Ionized accretion disc models of MCG–6-30-15

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

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ABSTRACT
We present results from fitting ionized disc models to three long ASCA observations of the Seyfert 1 galaxy MCG–6-30-15. All three datasets are well fit by a model consisting of ionized reflection from the inner region of the accretion disc (with twice solar Fe abundance) and a separate diskline component from farther out on the disc. The diskline is required to fit the height of the observed Fe Kα line profile. The model predicts that O VIII Kα, C VI Kα, Fe XVII Lα, and Fe XVIII Lα lines will appear in the soft X-ray region of the reflection spectrum. The equivalent width (EW) of O VIII Kα is about 5 eV and is 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. We find that increasing the O abundance or breaking the continuum below 2 keV will not significantly strengthen the line. The second Fe Kα line component in the model may arise from neutral reflection from a flared disc, or from a second illumination event. The data cannot distinguish between the two cases, but we point out that multiple illumination events will contribute to the complex Fe Kα variability.

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 years (e.g.,)pin80,pou86,nan89,nan90,fab94. These studies culminated in the first detection of a relativistically broadened iron Kα 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 Kα lines in other Seyfert 1 galaxies (Nandra et al., 1997), illustrating that these features may be common in type 1 Active Galactic Nuclei (AGN). Due to the proximity of MCG–6-30-15, its Fe Kα line has been studied many times at high signal-to-noise 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, 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 data can be interpreted as relativistically broadened Kα 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 fit 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.,)ros93,ros99,nkk00,bal01 to predict the reflection spectrum from an ionized disc. These models cannot be fit to grating data as there is no Fe Kα line or easily determined 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 Kα line and continuum to fix the parameters of the model. Although the model is fit 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 Sect. 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 Sect. 3. Finally, conclusions are drawn in Sect. 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.
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 with energies 0.3 keV depend weakly on the system parameters (such as black hole mass, accretion rate and radius along the disc), somewhat on the value of the irradiating flux, and strongly on the photon index of the incident spectrum (Γ) and the incidence angle of the radiation (see also Ballantyne 2001). The reflection spectra that were fit to the ASCA data of MCG–6–30–15 were computed assuming a black hole mass of 10^6 M_☉, an accretion rate of 0.001 times the Eddington rate (so the disc was gas pressure dominated), and that the reflection was occurring at 7 Schwarzschild radii from the black hole. These values are not appropriate for a self-consistent model of the central region of MCG–6–30–15, but the data will not be sensitive to the details of such a model. The choice of irradiating flux and incidence angle should ideally be determined by a specific model for how an accretion disc is illuminated. Again, since we are fitting only to data between 3–10 keV and taking into account relativistic blurring, the data will not be sensitive to these model details. Therefore, an illuminating flux of 6.4 × 10^{15} erg cm^{-2} s^{-1} and an incidence angle of 60 degrees to the normal was assumed. At this high flux level, the Fe Kα line is insensitive to small changes in illuminating flux (Ballantyne, 2001).

With these parameters fixed, two sets of reflection spectra were calculated with Γ varied between 1.5 and 2.1: 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 ≤ R ≤ 3.0) and then added to the illuminating power-law. Finally, both 2-dimensional grids were converted into a XSPEC ‘atable’ file for use in fitting the data. Relativistic blurring appropriate for a Schwarzschild metric and assuming a disc emissivity law (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 evaluating 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 × 10^{20} cm^{-2}, but will have a negligible effect at energies greater than 3 keV. XSPEC v.11.0.1.1 (Arnaud, 1996) was used for fitting, and the uncertainties in the model parameters are the 1-σ errorbars for one interesting parameter.

### 3 DISCUSSION

#### 3.1 Strength of the soft X-ray features

Figure 2 shows the prediction of the best fit ionized disc model to the 1994 ASCA data of MCG–6–30–15. Recall that the reflection fraction is one, so the illuminating power-law is included. The model predicts three soft X-ray features: the Kα lines of C vii and O viii, and a blended component comprised of Lo lines of Fe xvii and Fe xviii. Nitrogen is not included in our calculations, so we are unable to place constraints on its strength. The equivalent widths (EW) of these lines are shown in Table 2. We find the O and Fe lines have about the same strength with EWs about 5 eV. This is much smaller than the EW~150 eV O viii Kα line claimed by BR01 using their RGS observation of MCG–6–30–15. However, the comparison is not strictly valid, as BR01 requires that the continuum turn over so that Γ = 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 Γ = 1.95 for E > 2 keV and Γ = 1.33 for E < 2 keV, and fit this to the 1994 data (Figure 3).
Table 1. Results of fitting ionized disc models to the ASCA data of MCG–6-30-15. The parameters for the diskline are denoted with an $l$ superscript. All radii are in units of the gravitational radius, the inclination angle, $i$, is tabulated in degrees, and the energy of the diskline, $E_l$, is in keV.

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Gamma$</th>
<th>$R$</th>
<th>$r_{in}$</th>
<th>$r_{out}$</th>
<th>$i$</th>
<th>$E_l$</th>
<th>$r_{in}^l$</th>
<th>$r_{out}^l$</th>
<th>$\chi^2$/dof</th>
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<tbody>
<tr>
<td>1994</td>
<td></td>
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<tr>
<td>power-law$^a$</td>
<td>1.96±0.03</td>
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<tr>
<td>1xFe ion. disc</td>
<td>1.93</td>
<td></td>
<td>6.0$^p$</td>
<td>34.5</td>
<td>1.6</td>
<td>6.4$^l$</td>
<td></td>
<td></td>
<td>1721/1653</td>
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<td>6.0</td>
<td>30.1</td>
<td>3.7</td>
<td>6.4$^l$</td>
<td></td>
<td></td>
<td>1668/1652</td>
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<td>1xFe ion. disc + diskline</td>
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<td></td>
<td>6.0</td>
<td>37.4</td>
<td>0.01</td>
<td>6.4$^l$</td>
<td>30.0</td>
<td>998.5</td>
<td>1645/1650</td>
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<td>broken$^b$</td>
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<tr>
<td>power-law$^a$</td>
<td>1.93±0.03</td>
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<td>6.0</td>
<td>7.2</td>
<td>24.0</td>
<td>6.4$^l$</td>
<td>44.2</td>
<td>1000</td>
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<td>1999</td>
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<td>727/673</td>
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<tr>
<td>2xFe ion. disc + diskline</td>
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<td></td>
<td>6.0</td>
<td>7.6</td>
<td>28.0</td>
<td>6.4$^l$</td>
<td>10.0</td>
<td>140</td>
<td>1893/1893</td>
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<td>2.01</td>
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<td>7.6</td>
<td>28.0</td>
<td>6.4$^l$</td>
<td>11.8</td>
<td>277</td>
<td>1884/1892</td>
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<td>2.00</td>
<td>1.0$^l$</td>
<td></td>
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<td>7.8</td>
<td>20.2</td>
<td>6.62</td>
<td>42.4</td>
<td>105</td>
<td>1879/1892</td>
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<td>$^a$ 4–8 keV data not included in fit</td>
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<tr>
<td>$^b$ $\Gamma = 1.95$ for $E &gt; 2.0$ keV, $\Gamma = 1.33$ for $E &lt; 1.33$</td>
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<tr>
<td>$^l$ Parameter fixed at value</td>
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<td>$^p$ Parameter pegged at lower limit</td>
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</tbody>
</table>

Figure 1. Left: The unfolded 1994 ASCA SIS-0 spectrum of MCG–6-30-15 is plotted along with the best fit ionized disc models. The fit parameters for the model with solar Fe abundance ($\chi^2$/dof= 1721/1653) are: $\Gamma = 1.93$, $R = 1.0$ (fixed), $r_{in} = 6 r_g$ (pegged), $r_{out} = 34.5 r_g$, and $i = 16$. For the twice solar Fe model ($\chi^2$/dof= 1696/1653) the fit parameters are: $\Gamma = 1.90$, $R = 1.0$ (fixed), $r_{in} = 6 r_g$ (pegged), $r_{out} = 30.1 r_g$, and $i = 37$. Right: A similar plot as the other panel, but now showing the fit ($\chi^2$/dof= 1645/1650) using an ionized disc (with 2 times solar Fe) and a diskline from further out on the disc. Here, the ionized disc fit parameters are: $\Gamma = 1.95$, $R = 1.0$ (fixed), $r_{in} = 8.5 r_g$, $r_{out} = 9.0 r_g$ (pegged), and $i = 235$. For the diskline model component the fit parameters are: $E = 6.4$ keV (fixed), $r_{in} = 53.1 r_g$, and $r_{out} = 1000 r_g$.  

![Figure 1](source1.png)
Figure 2. The reflection spectrum predicted by the 2×Fe ionized disc +
diskline model when fit to the 1994 ASCA data of MCG–6-30-15. The in-
cident power-law is included in this prediction. The solid line denotes the
model with solar abundance of oxygen, while the dashed 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 inter-
polation and binning that XSPEC must do to produce the figure. Recall that
nitrogen is not included in the model.

Figure 3. The solid line shows the predicted reflection spectrum from an
atmosphere that is illuminated by a broken power-law continuum (Γ =
1.95 for E > 2 keV and Γ = 1.33 for E < 2 keV; short-dashed line). Both of
these curves have been scaled downwards by a factor of 10^{25}. When
the reflection spectrum is added to the continuum and fit to the 1994 ASCA
data of MCG–6-30-15 the resulting best-fit (χ^2/dof=1677/1651) is given
by the long-dashed and dotted lines. The resulting O VIII line is weak, and
Fe L emission dominates the soft part of the reflection spectrum.

We find that the hard incident spectrum at low energies results in a
very weak O VIII line (EW ~ 1 eV) and enhances the Fe L emission
in relation to the oxygen line.

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 5 times solar, O VII recombination lines are prominent, and, in our low-resolution figures, blended with the O VIII line (see Fig.2). The resolution of the RGS is high enough that lines from O VII should be distinguishable from O VIII Kα 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 Kα lines from Fe XVII and Fe XVIII which, when blended together, will have about the same strength as the O VIII Kα line. These are not seen\(^\dagger\) in the RGS spectra of MCG–6-30-15 (BR01). Since the ionization energies of Fe XVII and Fe XVIII are about 400 eV higher than O VIII, it would be very difficult to ionize Fe to states higher than Fe XVIII and leave sufficient quantities of O VIII to produce a line. If there is an O VIII line arising from an ionized disc, it must be accompanied by Fe Kα emission.

### 3.2 Multiple Fe Kα line components

In order to adequately fit the Fe Kα line in the ASCA spectra of
MCG–6-30-15, it was necessary to add a separate diskline compo-
nent to the model. This enabled the model to fit both the broad red
wing of the Fe Kα line (through the ionized disc component) and
the height of the profile (through the diskline) simultaneously. The
diskline is too wide to originate from a distant reflector, such as a
molecular torus (\(?, \text{ e.g.,})\) Kro94, 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 warp-
ning or flaring of the disc (\(?, \text{ e.g.,})\) Bla99, and reflection from a sec-
dond illumination event on the disc which might be expected from a
magnetically active and patchy corona (\(?, \text{ e.g.,})\) Gal79, Ha93.

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 diskline component was replaced by a constant density reflector
(Ross et al., 1999). This component had its photon-index fixed to
the same value as the inner reflector, and we fit 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

\(\dagger\) 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.

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

<table>
<thead>
<tr>
<th>O abundance</th>
<th>C VI</th>
<th>O VIII</th>
<th>Fe L blend</th>
</tr>
</thead>
<tbody>
<tr>
<td>solar</td>
<td>1.16</td>
<td>4.38</td>
<td>5.06</td>
</tr>
<tr>
<td>3× solar</td>
<td>1.79</td>
<td>8.29</td>
<td>6.49</td>
</tr>
<tr>
<td>5× solar</td>
<td>1.59</td>
<td>34.50(^a)</td>
<td>3.63</td>
</tr>
</tbody>
</table>

\(^a\) blended with O VII recombination lines
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 (Ross et al., 1999) which had its $\Gamma$ fixed to be the same as the hydrostatic model. The ionization parameter is $\xi = 4\pi F_{\lambda} / n_{H}$, where $F_{\lambda}$ is the illuminating flux and $n_{H}$ is the hydrogen number density of the slab. In the lower half of the table the second reflector is another hydrostatic model which was drawn from the same grid of models as the first.

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Gamma$</th>
<th>$r_{in1}$</th>
<th>$r_{out1}$</th>
<th>$r_{in2}$</th>
<th>$r_{out2}$</th>
<th>$i$</th>
<th>$\chi^2$/dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>2Fe ion. disc + 2Fe ion. disc (constant density)</td>
<td>1.94</td>
<td>7.5</td>
<td>8.0</td>
<td>26.7</td>
<td>12.3</td>
<td>1666/1649</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.95</td>
<td>8.3</td>
<td>8.6</td>
<td>3.46</td>
<td>9.0</td>
<td>22.0</td>
<td>1663/1649</td>
</tr>
<tr>
<td>2Fe ion. disc + 2Fe ion. disc</td>
<td>1.81</td>
<td>6.1</td>
<td>9.7</td>
<td>2.06</td>
<td>21.6</td>
<td>22.1</td>
<td>1659/1649</td>
</tr>
</tbody>
</table>

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 $\Gamma$ 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 good fit to the 1994 data was found with the inner reflector subject to a $\Gamma = 1.81$ power-law and the outer to a softer $\Gamma = 2.06$ power-law, although a lower value of the inclination angle was found in this case.

It is worth emphasizing that the data do not require such complicated models. However, multiple Fe $K_{\alpha}$ line components are a natural consequence of the magnetic flare model, and could provide the explanation to the perplexing variability of the Fe $K_{\alpha}$ line. It is worth noting that both the Fe $K_{\alpha}$ line and continuum of MCG–6-30-15 can be comprised from more than one reflection event.

4 CONCLUSIONS

The main results of this paper are:

- The 1994, 1997 and 1999 ASCA observations of MCG–6-30-15 are well fit with a relativistic ionized disc model which has twice solar Fe abundance. However, a diskline component must be included to fully account for the shape of the Fe $K_{\alpha}$ line.
- The ionized disc model predicts that the EW of the O viii $K_{\alpha}$ line is $\sim 5$ eV. This can be made larger by increasing the O abundance, but O viii lines will eventually become prominent.
- Fe xvi and Fe xiii $K_{\alpha}$ lines will be found along with the O viii line. This result casts 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.
- Emission from multiple regions on the disc are needed to adequately fit the Fe $K_{\alpha}$ line profile. The data are unable to distinguish between secondary reflection from a flared disc, or from other independent illumination/reflection events. If this interpretation is correct, then it will have important consequences on the understanding of Fe $K_{\alpha}$ line variability.

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