

Relativistic ionized accretion disc models of MCG–6-30-15

D. R. Ballantyne[★] and A. C. Fabian

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

Accepted 2001 October 8. Received 2001 September 14; in original form 2001 April 25

ABSTRACT

We present results from fitting of ionized accretion disc models to three long *ASCA* observations of the Seyfert 1 galaxy MCG–6-30-15. All three data sets can be fitted by a model consisting of ionized reflection from the inner region of the accretion disc (with twice solar Fe abundance) and a separate disc-line component from farther out on the disc. The disc-line is required to fit the height of the observed Fe $K\alpha$ line profile. However, we show that a much simpler model of reflection from a very weakly ionized constant-density disc also fits the data. In this case only a single cold Fe $K\alpha$ line at 6.4 keV is required to fit the observed line. The ionized disc models predict that O VIII $K\alpha$, C VI $K\alpha$, Fe XVII $L\alpha$ and Fe XVIII $L\alpha$ lines will appear in the soft X-ray region of the reflection spectrum, but are greatly blurred as a result of Compton scattering. The equivalent width (EW) of O VIII $K\alpha$ is estimated to be about 10 eV and seems to be as strong as the blend of the Fe L lines. This result creates difficulty for the claim of a strong relativistic O VIII line in the *XMM-Newton* grating spectrum of MCG–6-30-15, although we cannot strictly rule it out since MCG–6-30-15 was in an anomalously low state during that observation. We find that increasing the O abundance or breaking the continuum below 2 keV will not significantly strengthen the line. The second Fe $K\alpha$ line component in the ionized disc model may arise from neutral reflection from a flared disc, or from a second illumination event. The data cannot distinguish between the two cases, and we conclude that single-zone ionized disc models have difficulty fitting these hard X-ray data of MCG–6-30-15.

Key words: accretion, accretion discs – line: profiles – galaxies: active – galaxies: individual: MCG–6-30-15 – galaxies: Seyfert – X-rays: galaxies.

1 INTRODUCTION

MCG–6-30-15 is a bright nearby ($z = 0.008$) Seyfert 1 galaxy, and has thus been observed by various X-ray telescopes over the last 20 yr (e.g. Pineda et al. 1980; Pounds, Turner & Warwick 1986; Nandra et al. 1989; Nandra, Pounds & Stewart 1990; Fabian et al. 1994). These studies culminated in the first detection of a relativistically broadened iron $K\alpha$ line (Tanaka et al. 1995). The shape of the line is consistent with being emitted from fluorescing, optically thick material which is orbiting very close to a black hole (Fabian et al. 1989), and is difficult to explain by other processes (Fabian et al. 1995). Subsequent deep *ASCA* observations have found evidence for broad Fe $K\alpha$ lines in other Seyfert 1 galaxies (Nandra et al. 1997), illustrating that these features may be common in type 1 active galactic nuclei (AGN). Owing to the proximity of MCG–6-30-15, its Fe $K\alpha$ line has been studied many times at a high signal-to-noise ratio and has been shown to be variable, both in strength and in shape (Iwasawa et al. 1996, 1999; Lee et al. 2000; Vaughan & Edelson 2001).

Recently, Branduardi-Raymont et al. (2001, hereafter BR01) reported results from observations of MCG–6-30-15 and another Seyfert 1 galaxy, Mrk 766, using the Reflection Grating Spectrometer (RGS) on *XMM-Newton*. These authors claim that features in the soft X-ray band that were traditionally interpreted in lower resolution data as photoelectric absorption edges could actually be relativistically broadened $K\alpha$ lines of O VIII, N VII and C VI. However, a non-simultaneous observation of MCG–6-30-15 by the High-Energy Transmission Grating (HETG) on *Chandra* (which has higher spectral resolution than the RGS) does not confirm the above interpretation (Lee et al. 2001). These authors find that the spectral features in the soft X-rays are well fitted by a dusty warm absorber model.

Regardless of which interpretation is correct, the idea of other relativistic emission lines in the X-ray spectra of Seyfert galaxies is intriguing, and is worth further investigation. This can be done by employing ionized reflection models (e.g. Ross & Fabian 1993; Ross, Fabian & Young 1999; Nayakshin, Kazanas & Kallman 2000; Ballantyne, Ross & Fabian 2001) to predict the reflection spectrum from an ionized disc. These models cannot be fitted to grating data as there is no Fe $K\alpha$ line or easily determined

[★]E-mail: drb@ast.cam.ac.uk

continuum to ‘anchor’ the model. Therefore, in this paper, we pursue a complementary approach, and fit the hard X-ray spectrum of MCG–6-30-15 from *ASCA*, thereby taking advantage of the well-defined Fe $K\alpha$ line and continuum to fix the parameters of the model. Although the model is fitted only to the high-energy data, it will have specific predictions for the strength of the soft X-ray spectral features, which may be useful in the interpretation of the grating data.

The paper is organized as follows. First, in Section 2, we describe the ionized disc model that is used and present our fits to the *ASCA* data of MCG–6-30-15. Then we discuss the strength of the predicted low-energy features and other consequences of our model in Section 3. Finally, conclusions are drawn in Section 4.

2 IONIZED DISC MODELS AND FITTING

Long observations of MCG–6-30-15 were obtained by *ASCA* in 1994 (200 ks), 1997 (200 ks) and 1999 (400 ks). A description of the data reduction can be found in the paper by Iwasawa et al. (1996) for the 1994 data and in the paper by Iwasawa et al. (1999) for the 1997 data. Analogous procedures were used in the reduction of the unpublished 1999 data, except for the inclusion of a new charge transfer inefficiency (CTI) file (`sisph2pi_130201.fits`) to deal with recent calibration problems in the solid-state imaging spectrometer (SIS) detectors. Fits were performed using the time-averaged data from all four detectors between 3 and 10 keV. Since the *ASCA* detectors had yet to suffer much damage, and the calibration is now well established, the experimental fitting was done using the 1994 data. The model that best fitted this data set was then used on the 1997 and 1999 data sets to check the robustness of the model and to investigate variations in the parameters.

The ionized reflection models were computed with the code described by Ballantyne et al. (2001). These simulations compute the reflection spectrum as well as the temperature, ionization and density structure of the top five Thomson depths of an accretion disc that is irradiated by a power-law continuum of X-rays. As shown by Ballantyne et al. (2001), the features in the reflection spectrum depend on the system parameters (such as black hole mass, accretion rate and radius along the disc), on the value of the irradiating flux and photon index of the incident spectrum (Γ), and on the incidence angle of the radiation (θ). The reflection spectra that were fitted to the *ASCA* data of MCG–6-30-15 were computed assuming a black hole mass of $10^7 M_\odot$ and an accretion rate of 0.01 times the Eddington rate (so the disc was radiation pressure dominated), and that the reflection was occurring at 4 Schwarzschild radii from the black hole. These values are appropriate for a typical Seyfert 1 galaxy like MCG–6-30-15. The choice of irradiating flux and incidence angle should ideally be determined by a specific model for how an accretion disc is illuminated. We have chosen an illuminating flux to disc flux ratio of 10 (as might be appropriate for irradiation by magnetic flares, e.g. Nayakshin & Kallman 2001), and an incidence angle of $\theta = 54.7$ degrees to the normal (so that $\cos \theta = 1/\sqrt{3}$, a crude approximation to isotropic illumination).

With these parameters fixed, two sets of reflection spectra were calculated with Γ varied between 1.5 and 2.15: one with solar abundance of Fe (as given by Morrison & McCammon 1983) and the other with twice solar Fe abundance. Each set was weighted by the reflection fraction R ($0.0 \leq R \leq 3.0$) and then added to the illuminating power law. Finally, both two-dimensional grids were converted into an XSPEC ‘atable’ file for use in fitting the data.

Relativistic blurring appropriate for a Schwarzschild metric and assuming a disc emissivity law [i.e. emissivity $\propto (1 - \sqrt{6/r})/r^3$; Fabian et al. 1989] was applied to the spectra during fitting. The XSPEC command ‘extend’ was used to increase the energy range of the response matrices because this convolution requires evaluation of the model at energies outside the 3–10 keV range. Galactic absorption was also included in the fit and fixed at the value of $4.06 \times 10^{20} \text{ cm}^{-2}$, but will have a negligible effect at energies greater than 3 keV. XSPEC v.11.0.1z1 (Arnaud 1996) was used for fitting, and the uncertainties in the model parameters are the 2σ error bars for one interesting parameter.

2.1 Results of spectral fitting

The results of the spectral fitting are shown in Table 1. The first model tabulated is a simple absorbed power-law model that was fitted to the data in the ranges 3–4 and 8–10 keV. This fit gives a measurement of the underlying continuum in the data, and we would like the more complex ionized disc models to give a photon index that is compatible with this value.

Fitting the data with a straightforward ionized disc model does not give a very satisfactory result. The line in the model is not strong enough to fit the data, and the fit can only be improved by increasing the reflection fraction, R . Furthermore, the derived photon index is not consistent with the power-law fit, and the inclination angle is very small.

A more satisfying, although still problematic, fit can be obtained by doubling the Fe abundance in the disc model. That MCG–6-30-15 might have an overabundance of Fe was first suggested by Lee et al. (1999) in order to explain the strength of the Fe $K\alpha$ line seen in the 1997 *ASCA* spectrum. These authors also utilize higher energy data from *RXTE* to constrain the reflection fraction to be around 1. Indeed, the twice-solar Fe model lowers the reflection fraction, but the model still cannot account for all the flux in the Fe $K\alpha$ line. The problem is that the predicted Fe $K\alpha$ lines from the ionized disc models are not strong enough to fit both the large red wing and the large peak of the line profile simultaneously, and thus the Fe abundance in MCG–6-30-15 would have to be very large to account for the Fe $K\alpha$ line. A simple and straightforward way to resolve this problem is to add in another line component (cf. Misra 2001).

The idea that multiple Fe $K\alpha$ components may be common in the line profiles of Seyfert 1 galaxies has been gaining momentum with the recent detections of narrow 6.4-keV lines in NGC 3783 (Kaspi et al. 2001) and NGC 5548 (Yaqoob et al. 2001). However, in this case, a narrow line was not sufficient to account for the missing line flux, so a broadened disc-line (also calculated with a disc emissivity profile) was added to the model. With this addition the χ^2 dropped by ~ 80 for the addition of 3 degrees of freedom – clearly a significant improvement in the fit – and the inclination angle (which was fixed to be the same for the ionized disc and disc-line components) was now comparable to the results of Tanaka et al. (1995) and Iwasawa et al. (1999). With the addition of the disc-line, the iron-rich model now has a reflection fraction that is consistent with unity and the photon index is consistent with the one from the power-law fit. The centroid energy of the disc-line suggests that it arises from partially ionized Fe ($\Delta\chi^2 = -13$ from $E^1 = 6.4 \text{ keV}$) and originates from a distance greater than $40r_g$ (where $r_g = GM/c^2$ is the gravitational radius) from the black hole (Fig. 1). The relativistic ionized line has three times the flux of the disc-line component: $1.5 \times 10^{-4} \text{ photon cm}^{-2} \text{ s}^{-1}$ as compared with $5 \times 10^{-5} \text{ photon cm}^{-2} \text{ s}^{-1}$.

Table 1. Results of fitting ionized disc models to the ASCA data of MCG–6-30-15. The parameters for the disc-line are denoted with an ‘1’ superscript. All radii are in units of the gravitational radius, the inclination angle i is tabulated in degrees, and the energy of the disc-line E^1 is in keV and is reported in the rest frame of MCG–6-30-15.

Model	Γ	R	r_{in}	r_{out}	i	E^1	r_{in}^1	r_{out}^1	$\chi^2/\text{d.o.f.}$
1994									
Power-law ^a	1.96 ± 0.03								469/496
1 × Fe ion. disc	1.90	1.0^f	15	19	0.005				1754/1653
	1.92	$2.88^{+0.12p}_{-0.63}$	16	18	0.0				1684/1652
2 × Fe ion. disc	1.90	1.0^f	8.8	23	0.002				1722/1653
	1.91	$2.06^{+0.26}_{-0.49}$	6.0	34	0.001				1690/1652
1 × Fe ion. disc + disc-line	1.91	1.0^f	6.0	11	25	6.4^f	21	997	1653/1650
	1.92	$2.27^{+0.73p}_{-0.98}$	6.1	10	26	6.4^f	61	1000	1640/1649
	1.92	1.0^f	6.8	10	10	$6.78^{+0.07}_{-0.18}$	15	73	1633/1649
2 × Fe ion. disc + disc-line	1.91	1.0^f	7.6	8.8	25	6.4^f	35	1000	1643/1650
	1.92	$1.33^{+0.64}_{-0.32}$	8.0	8.4	25	6.4^f	53	968	1640/1649
	1.91 ± 0.02	1.0^f	8.35	8.51	19 ± 2	$6.55^{+0.07}_{-0.05}$	41	533	1630/1649
	broken ^b	1.0^f	8.36	8.51	19	6.53	35	151	1679/1650
1997									
Power-law ^a	1.93 ± 0.03								483/488
2 × Fe ion. disc + disc-line	$1.89^{+0.02}_{-0.03}$	1.0^f	6.4	7.0	23	6.4^f	35	971	1694/1619
	1.90	$1.89^{+0.48}_{-0.77}$	6.1	7.1	26.9	6.4^f	55	998	1689/1618
	1.89	1.0^f	6.6	7.0	20	6.53	30	154	1684/1618
1999									
Power-law ^a	2.02 ± 0.02								727/673
2 × Fe ion. disc + disc-line	$1.96^{+0.02}_{-0.01}$	1.0^f	6.9	7.1	26	6.4^f	20	999	1924/1893
	1.97	$1.94^{+0.52}_{-0.32}$	6.0	7.9	28	6.4^f	56	485	1893/1892
	1.96	1.0^f	6.0	7.8	19	6.66 ± 0.06	25	80	1868/1892

^a4–8 keV data not included in fit. ^b $\Gamma = 1.91$ for $E > 2.0$ keV; $\Gamma = 1.33$ for $E < 2.0$ keV. ^fParameter fixed at value. ^pParameter pegged at upper limit.

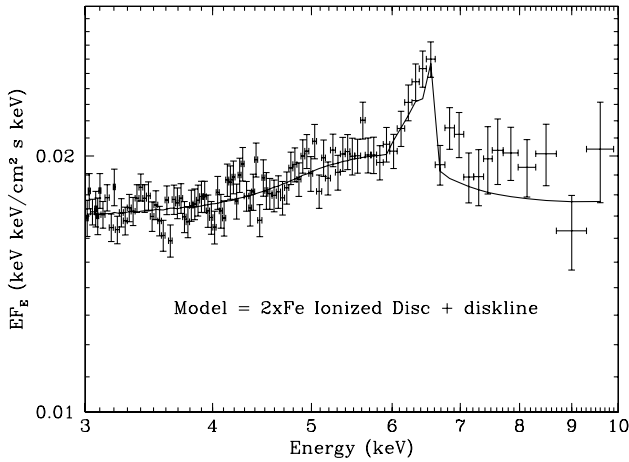


Figure 1. The unfolded 1994 ASCA SIS spectra of MCG–6-30-15 are plotted along with the best-fitting ionized disc (with twice-solar Fe) and disc-line model ($\chi^2/\text{d.o.f.} = 1630/1649$). The ionized disc fit parameters are $\Gamma = 1.91$, $R = 1.0$ (fixed), $r_{\text{in}} = 8.4r_g$, $r_{\text{out}} = 8.5r_g$ and $i = 18^\circ$. For the disc-line model component the fit parameters are $E = 6.55$ keV, $r_{\text{in}} = 41r_g$ and $r_{\text{out}} = 533r_g$. The fluxes in the disc-line and ionized line are 5×10^{-5} and 1.5×10^{-4} photon $\text{cm}^{-2} \text{s}^{-1}$, respectively.

Taking this model to be our best fit, we then apply it to the 1997 and 1999 data sets of MCG–6-30-15, and find a good fit in both cases. Interestingly, the lowest χ^2 are found when the disc-line component arises from partially ionized iron.

These ionized disc models are admittedly very model-dependent, so we also fitted the 1994 ASCA data of MCG–6-30-15 with the

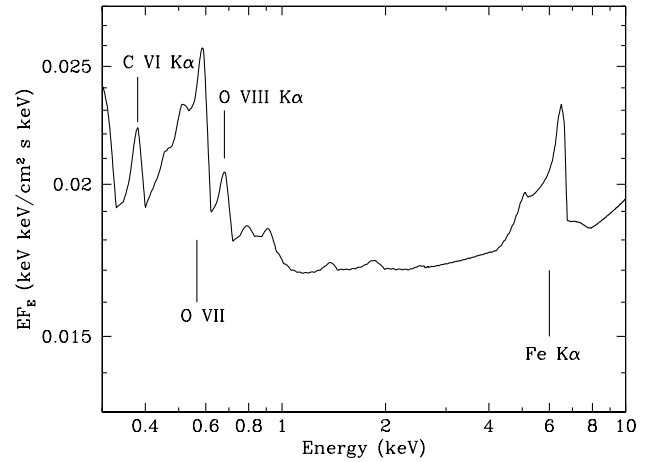


Figure 2. The reflection spectrum between 0.3 and 10 keV predicted by the constant-density models of Ross & Fabian (1993) after fitting to the 1994 ASCA spectrum of MCG–6-30-15 ($\chi^2/\text{d.o.f.} = 1659/1652$). The incident power law is included in this prediction. The fit parameters are $\Gamma = 1.98 \pm 0.01$, $\xi = 10\text{--}14$, $r_{\text{in}} = 7.5r_g$, $r_{\text{out}} = 13r_g$ and $i = 28^\circ$. Twice-solar Fe abundance was assumed in the model.

constant-density reflection models of Ross et al. (1999) which do not require an assumed black hole mass, accretion rate, etc. After taking the Fe abundance to be twice solar and a reflection fraction of unity, there are only three fit parameters: the normalization of the model, the photon index, and the ionization parameter $\xi = 4\pi F_x/n_H$, where F_x is the illuminating flux and n_H is the hydrogen number density of the slab. As before, models in which

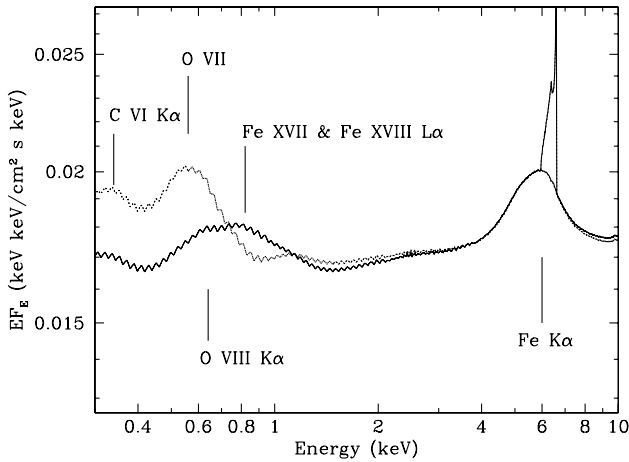


Figure 3. The reflection spectrum predicted by the $2\times\text{Fe}$ ionized disc + disc-line model when fitted to the 1994 ASCA data of MCG–6-30-15. The incident power law is included in this prediction. The solid line denotes the model with solar abundance of oxygen, while the dotted line shows the model (with the same fit parameters) with five times solar abundance of oxygen. Emission lines that are emitted by the disc are indicated in the plot. The high-frequency ‘bumpiness’ in the continuum is a result of the interpolation and binning that XSPEC must do to produce the figure. Recall that nitrogen is not included in the model.

the slab was ionized were unable to fit the Fe $K\alpha$ without a second component. However, we were able to find a good fit ($\chi^2/\text{dof} = 1659/1653$) with a $\xi \approx 10$ reflector (see Fig. 2). This model is practically equivalent to dropping the illuminating flux to disc flux ratio in the hydrostatic models by a factor $\sim 10^3$. Therefore the easiest fit to the 3–10 keV 1994 ASCA data of MCG–6-30-15 is with a very weakly illuminated accretion disc.

3 DISCUSSION

3.1 Strength of the soft X-ray features

Fig. 3 shows the prediction of the best-fitting ionized disc model to the 1994 ASCA data of MCG–6-30-15. Recall that the reflection fraction is 1, so the illuminating power law is included. The model predicts highly ionized features that have suffered significant Compton broadening due to the ionized gas at the surface of the illuminated atmosphere. These features include the $K\alpha$ lines of C VI and O VIII, and a blended component comprising $L\alpha$ lines of Fe XVII and Fe XVIII. Nitrogen is not included in our calculations, so we are unable to place constraints on its strength. As a result of the Compton broadening, it was difficult to measure the equivalent widths (EW) of the O line and the Fe L blend accurately. The EW estimate was made by assuming that the O line was equally as strong as the Fe L blend. The weakly ionized constant-density model does not suffer from much Comptonization, and so the EWs were calculated directly from the spectrum. All the EW results are shown in Table 2. We find that the O line has an EW of about 6 eV. This is much smaller than the EW ~ 150 eV O VIII $K\alpha$ line claimed by BR01 using their RGS observation of MCG–6-30-15. However, the comparison is not strictly valid, as BR01 require that the continuum turn over so that $\Gamma = 1.33$ below ~ 2 keV. To check how this break in the continuum will affect the strength of the soft X-ray features, we computed a model with $\Gamma = 1.91$ for $E > 2$ keV and $\Gamma = 1.33$ for $E < 2$ keV, and fitted this to the 1994 data (Fig. 4). The calculation shows that the hard incident spectrum at low energies ionizes the disc even more and therefore further weakens

Table 2. Equivalent widths in eV of the soft X-ray features predicted by ionized disc models of MCG–6-30-15.

O abundance	C VI	O VIII
solar	5.0	6 ^a
	4.2 [†]	5.4 [†]
3 \times solar	7.7	16 ^a
5 \times solar	7.3	12 ^a

^aEstimated as half the EW of the O VIII–Fe L blend. [†]From the constant-density model (Fig. 2).

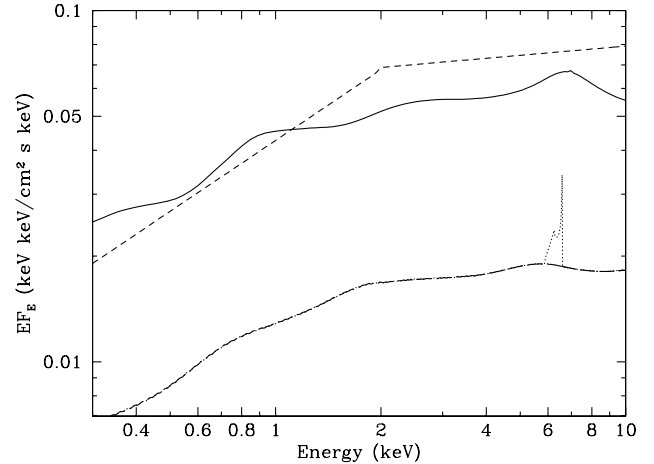


Figure 4. The solid line shows the predicted reflection spectrum from an atmosphere that is illuminated by a broken power-law continuum ($\Gamma = 1.91$ for $E > 2$ keV and $\Gamma = 1.33$ for $E < 2$ keV; short-dashed line). Both of these curves have been scaled downwards by a factor of 5×10^{25} . When the reflection spectrum is added to the continuum and fitted to the 1994 ASCA data of MCG–6-30-15, the resulting best fit ($\chi^2/\text{d.o.f.} = 1679/1650$) is given by the long-dashed and dotted lines. The resulting O VIII line is very weak.

the emission features. The EW of the O VIII line is estimated to be ~ 1 eV.

Returning to models with unbroken power laws, we investigated abundance effects by running computations with three times and five times solar oxygen abundances. Substituting these models for the solar abundance model did not greatly affect the χ^2 of the fit. The EWs of the soft lines in these models are also shown in Table 2. When the O abundance is increased to five times solar, O VII recombination lines are prominent and are blended with the O VIII line (see Fig. 3). The resolution of the RGS is high enough that lines from O VII should be distinguishable from O VIII $K\alpha$ even with extreme relativistic blurring, so a supersolar abundance of O cannot account for the strength of the line claimed by BR01. Finally, it is important to note that if there is another soft component in the spectrum, such as a soft excess, then the EWs will be even smaller than those measured here.

Another important prediction of these ionized disc models is that there should be $L\alpha$ lines from Fe XVII and Fe XVIII which, when blended together, seem to have about the same strength as the O VIII $K\alpha$ line. These are not seen¹ in the RGS spectra of MCG–6-30-15 (BR01). Although it is possible to ionize Fe to states

¹ We note in passing that there is a slight, unexplained excess at ~ 0.8 keV in the spectra of BR01 and Lee et al. (2001). It is possible that Fe L may contribute to this excess.

Table 3. Results of fitting the 1994 *ASCA* data of MCG–6-30-15 with two different ionized reflection spectra. The reflection fraction was frozen at unity for all models. As before, the inner and outer radii are reported in gravitational radii, and the inclination angle is in degrees. In the upper part of the table the second reflector is a constant-density model which had its Γ fixed to be the same as the hydrostatic model. In the lower region of the table the second reflector is another hydrostatic model which was drawn from the same grid of models as the first.

Model	Γ_1	r_{in1}	r_{out1}	$\log \xi/\Gamma_2$	r_{in2}	r_{out2}	i	$\chi^2/d.o.f.$
2 \times Fe ion. disc + 2 \times Fe ion. disc (constant density)	1.92	6.1	17	1.16	38	282	1.6	1665/1649
	1.91	6.0	10	3.39	22	25	6.7	1656/1649
2 \times Fe ion. disc + 2 \times Fe ion. disc	1.78	6.6	12	2.14	18	25	0.02	1672/1649

higher than Fe XVIII and leave sufficient quantities of O VIII to produce a line, this would result in a highly ionized atmosphere with a weak Fe $K\alpha$ line and would not increase the strength of the O line.

3.2 Multiple Fe $K\alpha$ line components

In order to fit the Fe $K\alpha$ line in the *ASCA* spectra of MCG–6-30-15 adequately with the ionized disc models, it was necessary to add a separate disc-line component to the model. This enabled the model to fit both the broad red wing of the Fe $K\alpha$ line (through the ionized disc component) and the height of the profile (through the disc-line) simultaneously. The disc-line is too wide to originate from a distant reflector, such as a molecular torus (e.g. Krolik, Madau & Życki 1994), so it must arise from elsewhere on the disc. Possible mechanisms for a second line component include reflection of X-rays from the central engine as a result of any warping or flaring of the disc (e.g. Blackman 1999), and reflection from a second illumination event on the disc which might be expected from a magnetically active and patchy corona (e.g. Galeev, Rosner & Vaiana 1979; Haardt & Maraschi 1993).

In the first scenario, the flared region of the disc would see the same Γ as the inner regions, but the illuminating flux would be much lower and neutral reflection would dominate. To test this idea, the disc-line component was replaced by a constant-density reflector. This component had its photon index fixed to the same value as the inner reflector, and we fitted for the value of the ionization parameter. These results are shown in Table 3. We find that neutral reflection from a large region of the disc can account for the second Fe $K\alpha$ line component. However, this result is not unique, as ionized reflection from a smaller, more central region of the disc can also fit the data.

If the second Fe $K\alpha$ line component results from another illumination event then it is not necessary for the Γ of the two events to be the same, and the observed photon index is a weighted sum of the two. Models of this type were constructed using two hydrostatic ionized disc models, and the results are also shown in Table 3. A decent fit to the 1994 data was found with the inner reflector subject to a $\Gamma = 1.78$ power law and the outer to a softer $\Gamma = 2.14$ power law, although a very low value of the inclination angle was found in this case, suggesting that further reflection components are necessary.

These results emphasize that it is very difficult to fit the 1994 hard X-ray spectrum of MCG–6-30-15 with a simple ionized disc model. At least two different reflection components are needed to fit the Fe $K\alpha$ line profile adequately, which suggests a very complicated illumination geometry. However, multiple Fe $K\alpha$ line components are a natural consequence of the magnetic flare model, and could provide the explanation for the perplexing variability of the Fe $K\alpha$ line. In contrast, a very acceptable fit to the same data

was obtained using just one reflection component from a predominantly neutral disc, which suggests a very simple illumination geometry. Unfortunately, current data cannot distinguish between the two cases, but our calculations show that measurements of soft X-ray disc emission features could lead to constraints on the ionization state of the accretion disc surface.

4 CONCLUSIONS

The main results of this paper are as follows.

(i) The 1994, 1997 and 1999 *ASCA* observations of MCG–6-30-15 can be fitted with a relativistic ionized disc model which has twice solar Fe abundance. However, a disc-line component must be included to account fully for the shape of the Fe $K\alpha$ line.

(ii) Alternatively, the 1994 data can be well fitted by a single reflection component from a weakly ionized ($\xi = 10$) constant-density disc with twice solar Fe abundance. In this case, one cold Fe $K\alpha$ line at 6.4 keV can completely describe the observed line.

(iii) Both reflection models predict that the EW of the O VIII $K\alpha$ line is ~ 10 eV. This can be made larger by increasing the O abundance, but O VII lines will eventually become prominent. The ionized disc models also predict that Fe XVII and Fe XVIII $L\alpha$ lines will be found along with the O VIII line.

(iv) These results cast doubt on the claims of relativistic lines found in the soft X-rays by BR01 because broad Fe L lines are not seen in their spectra, and they require EWs > 100 eV for the O VIII and C VI lines. However, MCG–6-30-15 was in an unusually low state when observed by BR01, so we cannot strictly rule out their result.

(v) Emission from multiple regions on the disc is needed to fit the Fe $K\alpha$ line profile adequately with the ionized disc models. The data are unable to distinguish between secondary reflection from a flared disc and from other independent illumination/reflection events.

ACKNOWLEDGMENTS

The authors thank S. Vaughan and R. Morales for valuable discussions, and K. Iwasawa for assistance with the *ASCA* data. DRB acknowledges financial support from the Commonwealth Scholarship and Fellowship Plan and the Natural Sciences and Engineering Research Council of Canada. ACF thanks the Royal Society for support.

REFERENCES

- Arnaud K. A., 1996, in Jacoby G., Barnes J., eds, ASP Conf. Ser. Vol. 101, *Astronomical Data Analysis Software and Systems V*. Astron. Soc. Pac., San Francisco, p. 17

- Ballantyne D. R., Ross R. R., Fabian A. C., 2001, MNRAS, 327, 10
 Blackman E. G., 1999, MNRAS, 306, L25
 Branduardi-Raymont G., Sako M., Kahn S. M., Brinkman A. C., Kaastra J. S., Page M. J., 2001, A&A, 365, L140 (BR01)
 Fabian A. C., Rees M. J., Stella L., White N. E., 1989, MNRAS, 238, 729
 Fabian A. C. et al., 1994, PASJ, 46, L59
 Fabian A. C., Nandra K., Reynolds C. S., Brandt W. N., Otani C., Tanaka Y., Inoue H., Iwasawa K., 1995, MNRAS, 277, L11
 Galeev A. A., Rosner R., Vaiana G. S., 1979, ApJ, 229, 318
 Haardt F., Maraschi L., 1993, ApJ, 413, 507
 Iwasawa K. et al., 1996, MNRAS, 282, 1038
 Iwasawa K., Fabian A. C., Young A. J., Inoue H., Matsumoto C., 1999, MNRAS, 306, L19
 Kaspi S. et al., 2001, ApJ, 554, 216
 Krolik J. H., Madau P., Życki P. T., 1994, ApJ, 420, L57
 Lee J. C., Fabian A. C., Brandt W. N., Reynolds C. S., Iwasawa K., 1999, MNRAS, 310, 973
 Lee J. C., Fabian A. C., Reynolds C. S., Brandt W. N., Iwasawa K., 2000, MNRAS, 318, 857
 Lee J. C., Ogle P. M., Canizares C. R., Marshall H. L., Schulz N. S., Morales R., Fabian A. C., Iwasawa K., 2001, ApJ, 554, L13
 Misra R., 2001, MNRAS, 320, 445
 Morrison R., McCammon D., 1983, ApJ, 270, 119
 Nandra K., Pounds K. A., Stewart G. C., Fabian A. C., Rees M. J., 1989, MNRAS, 236, 39P
 Nandra K., Pounds K. A., Stewart G. C., 1990, MNRAS, 242, 660
 Nandra K., George I. M., Mushotzky R. F., Turner T. J., Yaqoob T., 1997, ApJ, 477, 602
 Nayakshin S., Kallman T., 2001, ApJ, 546, 406
 Nayakshin S., Kazanas D., Kallman T., 2000, ApJ, 537, 833
 Pineda F. J., Delvaille J. P., Grindlay J. E., Schnopper H. W., 1980, ApJ, 237, 414
 Pounds K. A., Turner T. J., Warwick R. S., 1986, MNRAS, 221, 7P
 Ross R. R., Fabian A. C., 1993, MNRAS, 261, 74
 Ross R. R., Fabian A. C., Young A. J., 1999, MNRAS, 306, 461
 Tanaka Y. et al., 1995, Nat, 375, 659
 Vaughan S., Edelson R., 2001, ApJ, 548, 694
 Yaqoob T., George I. M., Nandra K., Turner T. J., Serlemitsos P. J., Mushotzky R. F., 2001, ApJ, 546, 759

This paper has been typeset from a \TeX/L\AA\TeX file prepared by the author.