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# *XMM-Newton* RGS observations of MCG −6-30-15 and Mrk 766: evidence for emission lines from a relativistic accretion disk

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**Abstract.** *XMM-Newton* Reflection Grating Spectrometer (RGS) spectra of the Narrow Line Seyfert 1 galaxies MCG −6-30-15 and Mrk 766 are inconsistent with standard models comprising a power-law continuum absorbed by either cold or ionized matter. We propose that the remarkably similar features detected in both objects in the 5 – 35 Å band are H-like oxygen, nitrogen, and carbon emission lines, gravitationally redshifted and broadened by relativistic effects in the vicinity of a Kerr black hole, and we discuss briefly the implications of our interpretation.

## 1. Introduction

The low-energy spectra of active galaxies have generally been modeled with a power-law continuum absorbed by neutral and/or partially ionized material

(Halpern 1984; Reynolds 1997); however, because of their complexity, the effects of interstellar absorption, and the moderate resolution of X-ray spectrometers available so far, the origin and location of the warm absorber are still unclear, and even the possible presence of discrete emission and absorption components is matter of debate.

Observations with the *XMM-Newton* Reflection Grating Spectrometer (RGS, den Herder et al. 2001) allow us to re-examine the soft X-ray emission of Active Galactic Nuclei (AGN) with much enhanced energy resolution. Here we report on RGS observations of MCG −6-30-15 and Mrk 766 which force us to propose a radically different approach to AGN soft X-ray spectra.

## 2. MCG −6-30-15 and Mrk 766

MCG −6-30-15 and Mrk 766 are bright ($L_{2-10\mathrm{keV}} \sim$ few $\times\ 10^{43}$ erg s$^{-1}$) and nearby (z = 0.008 and 0.013 respectively) Narrow Line Seyfert 1 galaxies with relatively low Galactic absorption in the line of sight ($4.1 \times 10^{20}$ cm$^{-2}$ and $1.8 \times 10^{20}$ cm$^{-2}$, respectively). Both objects show large and rapid variability in their X-ray fluxes, and variability in the slope of their power-law continua. Of the two, only Mrk 766 possesses a soft excess, which is less variable than the higher energy flux, and only MCG −6-30-15 shows Compton reflection in its spectrum. Broad features in the $< 1$ keV spectra of both sources have been interpreted in terms of absorption in ionized material at some distance from the nuclear black hole. The shape of the broad fluorescent Fe K$\alpha$ line which is observed in both objects at 6 – 7 keV is attributed to relativistic effects in a disk surrounding the central black hole (Tanaka et al. 1995).

## 3. RGS observations and spectral fits

MCG −6-30-15 was observed with *XMM-Newton* in July 2000 for a total of 120 ks, Mrk 766 in May 2000 for 55 ks. The RGS data were processed and calibrated with the *XMM-Newton* Science Analysis Software. The current RGS wavelength scale is accurate to $\sim 8$ mÅ.

The raw RGS spectra (shown in Fig. 1) are remarkably similar, being dominated by prominent "saw-tooth" features, which peak at around 15, 18, 24 and 33 Å. A single power-law fit with neutral absorption is clearly unacceptable; in particular, the neutral oxygen edge at 23 Å implies a column density in excess of what is required by the fit to the continuum, and there is no evidence of neutral absorption edges from other elements at their expected positions.

### 3.1. Warm absorber model

We attempted to fit the spectra with a warm absorber model including absorption edges and absorption lines associated with all ions of abundant elements (C, N, O, Ne, Mg, and Fe). The fits (shown in Fig. 2; see Branduardi-Raymont et al. 2001 for details) are unacceptable for both objects, for a number of reasons. Firstly, the observed, putative OVIII and OVII edges are redshifted with respect to their expected positions (14.23 Å and 16.78 Å for OVIII and OVII, respectively), and by very large amonts ($\sim 1$ Å), corresponding to *infall* veloci-

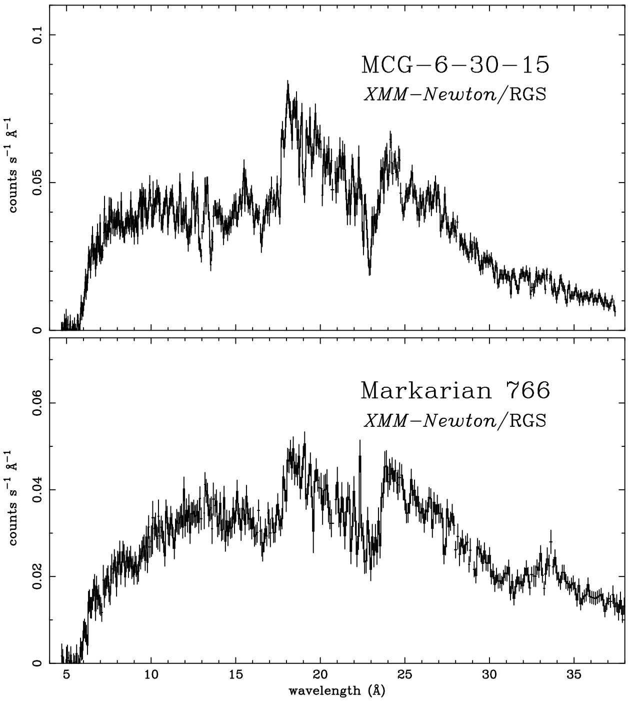


Figure 1. The raw RGS first order spectra of MCG −6-30-15 (top) and Mrk 766 (bottom), plotted in the observer's frame.

ties on the order of $\sim 16,000$ km s$^{-1}$. However, at the redshifts of the putative edges, no associated absorption lines are seen in either object (upper limit of $\sim$ 20 mÅ equivalent width), which implies that the infalling material would have a velocity width of $\leq 60$ km s$^{-1}$. This small velocity width is very difficult to reconcile with the apparent large redshifts of the edges. The radial inflow, in this case, would have to be at one particular velocity.

These fits still require a significant neutral absorbing component in excess of what is required to fit the data at longer wavelengths. An excess of flux is also present between 18 and 19 Å in MCG −6-30-15.

### 3.2. Disk-line emission model

Remarkably, both MCG −6-30-15 and Mrk 766 data are well fitted with a completely different model consisting of an absorbed power-law and emission lines, gravitationally redshifted and broadened by relativistic effects in a medium which is encircling a massive, rotating black hole. In this interpretation, the saw-toothed features in Fig. 1 are attributed to (in ascending wavelength order) H-like Ly$\alpha$ lines of OVIII, NVII, and CVI.

Our model includes a power-law continuum, with cold absorption fixed at the Galactic value, and three emission lines originating near a maximally rotating Kerr black hole (Laor 1991). The line wavelengths are fixed at their expected values at the redshifts of the sources. The continuum power-law slope is fitted, as are the disk inclination angle $i$, the emissivity index $q$ and the inner and outer

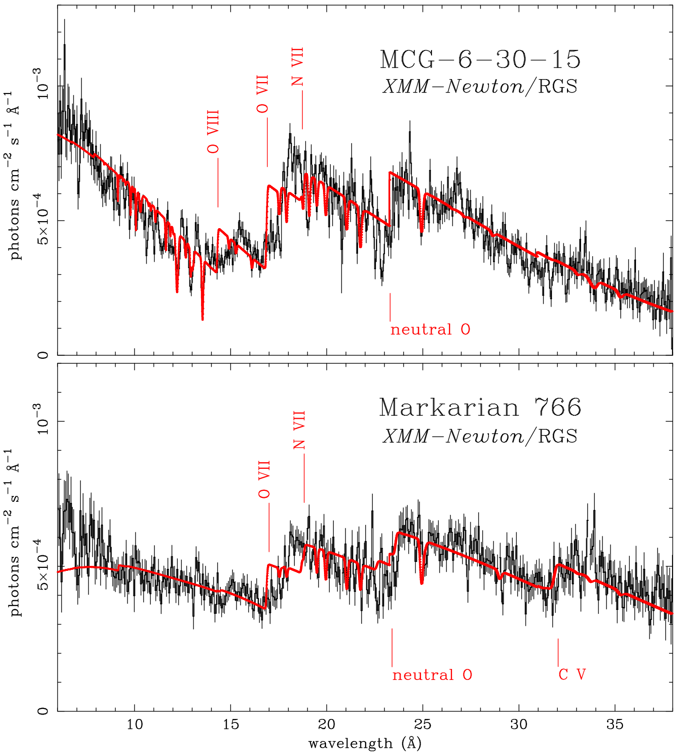


Figure 2. "Fluxed" spectra of the two sources (corrected for effective area) with the best-fit warm-absorber model, plotted in the observer's frame.

limits $R_{\rm in}$ and $R_{\rm out}$ of the disk emission region. These parameters are tied for all the lines in the fit.

The best fit parameters are listed in Table 1; data and best fit models are shown in Fig. 3 for both MCG −6-30-15 and Mrk 766. The errors quoted correspond to 90% confidence ranges for one interesting parameter. The derived emissivity index of $q \sim 4$ indicates that most of the line emission originates from the inner part of the disk. This explains why disk emission line profiles produced in a Schwarzschild metric (Fabian et al. 1989) do not provide an acceptable fit to the data (in this case the last stable orbit is substantially larger than that in the Kerr metric).

In our initial investigations of this model, we considered that the bump at $\sim$ 16 Å in the spectrum of MCG −6-30-15 could be OVIII Ly$\beta$ emission. However, we have concluded that this is unlikely for reasons related to the physical self-consistency of our model (see next section).

The observed RGS spectra require a flattening of the underlying continuum in both MCG −6-30-15 and Mrk 766 below $\sim$ 2.5 keV. A preliminary spectral analysis of the EPIC PN data of MCG −6-30-15 shows that a power-law slope of $\Gamma \sim 1.3$ can reproduce the 1 – 2 keV spectrum, with substantial excess soft emission below $\sim$ 1 keV.

We stress that both galaxies exhibit essentially an identical spectral structure in the RGS, with multiple broadened lines of H-like oxygen, nitrogen, and

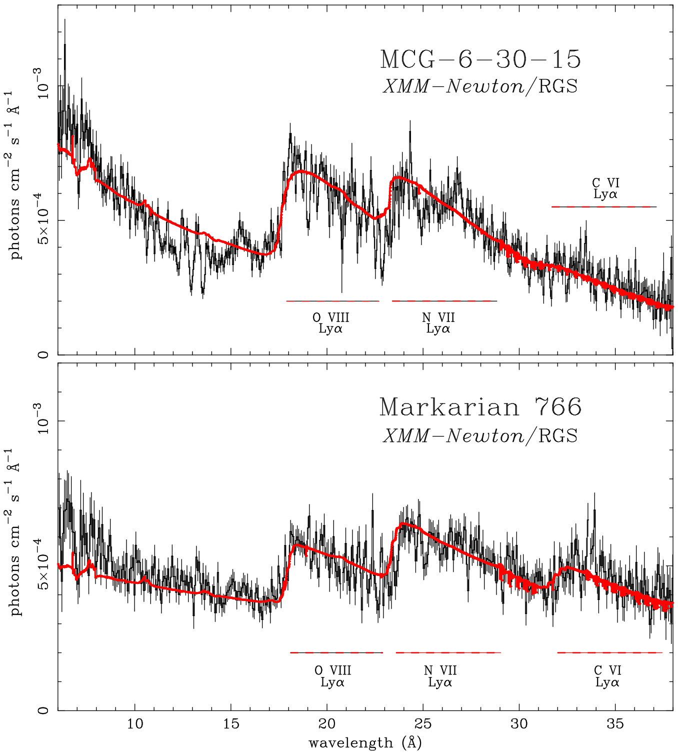


Figure 3. Same as in Figure 2 with the relativistically broadened line model. The parameters are listed in Table 1.

Table 1. RGS best fit parameters for isolated lines model

| Parameter | MCG −6-30-15 | Mrk 766 |
|---|---|---|
| $\Gamma$ | $1.33 \pm 0.012$ | $1.68 \pm 0.03$ |
| Inclination $i$ | $40.3^{\rm o} \pm 0.3^{\rm o}$ | $35.6^{\rm o} \pm 0.9^{\rm o}$ |
| Emissivity index $q$ | $3.78 \pm 0.05$ | $3.56 \pm 0.09$ |
| $R_{\rm in}$ | $1.24^{+0.7}_{-0.0}$ | $1.24^{+0.8}_{-0.0}$ |
| $R_{\rm out}$ | $110^{+90}_{-60}$ | $60^{+60}_{-15}$ |
| CVI Ly$\alpha$[a] | $(6.8 \pm 1.3)\,10^{-4}$ | $(1.2 \pm 0.1)\,10^{-3}$ |
| NVII Ly$\alpha$[a] | $(2.4 \pm 0.1)\,10^{-3}$ | $(1.9 \pm 0.1)\,10^{-3}$ |
| OVIII Ly$\alpha$[a] | $(4.6 \pm 0.1)\,10^{-3}$ | $(1.9 \pm 0.1)\,10^{-3}$ |

[a] Observed line intensities in units of ph cm$^{-2}$ s$^{-1}$ corrected for Galactic absorption.

carbon. The line energies are consistent with the galaxies systemic velocities, and all lines are consistent with having the same broad profiles. The fit residuals are also much less obvious and systematic than for the warm absorber model. Moreover, the disk line parameters are consistent with those derived for the Fe K$\alpha$ line ($i = 34^{o}{}^{+5}_{-6}$ and $36^{o}{}^{+8}_{-7}$, $q = 2.8 \pm 0.5$ and $3.0^{+0.8}_{-0.4}$ for MCG $-$6-30-15 and Mrk 766 respectively, Nandra et al. 1997). No additional column density to the Galactic value is required by the fits. All these factors are consistent with each other to a degree that makes chance coincidences unlikely, and make us conclude that the relativistic line model is the most probable explanation for the present observations.

## 4. Is the relativistic disk emission model physically self-consistent?

The lack of Fe L and He-like K emission lines in the RGS spectra suggests that the observed emission lines are most likely due to radiative recombination onto fully stripped ions (oxygen is fully ionized for kT $\geq$ 100 eV; Kallman & Krolik 1995). In this case one might expect to see also higher Lyman series and narrow radiative recombination continua (RRC). These features are definitely not present in the RGS spectra (see comments below).

For a maximally rotating black hole with $i \sim 40^{o}$ and $q \sim 4$, most of the emitted flux is beamed away from the observer: following Cunningham (1975), we find $F_{\rm obs} \sim 0.3\, L_{\rm em}/4\pi D^2$ for the observed flux ($L_{\rm em}$ is the emitted luminosity in the rest frame of the source, and $D$ the source distance). From the emitted luminosities we have derived ion emission measures for H-like carbon, nitrogen, and oxygen: e.g., for MCG $-$6-30-15 we find $EM_{\rm OVIII} = (3.3 \pm 0.1)\ T^{0.82}_{\rm 100eV}$.

For a plasma in which the material is nearly fully stripped, the ratios of the ion $EM$s provide the abundance ratios directly. The observed ratios are $A_{\rm C}/A_{\rm O} = 0.16 \pm 0.04$ and $A_{\rm N}/A_{\rm O} = 0.76 \pm 0.05$ for MCG $-$6-30-15, and $A_{\rm C}/A_{\rm O} = 0.65 \pm 0.2$ and $A_{\rm N}/A_{\rm O} = 1.2 \pm 0.3$ for Mrk 766. These are rather different from the solar values of $A_{\rm C}/A_{\rm O} = 0.43$ and $A_{\rm N}/A_{\rm O} = 0.13$ (Anders & Grevesse 1989). However, the strength of the nitrogen absorption lines in both sources also suggests that nitrogen is overabundant. Such anomalies are not uncommon, having been inferred also from UV observations of quasars (e.g., Hamann & Ferland 1992; Artymowicz, Lin, & Wampler 1993, and references therein).

From the above expression of $EM_{\rm OVIII}$ we derive the abundance-corrected total emission measure for MCG $-$6-30-15 to be

$$EM = 3.8 \times 10^{66}\ T^{0.82}_{\rm 100eV}\ A^{-1}_{\rm O\odot}, \tag{1}$$

where $A_{\rm O\odot}$ is the oxygen abundance relative to the solar value.

Assuming a disk-like geometry, we estimate the total emission measure to be $EM \sim \pi n_{\rm e}^2 R^2 H$, where $R$ is the characteristic radius and $H$ is the scale height of the emitting material. In the inner regions of a relativistic accretion disk where the pressure is dominated by radiation, the ratio of the scale height to the disk radius is on the order of $f = H/R \sim 10^{-3}$ (Kato, Fukue, & Mineshige 1998). Assuming that the characteristic emission radius is $R \sim 10\ R_{\rm g}$, where $R_{\rm g} = GM/c^2 = 1.5 \times 10^{12}\ M_7$ cm and $M_7$ is the mass of the black hole in multiples of $10^7 M_\odot$, we derive the average electron density to be

$$n_{\rm e} = 6.0 \times 10^{14}\ T_{100\rm eV}^{0.41}\ A_{\rm O\odot}^{-1/2}\ f_{-3}^{-1/2}\ M_7^{-3/2}\ {\rm cm}^{-3}, \tag{2}$$

where $f_{-3}$ is the ratio $H/R$ in multiples of $10^{-3}$. The implied electron scattering optical depth in the vertical direction of the disk is,

$$\tau_{\rm e} \sim n_{\rm e} H \sigma_{\rm T} = 6.0\ T_{100\rm eV}^{0.41}\ A_{\rm O\odot}^{-1/2}\ f_{-3}^{1/2}\ M_7^{-1/2}. \tag{3}$$

These simple estimates may be uncertain by as much as a factor of a few.

To check for consistency in the parameters derived above, we compute the upper limit for the average ionization parameter of the plasma to be

$$\xi = \frac{L}{n_{\rm e} R^2} = 7 \times 10^3\ L_{43}\ T_{100\rm eV}^{-0.41}\ A_{\rm O\odot}^{1/2}\ f_{-3}^{1/2}\ M_7^{-1/2}, \tag{4}$$

which is consistent with the observed level of ionization in that C, N, and O should be nearly fully stripped. The temperature at this level of ionization is $kT \sim 200$ eV. The same calculations have been applied to Mrk 766, with similar results.

The moderate to high optical depth may present a potential problem: for $\tau_{\rm e} \gtrsim 5$, broadening of the lines due to electron scattering is comparable to broadening from gravitational and relativistic effects. However, we could have $\tau_{\rm e} \lesssim 1$ if, for example, the emission region is much smaller than the scale height of the accretion disk (i.e., $f_{-3} \ll 1$). A medium with $\tau_{\rm e} \sim 1$ is required to explain the absence of the RRC and the higher Lyman series lines. With trace abundances of the H-like species, the emitting plasma is most likely optically thick to its own RRC. In this case, recombination to the ground state is suppressed and most of the expected RRC flux is eventually radiated in the Ly$\alpha$ line. A similar mechanism suppresses the higher series Lyman lines (see Branduardi-Raymont et al. 2001 for further discussion of these points).

Clearly our interpretation of the RGS spectra of MCG −6-30-15 and Mrk 766 in terms of line emission from a relativistic disk is a radical departure from the traditional warm absorber scenario, and calls for a careful re-assessment of the processes leading to the production of high energy radiation in the nuclei of active galaxies; in particular, a detailed radiative transfer calculation is required to characterize the opacity of the emitting medium.

## 5. Conclusions

A warm absorber interpretation of the RGS observations of MCG −6-30-15 and Mrk 766 is excluded on spectroscopic grounds. However, broad line emission from a relativistic disk surrounding a maximally rotating Kerr black hole appears to explain the data remarkably well. Preliminary considerations about the physical self-consistency of this scenario are encouraging. This result shows how the combination of large effective area and high energy resolution afforded by the *XMM-Newton* RGS can truly revolutionarise our understanding of the origin of soft X-ray emission in AGN.

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