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, respectively ($3.0 \times 10^{-11}$–4.3 $\times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, in the 2–10 keV band). We first phenomenologically fitted the Fe K complex of each single observation with a series of emission–absorption lines (see also Section 3.3), and checked that the results on the parameters of Fe K complex obtained in each observation are consistent within the errors (not a surprising result in light of the low statistics of the single spectra and weakness of the ionized features; see Section 3.4).

Hence, we concluded that the continuum variations do not strongly affect the observed shape of the narrow-band emission/absorption structures in the Fe K band. Thus, in order to improve the signal-to-noise ratio and thus to detail the fine structures of the Fe K band, the spectra of all the XMM–Newton observations have been summed (see Section 3.4 for the study of the source spectral variability). The summed mean EPIC-pn spectrum has been grouped in order to have at least 1000 counts in each data bin. Moreover, this binning criterion ensures to have at least 30 data points per keV in the 4–7 keV band, where the Fe Kα complex is expected to contribute. This guarantees a good sampling of the energy resolution of the instrument and the possibility of fully exploiting the spectral potentials of the EPIC instruments. Fig. 2 shows the ratio between the data and the best-fitting power-law model. The energy band used during the fit has been restricted to 3.5–5 and 8–10 keV, in order to avoid the Fe K band, hence measuring the underlying continuum. The resulting best-fitting power-law continuum has a photon index of $1.63 \pm 0.01$, and very well reproduces the source emission ($\chi^2 = 170.0$ for 163 degrees of freedom (d.o.f.)) outside the Fe K band. The inclusion of the Fe K band shows that other components are necessary to reproduce it ($\chi^2 = 753.9$ for 307 d.o.f.). The bad statistical result is explained by the presence of clear spectral complexity in the 6–7 keV band.

### 3.1 The 6.4 keV emission line

Panel (a) of Fig. 2 shows the clear evidence for a prominent emission line, consistent with a neutral Fe Kα line at 6.4 keV. We therefore added a Gaussian emission line to the model, obtaining a very significant improvement of the fit ($\Delta \chi^2 = 392.1$ for the addition of three d.o.f.). The best-fitting energy of the line is $6.42 \pm 0.02$ keV, consistent with emission from neutral or slightly ionized material. The line has an EW of $69 \pm 8$ eV and is clearly resolved ($\sigma = 0.12 \pm 0.02$ keV), as shown by the contour plot in the left-hand panel of Fig. 3. The residuals in panel (b) of Fig. 2 show no excess redwards of this emission line, which could have been indicative of emission from relativistically redshifted neutral material.

### 3.2 The ionized Fe K emission line

An excess is, however, present in the range 6.5–7 keV (Fig. 2, panel a). If modelled with a Fe Kβ component with the expected energy (fixed at 7.06 keV) and forced to have an intensity of 0.15 of the Kα (Basko 1978; Palmeri et al. 2003a,b; Molendi, Bianchi & Matt 2003) and a width equal to the Fe Kα line (i.e. assuming that the Kα and Kβ lines originate from one and the same material), the fit improves significantly ($\Delta \chi^2 = 20.3$). None the less, significant residuals are still present in the 6.5–6.9 keV band (panel b of Fig. 2). If this further excess is modelled with a narrow Gaussian line ($\Delta \chi^2 = 25$ for two additional d.o.f.), the feature (EW = $12 \pm 4$ eV) is found to peak at $E = 6.86 \pm 0.04$ keV (see panel c of Fig. 2 and right-hand panel of Fig. 3). Thus, the energy centroid is not consistent with the line being produced by either Fe XXV or Fe XXVI (right-hand panel of Fig. 3) in a scattering medium distant from the X-rays source (Bianchi & Matt 2002; Bianchi et al. 2004). The higher energy transition of the Fe XXV complex is the ‘resonant line’ expected at 6.7 keV (see e.g. Bianchi et al. 2005). Thus, to save this interpretation, it is required that the photoionized gas has a significant blueshift (~5700 km s$^{-1}$, if the line is associated with Fe XXV) or redshift (~4500 km s$^{-1}$, for Fe XXVI). Then, instead of fitting the ionized excess with a single line, we fitted it with two narrow lines forcing their energies to be 6.7 and 6.96 keV. The fit clearly worsens ($\chi^2 = 326.7$ for 302 d.o.f., corresponding to a $\Delta \chi^2 = -10.1$ for the same d.o.f.). However, if the gas is allowed to be outflowing, the fit improves ($\Delta \chi^2 = 4.3$ for the addition of
one new parameter, $\chi^2 = 312.3$ for 301 d.o.f.; the EWs are 8.9 and 12.4 eV for the Fe XXV and Fe XXVI lines, respectively) as respect to the single narrow emission line, and it results to have a common velocity of $3500^{+1000}_{-1200}$ km s$^{-1}$.

Alternatively, the excess could be produced by a single broad line coming from matter quite close to the source of high-energy photons (in this case, the Fe $K\alpha$ emission is composed of Fe $K\alpha + K\beta$ plus another Fe $K\alpha$ line). Leaving the width of the line free to vary, the fit improves, with $\chi^2 = 311.1$ (panel d, Fig. 2) and $\Delta \chi^2$ of 5.5, with respect to the single narrow ionized emission line fit, and $\Delta \chi^2$ of 1.3 for the same d.o.f. with respect to the best-fitting model with two narrow ionized lines. The resulting broad ionized Fe $K\alpha$ line has $E = 23 \pm 9$ eV and $\sigma = 0.14^{+0.08}_{-0.06}$ keV. The best-fitting energy of the line does not change significantly ($E = 6.86^{+0.16}_{-0.08}$ keV); however, in this case, the emission is consistent (at the 99 per cent confidence level) with either Fe XXV or XXVI. Although the statistical improvement is not highly significant, in the following we will consider that the $\sim 6.8$–6.9 keV excess is indeed associated with a resolved emission line.

### 3.3 Ionized absorption?

The XMM–Newton data also display a narrow absorption feature at $E \sim 7$ keV (observed frame; see Fig. 2, panel d). Since this feature is very close to the broad excess we just discussed, its significance and intensity are degenerate with the broad emission-line parameters. In order to gain some insight, we then fixed the broad emission-line parameters at the best-fitting ones obtained before the addition of a narrow ($\sigma$ fixed at 1 eV) Gaussian absorption line component. In this case, the line is significant at the $\sim 99$ per cent confidence level (dashed contours of Fig. 4; $\Delta \chi^2 = 15.5$ for two additional parameters; see also panel e of Fig. 2). Once the MOS data$^1$ are added, the significance of this feature increases to 99.9 per cent (solid contours of Fig. 4), in both cases, of a broad and a narrow ionized emission line. The best-fitting energy and EW of the line are $E = 7.28^{+0.02}_{-0.03}$ keV and $EW = -14.9^{+5.5}_{-6.2}$ eV, $E = 7.33^{+0.03}_{-0.04}$ keV and $EW = -13.1^{+2.6}_{-2.9}$ eV, in the pn alone and in the pn + MOS, respectively.

$^1$ The shapes of the emission/absorption lines in the MOS instruments appear slightly narrower, although consistent with the values obtained with the pn instrument.

### 3.4 Time-resolved spectral variability and total rms spectrum

One of the goals of the present analysis is to search for time variation of the emission/absorption features of the Fe $K\alpha$ complex. To measure possible variations in the Fe $K\alpha$ band, the mean EPIC-pn spectra of each of the five XMM–Newton observations have been studied. The spectra are fitted with the same model composed of a power law plus three emission lines for the Fe $K\alpha$, $K\beta$ (with the width fixed at the best-fitting value, $\sigma = 0.12$ keV) and the broad ionized Fe $K\alpha$ line. The low statistics of the spectra of the single observations prevent us from the detection of significant spectral variability of the weak ionized emission/absorption lines. The neutral Fe $K\alpha$ line is better constrained, and we find that its EW is anticorrelated with the level of the continuum, as expected for a constant line.

A different, more sensitive, way to detect an excess of spectral variability is the total rms function. The upper panel of Fig. 5 displays the shape of the summed spectrum in the Fe $K\alpha$ band. The lower panel shows the total rms spectrum (Revnivtsev, Borozdin & Emelyanov 1999; Papadakis, Kazanas & Akylas 2005) calculated with time bins of $\sim 4.5$ ks. The total rms is defined by the formula:

$$\text{rms}(E) = \sqrt{\frac{S^2(E) - \langle \sigma^2_{\text{stat}} \rangle}{\Delta E \times \text{arf}(E)}},$$

where $S^2$ is the source variance in a given energy interval $\Delta E$, $\langle \sigma^2_{\text{stat}} \rangle$ is the scatter introduced by the Poissonian noise and $\text{arf}$ is the telescope effective area convolved with the response matrix.\(^2\) This

\(^2\) The total rms spectrum provides the intrinsic source spectrum of the variable component. Nevertheless, we measure the variance as observed through the instrument. Thus, the sharp features in the source spectrum, as well as the effects of the features on the effective area, are broadened by the instrumental spectral resolution. For this reason, to obtain the total rms spectrum, we take into account the convolution of the effective area with the spectral response.
Figure 5. Lower panel: total rms variability spectrum of the XMM–Newton observations. The data (blue crosses) show the spectrum of the variable component. The best-fitting model is a power law with spectral index $\Gamma = 2.18$ (red line) plus a Gaussian emission line (improving the fit by $\Delta\chi^2$ of 8.9 for the addition of two parameters). The dashed line highlights the centroid energy of the neutral Fe $K\alpha$ line, while the dotted line is placed at the maximum of the variability excess, modelled with the Gaussian emission line. The excess variability energy corresponds to a drop of emission of the real spectrum.

Figure 6. XMM–Newton (black) and Suzaku XIS0 + XIS3 (red) summed mean spectra. The data are fitted, in the 3.5–5 and 7.5–10 keV bands, with a simple power law, absorbed by Galactic material, and the ratio of the data to the best-fitting model is shown in Fig. 6. The source emission varied between the XMM–Newton and the Suzaku observations. The best-fitting spectral index and the 3.5–10 keV band fluxes are $\Gamma = 1.63 \pm 0.01$ and $\Gamma = 1.71 \pm 0.02$ and $2.63 \times 10^{-11}$ and $3.11 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, during the XMM–Newton and Suzaku observations, respectively. The neutral and ionized Fe $K\alpha$ emission lines appear constant, while some differences are present at 6.7 keV, the same energy where the XMM–Newton data were suggesting an increase of variability. Other more subtle differences appear at ~7 keV, where the absorption line imprints its presence in the XMM–Newton data only.

4 THE SUZAKU VIEW OF THE FE K BAND EMISSION

As mentioned in Section 2, the source was also observed with Suzaku. The first 25 ks Suzaku observation is simultaneous with the last XMM–Newton pointing. The source spectra of all the instruments are in very good agreement, during the simultaneous observation. The spectrum is also consistent with the presence of the emission and absorption lines, as observed in the mean XMM–Newton spectrum, nevertheless, due to the low statistics of the 25 ks spectrum and the weakness of the ionized features, it is not possible to perform a detailed comparison. Only the presence of the strong Fe $K\alpha$ line can be investigated, the ionized emission and absorption lines are not constrained in the 25 ks Suzaku exposure.

Also, during the four Suzaku pointings, Mrk 509 has shown little variability, with flux changes lower than 10–15 per cent, hampering any spectral variability study. Fig. 6 shows the XMM–Newton (black) and Suzaku XIS0 + XIS3 (red) summed mean spectra. The data were fitted, in the 3.5–5 and 7.5–10 keV bands, with a simple power law and Galactic absorption: the ratio of the data to the best-fitting model is shown in Fig. 6. The source emission varied between the XMM–Newton and the Suzaku observations. The best-fitting spectral index and the 3.5–10 keV band fluxes are $\Gamma = 1.63 \pm 0.01$ and $\Gamma = 1.71 \pm 0.02$ and $2.63 \times 10^{-11}$ and $3.11 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, during the XMM–Newton and Suzaku observations, respectively. The neutral and ionized Fe $K\alpha$ emission lines appear constant, while some differences are present at 6.7 keV, the same energy where the XMM–Newton data were suggesting an increase of variability. Other more subtle differences appear at ~7 keV, where the absorption line imprints its presence in the XMM–Newton data only.
The Suzaku spectrum of Mrk 509 shows, in good agreement with the XMM–Newton one, a resolved neutral Fe K line smoothly joining with a higher energy excess, most likely due to ionized iron emission (see Fig. 6). Given that no absorption lines around 6.7 or 7.3 keV are present in the Suzaku data, the spectrum may be useful to infer the properties of the emission lines more clearly.

The XIS0 + XIS3 Suzaku summed spectrum has been fitted in the 3.5–10 keV band with a power law plus two resolved Gaussian emission lines to reproduce the emission from Fe Kα + β. The parameters of the Fe Kα line are free to vary, while the Fe Kβ ones are constrained as in Section 3.2. This fit leaves large residuals ($\chi^2 = 1379.8$ for 1337 d.o.f.) in the Fe K band. In this respect, it is difficult to describe the >6.5 keV excess with a single narrow ionized Fe line (either due to Fe XXV or Fe XXVI). In fact, although the addition of a narrow line is significant ($\Delta \chi^2 = 20.1$ for two more parameters), it leaves residuals in the Fe K band. This remaining excess can be reproduced ($\Delta \chi^2 = 5.9$ for one more parameter), in a photoionized gas scenario, by a blend of two unresolved ionized lines, requiring three emission lines to fit the Fe K band (Fe Kα + β, Fe XXV and Fe XXVI). In this case, such as in the analysis of the XMM–Newton mean spectrum, a blueshift of this component is suggested ($\sigma = 2600_{-2000}^{+2000}$ km s$^{-1}$). However, the best-fitting model (this scenario is strengthened by the lack of narrow peaks) suggests that the excess may be in fact associated with a broad ionized Fe line (over which the ~6.7 and ~7.3 keV absorption lines are most likely superimposed, but during the XMM–Newton observation only). In fact, considering a broad Fe line instead of the two narrow lines, we obtain an improvement of $\Delta \chi^2 = 9.7$ for the same d.o.f. (see Table 1, Model A).

Thus, the Suzaku data indicate that the broad excess at 6.5–6.6 keV is indeed due to a broad line rather than a blend of narrow ionized Fe lines. Since broad lines may arise because of relativistic effects in the inner regions of the accretion flow, we tested this hypothesis by fitting the excess at 6.5–6.6 keV with a diskl ine profile. The statistics of the spectrum are not such to allow us to constrain all the parameters of the ionized diskl ine profile. Thus, the disc reflectivity index has been fixed at the standard value ($\alpha = -3$, where the emissivity is proportional to $r^{-\alpha}$), the outer disc radius and inclinations to 400 gravitational radii ($r_g$) and 30$^{\circ}$, respectively. The broad line is consistent with being produced in the accretion disc (Table 1, Model B); however, the emission from the innermost part of the disc is not required, the lower limit on the inner disc radius being 10–15 $r_g$. As clear from Fig. 6, the Suzaku data do not require any ionized Fe K absorption structures.

In order to quantify the differences between the Suzaku and XMM–Newton spectra (and, in particular, the reality of the absorption structures at 6.7 and 7.3 keV appearing in the XMM–Newton spectrum only), we fixed all the parameters of the Suzaku model (apart from the intensity and spectral index of the direct power law) and fitted the XMM–Newton data with that model. This corresponds to assuming that the intrinsic line shapes do not vary between the two observations. Then, a narrow Gaussian line has been added to the XMM–Newton model to estimate the significance of the putative absorption structures. The improvement in the spectral fitting is evident, as indicated by the $\Delta \chi^2 = 28.3$ and 22 in the case of a line at $E = 6.72 \pm 0.04$ and 7.29 $\pm 0.04$ keV, respectively. The presence of these spectral features only in the XMM–Newton observations is thus indicative of variability at energies ~6.6–6.7 and ~7.3 keV.

### Table 1

| [3.5–10 keV] | Best fit | Spectra |
|--------------|----------|---------|
| **Suzaku**   |          |         |
| $\Gamma$     | pl norm$^a$ | $E_{\text{Int.}}$ (keV) | $\sigma_{\text{Int.}}$ (keV) | $\chi^2$/d.o.f. |
| A            | 1.72 ± 0.02 | 1.12 ± 0.02 | 6.42 ± 0.03 | <0.06 | 1.7 ± 0.5 (32) | 6.54 ± 0.09 | 4.0 ± 0.1 | 4.6 ± 1.2 (90) | 1344/1340 |
| B            | 1.72 ± 0.02 | 1.12 ± 0.02 | 6.42 ± 0.02 | <0.07 | 2.1 ± 0.5 (40) | 6.61 ± 0.08 | 24 ± 10 | 3.4 ± 0.8 (79) | 1346/1340 |
| **Self-consistent model** |          |         |
| XMM–Newton   |          |         |
| $\Gamma$     | pl norm$^a$ | $E_{\text{Int.}}$ (keV) | $\sigma_{\text{Int.}}$ (keV) | $\chi^2$/d.o.f. |
| C            | 1.70 ± 0.01 | 0.92 ± 0.04 | 6.41 ± 0.01 | 0.07 ± 0.01 | 2.2 ± 0.3 | 47 ± 2 | 11$^{+0.200}_{-0.179}$ | 0.9$^{+3.0}_{-0.5}$ |

$^a$In units of $10^{22}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV. $^b$In units of $10^{-2}$ photons cm$^{-2}$ s$^{-1}$. $^c$In units of eV. $^d$In units of $10^{22}$ atoms cm$^{-2}$.
4.1 The Suzaku pin data to constrain the reflection fraction

We add the pin data to measure the amount of reflection continuum. We note that the pin data provide a good quality spectrum up to 50 keV. The model used involves a direct power law plus a neutral reflection component (PEXRAV model in XSPEC; Magdziarz & Zdziarski 1995) plus the Fe Kα + β resolved lines and a broad (DISKLINE) component of the line. As for Model B, we fix some of the parameters of the DISKLINE profile (disc inclination = 30°, $r_{out} = 400 r_g$ and $\alpha = -3$). Moreover, we assume a high-energy cut off of 100 keV and solar abundance. Thus, by fitting the 3–50 keV band data, we obtained a reflection fraction $R = 0.4^{+0.6}_{-0.2}$ and a spectral index $\Gamma = 1.76^{+0.12}_{-0.05}$. The total EW of the emission lines above the reflected continuum (about 1.2 keV) is broadly consistent with the theoretical expectations (Matt, Fabian & Ross 1996) and with what observed in Compton thick type 2 Seyfert galaxies, where the primary continuum is absorbed and only the reflection is observed. Nevertheless, also for this source, as already known from previous studies (Zdziarski, Lubinski & Smith 1999), we observe that the spectral index and the reflection fraction are degenerate and strongly depend on the considered energy band. In fact, if the 2–10 keV band is considered, the reflection fraction increases, resulting to be $R = 1.1^{+0.2}_{-0.5}$ and the power-law photon index of $\Gamma = 1.88^{+0.03}_{-0.02}$. The total EW of the Fe emission lines above the reflected continuum are about 750 eV. Again these values are broadly in agreement with expectations (Matt et al. 1996).

5 A PHYSICALLY SELF-CONSISTENT FIT: POSSIBLE ORIGIN OF THE SPECTRAL FEATURES

The analysis of the XMM–Newton and Suzaku data shows evidence for the presence of (i) a resolved, although not very broad ($\sigma \sim 0.12$ keV), neutral Fe Kα line and associated Fe Kβ emission, (ii) an ionized Fe K emission line inconsistent with emission from a distant scattering material at rest and most likely produced in the accretion disc, (iii) an absorption line at $\sim 7.3$ keV, present in the summed spectrum of all XMM–Newton observations only, and (iv) an indication for an enhancement of variability – both by considering the XMM–Newton data alone and by comparison between the two data sets – at $\sim 6.7$ keV that could be either due to the high variability of the red wing of the broad ionized Fe K line, possibly associated with a variation of the ionization of the disc, or to a second ionized absorption line.

These emission/absorption components are partially interconnected to each other given the limited CCD resolution onboard XMM–Newton and Suzaku. Thus we refit the XMM–Newton (both the pn and MOS in the 3.5–10 keV energy band) data with a model containing components that better describe the physical processes occurring in the AGN. In particular, we consider two Gaussian lines for the Fe Kα and Kβ emission plus a neutral reflection component (PEXRAV in XSPEC) with a reflection fraction $R = 1$ (consistent with the constraints given by the Suzaku pin data). The Fe Kα line has an EW of 1 keV above the reflection continuum. Moreover, we fit the broad ionized Fe K line with a fully self-consistent relativistic ionized disc reflection component (REFLION model in XSPEC; Ross & Fabian 2005, convolved with a LAOR kernel; KDBLUR in XSPEC).

The statistics prevent us from constraining the parameters of the relativistic profile. Standard values for the relativistic profile are assumed, with the disc’s inner and outer radii and the emissivity of 6, 400 $r_g$ and $-3$, respectively. Finally, the $\sim 7.3$ keV absorption line has been fitted with a photoionized absorption model (ZXIPCF model in XSPEC; Miller et al. 2007; Reeves et al. 2008; Model C, Table 1), assuming a total covering factor.

Table 1 shows the best-fitting parameters. Once the presence of the reflection continuum is taken into account, the power-law slope becomes steeper ($\Gamma = 1.70 \pm 0.01$, $\Delta \Gamma \sim 0.07$) as compared to the fit with a simple power law and emission absorption lines (see Section 3). The best-fitting energy of the neutral Fe Kα line is $E = 6.41 \pm 0.01$ keV, consistent with being produced by neutral material, and results to be narrower ($\sigma = 0.07 \pm 0.01$ keV) than in the previous fits. The ionized emission line is fitted with an ionized disc reflection model. The only free parameters of such a component are the inclination and ionization parameter of the disc that result to be $47 \pm 2°$ and $\xi = 11^{+300}_{-300}$ erg cm s$^{-1}$ (Model C, Table 1). The material producing the 7.3 keV absorption feature in the XMM–Newton data has to be highly ionized, as also indicated by the absence of a strong continuum curvature. In fact, the best ionization parameter is $\log(\xi) = 5.15^{+1.25}_{-0.52}$ and the column density $N_H = 5.8^{+5.2}_{-2.8} \times 10^{22}$ cm$^{-2}$. Nevertheless, the observed energy of the absorption feature does not correspond to any strong absorption features, thus there is evidence for this absorption component to be outflowing with a shift $v = -0.0484^{+0.012}_{-0.013} c (\sim 14000 \pm 3600 \text{ km s}^{-1})$. The resulting $\chi^2$ is 894.3 for 876 d.o.f.

6 DISCUSSION

This study clearly shows that long exposures are needed to disentangle the different emitting/absorbing components contributing to the shape variability of the Fe K complex in Seyfert galaxies. Here, we discuss the origin of both neutral and ionized emission and absorption Fe lines in Mrk 509 which allow us to have insights in the innermost regions of the accretion flow.

6.1 Neutral/lowly ionized Fe emission line

Once the broad ionized line is fitted, the width of the Fe Kα line lowers to a value of 72 ± 11 eV (see Fig. 3) that corresponds to a full width at half-maximum (FWHM) (Fe Kα) = 8000 ± 1300 km s$^{-1}$ (see Model C, Table 1). This value is slightly higher than that measured by Yaqoob & Padmanabhan (2004) with a $\sim 50$ ks HETG Chandra observation (2820 $\pm$ 280 km s$^{-1}$). The FWHM of the Fe Kα line is larger than the width of the Hβ line [FWHM(Hβ) = 3430 ± 240 km s$^{-1}$; Marziani et al. 2003; Peterson et al. 2004], indicating that the Fe line is produced closer to the centre than the optical broad-line region (BLR) and, of course, than the torus postulated in unified models; we note that a wide range of FWHM values is observed for the BLR and the Fe K lines in local Seyfert galaxies (Nandra 2006). However, the ultraviolet (UV) and soft X-ray spectra of Mrk 509 show evidence for the presence of broad emission lines with FWHM of 11 000 km s$^{-1}$ (Kriss et al. 2000). The origin of these UV and soft-X lines is still highly debated, nevertheless they may indicate that the BLR is stratified, i.e. these lines are not produced in the optical BLR but in the inner part of a stratified BLR (see also Kaastra et al. 2002; Costantini et al. 2007), possibly as close as 2000 $r_g$ from the centre (about 0.012 pc, being the mass of the BH in Mrk 509 $M_{BH} \approx 1.43 \pm 0.12 \times 10^6 M_\odot$; Marziani et al. 2003; Peterson et al. 2004). Nevertheless, if the line is produced in the innermost part of a stratified BLR, it would require either a higher covering fraction or a higher column density than generally derived from the optical and UV bands. Simulations by Leahy & Creighton (1993) show that about 70 per cent of the sky, as seen by the central source, has to be covered in order to produce the Fe Kα line, if the broad-line clouds have
column densities of about $10^{23}$ cm$^{-2}$, while the typical values for the BLR clouds covering fractions are of the order of 10–25 per cent (Davidson & Netzer 1979; Goad & Koratkar 1998). Alternatively, the Fe Kα line may be produced by reflection from the inner part of the accretion disc.

6.2 Ionized Fe emission lines

The spectrum of Mrk 509 shows emission from ionized iron, consistent with either Fe xxv or Fe xxvi, implying photoionized gas outflowing or inflowing, respectively. Alternatively, the ionized Fe K emission may be produced by reflection from the inner part of the accretion disc.

In fact, both the XMM–Newton and the Suzaku data are consistent with the two scenarios, even if a slightly better fit ($\Delta \chi^2 = 5.5$ and 9.7 for XMM–Newton and Suzaku, respectively) is obtained in the case of broad line. Moreover, in the case of narrow emission lines, the emitting gas should have a significant outflow (for Fe xxv, $v \sim 3500$ and 2600 km s$^{-1}$ for XMM–Newton and Suzaku, respectively) or inflow (for Fe xxvi, $v \sim 4500$ km s$^{-1}$) with velocities higher than what is generally observed (Reynolds et al. 2004; Longinotti et al. 2007; but see also Bianchi et al. 2008). A hint of variability is observed around 6.7 keV both in the XMM–Newton and Suzaku data, and the Fe Kα line may be produced by reflection by the outer part of the XMM–Newton emission. The width of the line emission may be produced by reflection from the inner part of the XMM–Newton observations, with a column density $N_H = 5.4^{+4.8}_{-4.4} \times 10^{21}$ cm$^{-2}$ and ionization parameter $\log(\xi) = 2.04^{+0.44}_{-0.60}$. When the structure at 6.7 keV is fitted with such a component, an absorption structure appears around 7.3 keV, nevertheless its EW is not strong enough to reproduce the total absorption feature; moreover, it appears at slightly different energy, not completely fitting the ~7.3 keV line. Thus, the absorption structures at 6.7 and the one at 7.3 keV may be connected, and they may be indicative of another absorption screen. If this further lower ionization absorption component is present, different absorption features would be expected (due to the low ionization and high column density) at lower energies. Smith et al. (2007) analysed the RGS data and detected two absorption components with physical parameters similar [log(\xi)] = 2.14±0.19 and 3.26±0.18, $N_H = 0.75^{+0.19}_{-0.17}$ and $5.5^{+1.2}_{-1.0} \times 10^{21}$ cm$^{-2}$] to the ones that we infer, strengthening this interpretation. There is also evidence for another, higher ionization, mildly relativistic and variable ionized component in the XMM–Newton data. The study of this more extreme component is addressed in another paper (Cappi et al., in preparation).

The observation of highly ionized matter in the core of Mrk 509 is in line with its high BH mass and accretion rate. In fact, we re-emphasize that the Eddington limit the radiation pressure equals the gravitational pull, however the densities of the matter lower with the BH mass (Shakura & Sunyaev 1976). Thus the ionization of the material surrounding high accretion rate and BH mass AGN, such as Mrk 509, should be higher than normal. We stress, however, that in order to detail the physical parameters of the ionized emitter/absorber, further long observations are required.

7 CONCLUSIONS

The Fe K band of Mrk 509 shows a rich variety of emission/absorption components. The XMM–Newton and Suzaku data show evidence for the presence of the following.

(i) A resolved, although not very broad ($\sigma \sim 0.07$ keV), neutral Fe Kα line and associated Fe Kβ emission. The width of the line suggests that the 6.4 keV line is produced in the outer part of the accretion disc (the BLR or torus emission seem unlikely). The measured reflection fraction is consistent in this case with the intensity of the line, while a covering factor or column density higher than generally observed would be required if the line were produced in the BLR or in the torus.

(ii) Both the Suzaku and the XMM–Newton data show an excess due to ionized Fe K emission. Both data sets show a superior fit when a broad ionized line coming from the central parts of the accretion disc is considered. The data are inconsistent with narrow emission from a distant scattering material at rest, while it cannot be excluded if the gas is outflowing ($v \sim 3500$ km s$^{-1}$).

(iii) Both EPIC–pn and MOS data show an absorption line at ~7.3 keV, present in the summed spectrum of all XMM–Newton observations only. This component confirms the presence of highly ionized, outflowing ($v \sim 14000$ s$^{-1}$), gas along the line of sight. The comparison between XMM–Newton and Suzaku suggests a variability of this component.

(iv) A hint of an enhancement of variability – both by considering the XMM–Newton data alone and by comparison between the two
data sets – at ~6.7 keV that could be either due to the high variability of the red wing of the broad ionized Fe K line, possibly associated with a variation of the ionization of the disc, or due to the second ionized absorption line.

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