A PHOTOIONIZATION MODEL FOR THE SOFT X-RAY SPECTRUM OF NGC 4151

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ABSTRACT

We present an analysis of archival data from multiple XMM-Newton observations of the Seyfert 1 galaxy NGC 4151. Spectral data from the RGS instruments reveal several strong soft X-ray emission lines, chiefly from hydrogen-like and helium-like oxygen, nitrogen, neon, and carbon. Radiative recombination continua (RRC) from oxygen and carbon are also detected. Our analysis suggests that the emission data are consistent with photoionization. Using the Cloudy photoionization code, we found that, while a two-component, high column density model (10^23 cm^-2) with low covering factor proved adequate in reproducing all detected Lyman series lines, it proved insufficient in modeling the He-like triplets observed (neon, oxygen, and nitrogen). If resonance line data were ignored, the two-component model was sufficient to match flux from intercombination and forbidden lines. However, with the inclusion of resonance line data, He-like triplets could no longer be modeled with only two components. We found that observed oxygen G and R ratios in particular were anomalous in the parameter space investigated. We investigated, and were forced to dismiss, the possibility that a third, purely collisional component could be responsible for enhanced resonance line contributions. We succeeded in modeling the observed spectrum with the addition of a third, lower column density (10^20.5 cm^-2) component with nonzero microturbulence and high covering factor. While sufficient to reproduce observed soft X-ray flux, our model has certain shortcomings, particularly in a less-than-ideal visual fit to the line profile. Two of the three emission model components bear similarities to components determined by Kraemer et al. in their 2005 study of NGC 4151 absorption spectra.

Subject headings: galaxies: individual (NGC 4151) — galaxies: Seyfert — X-rays: individual (NGC 4151)

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1. INTRODUCTION

NGC 4151 is the nearest bright, if not prototypical, Seyfert type 1.5 galaxy (z = 0.003319,1 distance 14.20 Mpc, H_0 = 70 km s^-1 Mpc^-1), exhibiting both narrow- and broad-line emission in the optical and UV spectra, and has been well-studied over all wavelengths. Historical soft X-ray observations have indicated significant complex nuclear continuum absorption (Yaqoob et al. 1989; George et al. 1998), and models of X-ray absorbers subsequently predicted the presence of multiple emission lines in the spectrum below 1 keV (Netzer 1993, 1996). More recent X-ray observations indicate time-variable flux, and have further confirmed significant absorption of the nuclear continuum in the soft X-ray spectrum (Kraemer et al. 2005). In addition, contemporary kinematical models have postulated that the observational line of sight of NGC 4151 is oriented roughly halfway between the radio axis of the nuclear continuum source and the equatorial accretion disk (Crenshaw et al. 2000; Das et al. 2005). The availability of high-resolution instruments onboard the Chandra and XMM-Newton X-ray observatories have yielded new insights about previously unresolved soft X-ray emission lines.

The 0.4–1.2 keV soft X-ray spectrum of NGC 4151 is dominated by narrow-line emission and radiative recombination continua (RRC) from hydrogenic and He-like carbon, oxygen, neon, and nitrogen (Ogle et al. 2000; Schuch et al. 2004; Kraemer et al. 2005). While XMM-Newton Reflection Grating Spectrometer (RGS) instrumental resolution limitations place only an upper limit on emission-line widths (FWHM ~ 10^3 km s^-1), the spectrum itself is most likely created by reprocessing in the narrow emission line region (NLR). There is general agreement on the physical region of this emission, but the ionization mechanism itself continues to be a subject of debate. Photoionization and thermal collisional processes may both contribute to narrow-line emission, but the extent to which any one mechanism dominates in this spectrum is not agreed on (Ogle et al. 2000). Fortunately, diagnostics are now available which may provide detailed information about electron temperature and number density based on RRC width (Liedahl 1999) and the relative strengths of He-like triplets (Porquet & Dubau 2000; Porter & Ferland 2007), from which predictions can be made regarding the relative contributions of photoionization and collisional processes to emission spectra. Additional archival data available from Chandra and XMM-Newton have provided fertile new ground for analysis of the ionization processes in NGC 4151. Ogle et al. used Chandra data to conclude that a photoionization component must be present in NGC 4151 to account for observed narrow radiative recombination continuum (RRC) and high ratios of forbidden to resonance emission lines in He-like ions. Schurch et al., in their analysis of the XMM-Newton soft X-ray observations in 2000 on which this paper is based, found similar evidence to suggest photoionization as a contributor to emission.

Because of the relatively low electron temperatures deduced from RRC (~10^4–10^5 K), it is believed that collisional ionization plays at best a minor role in excitation and ionization in NGC 4151. Can we, however, account for the observed soft X-ray spectrum entirely from photoionization? To date, no self-consistent photoionization model has been proposed to re-create the observed NGC 4151 soft X-ray spectrum. Accordingly, we analyze archival XMM-Newton spectra from 2000 December, developing a model fit to the emission lines observed in the soft...
X-ray spectrum using the photoionization code Cloudy (Ferland et al. 1998).

2. OBSERVATION AND DATA PROCESSING

2.1. Observation Data

NGC 4151 was observed by the two XMM-Newton RGS instruments in High Event Rate mode in five separate observations over the 3 day period 2000 December 21–23. First-order spectral data were reprocessed using the rgsproc command in the XMM-Newton Science Analysis Software (SAS) package, version 6.1.0. The background-subtraction flag was disabled during reprocessing, essentially extracting source and background spectra, allowing subsequent XSPEC fits to handle background subtraction and error propagation. Possible flare contamination was filtered by limiting data to intervals with count rates lower than 0.2 s$^{-1}$. RGS2 data have a gap over the energy range 0.51–0.62 keV due to failure of CCD chip 4 within a week of launch; RGS1 data have a gap over the energy range 0.90–1.17 keV due to in-flight failure of CCD chip 7 in 2000 September.

We added data from the five observations to form a single spectral file for each instrument, using the SAS grppha command, and subsequently fit the data using XSPEC version 12.2.0. Since significant absorption of the source continuum precludes accurate modeling of the soft X-ray power law, any fitting of the underlying power law is essentially meaningless. In order to determine accurate relative emission flux, however, we have included a twice-broken power-law component to determine a baseline, with break points at 506 and 580 eV. In addition, we modeled Galactic absorption with a Wisconsin absorption component, $N_{\text{H}} = 2.1 \times 10^{20}$ cm$^{-2}$ (Morrison & McCammon 1983).

To model observed emission lines, we first ran a sliding Gaussian across the spectrum using the stepPHA command, and added ZGAUSS components for each line noted. To model radiative recombination continuum (RRC), we used the RSC model component. RGS2 data sets were constrained to those of RGS1, with an overall CONSTANT model component added to account for instrumental variations. The CONSTANT parameter model had a value of 0.96, with a 90% confidence interval from 0.94 to 0.97.

Employing $\chi^2$ statistics in our final fit, we regrouped each data set with a minimum of 20 counts per bin using the SAS grppha command. Our final fit showed a reduced $\chi^2$ value of 1.55 with 1236 degrees of freedom. Table 1 shows the resulting flux and widths for definitively resolved lines.

2.2. Instrumental Limitations

The RGS instruments onboard XMM-Newton each have a wavelength accuracy of ±8 mA (XMM-Newton Users Handbook, Issue 2.3) across their bandwidth, and wavelength-dependent FWHM resolution that varies from 600 km s$^{-1}$ at 0.3543 keV (35 Å) to 1700 km s$^{-1}$ at 1.2400 keV (10 Å) in first-order spectra. Since most observed emission-line widths fall below this minimum resolution range in a free fit, they have not been included in our data fit. Attempts to “group-fit” lines assumed a priori to have similar widths (e.g., He-like resonance lines) provided no additional information.

We also note the presence of an instrumental “bump” in the RGS instrument background spectrum around a wavelength of 0.3875 keV (32 Å) (XMM-Newton Users Handbook). The origin of this phenomenon is not yet fully understood, but it would certainly cast doubt on definitive flux calculations for emission lines and RRC in that region, namely those of C v RRC (0.3908 keV) and C vi Ly$\alpha$ (0.3676 keV). For this reason, although flux is clearly detected for C v RRC and C vi Ly$\alpha$, they will not be included in our data modeling. The instrumental bump also makes definitive fitting of the power-law components especially difficult.

3. OBSERVED EMISSION

3.1. Emission-Line Blueshift

Previous Chandra observational data models (Ogle et al. 2000) and other models of the XMM-Newton data set we examine here (Schurch et al. 2004) note a mean blueshift in the X-ray emission spectrum, consistent with the predictions of Crenshaw et al. (2000) that suggest a biconical outflow model of the NLR, with asymmetrical physical orientation to the observer. Using archival Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS) spectra, Das et al. (2005) subsequently constructed a kinematic model for NGC 4151 showing a biconical orientation that would favor measurements of bulk blueshift in emission.

### Table 1

| Emission Line ID | Redshift-Corrected Energy$^a$ (keV) | Rest Energy (keV) | Photon Flux$^a$ $(10^{-3}$ s$^{-1}$ cm$^{-2}$)$^3$ | $\sigma^a$ (km s$^{-1}$)$^1$ |
|------------------|-----------------------------|-----------------|-------------------------------|-----------------|
| N vi (f)         | 0.4202 $^{21}$ 4201       | 0.4199          | 10.674$^{23}$ 4389            | 182$^{25}$      |
| N vi (i)         | 0.4266 $^{22}$ 4265       | 0.4264          | 1.390$^{23}$ 4505             | 1.151           |
| N vi (r)         | 0.4310 $^{23}$ 4311       | 0.4307          | 5.547$^{23}$ 4249             | 2.506$^{23}$    |
| C vi (f)         | 0.4360 $^{24}$ 4361       | 0.4356          | 2.506$^{23}$ 4253             | 1.151           |
| N vi (c)         | 0.5008 $^{25}$ 5007       | 0.5004          | 8.506$^{23}$ 4339             | 1.151           |
| O vi (f)         | 0.5685 $^{26}$ 5689       | 0.5687          | 4.947$^{23}$ 4129             | 2.506$^{23}$    |
| O vi (b)         | 0.5691 $^{27}$ 5692       | 0.5692          | 4.947$^{23}$ 4129             | 2.506$^{23}$    |
| O vi (c)         | 0.5745 $^{28}$ 5742       | 0.5740          | 14.250$^{23}$ 4011            | 1.151           |
| N v (f)          | 0.5978 $^{29}$ 5954       | 0.5980          | 14.250$^{23}$ 4011            | 1.151           |
| O viii (c)       | 0.6541 $^{30}$ 6542       | 0.6537          | 15.900$^{23}$ 4395            | 172$^{23}$      |
| O vi (b)         | 0.7149 $^{31}$ 7146       | 0.7147          | 2.837$^{23}$ 3701             | 403$^{23}$      |
| Ne ix (f)        | 0.9064 $^{32}$ 9058       | 0.9052          | 5.616$^{23}$ 2022             | 2.506$^{23}$    |
| Ne ix (l)        | 0.9172 $^{33}$ 9165       | 0.9151          | 2.314$^{23}$ 2363             | 2.506$^{23}$    |
| Ne ix (r)        | 0.9229 $^{34}$ 9229       | 0.9221          | 2.552$^{23}$ 2363             | 2.506$^{23}$    |
| Ne x (c)         | 1.0224 $^{35}$ 1012       | 1.0219          | 2.845$^{23}$ 3319             | 2.506$^{23}$    |

* Values followed by 90% confidence intervals.

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4 See http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/.
lines in the NLR, due to far-side shielding by the host galaxy. Our analysis of strong emission lines agrees with an overall blueshift in the main value at around 200–300 km s⁻¹ (Table 2), although large 90% confidence intervals prevent more detailed conclusions.

3.2. Radiative Recombination Continua (RRC)

In observing the emitting gas surrounding an active nucleus, electron temperature can be inferred by analysis of radiative recombination continua (RRC) width (ΔE) relative to edge energy (E) (for details, see Liedahl & Paerels 1996; Liedahl 1999). Electron temperature determined from the ratio of RRC width to edge energy can indicate either a photoionization or collisional environment. For a given ionization state, electron temperature is expected to be much higher than that for photoionization. If the ratio ΔE/E ≪ 1, the primary mechanism for ionization is expected to be the incident radiation field (i.e., photoionization).

Several He-like and hydrogenic RRC were conclusively detected (Table 3). Approximating temperature width in eV to k_B T (Liedahl 1999; where k_B is the Boltzmann constant), we calculate temperatures ≥ a few ×10^4 K, noting the relatively higher temperature values for the hydrogenic C vi, O viii, and Ne x ions, ranging from 2 to 3 times the temperature of the detected He-like ions. Since the temperature of each of the RRCs is a few eV, and the edge energies are several hundred eV, the ratio of width to edge energy for each RRC is much less than unity, providing strong evidence against collisional ionization.

3.3. He-Like Triples

Relative emission strength ratios of the He-like 1s2p 1P₁ → 1s2 1S₀ (resonance), 1s2p 3P₂ → 1s2 1S₀, 1s2p 3P₁ → 1s2 1S₀ (intercombination, often blended), and 1s2s 3S₁ → 1s2 1S₀ (forbidden) transitions (indicated as r, i, and f, respectively) can indicate either a photoionization, collisional, or hybrid environment (Porquet & Dubau 2000; Bautista & Kallman 2000; Kahn et al. 2002). The resonance line arises from a purely electric dipole transition, and increases with energy above ionization threshold. Conversely, the 1s2p 3P₁ → 1s2 1S₀ intercombination transition and forbidden line transition are both electric dipole forbidden. Since excitation collision strength is dominated by electron impact, the ratio of the sum of intercombination and forbidden intensities to resonance line intensity is inversely proportional to electron temperature. In purely photoionized plasma, resonance line intensity is relatively weak compared to the sum of the forbidden and intercombination line intensities. Electron temperature increases as the plasma first becomes a hybrid of photoionization and collisional processes, and then is finally dominated by collision. As collisional de-excitation rates increase, a decrease in radiative de-excitation occurs, first in the forbidden, and then in the intercombination line, leading to a reduction in the (f + i)/r ratio.

For diagnostics of He-like emission line triplets (f, i, r), the following are defined, where z represents the forbidden line flux (f), x + y the blended intercombination lines (i), and w the resonance line (r):

\[ R = z/(x + y) = f/i, \]
\[ G = (x + y + z)/w = (f + i)/r. \]

Three triplets were detected and modeled in XSPEC (Table 4).

### Table 4

| Triplet | f(z) | i(x+y) | r(w) | G(f+i)/r | R(f/i) |
|--------|------|--------|------|----------|--------|
| O vi    | 0.95 | 0.141  | 0.523| 3.70     | 2.74   |
| Ne vi   | 0.96 | 0.098  | 0.236| 6.01     | 4.40   |
| Ne vi   | 0.98 | 0.087  | 0.170| 4.98     | 3.71   |
| Ne iv   | 0.99 | 0.080  | 0.164| 4.73     | 2.93   |
| Ne ix   | 0.99 | 0.079  | 0.161| 4.73     | 2.93   |
| Ne x    | 0.97 | 0.076  | 0.141| 6.16     | 4.16   |

Notes.—Values are followed by 90% confidence intervals; units for f, i, and r are (10⁻¹⁴ ergs s⁻¹ cm⁻²).

### Table 3

| Ion      | Temperature (eV) | Temperature (10⁴ K) |
|----------|------------------|---------------------|
| C vi     | 5.5 ± 0.2        | 6.1 ± 0.0           |
| N vi     | 0.4 ± 0.1        | 0.5 ± 0.2           |
| O vii    | 2.6 ± 0.1        | 3.1 ± 0.6           |
| O viii   | 9.9 ± 0.3        | 11.5 ± 4.3          |
| Ne vii   | 4.8 ± 0.4        | 5.6 ± 2.0           |
| Ne x     | 9.2 ± 0.7        | 10.7 ± 7.1          |

* Values followed by 90% confidence intervals.
abundances, relative to H by number, are as follows. He: $-1.00$; C: $-3.47$; N: $-3.92$; O: $-3.17$; Ne: $-3.96$; Na: $-5.69$; Mg: $-4.48$; Al: $-5.53$; Si: $-4.51$; S: $-4.82$; Ar: $-5.40$; Ca: $-5.64$; Fe: $-4.40$; and Ni: $-5.75$. Varied parameters include the ionization parameter ($U$), which corresponds to the dimensionless ratio of hydrogen-ionizing photon to total hydrogen densities; hydrogen column density ($N_{\text{H}}$, in $\text{cm}^{-2}$); hydrogen number density ($n_{\text{H}}$, in $\text{cm}^{-3}$); microturbulent velocity, in $\text{km s}^{-1}$; and a dimensionless geometric covering factor ($C$). The ionization parameter is related to flux, hydrogen number density, and radius to the model slab’s inner face by the formula

$$U = \frac{Q}{4\pi r^2 c n_{\text{H}}}.$$  

where $Q$ represents number of hydrogen-ionizing photons emitted per second by a central source of luminosity $L_{\nu}$.

$$Q = \int_{13.6 \text{eV}}^{\infty} \left( \frac{L_{\nu}}{h\nu} \right) dv.$$  

In constructing a photoionization model to reproduce observed emission data, we immediately observed that a single model proved insufficient to recreate the He-like and hydrogenic neon, oxygen, and nitrogen emission observed. One model was adequate to reproduce lines with relatively low ionization potentials, most notably the strong O vii and Ne vi forbidden lines (0.5611 and 0.4199 keV, respectively). However, this model proved insufficient in recreating higher ionization potential emission lines, including the O viii and Ne x Ly$\alpha$ lines (0.6537 and 1.0219 keV, respectively). Relative ionic abundances are highly sensitive to the ionization parameter; a comparatively low ionization parameter of unity, for instance, favors He-like states of the observed elements. As the ionization parameter is increased to 10, completely ionized states dominate, followed by hydrogenic and He-like states. If relative ionic abundances favor He-like emission, hydrogenic emission is negligible, and vice versa, and yet, significant lines were noted for both states. Therefore, two components were required, one with a comparatively lower ionization parameter (“Medium”), favoring He-like ionic states, and a second, with a sufficiently higher ionization parameter (“High”), in which hydrogenic ionic states dominate.

Assuming isotropic emission, we were able to directly compare predicted luminosity at the source with observed luminosity. By integrating predicted Cloudy model energy flux over $4\pi$ sr at the calculated inner slab face radius, we were constrained to a global geometric covering factor ($C$) between zero and unity, required to produce the observed emission luminosity. We note that, if the biconical structure physically modeled by Das et al. (2005) and Crenshaw et al. (2000) is accurate (see § 3.1), with a near ionization cone inclined toward the observer, and a far ionization cone located behind the host galaxy, screening may reduce the observed emission line flux by as much as one-half.

Since XSPEC fits of the soft X-ray power law often prove unreliable due to significant continuum absorption (§ 2.2), we have adopted the broken power law for spectral energy distribution (SED) of the form $L_{\nu} \propto \nu^{\alpha}$ proposed by Kraemer et al. (2005) as follows: $\alpha = -1.0$ for energies $<13.6$ eV, $\alpha = -1.3$ over the range $13.6$ eV $< h\nu < 0.5$ keV, and $\alpha = -0.5$ above 0.5 keV. With normalization, the broken power law described equates to a $Q$ value of $1.1 \times 10^{53}$ s$^{-1}$.

Modeling the total luminosity observed required a significant column density in order to ensure a source covering factor of less than unity. To determine the minimum required hydrogen column density, we selected the strong O vii forbidden line (0.5611 keV) as our luminosity benchmark. We found that, given the observed luminosity in this line, a minimum column density value of $10^{21} \text{cm}^{-2}$ in our grid was required in order for the source covering factor to remain at or below unity, independent of other model parameters. In order to adequately represent the observed spectrum of neon, oxygen, and nitrogen, we found $10^{23} \text{cm}^{-2}$ to be an optimal column density for our two-component model.

We then examined possible parameter combinations that would faithfully recreate the observed He-like $G$ and $R$ ratios. We were able to model the observed Ne ix and N vii $G$ and $R$ ratios within a wide range of parameter space investigated; however, the O vii $G$ and $R$ ratio values presented particular difficulties. The extremely high O vii $R$ ratio occupies only a small portion of investigated parameter space, and could only be modeled with a column density of $10^{22} \text{cm}^{-2}$ or higher. However, such a high O vii $R$ ratio created high $G$ ratios for all three triplets, corresponding to low resonance line luminosity. We expected similar fitting difficulty for the neon and nitrogen triplets, since the O vii ionization potential lies between that of N vii and Ne ix; however, this was not the case. We hypothesized that the particular case of extremely high O vii $R$ ratios was due to the fact that its assumed elemental abundance is roughly 5 times that of the other two noted elements. Accordingly, we ran test models over column densities from $10^{21.5}$ to $10^{23.5} \text{cm}^{-2}$, matching oxygen elemental abundance to that of nitrogen. We found that the O vii $R$ ratio behavior matched that of neon and nitrogen with roughly equal elemental abundances.

Porter & Ferland (2007) show that elevated $R$ ratios in O vii can result from high column densities. Porter & Ferland demonstrate that, in such an environment, the optical depth of the intercombination line increases, effectively increasing the $R$ ratio. They also show that low O vii $G$ ratios can be achieved at low column densities through enhancement of the resonance line by continuum pumping. However, we found that the required low column density for such resonance line enhancement was insufficient to produce the observed resonance emission line flux. We were therefore forced to look elsewhere for a mechanism to boost resonance emission at high column densities. Figure 1 shows Ne ix, N vii, and O vii $R$ ratios produced by Cloudy, with our assumed underlying continuum as a function of column density and ionization parameter for microturbulence values of 0 and 200 km s$^{-1}$.

Since our composite two-component model underpredicted resonances for all three species detected, we were led to incorporate a third component that would enhance resonance emission relative to other emission features. Ogle et al. (2000) proposed that a hybrid collisional/photoionization environment may be responsible for the observed X-ray emission in NGC 4151. To pursue this scenario, we considered the possibility that enhanced resonance line emission could be created from a purely collisional component. To recreate purely collisional model emission, we constructed a non-photoionization component at a temperature sufficient to favor the He-like oxygen state (the potential required to ionize oxygen from O vii to O vii is $38$ eV, or $1.58 \times 10^8$ K). We created a collisional component fixed at this temperature at column densities of $10^{20} - 10^{21} \text{cm}^{-2}$ and a number density of $10^9 \text{cm}^{-3}$. We subsequently found that the fit to observed emission was poor; Ne ix resonance line emission was grossly underpredicted, as were all three Ly$\beta$ lines observed. Furthermore, temperatures inferred from radiative recombination continua are well below those required for this component (Table 3). We were ultimately forced to abandon a hybrid model as a viable predictor of observed RRC and line emission.
While forbidden and intercombination emission lines in observed He-like triplets remain relatively insensitive to microturbulence up to tested limits, resonance lines are highly sensitive to this parameter. In their analysis of Chandra observations of Markarian 3, Sako et al. (2000) suggested that the relative strength of resonance lines in He-like triplets could be increased by photoexcitation by the AGN continuum. Although temperature-dependent strengthening of these lines is a contributing factor, microturbulence may add additional intensification of resonance lines in a plasma in photoionization equilibrium (PIE). We varied the Cloudy TURBULENCE parameter to create a third model component ("Low") that would successfully enhance resonance line emission, correspondingly depressing Gratios to acceptable values. Figure 2 shows Ne ix, N vi, and O vii R ratios produced by Cloudy with our assumed underlying continuum as a function of column density ($N_H$) and ionization parameter ($U$) for microturbulence values of 0 and 200 km s$^{-1}$.

**Fig. 1.** Cloudy R ratio contour plots for the Ne ix, N vi, and O vii He-like triplet R ratios as a function of column density ($N_H$) and ionization parameter ($U$) for microturbulence values of 0 and 200 km s$^{-1}$.
However, since this model component contributes significantly to O vii He-triplet resonance line luminosity, we would expect that, for microturbulence values at or above roughly 200 km s$^{-1}$, noticeable spreading in the line’s Gaussian tails would begin to be apparent. We noticed no such phenomenon in the observed resonance lines, and we have limited microturbulence values in the Low component to 200 km s$^{-1}$. Figure 3 shows XSPEC model fits to the O vii 0.5740 keV He-like triplet resonance line for single-Gaussian free fit, and for two-Gaussian composites with a narrow component and wide component fixed at microturbulent velocities of 200 and 400 km s$^{-1}$. The peak is underpredicted in all models tested, including the single-Gaussian free fit, and any increase in line width from microturbulence exacerbates this phenomenon. We also found that the addition of microturbulence in the “High” component provides a better fit to the high-ionization potential Lyman series lines.

The issue of the O vii resonance line visual fit presents the single most significant challenge to our model. Ideally, flux ratios are best fit with a high microturbulence component, since the O vii $R$ ratio becomes underpredicted by lower microturbulence values due to overprediction of the intercombination line. However, it is evident from the visual Gaussian fit that even a 200 km s$^{-1}$
component diverges from the ideal. Whether due to a non-photoionization component, or perhaps an ill-defined line-spread profile at this wavelength, the data quality prevents more detailed conclusions at this time.

Within the parameter space of our grid, we found hydrogen number density to be an unconstrained parameter as long as it remained below critical density values for each of the species of interest (approximately $10^9 - 10^{10}$ cm$^{-3}$; for details, see Porquet & Dubau 2000; Porter & Ferland 2007). However, once hydrogen column density is constrained, number density becomes limited by the requirement that the model slab thickness ($\Delta R = N_H/n_H$) divided by the radius to the cloud face be less than unity (the "thin shell" model requirement assuming plane-parallel geometry; see Kraemer et al. 2005). In addition, the He-like triplet $R$ ratios are highly sensitive to hydrogen number density. (For further theoretical details, see Porter & Ferland 2007).

Within the individual constraints of each model component, we optimized the combined multicomponent model to provide the best fit to observed spectra. Results are found in Table 5. Figure 4 shows the contributions of each of the model components to total predicted luminosity for each emission line of interest. Table 6 shows a comparison of predicted composite model luminosity to observed luminosities for the emission lines of interest. We have also included ratios of pertinent model to observed luminosities for the emission lines of interest.

4.2. Model Electron Temperatures, Radii, and Gas Pressures

The three-component Cloudy composite model predicts electron temperatures of $5.2 \times 10^5$ K (Low), $6.0 \times 10^5$ K (Medium), and $1.1 \times 10^6$ K (High). These values are well within the range consistent with photoionization, and generally agree with measured temperatures from RRC widths found in Table 3.

Calculated inner slab face radius is a function of the total number of hydrogen-ionizing photons emitted by the central object ($Q$, in s$^{-1}$), ionization parameter ($U$), and total hydrogen density ($n_H$, in cm$^{-3}$) (cf. § 4.1). Assuming a $Q$ value of $1.1 \times 10^{53}$ s$^{-1}$, the three model constituents lead to calculated inner slab face radii of $R_{\text{Low}} = 9.6 \times 10^{17}$ cm (0.31 pc), $R_{\text{Med}} = 1.7 \times 10^{17}$ cm (5.5 $\times 10^{-2}$ pc), and $R_{\text{High}} = 1.2 \times 10^{16}$ cm (3.9 $\times 10^{-3}$ pc).

The physical thickness of the modeled slab ($\Delta R$) can be determined by the ratio of total hydrogen column density ($N_H$, in cm$^{-2}$) to total hydrogen number density ($n_H$, in cm$^{-3}$). From Cloudy ideal model parameters, we calculate slab thicknesses for the three components of $\Delta R_{\text{Low}} = 3.2 \times 10^{14}$ cm ($1.0 \times 10^{-4}$ pc), $\Delta R_{\text{Med}} = 1.0 \times 10^{16}$ cm ($3.2 \times 10^{-3}$ pc), and $\Delta R_{\text{High}} = 1.0 \times 10^{15}$ cm ($3.2 \times 10^{-4}$ pc). The respective ratios of physical slab thickness to radial distance to inner slab face are thus $3.3 \times 10^{-4}$ (Low), $5.9 \times 10^{-2}$ (Medium), and $8.3 \times 10^{-2}$ (High).

Since the ratio of physical slab thickness to radial distance to inner slab face is ultimately inversely proportional to the square root of $n_H$, we can establish lower limits on $n_H$ by setting this

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**TABLE 5**

| Model     | $\log U$ | $\log N_H$ | $\log n_H$ | Microturbulence | $C_f$ |
|-----------|----------|------------|------------|-----------------|------|
| Low       | $-0.5$   | 20.5       | 6          | 200             | 0.700|
| Medium    | 0.0      | 23.0       | 7          | 0               | 0.035|
| High      | 1.3      | 23.0       | 8          | 200             | 0.110|

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[See the electronic edition of the Journal for a color version of this figure.]
radial ratio to unity, keeping all other parameters fixed. This requires a minimum log \( n_{HI} \) value in the Low component of \(-0.965\), a minimum Medium component log \( n_{HI} \) value of 4.53, and a minimum High component log \( n_{HI} \) value of 5.83. Keeping all other model parameters constant, these values predict maximum radii to inner slab faces of \( R_{Low} = 2.9 \times 10^{21} \) cm (940 pc), \( R_{Med} = 2.9 \times 10^{18} \) cm (0.94 pc), and \( R_{High} = 1.5 \times 10^{17} \) cm (0.049 pc), with corresponding maximum slab thicknesses.

Our model predicts gas pressures of \( 1.7 \times 10^{-5} \) dynes cm\(^{-2}\) (Low), \( 4.7 \times 10^{-7} \) dynes cm\(^{-2}\) (Medium), and \( 3.3 \times 10^{-6} \) dynes cm\(^{-2}\) (High). This implies that the Low and Medium model components may be collocated, and are in pressure equilibrium.

4.3. Predicted UV Emission

Table 7 shows Cloudy predicted UV luminosities compared against Hopkins Ultraviolet Telescope (HUT) observations on 1990 December 8 (Kriss et al. 1992). With the exception of the N\(\;v\) 1240 Å line, our X-ray photoionization model components are not a significant contributor to UV emission. We note that large error bars in the HUT observed N\(\;v\) line may still be consistent with this scenario.

The blended O\(\;v\) 1032/1038 Å line luminosity predicted by our model represents roughly 15% of that observed by Kriss et al. (1992) However, the observed emission includes significant flux from the broad emission line region (BLR). For a more rigorous examination, we compared the predicted model luminosity to \textit{FUSE} observation data, in which a low state broad-line-subtracted
O \textit{vii} 1032/1038 Å flux of $2 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ was calculated, corresponding to a luminosity of $4.83 \times 10^{40}$ ergs s$^{-1}$ (D. M. Crenshaw 2006, private communication). Our model-predicted luminosity represents over 150% of the observed broad-line-subtracted value. Even accounting for a possible observational deficit of a factor of 2 due to far-side galaxy emission (cf. § 4.1), we would be forced to conclude that our Low and Middle model component regions, which produce nearly all modeled emission for this line blend, are primarily responsible for the vast majority of all observed O \textit{vii} 1032 and 1038 Å emission.

Interestingly, similarities can be seen between our emission model components and the X-ray absorption components determined by Kraemer et al. (2005) in their analysis of simultaneous UV and X-ray spectra from NGC 4151. They note an “X-High” component ($\log U = 1.05, \log N_{\text{II}} = 22.5$) and a “D+Ea” component ($\log U = -0.27, \log N_{\text{II}} = 22.46$) as chiefly responsible for X-ray absorption. These components are generally correlated to our Medium and High components, which have similar column densities, and a lower and higher ionization parameter, respectively.

5. CONCLUSIONS

Using the Cloudy photoionization code, we were able to successfully reproduce the soft X-ray spectrum of NGC 4151. Three components, with disparate ionization parameters, were required to model the entire data set. Two components (labeled “Medium” and “High”) were sufficient to produce hydrogenic neon, oxygen, and nitrogen emission, as well as forbidden and intercombination spectra from He-like triplets of these three elements. However, resonance lines were underpredicted with these two components; in particular, the O \textit{vii} He-like triplet exhibited anomalous G and R ratios that proved difficult to re-create in model parameter space. We attribute this phenomenon to the large oxygen elemental abundance relative to neon and nitrogen. The data required a large column depth component to account for observed triplet spectra. To adequately model G and R ratios for the observed elements, a third model component (labeled “Low”) was required.

Although electron temperatures deduced from RRC widths of $10^5$–$10^6$ K were insufficient to suggest a collisional component, we attempted to account for the resonance line excess with a fixed temperature, non-photoionization component of a few $\times 10^6$ K, which would favor the O \textit{vii} ionization state. We found that even this artificially conceived model was a poor fit to observed resonance line spectra. Subsequently, we produced a superior fit to resonance line flux by introducing a third photoionization component that included microturbulence. Specifically, we found satisfactory fits to all significantly detected He-like triplets and Lyman series lines by a composite three-component model (see Table 5). Although we were able to model emission line flux with the composite model, we note a less than ideal visual fit to the O \textit{vii} resonance line profile (the strongest triplet resonance line observed). The model Gaussian profile is less peaked than the observed line, with somewhat broader wings. Whether the poor fit is due to a non-photoionization component, a poorly defined instrumental line-spread function, or some other cause, is undetermined at this time. We hope to examine the issue more closely with future XMM-Newton and Chandra observation data.

Hydrogen number density was unconstrained up to critical values of approximately $10^9$–$10^{10}$ cm$^{-3}$; however, the “thin spherical shell” plane-parallel model geometry assumption placed additional constraints on this parameter, subject to optimized ionization parameter and hydrogen column density values. Since both radial distance to the inner slab face and slab thickness are related to the aforementioned parameters, we were able to deduce these values from our optimized values. The optimized radial distance to the Low component inner slab face is $9.6 \times 10^{17}$ cm (0.31 pc), with slab thickness of $3.2 \times 10^{14}$ cm (1.0 $\times 10^{-4}$ pc). The optimized radial distance to the Medium component inner slab face is $1.7 \times 10^{17}$ cm ($5.5 \times 10^{-2}$ pc), with a slab thickness of $1.0 \times 10^{16}$ cm ($3.2 \times 10^{-3}$ pc). The optimized radial distance to the High component inner slab face is $1.2 \times 10^{16}$ cm ($3.9 \times 10^{-3}$ pc), with a slab thickness of $1.0 \times 10^{15}$ cm ($3.2 \times 10^{-4}$ pc). Since the hydrogen number density is a relatively unconstrained parameter, we were able to determine maximum radius values by setting the ratio of slab thickness to distance to inner slab face to its maximum value of unity. With this assumption, the maximum radial distance to the Low component inner slab face and corresponding slab thickness is $2.9 \times 10^{21}$ cm (940 pc); the maximum radial distance to the Medium component inner slab face is $2.9 \times 10^{18}$ cm (0.94 pc); the maximum radial distance to the High component inner slab face is $1.5 \times 10^{17}$ cm (0.049 pc). Assuming that the BLR extends to roughly 4 light days (0.003 pc; Clavel 1991), our radial predictions place all model components outside the BLR. We would thus expect little or no short time period variability in this emission profile.

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Table 7

| Line       | Cloudy Predicted Luminosity | 1990 HUT Observed Luminosity |
|------------|----------------------------|------------------------------|
| He ii (1058 Å) | 6.3                        | 4117                         |
| O vi (1032/1038 Å) | 738                        | 4900                       |
| N v (1240 Å)     | 39                         | 7.22                        |
| N iv (1487 Å)     | 5.4                        | 170                       |
| C iv (1549 Å)     | 90                         | 510                        |
| He ii (1641 Å)    | 10                         | 430                        |

a Values followed by 90% confidence intervals.
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