Exploring the X-ray spectral variability of MCG–6-30-15 with \textit{XMM-Newton}

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\textbf{ABSTRACT}

We present a study of the spectral variability of the Seyfert I galaxy MCG–6-30-15 based on the two long \textit{XMM-Newton} observations from 2000 and 2001. The X-ray spectrum and variability properties of the 2001 data have previously been well described with a two-component model consisting of a variable power law and a much less variable reflection component, containing a broad relativistic iron line from the accretion disc around a rapidly rotating Kerr black hole. The lack of variability of the reflection component has been interpreted as an effect of strong gravitational light bending very close to the central black hole. Using an improved reflection model, we fit the two-component model to time-resolved spectra of both observations. Assuming that the photon index of the power law is constant we reconfirm the old result and show that this does not depend on the time-scale of the analysis.

\textbf{Key words:} galaxies: active – galaxies: individual: MCG–6-30-15 – galaxies: Seyfert – X-rays: galaxies

\section{INTRODUCTION}

The Seyfert I galaxy MCG–6-30-15 is a S0-type galaxy located at a distance of 37 Mpc ($z = 0.00775$) in the constellation of Centaurus. Because of a very prominent broad, relativistic iron line in its X-ray spectrum (first observed by ASCA, Tanaka et al. 1995), this object has come to play an important role in studies of accretion onto black holes.

The spectrum of MCG–6-30-15 can be decomposed into two main components, a simple power law component and a relativistically-blurred reflection component. The reflection component arises as the power law continuum irradiates the disc, and its appearance is affected by relativistic effects close to the central black hole. The most prominent feature in the resulting 3–10 keV reflection spectrum is the broad, skewed Fe K\(^\alpha\) line extending from about 3 to 7 keV and peaking at 6.4 keV. The observed line profile and the shape of the overall reflection spectrum in this source represents a fundamental tool for investigating the properties of the accretion flow and the space time geometry close to the black hole. In particular, the red wing of the iron line can be used to determine the inner radius of the accretion disc and thereby the spin of the black hole (see Brenneman & Reynolds (2006) for a recent determination of the black hole spin of MCG–6-30-15).

If the iron line is due to reflection one would, in a simple picture, expect that its strength (and the strength of the whole reflection component) follows the intensity of the power law continuum, which irradiates the disc and gives rise to the reflection component. Analysis of the variability of the two components has however shown that the reflection component remains nearly constant while the power law shows large variations (Shih et al 2002; Fabian et al 2002; Fabian & Vaughan 2003; Taylor, Uttley & McHardy 2003, Papadakis, Kazanas & Akylas 2005). The lack of a correlation between the two components and the small variability of the reflection component can be explained by effects of strong gravitational light bending close to the central black hole (Fabian & Vaughan 2003; Miniutti et al. 2003; Miniutti & Fabian 2004), or by an inhomogeneous accretion disc (Merloni et al. 2006). In both cases, the reflection spectrum has to be emitted from the innermost regions of the accretion disc where relativistic effects dominate.

In this Paper, we use the two long \textit{XMM-Newton} observations from 2000 and 2001 to re-analyse the spectral variability of MCG–6-30-15 by fitting time-resolved spectra. This has previously been done for 10 ks spectra of the 2001 observation (Vaughan & Fabian 2003), showing that the power law varies with an almost constant slope while the reflection component varies by less than 25 per cent.

Since the time of this analysis, a new, more complete reflection model has been made available (Ross & Fabian, 2005). The new model includes all energetically important ionisation states and transitions in the accretion disc and should therefore be a better approximation of the real conditions. The most notable difference in the 3–10 keV reflec-
tion spectrum is that the Fe K edge is much smoother than before due to the presence of a larger range of ionisation states of iron. It is important to test if (or how) the results change when using this refined reflection model and this is an important reason for repeating the analysis by Vaughan & Fabian (2003).

We also extend the original analysis by including the observation from 2000 which catches MCG–6-30-15 in a low flux state. This observation makes up nearly half the data below the mean flux of both observations and thereby adds valuable information about the source, which seems to behave differently at low fluxes. For the low flux (2000) observation Ponti et al. (2004) found possible iron line variations and Reynolds et al. (2004) reported on a correlation between the iron line intensity (representative of the whole reflection component) and the continuum flux. A correlation between the two components at low fluxes and no correlation at higher fluxes is consistent with the predictions of the light bending model. By including the data from 2000 we aim to confirm this result by performing the same analysis on both observations.

It is also of interest to investigate whether the variability shows any dependence on the time-scale. We therefore perform the fitting on 3 ks and 30 ks spectra as well as on 10 ks spectra.

2 OBSERVATIONS AND DATA REDUCTION

MCG–6-30-15 has been observed by XMM-Newton during revolution 108 (2000 July 11-12) and revolutions 301-303 (2001 July 31-August 5). The observations are described in detail in Wilms et al. (2001) and Vaughan & Fabian (2004). For this work the data was reprocessed entirely using the XMM-Newton Science Analysis System (SAS v6.5.0), following the procedure described in Vaughan & Fabian (2004), but only using the data from the EPIC-pn camera. The total amount of good exposure time selected was 84 ks and 318 ks for the 2000 and 2001 observations.

3 SPECTRAL ANALYSIS

The goal of the following analysis is to investigate the relative variability of the power law and reflection components. This is done by fitting the same model to time-resolved spectra from both observations, leaving the relevant parameters free. In order to determine the exact model to be used when fitting the time-resolved spectra, we first fit the time-averaged spectra from all 4 orbits.

All spectra were fitted using XSPEC v11.3.2 (Arnaud 1996) and all fit parameters are quoted at the rest frame of the source. The analysis is limited to the 3–10 keV range in order to avoid problems due to the complex warm absorption at soft X-ray energies.

3.1 Time-averaged spectra

Time-averaged spectra of all four orbits were fitted simultaneously with a spectral model consisting of a power law, a relativistically-blurred reflection component, a narrow emission line at 6.4 keV (from distant neutral iron), and a narrow absorption line at 6.7 keV (from Fe XXV) as in Vaughan & Fabian (2004) and Young et al. (2005).

To calculate the reflection spectrum, the model reflionx (a high-resolution version of reflion, Ross & Fabian 2005) was used. The model calculates the emission from a photoionised accretion disc in thermal and ionisation equilibrium. The input parameters are the photon index of the incident power law (\(\Gamma\)), the iron abundance, the ionisation parameter of the disc (\(\xi = 4\pi F_\nu / n_H\)), and the normalisation. To account for Doppler and gravitational effects, the reflection spectrum was convolved with the relativistic kernel kdblur2 which is a modified version of the laor code (Laor 1991). The relativistic kernel model assumes an emissivity profile of the form \(\epsilon = r^{-\alpha_a}\) inside a breaking radius, \(r_b\), and \(\epsilon = r^{-\alpha_o}\) outside. In addition to the parameters describing the emissivity profile, the model takes as input parameters the inner and outer radii of the disc (\(r_{in}, r_{out}\)) and the inclination (i).

The time-averaged spectra were fitted simultaneously with only the normalisations for the power law and reflection components allowed to vary between the orbits. The best-fitting parameters (\(\chi^2 = 4384/4493\) dof) correspond to a weakly ionised disc (\(\xi = 43.7^{+2.8}_{-1.3}\) erg cm s\(^{-1}\)) with an iron abundance of 3.4\(^{+0.2}_{-0.1}\) times solar, extending from \(r_{in} = 1.9^{+0.1}_{-0.0}\) to \(r_{out} = 400\) \(r_g\) (the maximum allowed
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value), where $r_g = GM/c^2$ is the gravitational radius. The emissivity profile of the disc is given by $q_{\text{in}} = 5.3^{+0.2}_{-0.2}$, $q_{\text{out}} = 2.3^{+0.1}_{-0.1}$, and $r_{\text{be}} = 6.7^{+0.1}_{-0.1} r_g$. The inclination angle is $i = 39.1^{+0.8}_{-0.6}$ and the photon index was found to be $\Gamma = 2.19^{+0.04}_{-0.04}$. When fitted separately, this model gave equally good fits to all the time-averaged spectra, and there was no indication of the disc parameters changing between the observations. The spectrum of the second orbit in 2001 fitted with the model is shown in Fig. 1 and the model together with its main components is shown in Fig. 2.

Figure 3 shows a comparison between the old and new reflection models for $\xi = 40$ erg cm$^{-2}$ s$^{-1}$. In the new model the Fe K edge is smeared due to the presence of a larger range of ionisation states. Note also the sulphur line at low energies which is not present in the old model.

Figure 4. Results from fits to 10 ks spectra. Top panel: the reflection normalisation plotted against the power law normalisation for $\Gamma$ frozen at 2.15. Bottom panel: the reflection normalisation plotted against the power law normalisation for the case when $\Gamma$ is left as a free parameter. Black dots indicate the 9 over 39 spectra for which a free $\Gamma$ value significantly improves the fit ($> 95$ per cent level in an F-test). Note that these spectra tend to be the outliers.

2.19, and $\Gamma$ was therefore frozen at this value). The results are shown in the upper panel of Fig. 4. The two components do not show any correlation and the reflection component is seen to be much less variable than the power law, in excellent agreement with previous findings. Although the variability of the reflection component is small it is not consistent with being constant; a $\chi^2$ fit to a constant gives $\chi^2 = 145/38$ dof, which implies an intrinsic rms variability of about 10 per cent.

In order to investigate the robustness of these results all the fits were performed with each of the parameters describing the accretion disc left free. There was no parameter which significantly altered the result or showed any correlation with continuum flux or time, justifying our approach of using the same disc parameters to fit all the spectra.

We also investigated the effect of leaving the photon index $\Gamma$ free. The resulting values of the two normalisations are shown in the lower panel of Fig. 4. The two components for $\Gamma$ frozen at 2.15. Bottom panel: the reflection normalisation plotted against the power law normalisation for the case when $\Gamma$ is left as a free parameter. Black dots indicate the 9 over 39 spectra for which a free $\Gamma$ value significantly improves the fit ($> 95$ per cent level in an F-test). Note that these spectra tend to be the outliers.

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Figure 3 shows a comparison between the old and new reflection models for $\xi = 40$ erg cm$^{-2}$ s$^{-1}$ and an iron abundance of 3. The two models differ significantly around the iron line and edge between 6 keV and 8 keV. This is due to the presence of lower ionisation states of iron in the new model. For the given parameters the dominant ion of iron in the new model varies from Fe VI (the least ionised species treated) to Fe XVIII with decreasing Thomson depth, and as a consequence the iron K edge runs from 7.2 keV to 7.8 keV. In the old model the least ionised species is Fe XVI and the edge runs from 7.6 keV to 7.8 keV. Another noticeable difference in the 3–10 keV range is the sulphur line around 3.3 keV which is not present in the old model. As a consequence of the larger number of species included, the new model is also less ionised than the old one for a given value of $\xi$. In terms of best fitting parameters these important differences mainly manifest themselves in that the new model favours a higher inclination (40° compared to previous results of around 30°), due to the change of the blue end of the line seen in Fig. 3.

3.2 Spectral variability

The observations were split into 39 x 10 ks intervals (8 intervals from the 2000 observation and 31 from the 2001 observation), and spectra were extracted in each interval. All the 10 ks spectra were then fitted with the model described in the previous section, with all parameters apart from the power law and reflection normalisations frozen. (Experimentation showed that the 10 ks spectra favoured a slightly lower $\Gamma$ than the time-averaged spectra, 2.15 rather than

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In order to investigate the robustness of these results all the fits were performed with each of the parameters describing the accretion disc left free. There was no parameter which significantly altered the result or showed any correlation with continuum flux or time, justifying our approach of using the same disc parameters to fit all the spectra.

We also investigated the effect of leaving the photon index $\Gamma$ free. The resulting values of the two normalisations are shown in the lower panel of Fig. 4. Spectra for which thawing $\Gamma$ significantly improves the fit ($> 95$ per cent level in an F-test) are shown as black dots (9 spectra over 39). Only one spectrum requires a different $\Gamma$ at the three sigma confidence level and for the majority of spectra the fits improved only slightly or not at all. The variability of the reflection component is seen to be roughly the same as that of the power law (excluding the extreme 10 per cent of both components) and about twice as high as that found by Fabian & Vaughan (2003).

The resulting values of $\Gamma$ as a function of the power law and reflection normalisations are shown in Fig. 5. $\Gamma$ lies around 2.1–2.2 in agreement with previous findings and we also note that there is a correlation between the reflection normalisation and $\Gamma$. Such a correlation has previously been
reported by e.g. Vaughan & Edelson (2001), who found that the correlation was present even when fitting spectra which were simulated with a constant reflection fraction. We carried out a similar experiment and simulated 50 spectra with the same $\Gamma$ and reflection normalisation but different power law normalisations. In order to mimic the real data as closely as possible the reflection normalisation and $\Gamma$ were fixed at their average values obtained from the 10 ks fits, and the power law was given normalisations uniformly distributed over the range seen in Fig. 4. Fitting of the simulated spectra did indeed reveal similar results to those in the lower panel of Fig. 5, showing that the relation is most likely an artifact of the degeneracy of the two components. Since the reflection spectrum is very hard in the 3–10 keV band, it is obvious that a steeper continuum photon index requires more reflection than a flatter one. This explains the observed spectral degeneracy between the continuum slope and the reflection normalisation.

Fig. 6 shows contours of 1, 2 and 3 sigma in the reflection normalisation, $\Gamma$–plane for one of the fitted spectra. It is clear from the figure that a spread in $\Gamma$ of about 0.2 will result in a spread in reflection normalisation of the same order of magnitude as that seen in the lower panel of Fig. 5. Because of this and of the spurious correlation between the reflection normalisation and $\Gamma$ discussed above, it seems most likely that the additional variability seen in the lower panel of Fig. 5 is induced by the parameter degeneracy.

It should however be noted that the values of $\Gamma$ are systematically lower at low fluxes (power law norms below 0.01) and that freezing $\Gamma$ at 2.15 is not a good approximation in this region. This is further confirmed by the fact that there is a correlation between the two normalisations in this region when $\Gamma$ is free. A correlation at low fluxes and no correlation for higher fluxes is consistent with previous findings (Reynolds et al. 2004; Fabian & Vaughan, 2003) and with the predictions of the light bending model (Miniutti & Fabian 2004).

Leaving each of the disc parameters free in the fits with a free $\Gamma$ does not affect the relationships between the parameters shown in Figs. 4 and 5 in any other way than by introducing a larger spread. The only disc parameter which changes significantly when left free is the iron abundance, which goes all the way up to 10 times solar. An iron abundance this high has also been found by Brenneman & Reynolds (2006) when using the same reflection model. The fact that the new reflection model favours a higher iron abundance is probably due to the difference in shape of the iron edge seen in Fig. 5. Even though the iron abundance in MCG–30-6-15 is known to be high, a value of 10 does not seem plausible and we do indeed find it to be around 2–3 when including high-energy data from BeppoSAX, RXTE or Suzaku (Miniutti et al. 2006), as well as in the time-averaged fit described in section 3.1 and in all the fits where $\Gamma$ was frozen (see also Lee et al. 2000).

In order to investigate whether the variability is dependent on the time-scale of the analysis the same fits were also performed on 30 ks and 3 ks spectra. These spectra give fits which are fully consistent with the results from the 10 ks analysis, although the 3 ks fits have much larger error bars due to the limited statistics. By making a finer grid in the reflection model we also established that the results are not dependent on the resolution of the model.

4 CONCLUSIONS AND DISCUSSION

We have re–analysed the spectral variability of MCG–6-30–15 in terms of the two-component model (power law + reflection from the accretion disc) by fitting the model to time–resolved spectra taken from the two long XMM–Newton observations of the source for a total of $\sim$390 ks. We used a new reflection model (REFLIONX) and performed the analysis on 3 ks, 10 ks and 30 ks spectra. The results were the same for all three time-scales. When only the normalisations of the two components are allowed to vary the results are consistent with previous findings in showing the reflection component to be much less variable than the power law.

When the photon index $\Gamma$ of the power law is left as
The difference spectrum of MCG–6-30-15 based on both the 2000 and 2001 data is shown in Fig. 7 as a ratio to a power law with $\Gamma = 2.2$, modified by Galactic absorption and fitted over the 3–10 keV range.

Although none of these methods can rule out that there is a relatively large variability in the reflection component (which is however uncorrelated with the power law), they all indicate that the reflection component varies much less than the power law and that the photon index is nearly constant. Because of this, and because most of the fits do not improve significantly when $\Gamma$ is left as a free parameter, we conclude that it is a safe assumption to freeze $\Gamma$ in the spectral fitting. Both the best-fitting model for the time-averaged spectra and the difference spectrum give $\Gamma \approx 2.2$, and most of the 10 ks fits with $\Gamma$ free agree with this value. The only time it does not seem to be appropriate to freeze $\Gamma$ at around 2.2 is at very low fluxes, where $\Gamma$ is seen to be lower by $\Delta \Gamma \sim 0.2$. With a low $\Gamma$ in this region we do see the previously reported correlation between the two normalisations. Under these assumptions we thus confirm the conclusion that the strength of the reflection increases with increasing continuum flux at low fluxes but then saturates when the source reaches its normal state, in agreement with the predictions of the light bending model, as reported also for e.g. NCG 4051 (Ponti et al. 2006), 1H 0707–495 (Fabian et al. 2004), and the Galactic black hole XTE J1650–500 (Miniutti, Fabian & Miller 2004; Rossi et al. 2005).

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mean-squared spectra, which measure the the variability as a function of energy, and flux–flux plots (Taylor, Uttley & McHardy 2003), which show the relationship between fluxes in different energy bands (see e.g. Vaughan & Fabian 2004 for root-mean-squared spectra and flux–flux plots of MCG–6-30-15).

One such tool is the difference spectrum between a high-flux and a low-flux spectrum (e.g. Fabian & Vaughan 2003). Under the assumption that the total spectrum can be described by one constant and one variable component, subtracting a low-state from a high-state spectrum should remove the contribution of the constant component, leaving only the variable component, modified by absorption. A difference spectrum of MCG–6-30-15 based on both the 2000 and 2001 data is shown in Fig. 7 as a ratio to a power law (and Galactic absorption of $4.06 \times 10^{20}$ cm$^{-2}$). The high and low states were constructing by summing the third of the 10 ks spectra with the highest and lowest fluxes respectively. The power law was fitted over the 3–10 keV energy range and has a photon index of 2.2 fully consistent with the time-averaged value. The spectrum above 3 keV is clearly very small for most fluxes. Since we also find an artificial correlation $\Gamma$ and the amount of reflection by direct spectral fitting, and we therefore have to consider the results of other, model-independent tools to assess the variability of the two components.

Figure 7. Difference spectrum produced by subtracting a low-state spectrum from a high-state spectrum. The difference spectrum is shown as a ratio to a power law with $\Gamma = 2.2$, modified by Galactic absorption and fitted over the 3–10 keV range.
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