The complex soft X-ray spectrum of NGC 4151

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ABSTRACT

We present a detailed analysis of the complex soft X-ray spectrum of NGC 4151 measured by the RGS instruments aboard XMM-Newton. The XMM-Newton RGS spectra demonstrate that the soft X-ray emission is extremely rich in X-ray emission lines and radiative recombination continua (RRC), with no clear evidence for any underlying continuum emission. Line emission, and the associated RRC, are clearly detected from hydrogen-like and helium-like ionization states of neon, oxygen, nitrogen and carbon. The measured lines are blueshifted with a velocity of between \(\sim 100-1000 \text{ km s}^{-1}\), with respect to the systemic velocity of NGC 4151, approximately consistent with the outflow velocities of the absorption lines observed in the UV spectrum of NGC 4151 (Kriss et al. 1995), suggestive of an origin for the UV and soft X-ray emission in the same material. Plasma diagnostics from the observed helium-like triplets, imply a range of electron temperatures of \(\sim 1-5 \times 10^4 \text{ K}\) and electron densities of between \(10^8 - 10^{10} \text{ cm}^{-3}\). The soft X-ray spectrum of NGC 4151 is extremely similar to that of NGC 1068, both in terms of the atomic species present and in terms of the relative strengths of the observed emission lines and RRC (Kinkhabwala et al. 2002), suggesting that the soft X-ray excesses observed in many Seyfert 2 galaxies may be composed of similar emission features. Modelling the RGS spectra in terms of emission from photoionized and photoexcited gas in an ionization cone reproduces all of the hydrogen-like and helium-like emission features observed in the soft X-ray spectrum of NGC 4151 in detail and confirms the correspondence between the soft X-ray emission in NGC 4151 and NGC 1068. NGC 4151 shows somewhat lower individual ionic column densities than those measured for NGC 1068 indicating that the material in the ionization cones of NGC 4151 may be somewhat more dense than the material in the ionization cones of NGC 1068.

Key words: galaxies: active - galaxies: Seyfert - X-rays: galaxies - galaxies: NGC 4151.

1 INTRODUCTION

Prior to the advent of XMM-Newton and Chandra, the origin of the soft X-ray emission from heavily obscured AGN remained very uncertain. Recently, however, observations with XMM-Newton and Chandra have revolutionized our understanding of heavily obscured AGN (for a complete description of XMM-Newton, Chandra and their relative capabilities see Jansen et al. 2001, Weisskopf et al. 2002 and references therein). The combination of the high spatial resolution afforded by Chandra, the large collecting area of XMM-Newton and the high spectral resolution X-ray spectrophotocapabilities (in the form of X-ray grating and CCD instruments) of both missions across the 0.1-12 keV band is beginning reveal many new details of the X-ray emission from heavily obscured AGN, particularly with regard to the soft X-ray emission from these objects. Chandra observations of several heavily obscured AGN have revealed considerable extended soft X-ray emission in each source, that is tightly correlated with the O[III](\(\lambda 5007\)) emission observed with the Hubble Space Telescope (HST; NGC 1068 - Young et al. 2001; Mrk 3 - Sako et al. 2000; NGC 4151 - Ogle et al. 2000; Circinus - Sambruna et al. 2001). In several of these sources (e.g. NGC 1068 - Young et al. 2001), the extended X-ray emission and the O[III](\(\lambda 5007\)) emission clearly traces the spiral arms and other large-scale structures out to a considerable distance from the active nucleus of the galaxy. Similarly recent spectral observations of these AGN with the X-ray grating instruments on Chandra (NGC 1068 - Brinkman et al. 2002, Ogle et al. 2002; Mrk 3 - Sako et
al. 2000; NGC 4151 - Ogle et al. 2000; Circinus - Sambruna et al. 2001) and XMM-Newton (Kinkhabwala et al. 2002) have revealed soft X-ray spectra dominated by prominent emission lines from a range of light elements (e.g. C, N, O, Ne etc). These observations constitute a growing body of evidence that suggests that the soft X-ray emission from heavily obscured Seyferts is largely composed of soft X-ray emission lines that originate in gas that is photoionized (and photoexcited) by the central AGN.

The Seyfert 1.5 galaxy NGC 4151 was identified as an X-ray source over thirty years ago (Gursky et al. 1971). One of the brightest AGN accessible in the X-ray band, NGC 4151 has been extensively studied by missions such as EXOSAT, Ginga, ROSAT, ASCA, CGRO and more recently RXTE, BeppoSAX, Chandra and XMM-Newton. This observational focus has revealed that the spectrum of NGC 4151 from 0.1-100 keV is comprised of a complex mixture of emission and absorption components, probably originating in a variety of locations from the innermost parts of the putative accretion disk in NGC 4151, out to the extended narrow-line region of the galaxy. Despite the relatively poor quality of the spectra, previous observations (particularly observations with ASCA) did tentatively reveal several unresolved soft X-ray features, suggesting that the soft X-ray emission was somewhat more complex than had been previously suggested. The most prominent feature found with ASCA was at an energy of ~0.88 keV and was tentatively associated with O VIII Lyα RRC (Weaver et al. 1994; Griffiths et al. 1998). The detailed nature of the soft X-ray emission in NGC 4151 has only recently been revealed through a Chandra HETG observation (Ogle et al. 2000, Yang et al. 2001). This observation demonstrated that the soft X-ray spectrum was composed almost entirely of emission lines and RRC, with little or no detected continuum emission of any form (and hence no absorption features). Utilizing the excellent spatial resolution of Chandra, Ogle et al. (2000) resolved ~70% of the soft X-ray emission as extended emission, originating up to 11.5′′ from the AGN, that demonstrated an excellent correspondence with the bi-

The Chandra analysis finds evidence for both photoionized and collisionally ionized (thermal) gas in the ENLR, however many of the details of the ionized medium remained elusive, due to the large number (33 in total) and low significance of the features detected.

This paper is organized as follows. Section 2 details the XMM-Newton observations of NGC 4151. Section 3 presents the XMM-Newton RGS spectra and discusses the spectral modelling in terms of emission from an ionization cone. Section 4 compares the RGS spectra of NGC 4151 with the soft X-ray spectra of NGC 1068 and Mrk 3. Section 5 presents a preliminary look at the correspondence between the XMM-Newton RGS and the XMM-Newton EPIC soft X-ray spectra of NGC 4151.

2 THE XMM-NEWTON OBSERVATIONS

NGC 4151 was observed with XMM-Newton five times during December 21st–23rd, 2000. The RGS instruments were active for all five observations and the data were processed with the standard RGS pipeline processing chains incorporated in the XMM-Newton SAS v5.4.1. Dispersed source spectra and background spectra were extracted with the automated RGS extraction tasks in the SAS. The SAS filters the RGS events in dispersion-channel vs CCD-pulse-height space to separate the data from the different spectral orders. Investigation of the individual spectra indicate that the 2nd order RGS spectra contain a negligible amount of information (a count rate of ≤10% of that in the 1st order spectra, despite having ~60% of the effective area below 10Å) and as a result only the 1st order spectra are presented here. The resulting spectra have a total effective exposure time of ~128 ks and ~125 ks for the RGS 1 and 2 instruments respectively. A previous investigation of the XMM-Newton EPIC spectra confirms that the soft X-ray spectrum of NGC 4151 remained relatively constant for the duration of the observation (Schurch et al. 2003). The spectra from the five observations were co-added to produce a single high signal-to-noise source spectrum and a single background spectrum for each RGS instrument. The full spectra and individual lines were analyzed with both maximum likelihood and χ² minimization techniques. For the maximum likelihood analysis the spectra were left unbinned however, for the χ² minimization techniques (which, in general, are not particularly well-suited to fitting the sharp features observed in this and similar high resolution soft X-ray spectra) the spectra were binned to a minimum of 20 counts per spectral channel. Investigation of the spatial extent of the X-ray emission observed by XMM-Newton reveals that the soft X-ray emission is not significantly extended on scales greater than the mirror PSF, consistent with the details of the previously reported Chandra observation of NGC 4151 (Ogle et al. 2000).

3 MODELLING THE RGS SPECTRA

Figure 1 shows the XMM-Newton RGS spectra from the combined observations of NGC 4151. The spectrum is completely dominated by line emission and radiative recombination continua (RRC). Line emission is clearly detected from hydrogen-like and helium-like ionization states of neon, oxygen, nitrogen and carbon and in many cases the line emission associated with these ions is not limited to the Lyα (2p-1s) transition but includes higher order resonance transitions (np-1s) labeled β-ε for the different hydrogen-like and helium-like species respectively. Much of the unidentified line emission below ~16Å can be associated with a multitude of unresolved iron L-shell emission lines, along with some contribution from hydrogen-like and helium-like silicon and magnesium. The spectra show no significant continuum emission and no fluorescent line emission (there may be a marginal detection of silicon Kα fluorescence at ~7.1Å, how-

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ever without a good knowledge of the iron L-shell emission in this region it is not possible to measure the line cleanly).

3.1 The emission lines

The spectrum is remarkably similar to the soft X-ray spectrum of the archetypal bright Seyfert 2 galaxy, NGC 1068, reported by Kinkhabwala et al. (2002). Both sources show strong emission line triplets from helium-like nitrogen and oxygen, with a similar pattern of resonance, intercombination and forbidden line strengths. Following the analysis of the XMM-Newton RGS observation of NGC 1068 presented in Kinkhabwala et al. (2002), line fluxes, centroid energies and line widths were determined for the bright, unambiguously identified, emission lines observed in the spectra. The spectral fits quoted here for individual strong line features were performed with $\chi^2$ minimization techniques (and correspondingly the data were binned to a minimum of 20 counts per spectral channel). An examination of the fit properties using maximum likelihood fitting techniques for individual lines reveals that the best-fit parameters are not significantly different using these statistical techniques in comparison with the $\chi^2$ fits, as expected given the bright nature of the features examined here. The intrinsic profiles of the emission lines are represented by a line model with a Gaussian profile (we caution, however, that the original line profile may in fact not be Gaussian, although it does appear to be a good approximation for the lines presented here) which allows the determination of accurate line centroid energies, fluxes and, in some cases, line widths. The results of fitting this profile to the brightest emission lines are given in Table 1.

The measured fluxes take account of the Galactic column density ($2.1 \times 10^{20} \text{ cm}^{-2}$; Warwick et al. 1995) using the tbabs model in XSPEC, and the line shifts are measured with respect to the source redshift of $z=0.00332$. The systematic uncertainty on measuring the centroid line energies of the lines is estimated to be $\Delta \chi^2=2.71$ criterion (i.e. assuming one interesting parameter) and include the systematic uncertainty added in quadrature. Most of the measured line centroid energies are consistent with a mild blueshift, of between $\sim 100-1000 \text{ km s}^{-1}$, with respect to the systemic velocity of the lines. This implies a line-of-sight outflow velocity for the ionized material of $\lesssim 1000 \text{ km s}^{-1}$, consistent with the line shifts of the absorption lines observed in the UV spectrum of NGC 4151 ($\sim 600 \text{ km s}^{-1}$; Kriss et al. 1995). Many of the observed line widths are largely unconstrained, with the spectral fitting only yielding upper limits (these are not quoted in Table 1); however the seven line widths that are con-
the only transition considered during the spectral modelling.

The radiative recombination continua (RRC) identified in the previous section) with such a low

electron temperatures imply electron temperatures of ∼1000 K (see Section 3.4). The derived electron tem-

peratures are narrow, prominent, features. The velocity dis-

persion of the emitting material will affect the RRC in ex-

actly the same manner as it affects the emission lines dis-

cussed previously, however this effect is negligible here due
to the low velocities of the ions involved compared to that
of the electrons. RRC from hydrogen-like and helium-like
ionization states of Ne, O, N and C are clearly identifiable
in Figure 1. Electron temperatures were determined for the
bright, unambiguously identified, RRC (Table 2) using the
RRC profiles generated by the 'ionization cone' model dis-
cussed in Section 3.4 fit, using χ² minimization techniques,
to the individual RRC. Again, an examination of the fit
properties using maximum likelihood fitting techniques
for individual features reveals that the best-fit parameters are
not significantly different using these statistical techniques
in comparison with the χ² fits. The derived electron tem-
peratures imply electron temperatures of ∼2-4×10⁴ K. The
association of high-ionization emission lines (e.g. O VIII,
Ne X etc; identified in the previous section) with such a low

temperature plasma is strongly indicative of a plasma whose

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peratures imply electron temperatures of ∼2-4×10⁴ K. The

association of high-ionization emission lines (e.g. O VIII,
Ne X etc; identified in the previous section) with such a low

temperature plasma is strongly indicative of a plasma whose

ionization state is governed by photoionization as opposed

on transitions from the n=2 shell to the

C VI α 33.65^{+0.01}_{-0.01} 33.736 -440^{+40}_{-90} 0.37^{+0.05}_{-0.05} 1.79^{+0.16}_{-0.16}

a Vainshtein & Safronova, 1978

straining the spectral fitting appear to show a bimodal
distribution with the shorter wavelength lines having an aver-
age line width of σ∼0.025 ˚A (∼1000 km s⁻¹ FWHM) and
the longer wavelength lines having an average line width of
∼0.005 ˚A (∼200 km s⁻¹ FWHM). The observed line widths
imply that the intrinsic velocity dispersion of the outflow-
ning material is ≲1000 km s⁻¹ which is somewhat lower than
the line widths of the absorption lines observed in the UV
(1000-2500 km s⁻¹; Kriss et al. 1995). The bimodal distri-
bution of the line widths as a function of the wavelength of
the line is suggestive of a scenario in which individual clouds
of emitting material close to the source of the ionizing con-
tinuum are moving more rapidly than clouds further from
the continuum source. The large majority of the soft X-ray
flux of NGC 4151 as measured by Chandra is not extended
on scales larger than ∼2′, demonstrating that the reported
extended soft X-ray flux will not contribute considerably to
the line widths measured in the RGS spectrum.

3.2 Temperature diagnostics with Radiative
Recombination Continua

The radiative recombination continua (RRC) identified in
the RGS spectra are the result of a free electron recombin-
ing directly into a bound state of an ion. Recombination to
the ground state represents the dominant transition and is
the only transition considered during the spectral modelling.
The free electrons can have any energy above the recombi-
nation threshold and hence the feature produced is neither
symmetrical or narrow. The energy of the electrons prior to
the recombination process is dependent upon the electron
temperature of the emitting plasma and hence the width
of the RRC features provides a direct measurement of the
recombining electron temperature, T_e (Liedahl & Paerels,
1996; Liedahl 1999). RRC originating in hot plasmas are
broad and often subtle features however, RRC from cool
plasmas are narrow, prominent, features. The velocity dis-

Table 1. Line properties of individual emission lines observed in the RGS spectra of NGC 4151

| Line ID | λ_{Oba} Å | λ_{rest} Å | Line Shift km s⁻¹ | σ_{Oba} Å | X Flux Photons s⁻¹ cm⁻² |
|---------|-----------|-----------|------------------|----------|--------------------------|
| Ne X α  | 12.13±0.01| 12.134    | -120±250          | 2.6±1.0  | 0.42±0.05                |
| Ne IX r | 13.47±0.02| 13.437    | -130±260          | 2.4±1.9  | 0.47±0.05                |
| Ne IX i | 13.55±0.01| 13.550    | -120±240          | 2.0±1.6  | 0.46±0.15                |
| Ne IX f | 13.69±0.01| 13.697    | -130±220          | 1.6±0.9  | 1.03±0.09                |
| O VIII β| 16.00±0.02| 16.006    | -150±230          | 3.1±0.6  | 0.37±0.04                |
| O VIII α| 18.96±0.01| 18.969    | -210±130          | 1.0±0.4  | 1.0±0.10                 |
| O VII  | 21.59±0.01| 21.603    | -230±140          | 1.1±0.9  | 1.0±0.09                 |
| O VII i | 21.79±0.01| 21.798    | -230±120          | 0.7±0.7  | 0.75±0.07                |
| O VII f | 22.08±0.01| 22.101    | -300±110          | 0.68±0.9 | 3.89±0.17                |
| N VII β | 20.89±0.01| 20.910    | -230±160          | 0.7±0.5  | 0.22±0.04                |
| N VII α | 24.77±0.01| 24.781    | -190±110          | 0.8±0.9  | 1.0±0.08                 |
| N VI  | 28.75±0.01| 28.792    | -350±110          | 0.47±0.6 | 0.47±0.07                |
| N VI i | 29.09±0.02| 29.075    | -30±160           | 0.36±0.6 | 0.36±0.06                |
| N VI f | 29.51±0.01| 29.531    | -290±100          | 1.15±0.12| 1.15±0.12                |
| C VI β | 28.43±0.01| 28.466    | -390±130          | 0.9±0.3  | 0.37±0.05                |
| C VI α | 33.65±0.01| 33.736    | -440±90           | 1.79±0.16| 1.79±0.16                |
The importance of the helium-like triplet lines and used plasmas. Gabriel & Jordan (1969) were the first to recognize a diagnostic of the electron density and temperature in hot combination and forbidden lines from helium-like ions provide the sum of the intensities of the forbidden and intercombination lines to the intensity of the resonance line \( G \), where \( G = i + f / r \) is sensitive to the electron temperature of the plasma. For a detailed discussion of the manner in which the ratios depend on the electron density and the plasma temperature see Pradhan et al. (1981), Porquet & Dubau (2000), Porquet et al. (2002) and references therein.

The R and G ratios for the Ne, O and N triplets observed in the RGS spectrum of NGC 4151 are given in Table 3. The G-values imply an electron temperature of \( \sim 10^5 \) K, consistent with the electron temperatures implied from the properties of the observed RRC and consistent with photoionization being the dominant ionization mechanism in the plasma (Porquet & Dubau, 2000). The R-values imply electron densities of \( \sim 10^{10} - 10^{11} \) cm\(^{-3}\) in nitrogen and oxygen and \( \sim 10^{10} - 10^{11} \) cm\(^{-3}\) from neon (Porquet & Dubau, 2000).

In particular the ratios calculated from the oxygen triplet (which is both the strongest and the least confused of the helium-like triplets) strongly imply a photoionized plasma, however, extracting detailed values of density and temperature for the emitting material is complicated by the possibility that a strong radiation field (i.e. photoexcitation) can mimic the effect that a relatively high density has on the line strengths. In such a situation the electron density, and to a lesser extent, the electron temperature can be overestimated (Porquet et al. 2002). We note that the expected contribution of blended dielectronic satellite lines to these ratios has not been taken into account in the values quoted here. For the N and O triplets this contribution is negligible; however the Ne triplet is significantly affected. For a high temperature, collisionally dominated, plasma the additional contribution can result in an error of \( \sim 1\% \) and \( \sim 9\% \) for the R and G ratios respectively, however for a photoionized plasma, where the temperatures are several orders of magnitude lower, this effect can be considerably greater (Porquet et al. 2002).

### Table 2. Electron temperatures (in eV) from RRC

| RRC  | \( T_e \) |
|------|----------|
| C V  | 2.5 \( ^{+1.5}_{-0.5} \) |
| C VI | 4.0 \( ^{+1.0}_{-1.0} \) |
| N VI | 3.0 \( ^{+3.0}_{-1.0} \) |
| N VII| 4.0 \( ^{+2.0}_{-1.5} \) |
| O VII| 4.0 \( ^{+0.5}_{-0.5} \) |
| O VIII| 6.0 \( ^{+1.0}_{-2.0} \) |

### Table 3. Helium-like triplet plasma diagnostic ratios

| Triplet ID | R   | G   |
|------------|-----|-----|
| NeIX       | 2.3 \( ^{+0.7}_{-0.7} \) | 3.2 \( ^{+1.2}_{-0.9} \) |
| OVII       | 3.4 \( ^{+0.4}_{-0.3} \) | 3.9 \( ^{+0.5}_{-0.5} \) |
| NVI        | 3.0 \( ^{+1.1}_{-0.8} \) | 3.4 \( ^{+1.0}_{-0.8} \) |

Figure 2. Schematic cartoon of the ‘ionization cone’ model (not to scale). The central nuclear components (black hole and accretion disk), denoted by the black spot, are surrounded by a dense absorbing torus of neutral dust and gas. The optically thin material perpendicular to the plane of the absorbing torus sees the direct continuum from the X-ray source and becomes strongly ionized forming ionization cones. The line emission from these cones is observable from Seyfert 2 galaxies due to the suppression of the direct continuum, whereas the ionization cones in Seyfert 1 galaxies are only seen through their absorption of the direct continuum (Kinkhabwala et al. 2002).

3.4 The ionization cone model

Given the similarity between the RGS spectra of NGC 1068 and NGC 4151, we utilize the ‘ionization cone’ model developed by Kinkhabwala et al. (2002) in their analysis of the RGS spectrum of NGC 1068, to fit the RGS spectrum of NGC 4151. This model, which was incorporated into XSPEC for ease of spectral fitting, reproduces the hydrogen-like and helium-like line emission, and the associated RRC, from an irradiated cone of optically thin plasma (c.f. the ionization cones observed in O[III] by HST) shown schematically in Figure 2. The model includes the effects of both photoionization...
ization and, crucially, photoexcitation. Photoexcitation is the process by which the absorption of a photon with insufficient energy to ionize the atom, results in the transition of an inner-shell electron to a higher energy level within the atom. The excited electron will rapidly undergo one or more radiative transitions, decaying back to its original energy state. For each atomic species, photoexcitation is expected to enhance the intensity of the higher order resonance transition lines relative to the 1st order resonance line. Photoexcitation was observed to play a significant role in the spectrum of NGC 1068 where the Lyβ, Lyγ and Lyδ lines were significantly stronger than predicted by models based on pure photoionization or collisional ionization.

Here, as with NGC 1068, the plasma is irradiated by the unabsorbed intrinsic power-law continuum, the slope of which in the case of NGC 4151 is fixed at $\Gamma=1.65$, based on the analysis of the hard X-ray XMM-Newton EPIC spectrum presented in Schurch et al. (2003). The luminosity of the central source, $L_X$, and the covering fraction of the cone, $f$, are fixed at $L_X=6\times10^{43}$ erg s$^{-1}$ and $f=0.1$, respectively. The modelling includes both Galactic column density ($2.1\times10^{20}$ cm$^{-2}$; Warwick et al. 1995) using the `tabls` model in XSPEC and a source redshift of $z=0.00332$. The electron temperatures for each atomic species were fixed at the temperatures found from the analysis of the RRC (Table 2), where possible, and the remaining RRC temperatures were fixed at the temperatures identified for NGC 1068 by Kinkhabwala et al. (based on the similarity between the observed bright RRC in NGC 4151 and the corresponding RRC in NGC 1068). The remaining free parameters of the model are the transverse velocity distribution of the lines, $\sigma_v^{\text{obs}}$, the radial velocity distribution of the lines, $\sigma_v^{\text{rad}}$, and the radial column density of each individual atomic species, $N_{\text{ion}}^{\text{rad}}$. The modelling presented in the next section includes a significant contribution from iron L-shell emission lines. Iron L-shell emission, known to be present in the soft X-ray spectrum of both Mrk 3 and NGC 1068, will contribute significantly between $\sim9$-16Å (0.75-1.4 keV) and will results in an artificially high measure of the ionic column densities of Neon and Magnesium if it is not incorporated in the modelling.

### 3.5 Fitting the ionization cone model to the RGS spectra

The ionization cone model was fitted to the RGS spectra in XSPEC for simplicity. We note that the $\chi^2$ minimization techniques, used earlier in the paper to fit specific bright spectral features, are, in general, not well-suited to fitting wide-band X-ray grating spectra which often incorporate many additional low-significance spectral features. With this in mind, the ionization cone model is fit to the RGS spectra of NGC 4151 using maximum likelihood fitting techniques. The complexity of this specific model makes the accurate determination of individual parameter errors problematic. Despite this caveat, the model provides a “good fit” to all the hydrogen-like and helium-like line emission and RRC observed in the RGS spectra. Here, the term “good fit” here refers only to a set of parameters that correctly reproduces the distinct features observed in the spectrum (i.e. it is not a statistical measure of the goodness of fit of the model). Because of this, statistical errors are not quoted for either the column densities or the velocity measurements. Figure 3 shows the best-fit of the ionization cone model to all the hydrogen-like and helium-like emission lines and RRC in the RGS spectrum of NGC 4151. The best-fit radial ionic column densities and the associated RRC electron temperatures are given in Table 4: $\sigma_v^{\text{rad}}$ has a best-fit value of $\sim400$ km s$^{-1}$ and $\sigma_v^{\text{rad}}$ has a best-fit value of $\sim330$ km s$^{-1}$. We do not quote any specific best-fit values for the ionic column densities of iron responsible for the iron L-shell emission (Fe XVI-XXIII) due to the unresolved nature of the specific iron L-shell lines. Typically the ionic iron column densities are of the order of $\sim$few $\times10^{16}$ cm$^{-2}$.

Both the velocity measurements are in reasonable agreement with the average line widths and line shifts measured from the individual line centroid energies. Kinkhabwala et al. (2002) quote, based on the NGC 1068 data, an estimate for the uncertainties on the individual model parameters of approximately a few tens of percents for the ionic column densities and approximately a factor of 2 for the transverse and radial velocities. Here, the data are of somewhat worse statistical quality than the NGC 1068 spectra and so we expect the parameters to be less well constrained. NGC 1068 is a factor of $\sim3$ times brighter than NGC 4151 and hence the errors on the fit parameters from the NGC 4151 spectrum will be a factor of $\sim2$ times greater than the errors estimated for the NGC 1068 fit parameters. Using a fractional ionic abundance of 0.5 for O VIII, the column density of O VII quoted in Table 4 yields an equivalent hydrogen column density of $N_H\geq2\times10^{21}$ cm$^{-2}$.

### 4 A COMPARISON WITH NGC 1068 AND MRK 3

The archetypal Seyfert 2 galaxies, NGC 1068 and Mrk 3 have both been the targets of recent X-ray grating observations. The soft X-ray emission in both of these sources is extremely similar to the soft X-ray emission from NGC 4151; it is extended on scales of hundreds of parsecs, shows

### Table 4. Best-fit parameters for the ‘ionization cone’ model fit to the RGS spectra of NGC 4151

| ion     | $N_{\text{ion}}^{\text{rad}}$ (cm$^{-2}$) | $kT_v$ (eV) |
|---------|------------------------------------------|------------|
| C V     | $2.9\times10^{17}$                      | 2.5        |
| C VI    | $4.0\times10^{17}$                      | 4.0        |
| N VI    | $1.4\times10^{17}$                      | 3.0        |
| N VII   | $2.4\times10^{17}$                      | 4.0        |
| O VII   | $7.6\times10^{17}$                      | 4.0        |
| O VIII  | $7.9\times10^{17}$                      | 6.0        |
| Ne IX   | $4.6\times10^{17}$                      | 4.0$^a$    |
| Ne X    | $4.7\times10^{17}$                      | 4.0$^a$    |
| Mg XI   | $2.2\times10^{17}$                      | 4.0$^a$    |
| Mg XII  | $4.0\times10^{17}$                      | 4.0$^a$    |
| Si XIII | $6.2\times10^{17}$                      | 4.0$^a$    |
| Si XIV  | $1.1\times10^{18}$                      | 4.0$^a$    |

$^a$ Unconstrained parameter. Value fixed at the value used in Kinkhabwala et al. (2002).
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4.1 The comparison with the XMM-Newton RGS spectrum of NGC 1068

The soft X-ray XMM-Newton RGS spectrum of NGC 4151 is remarkably similar to that of NGC 1068. Both sources show strong hydrogen-like and helium-like line emission and RRC from carbon, nitrogen, oxygen, neon, magnesium and silicon. The resemblance between the spectra is apparent in the details of the spectra as well as on a more general level. For example, both sources show similar patterns of resonance, intercombination and forbidden line strengths for the helium-like triplets of nitrogen and oxygen and both show significant (but unresolved) iron L-shell emission. The properties of the detected emission lines are remarkably alike in the two sources, both in terms of the lines present and the scale of their energy shifts. In both sources the prominent emission lines are blue-shifted by \(<1000 ~\text{km s}^{-1}\) with average line shifts of \(305 ~\text{km s}^{-1}\) and \(375 ~\text{km s}^{-1}\) for NGC 4151 and NGC 1068, respectively (Kinkhabwala et al. 2002). The line widths measured for NGC 1068 do not show the bimodal distribution observed in NGC 4151. However, since only 7 lines have constrained line widths in the NGC 4151 spectrum, compared to 23 lines with constrained widths in the NGC 1068 spectrum, caution should be strongly emphasized in interpreting the validity of the distribution of line widths in NGC 4151. Interestingly the average line width found in the NGC 1068 data \((\sim1100 ~\text{km s}^{-1} \text{ FWHM})\) is comparable to the average line width of the group of broader lines in the NGC 4151 spectrum \((\sim1000 ~\text{km s}^{-1} \text{ FWHM})\).

It is tempting, based upon a comparison of the helium-like triplet plasma diagnostic ratios \((R \text{ and } G; \text{Section 3.3})\) to infer that the ionization cones in NGC 4151 have a somewhat lower electron temperature and a somewhat higher electron density than those in NGC 1068 (Kinkhabwala et al. 2002). Unfortunately the situation may not be as clear as cut as this simple comparison suggests, primarily due to the unknown effect of photoexcitation on the diagnostic ratios (discussed previously in Section 3.3). The best-fit ionic column densities for NGC 1068 were found to be similar to those observed in absorption for Seyfert 1 galaxies, implying either radially stratified ionization zones or, more likely, a broad distribution of densities at any given radius. An inspection of the radial column densities fit to the RGS spectrum reveals that NGC 4151 appears to have less ionized material in its ionization cones, by a factor of \(\sim 3.5\) on average. The best-fit ionic electron temperatures, based on the widths of the RRC features, are also extremely similar between NGC 4151 and NGC 1068.
NGC 1068 (although the comparatively large errors on these temperatures prevents any definite conclusions being drawn regarding this similarity). The ionic column densities are dependent on a combination of factors including, cone length, density, ionization parameter and the filling factor of the material. Lower ionic column densities could be the result of lower ionizing flux or less material in the ionization cones, however a somewhat more plausible explanation, in line with the smaller R-values from the helium-like line triplets, could be that the material in the ionization cones of NGC 4151 is rather more dense than the material in the ionization cones of NGC 1068. Since the recombination rate is dependent on the density of the material, this can result in a smaller ionized fraction for a similar ionizing continuum.

4.2 The comparison with the Chandra HETG observation of Mrk 3

The Chandra HETG observation of Mrk 3 was the first published high resolution soft X-ray spectrum of a Seyfert 2 galaxy and showed unambiguously that the soft X-ray emission in Mrk 3 is composed almost entirely of emission lines and RRC, with little or no continuum emission. The soft X-ray spectrum of Mrk 3 is, again, remarkably analogous to the soft X-ray spectrum of NGC 4151, though with somewhat less statistical significance due to the rapidly decreasing effective area of the HETG instrument at wavelengths above ~9Å. In both sources there is strong evidence to suggest that the observed emission lines are produced in a photoionized and photoexcited plasma (Sako et al. 2000). The importance of photoexcitation in the spectrum of Mrk 3 is highlighted by the observed weak iron L-shell emission, rather than by the enhanced higher order resonance transitions, rejecting explanations from a recombination dominated or a collisionally dominated plasma. Despite this impressive spectrum, the Chandra observation of Mrk 3 only partially resolves two of the helium-like line triplets detected in the RGS spectrum of NGC 4151 (oxygen and neon), due to the limited number of photons in each feature, and as a result many of the properties of the plasma are not well constrained. In particular, the resonance and intercombination lines of these triplets cannot be separated and as a result Sako et al. (2000) quote a different diagnostic line ratio (i.e. (r+i)/f) to the line ratios used here.

At wavelengths shorter than ~9Å the Chandra spectrum shows evidence for a reflection dominated continuum along with clear detections of emission lines that are either extremely difficult or impossible to detect with the RGS (given its limited spectral bandpass), namely Fe XXVI, Fe XXV, Fe Kα, S XVI, S XV, S Kα, Si XIV, Si XIII, Si Kα, Mg XII and Mg XI (Sako et al. 2000). This plethora of lines highlights the complimentary capabilities of XMM-Newton and Chandra and strongly supports future observations of bright, heavily obscured AGN with both Chandra (using the HETG) and XMM-Newton, to obtain the highest possible resolution X-ray spectra over the widest possible energy range. The line ratios calculated from the Chandra detections of the helium-like silicon and magnesium line triplets (i.e. Si XIII and Mg XI) are all inconsistent with the expected values for a collisionally ionized plasma and are marginally consistent with the predictions from a photoionized plasma, similar to the conclusions from the triplet ratios for both NGC 4151 and NGC 1068.

5 A BRIEF COMPARISON WITH THE XMM-Newton EPIC SPECTRA

One of the strengths of XMM-Newton is that all the science instruments operate simultaneously during each observation, allowing a direct comparison between the high resolution spectra from the RGS instruments and the lower resolution spectra from the EPIC CCD detectors. This comparison is particularly useful in exposing features in each source spectrum that the other detectors struggle to detect. For example, broad features present in the 0.3-2.5 keV range are not easily identified in RGS spectra, but will be more clearly observed by the EPIC instruments. Conversely, features that appear to be broad in the EPIC spectrum may be resolved into a set of individual narrow lines by the RGS instruments. Conclusions from the process of comparing the EPIC and RGS spectra are complicated by the need for good calibration and cross-calibration for each instrument involved.

Figure 4 shows the full window mode EPIC PN spectra fit with a model that combines the best-fit of the hard X-ray model developed in Schurch et al. (2003) and the ‘ionization cone’ soft X-ray model presented in Section 3.4. Lower Panel The ratio of the data to the model prediction.
widths that are constrained by the data tentatively suggest the systemic velocity of NGC 4151. The seven observed line blueshifts are generally consistent with the outflow velocities of the absorption lines observed in the UV spectrum of NGC 4151 (Kriss et al. 1995), implying that the UV and X-ray line features originate in the same material.

- Plasma diagnostics, based on the ratios of the resonance, intercombination and forbidden lines of the observed helium-like triplets, imply electron temperatures of \(100-1000\) K and electron densities of \(10^8\) \(\text{cm}^{-3}\) in nitrogen and oxygen and \(10^{10}\) \(\text{cm}^{-3}\) from neon (Porquet & Dubau 2000). We note again that the effects of photoexcitation may have a considerable effect on the values of electron temperature and density determined by these diagnostic ratios (see Section 3.3). The wide range of the calculated electron densities is suggestive of either a ‘clumpy’ extended NLR or a region in which the material has grossly non-solar elemental abundances.

- The soft X-ray spectrum of NGC 4151 is remarkably similar to the soft X-ray spectrum of NGC 1068 (Kinkhabwala et al. 2002). The correspondence between the two source spectra is evident on the general scale from the strong emission lines and RRC associated with the same ionic species, which dominate the spectra of both sources. The resemblance of the NGC 4151 and NGC 1068 soft X-ray spectra is also apparent in the details of the spectra (i.e. the similar helium-like triplet ratios and RRC temperatures).

- The ‘ionization cone’ model, developed by Kinkhabwala et al. (2002) to model the RGS spectra of NGC 1068, reproduces all of the hydrogen-like and helium-like emission features observed in the soft X-ray spectrum of NGC 4151 in detail. The best-fit radial and transverse velocities of the material in the ionization cones agree well with the blueshift and velocity dispersion measured from the individual line centroid energies, and are similar to the radial and transverse velocities measured from the soft X-ray spectrum of NGC 1068. The individual ionic column densities are somewhat smaller than those measured for NGC 1068, which, in combination with the plasma diagnostic ratios from the helium-like triplets, suggests that the material in the ionization cones of NGC 4151 may be somewhat denser than the material in the ionization cones of NGC 1068.

6 SYNOPSIS

We present a detailed analysis of the RGS spectrum of NGC 4151 from a total of \(\sim 125\) ks of XMM-Newton observations. The EPIC spectra from these observations are presented in Schurch et al. (2003). The analysis uses the high spectral resolution of the RGS instruments to characterize the nature and origin of the soft X-ray spectrum of NGC 4151.

- The soft X-ray spectrum of NGC 4151 (Figure 1) is completely dominated by line emission and radiative recombination continua. Line emission, including higher order (\(\beta\)-\(\varepsilon\)) resonance transitions, is clearly detected from hydrogen-like and helium-like ionization states of neon, oxygen, nitrogen and carbon. Much of the unidentified line emission below \(\sim 16\AA\) can be associated with a combination of iron L-shell emission and lines from hydrogen-like and helium-like silicon and magnesium.

- The RGS spectra show no significant continuum emission and no fluorescent line emission associated with neutral material.

- The measured line centroid energies are consistent with a blueshift of between \(\sim 100-1000\) km s\(^{-1}\), with respect to the systemic velocity of NGC 4151. The seven observed line widths that are constrained by the data tentatively suggest a bimodal distribution, with average line widths of \(\sim 1000\) km s\(^{-1}\) and \(\sim 200\) km s\(^{-1}\) (FWHM). The measured line blueshifts are generally consistent with the outflow velocities of the absorption lines observed in the UV spectrum of NGC 4151 (Kriss et al. 1995), implying that the UV and X-ray line features originate in the same material.

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